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Towards Sustainable Pavement Systems:
A Reference Document

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16. Abstract

All stakeholders in the pavement community—from owner/agencies to designers, and from material suppliers to contractors and consultants—are embracing the need to adopt more sustainable practices in all aspects of their work, and are continually seeking the latest technical information and guidance available to help improve those practices. This reference document has been prepared to provide guidance to the pavement community on sustainability considerations in pavement systems, drawing from and synthesizing the large and diverse body of knowledge that exists on pavement sustainability. As such, it provides the currently available knowledge and information for designing, constructing, and maintaining pavement structures more sustainably, and has been structured so that it can adapt to new findings and new information as sustainability considerations continue to develop and evolve. Key information is presented on pavement sustainability concepts, sustainable materials for paving applications, design of sustainable pavements, sustainable pavement construction practices, use phase considerations, sustainable maintenance and preservation practices, sustainable end-of-life considerations, pavement sustainability and livable communities, and assessment of pavement sustainability.

It is important to recognize that there is no universal definition of a "sustainable" pavement. Sustainability is very much context sensitive in that each project is unique, with specific needs depending on the location, climate, available materials, facility type, and required level of service, as well as on the overall goals of the organization. In essence, sustainability is very much a system characteristic, and pavements represent but one small part of the transportation infrastructure system; consequently, any improvements to the sustainability characteristics of pavement systems cannot be done in isolation from the transportation infrastructure system or from other systems with which pavements interact.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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ACRONYMS

AADT	Average Annual Daily Traffic
AAR	Alkali-Aggregate Reactivity
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACAA	American Coal Ash Association
ACBFS	Air-Cooled Blast Furnace Slag
ACEC	American Council of Engineering Companies
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ACR	Alkali-Carbonate Reactivity
AEAs	Air-Entraining Admixtures
AEP	Association of Environmental Professionals
AI	Asphalt Institute
AISC	American Institute of Steel Construction
APT	Accelerated Pavement Testing
APWA	American Public Works Association
ARRA	Asphalt Recycling and Reclaiming Association
ASR	Alkali-Silica Reactivity
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
ATB	Asphalt Stabilized Bases
BCA	Benefit-Cost Analysis
BMP	Best Management Practice
BTS	Bureau of Transportation Statistics
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
CAC	Cement Association of Canada
Caltrans	California Department of Transportation
$CaCO_3$	Calcium Carbonate/Limestone
CaO	Lime
CARB	California Air Resources Board
CCPR	Cold Central Plant Recycling
CDG	Conventional Diamond Grinding
CEQ	Council on Environmental Quality
CEQA	California Environmental Quality Act
CGS	California Geological Society
CH4	Methane
CI	Compression Ignition
CIR	Cold In-place Recycling
CKD	Cement-Kiln Dust
CKRC	Cement Kiln Recycling Coalition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CP Road Map	Long-Term Plan for Concrete Pavement Research and Technology
CPB	Controlled Pass By
CPR	Concrete Pavement Restoration

CPX	Close Proximity
CRCP	Continually Reinforced Concrete Pavements
CRM	Crumb Rubber Modifier
CSD	Context-Sensitive Design
C-S-H	Calcium Silicate Hydrate
CTB	Cement Treated Base
CTE	Coefficient of Thermal Expansion and Contraction
dB	Decibels
dBA	Adjusted Decibels
DBB	Design-Bid-Build
DB	Design-Build
DBM	Design-Build-Maintain
DLM	Dynamic Lane Merge
DOT	Department of Transportation
EAPA	European Asphalt Pavement Association
EDC	Every Day Counts
EIO	Economic Input-Output
EIR	Environmental Impact Review
EO	Executive Order
EOL	End-of-Life
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
ESAL	Equivalent Single-Axle Load
EUAC	Equivalent Uniform Annual Cost
FDR	Full-Depth Reclamation
FDR-FA	Full-Depth Reclamation using Foamed Asphalt
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GDP	Gross Domestic Product
GGBFS	Ground Granulated Blast Furnace Slag
GHG	Greenhouse Gas
GPR	Ground Penetrating Radar
GreenLITES	Green Leadership in Transportation and Environmental Sustainability
GSI	Gomaco Smoothness Indicator
GSSI	Geophysical Survey Systems, Inc.
GWP	Global Warming Potential
H_3PO_4	Orthophosphoric Acid
HC	Hydrocarbons
HCC	Hydraulic Cement Concrete
HFCs	Hydrofluorocarbons
HIPERPAV	HIgh PERformance Concrete PAVing
HIR	Hot In-place Recycling
HMA	Hot-Mix Asphalt
HOV	High-Occupancy Vehicle
HRWRA	High-Range Water-Reducing Admixtures
HSIP	Highway Safety Improvement Program
IC	Intelligent compaction
ICPI	Interlocking Concrete Pavement Institute
IEA	International Energy Agency

INVEST	Infrastructure Voluntary Evaluation Sustainability Tool
IPCC	Intergovernmental Panel on Climate Change
IRI	International Roughness Index
IRT	Infrared Thermography
ISI	Institute for Sustainable Infrastructure
ISO	International Organization for Standardization
ITS	Intelligent Transportation Systems
JPCP	Jointed Plain Concrete Pavement
JRCP	Jointed Reinforced Concrete Pavement
KDOT	Kansas Department of Transportation
LAB	Los Angeles Abrasion
LCA	Life Cycle Assessment
LCB	Lean Concrete Base
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LED	Light-Emitting Diode
LEED®	Leadership in Energy and Environmental Design
LFATB	Lime and Fly Ash Binder
LNG	Liquefied Natural Gas
LWA	Light Weight Aggregate
MAP-21	Moving Ahead for Progress in the 21st Century Act
MDPDG	AASHTO DARWin-ME™ Mechanistic-Empirical Design Guide
ME	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MGGRA	Midwest Greenhouse Gas Reduction Accord
MoDOT	Missouri Department of Transportation
MOVES	Motor Vehicle Emission Simulator
MPD	Mean Profile Depth
MPO	Metropolitan Planning Organizations
MRD	Material-Related Distress
MRWRA	Mid-Range Water Reducing Admixture
MTD	Mean Texture Depth
MTV	Material Transfer Vehicle
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCPTC	National Concrete Pavement Technology Center
NDT	Nondestructive Testing
NEPA	National Environmental Policy Act
NGCS	Next Generation Concrete Surface
NHPP	National Highway Performance Program
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
NLA	National Lime Association
NMAS	Nominal Maximum Aggregate Size
NMHC	Non-Methane Hydrocarbons
NO_x	Nitrogen Oxides

NPC	Net Present Cost
NPS	National Park Service
NPV	Net Present Value
NRCS	Natural Resources Conservation Service
NRMCA	National Ready-Mix Concrete Association
NYSDOT	New York State Department of Transportation
OBSI	On-Board Sound Intensity
OGFC	Open-Graded Friction Course
PAPA	Pennsylvania Asphalt Pavement Association
PCA	Portland Cement Association
PCC	Portland Cement Concrete
PCR	Pavement Condition Rating
PDC	Positive Dust Control
PE-2	Project Emissions Estimator
PFCs	Perfluorocarbons
PG	Performance Grade
PI	Profile Index
PLC	Portland Limestone Cement
PM	Particulate Matter
PM_{10}	Fugitive Particulate Matter/Fugitive Dust
PMA	Polymer-Modified Asphalt
PMS	Pavement Management Systems
PPA	Polyphosphoric Acid
PPCPS	Precast Pre-Stressed Concrete Pavement Systems
PWL	Percent within Limits
QA	Quality Assurance
QC	Quality Control
QPPP	Quiet Pavement Pilot Program
QPR	Quieter Pavement Research
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles
RCA	Recycled Concrete Aggregate
RCC	Roller Compacted Concrete
RCC	Roller-Compacted Concrete
RCWM	Recycled, Co-product, or Waste Material
RGGI	Regional Greenhouse Gas Initiative
ROW	Right of Way
RTP	Real-Time Profiler
SAEFL	Swiss Agency for the Environment, Forests and Landscape
SCA	Slag Cement Association
SCM	Supplementary Cementitious Material
SEAM	Sulfur Extended Asphalt Modifier
SETAC	Society of Environmental Toxicology and Chemistry
SF6	Sulfur Hexafluoride
SFS	Steel Furnace Slag
SHAs	State Highway Agencies
SHRP	Strategic Highway Research Program
SIT	State Inventory Tool
SLWA	Saturated Lightweight Aggregate

SMA	Stone Mastic Asphalt
SO_x	Sulfur Oxides
SPB	Statistical Pass By Method
SPL	Sound Pressure Levels
SRI	Surface Reflectivity Index
SRTT	Standard Reference Test Tire
TCP	Thin Concrete Pavement
TEA-21	Transportation Equity Act for the 21st Century
TiO_2	Titanium Dioxide
TNM	Traffic Noise Model
TRB	Transportation Research Board
TWh	Terawatt Hours
UCPRC	University of California Pavement Research Center
UHI	Urban Heat Island
UHPC	Ultra-High-Performance Concrete
ULSD	Ultra Low Sulfur Diesel
UNFCCC	United Nations Framework Convention on Climate Change
US DOE	U.S. Department of Energy
USGBC	U.S. Green Building Council
USGS	U.S. Geological Survey
UTW	Ultra-Thin Whitetopping
VMT	Vehicle-Miles Traveled
VOC	Volatile Organic Carbon
WCED	World Commission on Environment and Development
WCI	Western Climate Initiative
WHO	World Health Organization
WMA	Warm-Mix Asphalt
WRAs	Water-Reducing Admixtures

EXECUTIVE SUMMARY

This document has been prepared to provide guidance to the pavement community on sustainability considerations in pavement systems, drawing from and synthesizing the large and diverse body of technical information that exists on the subject. Sustainability considerations throughout the entire pavement life cycle are examined (from material extraction and processing through the design, construction, use, maintenance/rehabilitation, and end-of-life phases) and the importance of recognizing context sensitivity and assessing trade-offs in developing sustainable solutions are emphasized. Key points from each of the eleven chapters contained in the document are summarized in the following sections.

Chapter 1. Introduction

Chapter 1 provides a broad introduction to sustainability and its importance in pavement engineering. It also describes the overall scope and target audience for the document.

- **What is sustainability?** Most definitions of sustainability begin with that issued by the World Commission on Environment and Development (WCED, often referred to as the Brundtland Commission) in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Moreover, sustainability is often described as a quality that reflects the balance of three primary components: economic, environmental, and social impacts, which are often collectively referred to as the "triple-bottom line." A focus on sustainability can be interpreted as a recognition of the importance of all three triple-bottom line components. However, the relative importance and consideration of each of these factors are context sensitive and very much driven by the goals, demands, characteristics, location, materials, and constraints of a given project, as well as the overarching goals of the sponsoring agency.
- **Systems approach to sustainability**. In this context, more sustainable pavement systems are achieved through the balanced consideration of a number of trade-offs and competing priorities for a given project. It is important to recognize that, in some cases, it may not be productive (and it may even be counterproductive) to introduce certain features that are thought to be sustainable. For example, the use of recycled materials may not improve project sustainability when the economic and environmental costs of transporting the material over a great distance outweigh the benefits of using that material. This is the type of trade-off that must be continually assessed as the pavement industry moves towards more sustainable solutions.
- **Scope of the document**. This document focuses exclusively on the sustainability considerations associated with the pavement structure and pavement materials, and only those pavements constructed with a semi-permanent surface.
- **Target audience**. The primary audience for this document are practitioners doing work within and for state Departments of Transportation (DOTs), and it is intended for designers, maintenance, material and construction engineers, inspectors, and planners who are responsible for the design, construction, and preservation of the nation's highway network.

Chapter 2. Concepts of Pavement Sustainability

This chapter presents the basic concepts of pavement sustainability, and includes definitions, an overview of the pavement life cycle, an outline of sustainability issues and trade-offs, and an overview of how sustainability can be measured.

- **Sustainable pavements defined**. "Sustainable" in the context of pavements refers to system characteristics that encompasses a pavement's ability to (1) achieve the engineering goals for which it was constructed, (2) preserve and (ideally) restore surrounding ecosystems, (3) use financial, human, and environmental resources economically, and (4) meet basic human needs such as health, safety, equity, employment, comfort, and happiness.
- **Sustainability is an aspirational goal**. It is unlikely a truly "sustainable" pavement will be constructed in the near future so pursuit of sustainability should be viewed as a process of continual improvement towards an ultimate goal. This document, therefore, highlights "sustainability best practices," which are processes, actions, and features that advance the state of the practice towards more sustainable pavements.
- **Sustainability is context sensitive**. There needs to be a full accounting of surrounding systems and a pavement's influence on them in order to define the most appropriate sustainability practices associated with a particular pavement system. Furthermore, the approach must be tailored to fit into the overall goals and objectives of the agency.
- **Pavement sustainability includes a large range of issues**. Among other items, this can include such things as greenhouse gas (GHG) emissions, energy consumption, impacts on habitat, water quality, changes in the hydrologic cycle, air quality, mobility, access, freight, community, depletion of non-renewable resources, and economic development. Again, these must be considered within the confines of the particular project and the goals of the agency.
- **Sustainability measurement is an evolving field**. The "measurement" of sustainability is the first step in being able to establish benchmarks and assess progress. Currently, four general measurement tools, or methods, can be used to quantify sustainability: performance assessment, life-cycle cost analysis (LCCA), life-cycle assessment (LCA), and sustainability rating systems. These methods can be used alone or in concert to measure sustainability. Using them in concert provides a more holistic assessment of sustainability since each system tends to either address one specific component of sustainability in detail or address all components in less detail. Considerable work remains on establishing the framework and boundaries for pavement LCA, and outside of some treatment by rating systems, metrics to measure equity/social impacts associated with pavement systems do not currently exist.
- **Considerations of trade-offs is important**. The considerations of trade-offs is essentially a benefit/cost analysis performed in a more holistic sense (i.e., considering more than just economics). Even if benefits and costs are difficult to quantify, it is important to use a consistent approach in analyzing trade-offs to avoid introducing unintended bias. In general, these considerations should include the priorities and values of the organization or project, costs, impact magnitude and duration, and risk.

Chapter 3. Materials Considerations to Improve Pavement Sustainability

Chapter 3 reviews the materials commonly used in paving applications—including aggregate, asphalt, and cementitious materials—and describes how the production and use of those materials affect the overall sustainability of the pavement system. The scope is from the production or manufacture of materials to the point where the materials arrive at the construction site, either on grade or before leaving the plant. Sustainability impacts of other materials commonly used in pavements (such as steel, reinforcing fibers, interlocking concrete pavers, soil modifiers and stabilizers, and geosynthetics) are also discussed.

- **Consideration of life-cycle impacts of materials is important**. Impacts from material acquisition through processing, construction, use, and ultimately to the end of life need to be considered. Discussions are presented concerning the decision-making process inherent in material selection, the use of recycled, co-product, and waste materials (RCWMs), overall constructability considerations, trade-offs between higher quality materials and transportation costs/impacts, and the unintended consequences of restrictive specifications.
- **Sustainability impacts of aggregates**. Specific strategies are presented to improve the sustainability of aggregate production. In general, reducing the use of virgin materials and increasing the use of locally available materials and the use of durable RCWMs improves overall sustainability. Future challenges include more widespread use of RCWMs as aggregate, the ability to successfully incorporate “marginal” aggregates into pavement systems, and more sustainable transportation of aggregate over greater distances.
- **Sustainability impacts of asphalt materials**. Asphalt-based materials have evolved significantly in recent years, with increased amounts of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) being used to replace virgin binder. Moreover, increased levels of polymerization and the addition of rubber are being used to develop binders that are better suited to modern paving and preservation needs, to create specialized mixtures to provide improved structural support, and to enhance safety and reduce noise. Multiple approaches for improving sustainability with regards to asphalt materials are presented, including reducing virgin binder and virgin aggregate content in hot-mix asphalt (HMA) and warm-mix asphalt (WMA) mixtures, reducing energy consumed and emissions generated in mixture production, use of alternative binders, extending the life of asphalt mixtures, reducing materials transportation impacts, extending lives of seal coats, reducing the need for new materials, and increasing surface reflectivity (where warranted).
- **Sustainability impacts of concrete materials**. The major challenge facing cementitious materials is that the production of the primary binder (portland cement), is energy- and GHG-emission intensive. Reductions in those energy and emission levels is best met by expanding efforts to reduce the amount of portland cement used in paving mixtures. Several strategies are presented to achieve this, including the use of improved aggregate gradations, the use of portland limestone and blended cements, and the increased use of supplementary cementitious materials (SCMs) added at the concrete plant. Other approaches for improving the sustainability of concrete materials includes reducing water use in concrete production, increasing the use of RCWMs and marginal aggregates, and improving the durability of paving concrete.

Chapter 4. Pavement and Rehabilitation Design to Improve Sustainability

This chapter describes sustainability considerations through the design process for both asphalt and concrete pavements. The focus is on new pavement design and structural rehabilitation, including reconstruction and structural overlays. Pavement design considerations are described, as is the concept of "payback time," which is useful when evaluating the sustainability of design approaches that incur a larger initial economic or environmental impact as compared to standard practices.

- **Improved pavement design procedures.** Mechanistic-empirical pavement design procedures offer the promise of more efficient pavement designs for the prevailing traffic, climatic, and locational design conditions, which contributes to the overall sustainability of the resultant design.
- **Optimized use of materials**. Innovative pavement designs that incorporate the optimized use of materials and cross sections are an attractive means of meeting performance requirements while achieving environmental and economic benefits.
- **Evaluation of pavement designs**. Pavement designs can be evaluated by using LCA, LCCA, and rating systems to assess their environmental and societal impacts so that they can be improved. Moreover, several key use-phase issues, such as smoothness, noise, and stormwater management, can be considered in the design stage to help control later use-phase impacts.
- **Sample design strategies**. Some sample design strategies that may address sustainability issues for given projects are described, including long-life asphalt and concrete pavements, use of inlays, structural designs using local materials/low-impact transportation, accelerated construction, noise-reducing surfaces, modular pavement systems (including concrete pavers), pavement strategies for stormwater management, and consideration of use-phase impacts in the design phase.
- **Emerging trends in pavement design**. Among the emerging trends in the pavement design area are ongoing improvement to mechanistic-empirical pavement design procedures, the integration of design and environmental impact analyses, the consideration of emerging materials and future maintenance and rehabilitation in design, the possible integration of performance-related specifications, and improved smoothness prediction models.

Chapter 5. Construction Considerations to Improve Pavement Sustainability

This chapter briefly reviews the key elements to be considered to enhance the sustainability of construction for both asphalt and concrete pavements. This includes discussions on specifications, construction setup and operations, reduction of construction equipment fuel and emissions, management and handling of construction materials, construction quality assurance, and effective lane closures.

- **Pavement construction affects sustainability**. Pavement construction has an effect on the overall sustainability of a project. For example, construction-related fuel consumption, exhaust emissions, particulate generation, noise generation, and traffic delays and congestion are typical construction-related impacts. Furthermore, the area surrounding the construction site is also impacted by the pavement construction due to possible effects on residents, businesses, and local ecosystems.

- **Improving sustainability of pavement construction operations**. Sustainability improvements in the pavement construction process can be gained through the optimization of construction planning and sequencing, the control of erosion and sedimentation, the management of construction-related traffic delays, the control of on-site equipment- and construction-related noise, and the management of construction waste. At the same time, regulations continue to require improvements in the operation efficiency of construction equipment, lowering combustion emissions such as VOC and NO_x, diesel particulates, and fugitive particulate matter. Quality assurance is an essential element in constructing a durable pavement and, consequently, is essential in improving the overall sustainability.
- **Emerging technologies and construction techniques**. A number of innovative technologies are being adopted to improve construction efficiency, quality, and monitoring, including techniques such as intelligent compaction, stringless paving, infrared thermographic scanning, and real-time smoothness measurement. At the same time, new construction techniques, such as two-lift concrete paving and the use of cold plant asphalt mixes, have the potential to revolutionize construction, minimizing the use of non-renewable virgin materials and maximizing the use of RCWMs.

Chapter 6. Use-Phase Considerations

Chapter 6 identifies the critical sustainability impacts associated with pavement structures while they are in service, commonly referred to as the use phase. This chapter includes discussions of rolling resistance and fuel consumption, tire-pavement noise, stormwater management, pavement thermal performance, lighting, and safety, all of which, in turn, can also affect water quality, air quality, and, ultimately, human health.

- **Achieving and maintaining smoothness**. Achieving the highest level of smoothness during initial construction and maintaining that level throughout the service life is a key factor in improving fuel economy and reducing vehicle emissions, especially for heavily trafficked pavements.
- **Utility cuts.** In urban areas, pavement roughness is often affected by the quantity of utility cuts and the quality of the repairs. The smoothness of pavements in locations where there are utilities should be preserved by avoiding utility cuts where possible, and by obtaining the best possible repairs to cuts where they must be performed. An alternative for new pavement construction is to place utilities in locations on the right of way outside of heavily trafficked portions of the paved areas.
- **Structural responsiveness and vehicle fuel economy.** Several mathematical models have been developed and a number of field studies have been performed to assess fuel economy on different pavement structures. These provide indications that under various conditions the structural responsiveness of different pavements to vehicle loading can have a measureable effect. However, unlike roughness, this effect is highly dependent on pavement temperatures and is much more sensitive to vehicle type and speed. The calibration of models that will allow definitive conclusions to be drawn based on general application of the models to a wide range of pavements under a broad range of traffic and climatic conditions in various locations has not yet been completed.
- **Noise emissions**. Although other factors are typically more important than the pavement in determining noise levels, noise attributable to the pavement surface characteristics can

be detrimental to surrounding communities and habitat. Tire-pavement noise emissions can be partly addressed through the selection of appropriate paving materials and/or surface textures.

- **Stormwater management**. Permeable pavements are an effective means of providing stormwater management by capturing and storing runoff, reducing contaminants in waterways, and recharging groundwater supplies. They also make for more efficient land use by eliminating the need for retention ponds and swales. These pavements are currently limited to low-volume roadways and parking lots.
- **Urban Heat Island Effect (UHIE)**. Relationships between the pavement surface reflectivity and the UHIE are very complex; influencing factors include such items as the size of urban area, the pavement density, solar reflectance, tree canopy, building patterns, and the climate. In certain cases, surface reflectivity may be significant and thus should be evaluated within the specific context of a given project. At this time, it is unclear to what degree pavement solar reflectance impacts the development of the UHIE for different urban architectures, climate regions, and other variables. Research is underway to provide a more comprehensive understanding of the UHI phenomenon.
- **Lighting.** The high energy demand of current lighting systems has a significant economic and environmental footprint. Pavement surface luminance is known to influence the amount of artificial lighting required, but practical application of this knowledge is currently unclear as surface luminance changes with time. Development and implementation of new adaptive lighting systems, which provide lighting only when it is needed, is currently underway and has the strong potential to significantly lower economic, environmental, and societal costs associated with artificial lighting.
- **Safety**. Pavement characteristics that impact safety include smoothness, friction, cross slopes, porosity, and constructed features such as rumble strips. Smoother pavements provide a comfortable riding surface and cause less distractions for the driver, high friction levels are especially important in specific cases such as ramps and curves, adequate cross slope is required to promote surface drainage and prevent hydroplaning, porous pavements minimize splash and spray (thereby improving visibility in wet weather conditions), and rumble strips alert drivers of changing conditions.

Chapter 7. Maintenance and Preservation Treatments to Improve Sustainability

This chapter presents the maintenance and preservation treatments most commonly used on asphalt and concrete pavements. Currently there is limited information available on quantifying the sustainability of pavement maintenance and preservation practices, so much of the current analysis is subjective. Still, opportunities exist for enhancing pavement system sustainability through careful treatment selection, materials considerations, treatment timing and application, and treatment design and construction.

- **Linking pavement management systems and pavement preservation**. The need for the further integration of various asset management systems and overall pavement sustainability considerations is stressed, including the consideration of environmental factors in the analysis of pavement performance.
- **Effect of traffic volumes**. On higher traffic routes, the higher economic cost of more frequent treatments (including lane closures/traffic disruptions) may be offset by large reductions in environmental impacts due to vehicle operations on smoother pavements.

For lower traffic routes, the minimization of agency life-cycle cost through proper timing of the right treatment also generally improves sustainability.

- **Treatment selection factors**. Critical factors for consideration in selecting a suitable maintenance or preservation treatment includes performance history of the treatments, overall performance needs or requirements, construction constraints, LCCA, and LCA.
- **Favorable factors for sustainable treatments**. The sustainability value of any given treatment is difficult to judge as there are multiple factors at work; however, in general, treatments that use the least amount of material to maintain smoothness over the longest period of time have the greatest positive effect. Moreover, understanding the complete life-cycle impacts is an essential element in establishing the advantages and disadvantages of any given treatment. Unfortunately, available data are currently insufficient to support detailed environmental analyses to characterize maintenance and preservation treatments.

Chapter 8. End-of-Life Considerations

Chapter 8 discusses the impacts of the end-of-life phase on the sustainability of both asphalt and concrete pavements. Critical end-of-life issues and strategies for improving pavement system sustainability are presented.

- **Increase use of RCWMs**. These materials can be incorporated in virtually every layer of the pavement structure and are effective means of increasing the sustainability of pavements. Recycling processes can be conducted off site (e.g., in central plants) or on site, using various technologies.
- **"Highest use" of recycled materials**. The "highest use" refers to the preferred use of a recycled material in order to extract the greatest payback in terms of sustainability. This requires the consideration of all of the costs involved in recycling and using a particular material. Under such an approach, a material such as RAP, for example, would find its highest use as a replacement for both binder and aggregate in a new asphalt mixture instead of being used as an aggregate base. This approach also considers the costs of transporting materials and landfilling to ensure that materials are employed according to their highest value.
- **Specific end-of-life strategies**. Multiple end-of-life strategies are discussed for both asphalt and concrete pavements, including central plant recycling and full-depth reclamation for asphalt pavements and the use of recycled concrete as base material or as aggregate in new concrete or asphalt. The specific incorporation of these strategies on a given project is based on the project needs, context sensitivity, and agency goals. Landfilling as an end-of-use option is becoming less attractive because of dwindling landfill space and the value associated with recycling and reusing pavement demolition products.

Chapter 9. Pavement Sustainability within Larger Systems

This chapter presents various sustainability considerations that are not addressed elsewhere in the manual. These impacts can influence decisions even though they are often not easily quantifiable.

- **Systems approach required**. When evaluating and incorporating other aspects, an overall "systems" approach is required to consider the entire reach and totality of the pavement and roadway setup.
- **Role of pavements**. The role of pavements in a larger system is discussed in terms of aesthetics, historical and cultural identity, the impact of utility cuts, and the impact of odor, soot, and particulate matter. An example of aesthetics impacting pavement design is documented along State Road 9 in Utah, in which a chip seal surfacing that uses local red volcanic cinders was placed to ensure that the pavement surface matched the aesthetics of the surroundings.
- **Emerging technologies**. A number of technologies are emerging in this area, with examples including the use of photocatalytic pavement, the ongoing evolution of modular pavement systems, and the development of pavements that produce energy.

Chapter 10. Assessing Pavement Sustainability

This chapter provides information on measuring pavement sustainability and why it is important. An overview of sustainability rating systems is provided, along with a summary of LCCA and LCA procedures.

- **Need for measuring sustainability**. In order to move forward with sustainability considerations in pavements, it is important that there be ways to measure it so that baseline levels can be established and future progress can be assessed. Together, LCCA, LCA, and sustainability rating systems provide a means of quantifying economic, environmental, and societal factors in pavement sustainability.
- **LCCA**. LCCA is a widely accepted technique for evaluating the economic impacts of pavement systems. At its very core, it is a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment. The most widely accepted and adopted LCCA tool for pavement applications in the U.S. is the FHWA's *RealCost* Software.
- **LCA**. LCA is an emerging technology that works to quantify environmental impacts over the entire life cycle of the pavement system; results are expressed, in terms of a number of key environmental factors (commonly energy usage and greenhouse gas emissions, but there are many others). Pavement-specific LCA tools are not available yet, but several software programs can be used with customization to assess pavement environmental impacts.
- **Sustainability rating systems**. A sustainability rating system is essentially a list of sustainability best practices with an associated common metric (commonly expressed as "points"). In this way, the diverse measurement units of sustainability best practices (e.g., pollutant loading in stormwater runoff, pavement design life, tons of recycled materials, energy consumed/saved, pedestrian accessibility, ecosystem connectivity, and even the value of art) can all be compared using a common unit (points). A number of rating systems relevant to pavements are described (e.g., Greenroads®, INVEST, Envision™, GreenLITES).
- **Integration of assessment methods**. LCA, LCCA, and rating systems can be used independently or in concert to quantify various aspects of sustainability, but ultimately

the priorities of the owner/agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems, will determine which approach (or set of approaches) is most appropriate.

Chapter 11. Concluding Remarks

This chapter summarizes several of the technologies and innovations that are contributing to sustainability initiatives along with recommended implementation activities for helping to move the process forward.

- **Technologies and innovations**. A number of technologies and innovations are being used to improve pavement sustainability, including, among others, the increased use of recycled materials, adoption of WMA technologies as a standard practice, reduction of portland cement and increased use of SCMs and RCWMs in concrete, optimization of materials and cross sections, and the expanded use of preservation treatments.
- **Sustainability trends**. Several trends emerging in the area of pavement sustainability include a growing understanding of the importance of the use phase, a recognition that pavement systems are a small part of much larger systems, and the development/enhancement of sustainability tools.
- **Sustainability is context sensitive**. Sustainability is very much context sensitive, and that sustainable strategies will depend on the characteristics of the project, the materials and technologies that are readily available, and the specific economic, environmental, and societal goals of the agency.
- **Implementation of sustainability**. Key factors essential to the implementation of sustainability considerations within the pavement community include leadership at the national and state levels, partnerships between key stakeholders, effective education and outreach, identification of knowledge gaps, development of focused research strategies, and the development and application of useful LCA tools.

CHAPTER 1. INTRODUCTION

Background

An ever-growing number of agencies, companies, organizations, institutes, and governing bodies are embracing principles of sustainability in managing their activities and conducting business. This approach focuses on the overarching goal of emphasizing key environmental, social, and economic factors in the decision-making process. In many ways, sustainability considerations are not new, since they were often considered indirectly or informally in the past, but recent years have seen increased efforts to quantify their effects and to incorporate them in a more systematic and organized fashion.

There are many reasons for this emphasis on applying sustainability, among which are a growing recognition of how human activity affects the environment (e.g., climate change, ecosystem changes, non-renewable resource depletion) and a better appreciation for considering key societal factors (e.g., land use, access, aesthetics) and economic considerations (net benefits, life-cycle costs) in decision making. Thus, a focus on sustainability reflects a commitment to address the entirety of impacts associated with human existence, not only in monetary terms but also in terms of environmental and social impacts.

The criticality of implementing sustainability has become more acute in light of growing evidence suggesting that human activities are jeopardizing the health of the planet at a global scale and, by extension, the welfare and prosperity of future generations (IPCC 2007; IPCC 2014). For example, greenhouse gas (GHG) emissions, a commonly used surrogate for assessing environmental sustainability, are known to trap heat in the atmosphere and contribute to climate change (see call-out box on next page). The burning of fossil fuels (in manufacturing, electricity production, and transportation) is the largest contributor of GHG emissions, the most prevalent of which is carbon dioxide (CO_2). According to the Environmental Protection Administration (EPA 2013), and using 2011 data as the basis, the transportation industry (including cars, trucks, aircraft, rail, ships, and pipelines) accounts for over 27 percent of all human-caused GHG emissions in the U.S. (see figure 1-1); this is second only to the amount of GHG emissions attributed to the electric power industry. In addition, the construction of transportation facilities also contributes to GHG emissions, which are represented as part of the industry section. As a result, any significant reductions in GHG emissions made in the transportation sector will have an effect on the total amount of GHG emissions in the U.S.

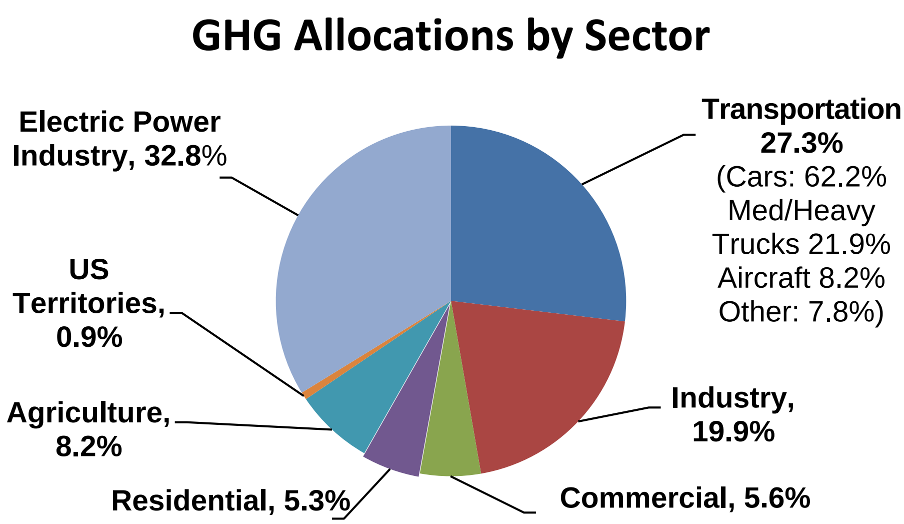

Figure 1-1. GHG emissions by economic sector in the U.S. (EPA 2013).

What is Sustainability?

Most definitions of sustainability begin with that issued by the World Commission on Environment and Development (WCED), often referred to as the *Brundtland Commission Report* (WCED 1987):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

This definition is focused on the concept of "needs" and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs. In a shorter version of this, sustainability is often described as being made up of the three components of environmental, social, and economic needs, collectively referred to as the "triple-bottom line."

For many years, the economic component has been the dominant decision factor, but more recent years have seen the growing emergence of both the environmental and social components (even though there are some current limitations associated with their measurement and assessment). A focus on sustainability can then be interpreted in such a way that all triple-bottom line components are considered important, but the relative importance of these factors (and how each are considered) are case sensitive, very much driven by the goals, demands, characteristics, and constraints of a given project. Chapter 2 provides a more detailed discussion on this topic.

GHGs, GWP, and CO_2 e

Gases that trap infrared radiations (heat) in the Earth's atmosphere are referred to as greenhouse gases (GHGs). Once present in the atmosphere, most of these gases do not break down very quickly and thus can contribute to planetary warming over an extended period. Although the presence of GHGs makes our planet livable, excess GHGs produced due to human activity are believed to be contributing to global warming.

GHGs are generated by a variety of agricultural and industrial processes including raising livestock, burning of fossil fuels, solid waste, wood products, and production of portland cement and asphalt. GHGs of greatest concern are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, with each exhibiting differences in their atmospheric concentration, the amount of time they remain in the atmosphere, and their ability to trap radiation.

Because each individual GHG has a different impact on global warming, it is useful to express them in a single equivalent unit so they can be compared. ***Global Warming Potential (GWP)*** *is a measure of the total energy that a gas absorbs over a period of time (typically 100 years) using CO_2 as the base unit. By definition,* ***CO_2****, which accounts for over 80 percent of all U.S. GHG emissions, has a 100-year GWP of 1. For comparison, according to the IPCC (2013):*

- ***Methane, which*** *accounts for about 10 percent of all U.S. GHG emissions, has a 100-year GWP of 34.*
- ***Nitrous oxide, which*** *accounts for approximately 5 percent of all U.S. GHG emissions, has a 100-year GWP of 298.*
- ***Fluorinated gases*** *[hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride(SF_6)] are synthetic GHGs that are typically emitted in smaller amounts; however, they are potent and sometimes referred to as High GWP Gases. The 100-year GWP of these materials is 140 to 11,700 for HFCs, 6,500 to 9,200 for PFCs, and 23,900 for SF_6.*

Carbon Dioxide Equivalent (CO_2e) *is the metric used to compare emissions from various GHGs based on their GWP. The CO_2e is computed by multiplying the amount of the GHG (usually mass) by its GWP. The GWP values are dependent on the time period considered, with 100-year GWP values commonly used for comparison.*

Additional information on GHGs is available on the EPA website:

http://www.epa.gov/climatechange/ghgemissions/gases.html

Importance of Sustainability in Pavement Engineering

The nation's roadway system is one part of a transportation network that provides mobility and access to a range of users. The roadway network is not only important to the nation's overall economic vitality by providing for the movement of freight and commodities, but it also provides societal benefits as well (e.g., access to schools, services, and work; leisure travel; and general mobility). There are more than 4 million miles of public roads in the United States, which includes 1 million miles of Federal-Aid roadways (FHWA 2013). In 2010, nearly 3 trillion vehicle miles traveled (VMT) were logged over those roadways, consuming more than 169 billion gallons of fuel in the process (FHWA 2010). And, based on 2008 data (the most recent available), the total expenditures for highways in the U.S. was $182.1 billion (FHWA 2010). Taken together, these numbers are staggering and demonstrate the magnitude of the investment in public roadways and the positive impacts of the system in providing movement, access, and mobility.

Pavements are an integral part of this roadway network. Pavements provide a smooth and durable all-weather traveling surface that benefits a range of vehicles (cars, trucks, buses, bicycles) and users (commuters, commercial motor carriers, delivery and service providers, local users, leisure travelers). Given their key role and widespread use, there is a unique opportunity to improve the sustainability of pavement structures with the potential to deliver tremendous environmental, social, and economic benefits. With regard to those components, listed below are just a few examples of how pavements can impact sustainability:

- Environmental component: energy consumption; GHG emissions; noise; air quality; stormwater treatment.
- Social component: safety (fatalities, injuries, property damage); smoothness; vehicle operating costs; GHG emissions; access, mobility; aesthetics.
- Economic: construction, maintenance, and rehabilitation costs; vehicle operating costs; crash costs.

Moreover, the current timing is such that transportation agencies and the general public alike are demanding increased consideration of sustainability principles and practices. This evolution in the role that transportation plays in society is well summarized as follows (AASHTO 2009):

> *Transportation's mission is no longer about just moving people and goods. It's much broader. Transportation fundamentally allows us to achieve economic, social, and environmental sustainability. Transportation supports and enhances our quality of life. As state transportation professionals, we need to model the way toward achieving a sustainable future…Sustainable transportation requires innovative approaches and partnerships like never before.*

Transportation and highway agencies are already making advancements to improve and enhance overall sustainability. Recent years have seen significant strides being made to better align current practices and technologies with more long-term sustainable strategies. In fact, the pavement engineering community has adopted a number of technologies as a way of improving sustainability, such as the increased use of recycled materials in pavement structures, the incorporation of modified binders to increase pavement performance, and the development of rating systems to measure sustainability. At the same time, there is considerable research being conducted on energy use, GHG emissions, and other impacts associated with pavement materials and construction activities to support the development of life-cycle assessment tools.

Nevertheless, there are no universal characteristics or design features that describe a sustainable pavement. Although a general sustainability framework for pavement can be defined, it is context sensitive in that each situation is unique, with specific needs depending on the location, climate, available materials, facility type, required level of service, and so on, as well as on the overall goals of the organization. Furthermore, it is important to recognize that, in some cases, it may even be counterproductive to try to introduce certain features that are thought to be sustainable without a complete assessment; for example, trucking in recycled materials from a great distance when an acceptable local aggregate is readily available could actually have negative environmental consequences.

About This Document

Although significant progress has been made in advancing the sustainability of pavements and pavement systems, there remain a number of complex issues and difficult challenges; a few of these are listed below:

- What are the appropriate sustainability factors to be considered over the life cycle of a pavement (from material extraction to the end-of-life)?
- How do the various materials used in paving applications impact the overall sustainability of the pavement system?
- How can pavements be effectively designed and constructed to meet the specific sustainability needs of a given project?
- How can the pavement community make more sustainable choices, given different facility types (interstates, state highways, local roads/streets), locations (climatic regions, urban vs. rural settings), and paving situations (new alignment, overlays, varying project sizes)? How does one consider trade-offs in the process?
- What methods are available to assess the sustainability of pavement systems?
- What implementation strategies are available for highway agencies to adopt more sustainable pavement practices?

All stakeholders in the pavement community—including owner agencies, designers, material producers and suppliers, contractors, consultants, and the traveling public—are embracing the need to adopt more sustainable practices in all aspects of their work, and are continually seeking the latest technical information and guidance available to help improve those practices. This document has been prepared to provide guidance to the pavement community on sustainability considerations in pavement systems, drawing from and synthesizing the large and diverse body of knowledge that currently exists on pavement sustainability. As such, it provides the currently available knowledge and information for designing, constructing, and maintaining pavement structures more sustainably, and has been structured so that it can adapt to new findings and new information as sustainability considerations continue to develop and evolve.

Scope

It is recognized that sustainability is a system characteristic, and pavements are but one part of the transportation system. It is the scope of this document to focus on pavements and describe how more sustainable pavement systems can be designed and constructed, but this cannot be done in total isolation from the transportation infrastructure system or from other systems in which pavements interact. Moreover, as described in chapter 2, the entire pavement life cycle is covered, from materials to design, from construction through the use phase, and from maintenance/rehabilitation to the end-of-life.

In this document, the pavement is defined as the structure constructed above the native subgrade soil, typically constructed in distinct layers and including compacted or stabilized subgrade, a bound or unbound subbase/base, and the riding surface (see figure 1-2). Broadly, this encompasses pavement structures in a number of different facility types, such as highways, streets, roads, shoulders, and parking areas, but the focus of this document is on pavement structures used in mainline paving and shoulders of highways/roadways. Furthermore, only paved roadways consisting of a semi-permanent surface are considered; this includes asphalt concrete (AC) pavements, which may be constructed with hot-mix asphalt (HMA) or warm-mix asphalt (WMA) technologies, and hydraulic cement concrete (HCC) pavements, which includes portland cement concrete (PCC). For the purposes of this document, all permanent surfaces constructed with asphalt materials are generically referred to as “asphalt” pavements, whereas all permanent surfaces constructed with hydraulic cement materials are generically referred to as “concrete” pavements.

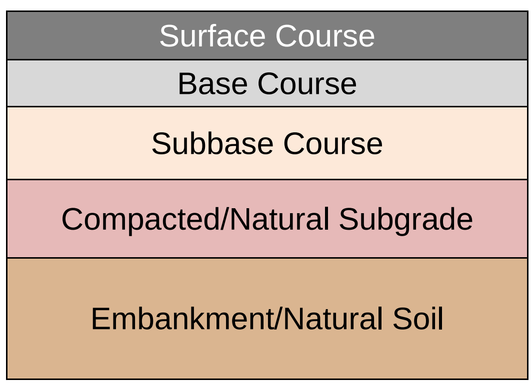

Figure 1-2. Basic components of a typical pavement system.

As a point of clarification, it is noted that there are a number of items related to a highway or roadway that are <u>not</u> included or considered in this document; examples include:

- Planning.
- Capacity.
- Roadway striping.
- Roadway signage and message boards.
- Barriers and other safety appurtenances.
- Ice and snow management.

- Roadside management.
- Drainage structures.
- Bridges and other structures.

Thus, it is reiterated that this document focuses exclusively on the sustainability considerations associated with the pavement structure and pavement materials, and only on those pavements constructed with a semi-permanent surface.

Target Audience

The primary audience for this document is state Department of Transportation (DOT) practitioners, and it is intended for designers, maintenance, material and construction engineers, inspectors, and planners who are responsible for the design, construction, and preservation of the nation's highway network. The overarching goal is to provide state DOT practitioners information to help design, specify, and construct a more sustainable pavement. However, other key stakeholders in the pavement community are also expected to benefit from the information contained in this document, including local roadway agencies, industry (suppliers, producers, contractors, and consultants), academia, and various public interest groups.

Document Overview

This document consists of eleven chapters, including this introductory chapter. The chapters closely mirror the critical phases in the pavement life cycle, allowing users to quickly and easily locate desired information. Each chapter generally follows the same layout, first providing general background information on the topic, then describing sustainability-related issues associated with the topic, followed by strategies or methodologies to address the issues identified, including the consideration of trade-offs. The chapter then concludes with a brief look at future directions and emerging technologies.

A description of the primary chapters in this document is provided below:

- **Chapter 2. Concepts of Pavement Sustainability**. This chapter presents the basic concepts of pavement sustainability and includes definitions, an overview of the pavement life cycle, a framework for considering sustainability issues and trade-offs, and an overview of how sustainability can be quantified and measured.
- **Chapter 3. Materials Considerations to Improve Pavement Sustainability**. Chapter 3 reviews the common materials used in paving applications—including aggregate, asphalt, and cementitious materials—and describes how these materials affect the overall sustainability of the pavement system. The scope is from the materials acquisition until the materials arrive at the construction site, either on grade or at the plant.
- **Chapter 4. Pavement and Rehabilitation Design to Improve Sustainability**. This chapter addresses techniques for improving the sustainability of pavements during the design process, for both asphalt and concrete pavement structures. The focus is on new pavement design and structural rehabilitation, including reconstruction and overlays.
- **Chapter 5. Construction Considerations to Improve Pavement Sustainability**. This chapter briefly reviews the key elements to be considered to enhance the sustainability of construction for both asphalt and concrete pavements. The chapter includes discussions on specifications, construction setup and operations, construction equipment fuel and

emission reduction, management and handling of construction materials, construction quality assurance, and effective lane closures.

- **Chapter 6. Use-Phase Considerations**. Chapter 6 identifies the critical sustainability impacts associated with pavement structures while they are in service, and includes discussions on rolling resistance, safety, noise, heat island effects, lighting, and stormwater management.
- **Chapter 7. Maintenance and Preservation Treatments to Improve Sustainability**. This chapter presents common maintenance and preservation treatments used for asphalt and concrete pavements and describes opportunities for enhancing their sustainability through careful treatment selection, material considerations, treatment timing and application, and treatment design and construction.
- **Chapter 8. End-of-Life Considerations**. Chapter 8 discusses the impacts of the end-of-life (EOL) phase on the sustainability of both asphalt and concrete pavements. Critical issues and strategies for improving the sustainability of this phase of the pavement life cycle are presented.
- **Chapter 9. Pavement Sustainability within Larger Systems**. This chapter presents various sustainability impacts that are not addressed elsewhere in the manual, including such items as aesthetics, historic and cultural identity, multi-modal design, and local ecosystems. These impacts can influence decisions even though they are often not easily quantifiable.
- **Chapter 10. Assessing Pavement Sustainability**. Chapter 10 provides information on measuring pavement sustainability and why it is important. An overview of sustainability rating systems is provided, along with a summary of life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) procedures.
- **Chapter 11. Concluding Remarks**. This chapter offers some concluding remarks by briefly summarizing some of the technologies, innovations, and trends in pavement sustainability and by providing a listing of recommended implementation activities for moving forward.

An appendix is included that presents a glossary of terms used throughout the document. In addition, a stand-alone executive summary has been prepared that summarizes the contents of each chapter and captures the main points and primary considerations.

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CHAPTER 2. CONCEPTS OF PAVEMENT SUSTAINABILITY

This chapter introduces the basic concepts of sustainability as they relate to pavements. It includes discussions on (1) the definition of sustainability and its implications, (2) the role of pavements in sustainability, (3) the pavement life cycle, (4) different ways of measuring sustainability, and (5) an introduction to the framework used in this document for considering potential sustainability trade-offs.

Sustainability Defined

In a broad sense, the "sustainability" of a human-devised system refers to its ability to (1) exist and function within a larger system without degrading it, and (2) provide for and meet the human needs for which the system was developed. There are a number of popular definitions of sustainability, but as described in chapter 1 these often start with the short definition issued by the World Commission on Environment and Development (WCED 1987):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

And, as also noted in chapter 1, most sustainability definitions also reference three discrete components (environmental, social, and economic) that are to be considered; however, they usually do not direct how those components are to be prioritized beyond generally stating that they should be "balanced" without offering much direction on the definition of "balanced" or how such balancing is to occur.

This document uses a sustainability definition that is consistent with and complementary to the approach described in the *National Cooperative Highway Research Program (NCHRP) Report 708: A Guidebook for Sustainability Performance Measurement for Transportation Agencies* (Zietsman et al. 2011).[1] This approach emphasizes the underlying sustainability principles as the basis for guidance, with the actual definition being of secondary importance. Thus, "sustainable" in the context of pavements refers to system characteristics that encompasses a pavement's ability to (1) achieve the engineering goals for which it was constructed, (2) preserve and (ideally) restore surrounding ecosystems, (3) use financial, human, and environmental resources economically, and (4) meet basic human needs such as health, safety, equity, employment, comfort, and happiness.

Sustainable Pavements Should:

- ✓ *Achieve the engineering goals for which they were constructed.*
- ✓ *Preserve and (ideally) restore surrounding ecosystems.*
- ✓ *Use financial, human, and environmental resources economically.*
- ✓ *Meet human needs such as health, safety, equity, employment, comfort, and happiness.*

[1] This approach has also been adopted by other highway sustainability efforts, including NCHRP Project 20-83(07), *Sustainable Transportation Systems and Sustainability as an Organizing Principle in Transportation Agencies*. It is also complimentary to the FHWA's *Infrastructure Voluntary Evaluation Sustainability Tool* (INVEST).

Sustainability Direction at the Federal Level: Executive Order 13514

Presidential Executive Order (EO) 13514, "Federal Leadership in Environmental, Energy, and Economic Performance" expands on EO 13423, "Strengthening Federal Environmental, Energy, and Transportation Management" in order to, "…establish an integrated strategy towards sustainability in the Federal Government and to make reduction of GHG a priority for Federal agencies." EO 13514 states, "'sustainability' and 'sustainable' mean to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generation…" (Bush 2007; Obama 2009). This executive order constitutes direction from the President to various Federal Agencies on how they are to be "sustainable." While its specific definition of "sustainability" is important, it is most significant because it sets specific targeted requirements for Federal agencies including reductions in GHG emissions, petroleum consumption, water use, and waste.

EO 13514's definition of "sustainability" is a paraphrasing of the United Nations 1987 Report of the World Commission on Environment and Development (commonly called the Brundtland Commission Report), in which sustainable development is defined as "…meeting the needs of the present without compromising the ability of future generations to meet their own needs…" (WCED 1987).

The Sustainability Continuum

As defined here, a "sustainable pavement" is, at present, an aspirational goal. That is, it is unlikely any pavement system based on current knowledge and technology could satisfy all or even most of the characteristics in the previous sustainability definition. However, continual improvement with an emphasis on each of these characteristics leads to more sustainable pavements, and, ultimately, to pavements that actually meet the rather demanding standards of sustainability. Progress towards sustainability may at first mean reducing bad outcomes (e.g., less pollution, reduced extraction of non-renewable resources, less waste). Further progress would transition to achieving a pavement system that is essentially a neutral player in the larger and surrounding systems (i.e., it does no harm). Importantly, however, progress should continue so that the pavements could ultimately produce positive outcomes (e.g., pavements that produce more energy than they consume, construction that restores more land than it uses). Current efforts at reducing the impact or amount of bad outcome and improving efficiency should be viewed as good transitional strategies on the long path towards the ultimate goal of producing only positive outcomes. This interpretation of sustainability is substantially different, and ultimately more positive, than one limited to reducing negative outcomes.

Sustainable Best Practices

Recognizing the aspirational nature of a truly "sustainable pavement," this document highlights processes, actions, and features that advance the state of the practice towards more sustainable pavements rather than those that actually achieve the definition. Specifically, "sustainable best practices" are those practices that work to either (1) go above and beyond required regulatory minimums or standard practice, or (2) show innovation in meeting these minimums and standards.

Sustainability is Context Sensitive

Because a pavement must exist and function within larger systems, practices that support sustainability must contribute to more sustainable systems and thus depend on context. As a result, a full accounting of surrounding systems and a pavement's influence on them is necessary in order to define the most appropriate sustainability practices associated with a particular pavement system.

Importance of a Sustainability Definition

The specific definition of sustainability is considered to be of secondary importance to understanding the basic principles of sustainability; this is because a definition typically addresses what should be considered but does not give direction on how those considerations are to be prioritized or implemented. This is especially relevant because sustainability often requires the consideration of trade-offs in the decision-making process. For example, should a pavement use locally available extracted materials or make use of recycled materials that require long distance hauling? Should the benefit of a quieter surface course be selected over a pavement with a longer service life? Often, both alternatives have legitimate sustainability arguments, but the option that is ultimately selected (in other words, how sustainability is actually implemented) reflects agency, stakeholder, and project priorities and limitations. These priorities and limitations are the appropriate focal point in approaching sustainability.

Integrating Sustainability into a System

As a system characteristic that encompasses environmental, social, and economic dimensions, sustainability is necessarily the highest-level strategy or goal of an organization. In short, sustainability tends to mean "consider everything." Other organizational strategies and goals (e.g., safety, conservation, ecosystem health, education, open space, and so on) are an expression of (1) which sustainability components an organization particularly values, (2) the order of precedence for these values, and (3) a plan to operationalize those values and precedence. This is why Amekudzi et al. (2011) and others have been able to identify many sustainability components that are already present in current transportation organization mission statements. Consequently, incorporating sustainability into an organization or into a particular system (such as pavement infrastructure) is not adding a separate value to the system but instead is assessing the current prioritization of values within that system and making changes as needed. The outcome is an alignment of the system's goals and the organization's sustainability goals. In many cases, the results of sustainability efforts are that an organization or project elevates the priorities of environmental and social issues above the levels where they were previously. However, in the strictest sense, these are only part of the overall sustainability principles discussed previously. Thus, sustainability considerations for a particular system (like pavement structures) can often be reduced to understanding how each system component affects sustainability (this is often broken down into how each component affects environmental, social, and economic outcomes) and which outcomes are most desirable given the (1) priorities of the organization, and (2) the outcomes within larger systems.

Context: The Role of Pavements in Sustainability

While it may not be possible to quantify the "sustainability" of the planet as a whole, a few useful proxy measurements are often used as an indication of the role and relative impact of transportation and roads. As described in chapter 1, human-caused GHG emissions are often used as a simple proxy to quantify the impact of human activity on the planet. This metric can be further broken down to quantify and understand the relative contributions made by various countries, industry sectors and practices. While GHG emissions do not account for all pavement sustainability impacts, they are a useful starting point.

Beyond Greenhouse Gas

Chapter 1 presented a brief discussion on the human-caused GHG emissions by economic sectors in the U.S. It is important to recognize that roads have sustainability impacts beyond just GHG emissions. Some of these major impacts (both positive and negative) include:

- **Energy consumption**. Roads take energy to construct, maintain, rehabilitate, and recycle. Furthermore, and often of much greater impact, roads affect the energy consumption of the vehicles using them through their interaction with those vehicles to include such properties as geometric design, surface roughness, and rolling resistance. Since the consumption of energy also tends to produce GHG, the emission of GHG is also affected by these features.
- **Habitat loss, fragmentation, and change**. Roads cause direct habitat loss over their footprint and diminish adjacent habitat, impede wildlife movement, and can change wildlife distribution in an area based on their barrier effects, roadkill, and dispersal function (Bissonette and Cramer 2008).
- **Water quality**. Pavement surfaces generally collect significant pollutants from the vehicles that use the facility, and rainwater can carry those pollutants into nearby bodies of water unless properly managed. Runoff from pavements is also often warmed, thereby affecting the temperature of streams and potentially the suitability of the habitat for some species.
- **Hydrologic cycle changes**. Pavements represent significant amounts of impervious surface and, as such, can alter the natural hydrological cycle resulting in greater stormwater runoff (and less evapotranspiration and infiltration) when compared to the same area before development.
- **Air quality**. Vehicles that use a pavement facility, as well as the equipment used to process the necessary raw materials and construct the roads, degrade overall air quality. This degradation includes not only emission from the combustion of fuel but also fine airborne particulate (less than 0.01 mm [10 micron or < PM10] in size).
- **Mobility**. Roads can contribute to a population’s mobility by providing greater capacity and desirability of all transportation modes: pedestrian, bicycle, car, and transit.
- **Access**. Roads can provide greater modal access to locations. This could be vehicular access to a rural area, or it could be pedestrian, bicycle, or transit access in urban areas.
- **Freight**. Roads carry a significant amount of commercial freight across the U.S. In fact, trucking constitutes the largest share of the U.S. commercial freight industry based on value (71.3 percent) and weight (70.0 percent) (USDOT/USDOC 2010). In 2007, over $8.3 trillion worth of freight was moved via the trucking industry (USDOT/USDOC 2010).
- **Community**. Roads are long, linear forms of infrastructure exhibiting many access points and providing access and mobility. As such, they can have large community impact both positive (e.g., gathering area, sense of place, modal access, mobility) and negative (e.g., fragmentation, health issues, safety).
- **Depletion of non-renewable resources**. Roads, in their current state, require the use of a significant amount of nonrenewable natural resources (e.g., aggregate, petroleum, limestone) to construct, maintain, and rehabilitate.

- **Economic development**. Road construction and maintenance can create local employment opportunities and contribute to the ability of other businesses to function (e.g., freight transport, workers getting to/from work).

The Role of Pavements

Within the transportation sector, GHG emissions associated with pavement construction are significant, but they are generally much less than GHG emissions associated with vehicle operations. Although there are no official statistics to quantify the magnitude of GHG emissions due solely to pavement construction, a reasonable estimate can be made using available data. First, based on a seasonally adjusted activity of $80.85 billion of highway and street construction work done in 2012 (U.S. Census Bureau 2012), and using the Economic Input-Output Life Cycle Assessment (EIO-LCA) online calculator[2] available from Carnegie Mellon University (2008), the total GHG emissions due to all highway and street construction is estimated at 117 million tons (106 million mt) CO_2e, or about 7 percent of the U.S. transportation total. Then, given that pavements account for about 70 percent of the highway and street construction expenditures (USDOT 2010), it can be roughly estimated that pavement construction, maintenance, and rehabilitation in the U.S. produces about 83 million tons (75 million mt) CO_2e of GHG emissions, which, for comparison, is about 5 percent of the U.S. transportation GHG emission total and about 1.4 percent of the total U.S. GHG emission amount.[3] According to the EPA (2013), about 80 percent of the total emissions from the transportation sector come from cars and truck fuel combustion. Pavements also have significant potential to influence these emissions based on their design and surface characteristics largely because these can influence vehicle fuel efficiency.

This overview provides a rather crude estimate while ignoring many other important impacts, but it nonetheless gives an idea of the role of pavements in contributing to the larger GHG emissions picture. In terms of impacts beyond GHG, pavements also play a significant role but are likely secondary to roadway planning, design, and operation.

The Pavement Life Cycle

In order to better understand the effects of pavements on sustainability, it is useful to divide a pavement's life cycle into several significant phases (see figure 2-1). This document uses the following phases:

- Materials production.
- Pavement design.
- Construction.
- Use.
- Maintenance and preservation.
- End-of-life.

[2] Using the 1997 Industry Benchmark U.S. Department of Commerce EIO dataset and selecting the "construction" industry with a "highway, street, bridge, and tunnel construction" sector.

[3] The emissions associated with pavement construction span at least three of EPA's five defined major fuel consuming sectors: electricity generation, transportation, industrial, residential, and commercial. In a strict sense, using the EPA's sector definitions pavement construction is not an exclusive subcategory of transportation.

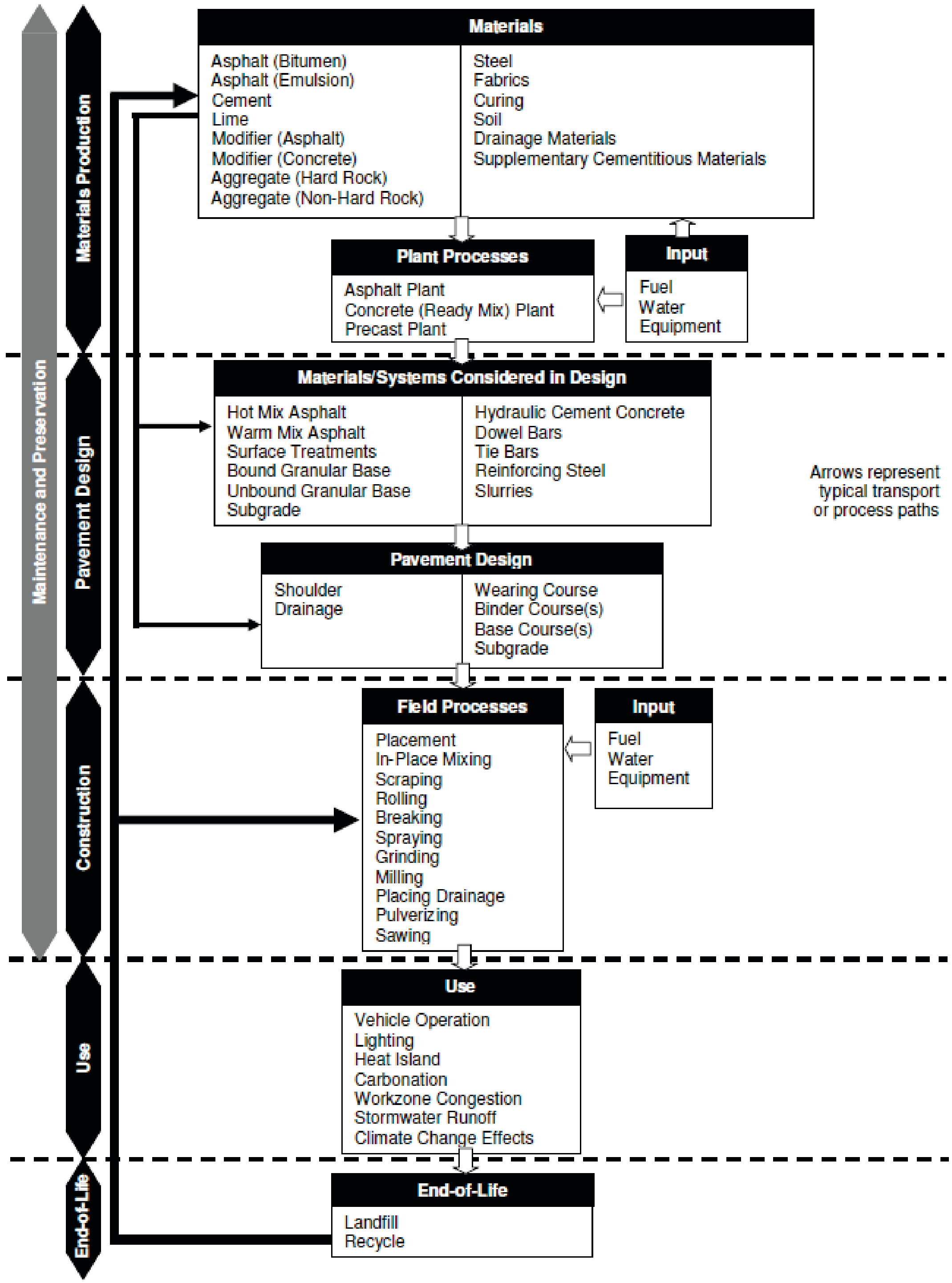

Figure 2-1. Pavement life-cycle phases (UCPRC 2010).

This section introduces each phase, how they are related, and how this document associates pavement-related processes with each of these phases. Most processes are interrelated and can conceivably be included in several different phases. However, this discussion addresses each process primarily within one particular phase. If the process is relevant to other phases, the reader is referred to the primary phase location for its discussion.

Materials Production

Pavement materials production refers to all processes involved in pavement materials acquisition (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing). This document includes plant processes (e.g., production of AC by mixing aggregate, asphalt cement and additives; production of concrete by mixing aggregate, cementitious materials and additives) used in the materials production phase. Materials production affects such sustainability factors as air/water quality, ecosystem health, human health and safety, depletion of non-renewable resources, and life-cycle costs. Chapter 3 addresses materials production and includes discussions on aggregates, asphalt binder, and hydraulic cements, as well as some other common construction materials used in pavement applications.

Pavement Design

Pavement design refers to the process of identifying the structural and functional requirements of a pavement for given site conditions (subgrade, climate, existing pavement structure, traffic loadings) and then determining the pavement structural composition and accompanying materials. Included in this phase are the design processes for not only new pavement design, but also those processes associated with pavement rehabilitation (e.g., structural overlays, bonded/unbonded concrete overlays, crack-and-seat, rubblization). Structural design affects such sustainability factors as performance life, durability, life-cycle costs, construction (e.g., constructability, sequencing, schedule), and materials use. Chapter 4 addresses structural design considerations in detail for:

- **Asphalt pavements**. Asphalt pavements (constructed with AC) that may or may not incorporate underlying layers of stabilized or unstabilized granular materials on a prepared subgrade. These types of pavements are sometimes referred to as “flexible” pavements since the total pavement structure bends (or flexes) to accommodate traffic loadings.
- **Concrete pavements**. Concrete pavements (constructed with HCC) that may or may not incorporate underlying layers of stabilized or unstabilized granular materials. These types of pavements are sometimes called “rigid” pavements.

Designs that are primarily used as maintenance and preservation treatments are addressed in chapter 7, while those that are done at the end-of-life are addressed in chapter 8. Structural designs for gravel and dirt roads are outside of the scope of this document.

Construction

Pavement construction refers to all processes and equipment associated with the construction of pavement systems. Generally, construction activities are associated with initial construction as well as subsequent maintenance and rehabilitation efforts. For the purposes of this document, construction activities are confined to actions and equipment within the project limits as well as materials transported to the project site. Production of mixtures (most notably AC and HCC) is addressed in the materials production phase. Construction activities affect such sustainability factors as air and water quality, human health and safety, durability, and work zone traffic delay, as well as project costs and time. Chapter 5 addresses construction activities in detail and includes equipment, construction sequencing, work zone traffic delay, and construction processes.

Use

Pavement use refers to interactions with vehicle operations and the environment. A number of key pavement factors (e.g., roughness, viscoelastic energy dissipation, deflection, macrotexture) can have large effects on most sustainability metrics, including fuel economy, vehicle operating costs, and associated GHG emissions and energy use. Environmental interactions (e.g., stormwater disposition, heat capacity/conductivity, and reflectivity) can also impact other sustainability factors such as human health and safety, the urban heat island effect, and radiative forcing on a global scale. Chapter 6 addresses use factors in detail, including rolling resistance and vehicle fuel consumption, safety, noise, heat island effect, lighting, and stormwater.

Maintenance and Preservation

Pavement maintenance and preservation refer to actions that help slow the rate of deterioration of a pavement by identifying and addressing specific pavement deficiencies that contribute to overall deterioration. This document classifies the following as maintenance and preservation: sealing, patching, seal coats, chip seals, thin overlays, in-place recycling of pavement surfaces, diamond grinding, load transfer restoration, and concrete pavement repairs. Maintenance and preservation impacts sustainability factors such as performance life, durability, life-cycle costs, construction (e.g., constructability, sequencing, schedule), and materials use. Chapter 7 addresses maintenance and preservation treatments.

End-of-Life

Pavement end-of-life refers to the final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its useful life. This document classifies the following as end-of-life considerations: full-depth reclamation, recycled materials including reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA), and landfilling. Specific materials, designs, and construction techniques associated with end-of-life treatments are covered in other chapters, whereas the treatment and disposition of the material itself is addressed by chapter 8. End-of-life considerations impact sustainability factors such as waste generation and disposition, air and water quality, and materials use.

Measuring Sustainability

Sustainability measurement is an evolving area of research within both the pavement and transportation fields, as it is in other areas as well (e.g., consumer products). Inconsistencies associated with definitions, system boundaries, and valuations generally make it difficult to compare the few measurement efforts that have been done to date with pavements. Currently, four general measurement tools, or methods, tend to be used either in isolation or in concert to quantify various aspects of sustainability: performance assessment, LCCA, LCA, and sustainability rating systems. Notably, there are few, if any, generally accepted metrics able to measure equity/social impacts associated with pavement systems. All the above mentioned approaches are introduced in this chapter. Chapter 10 describes in more detail the approaches and methods used for measuring and assessing pavement sustainability.

Performance Assessment

Performance assessment involves evaluating pavement performance in relation to its intended function and specified physical attributes deemed necessary to meet that function. Metrics that provide information for performance assessment vary but include traditional condition and distress ratings (e.g., roughness, rutting, cracking, faulting), composite condition rating systems, pavement structural capacity, material design attributes (e.g., thickness, asphalt content, compressive strength, gradation), as well as mechanisms to compare these attributes to expected or design parameters. Most often, performance is addressed in relation to the current standard practice; for instance, if the current standard asphalt pavement surfacing is expected to last 15 years, the value of alternative surfacings (e.g., open-graded, stone matrix, rubber asphalt) are determined based on how their projected service life compares to the standard 15 years. While it may be a narrow view (since it does not consider added benefits), the most common sentiment is that alternatives must perform equal to or better than the current standard practice.

Because performance assessment is a longstanding method of evaluation and is essentially built into current standards, it is not addressed in detail as a measurement tool in this document. However, this document makes frequent reference to pavement performance as a critical consideration in choosing between alternatives.

Life-Cycle Cost Analysis

LCCA is an analysis technique that uses economic analysis to evaluate the total cost of an investment option over an analysis period. As such, it is principally used to address the economic component of sustainability. The underlying assumption is that the benefits of considered alternatives are equal, and thus only costs (or differential costs) must be considered. LCCA does not address equity or environmental issues (e.g., environmental justice, clean air/water, habitat impacts) unless such issues can be monetized and treated purely as costs. Guidance for using LCCA as a decision-support tool was promulgated in the National Highway System (NHS) Designation Act of 1995 for large NHS projects (those greater than $25 million) but later rescinded in the 1998 Transportation Equity Act for the 21st Century (TEA-21) (Walls and Smith 1998) based on a perceived lack of guidance. Nevertheless, many government documents and agencies recognize the utility of LCCA and related financial analyses (e.g., Executive Order 13123, OMB Circular No. A-94) and most highway agencies practice LCCA (largely guided by Walls and Smith, 1998) to some degree in selecting pavement type for major projects (Rangaraju, Amirkhanian, and Guven 2008). The most prevalent LCCA software tool is the FHWA's *RealCost* program (FHWA 2011).

Life-Cycle Assessment

LCA is a technique that can be used for analyzing and quantifying the environmental impacts of a product, system, or process. The International Organization for Standardization (ISO 2006) states that LCA is a process that "addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition, through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle to grave)."

LCA is a field of science that is still very much evolving, yet it has demonstrated real-world value over the last two decades by helping manufacturers, companies, governments, and other groups identify what is environmentally important to them and then to define needed action to lower those environmental impacts. It is widely used for material profiling and is increasingly being looked at for use in a number of applications, one of them being pavements. LCA is very powerful in that it relates environmental impacts to the overall performance of a system (such as a pavement) over the lifespan of the application and over a wide set of environmental performance indicators. This systematic approach identifies where the most relevant impacts occur and where the most relevant improvements can be made while identifying potential trade-offs to other life-cycle phases or impact categories.

Rating Systems

A sustainability rating system is essentially a list of sustainability best practices with an associated common metric. This metric, usually expressed in terms of points, quantifies each best practice in a common unit. In this way, the diverse measurement units of sustainability best practices (e.g., pollutant loading in stormwater runoff, pavement design life, tons of recycled materials, energy consumed/saved, pedestrian accessibility, ecosystem connectivity, and even the value of art) can all be compared using a common unit (points). In its simplest form, a rating system can count every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used. In more complex forms, rating systems weight best practices (usually in relation to their impact on sustainability or priority), which can assist in choosing the most impactful best practices to use given a limited scope or budget. Currently, there are a number of national and international rating systems available in the transportation community.

Integrating Measurement Systems

The previously discussed methods can be used alone or in concert to measure sustainability. Using them in concert provides a more holistic assessment of sustainability since each system tends to either address one specific component of sustainability in detail or address all components in less detail. For instance, performance assessment can provide a quantitative assessment of fitness for use, but does not address cost or environmental impact. LCCA and LCA could supplement a performance assessment by providing quantitative assessments of cost and environmental impact. Using performance assessment, LCCA, and LCA in concert can provide a good, yet still incomplete, picture of the overall sustainability impact of a pavement system. It is incomplete because (1) there are no common existing systems that provide quantitative assessments of social issues associated with pavements, and (2) it can be unclear how to relate the values obtained from performance assessment, LCCA, and LCA (i.e., which is most important and to what degree?). Rating systems can address these issues to some extent in that they attempt to incorporate all components of sustainability and usually relate them to one another using a common point system. However, in order to do this, they tend to sacrifice detail, and the inclusion/exclusion of sustainability best practices and their relative weighting within a rating system is somewhat subjective.

Ultimately, the sustainability measurement systems used depend upon the priorities and limitations of the agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems. For instance, a statewide GHG reduction goal lends itself to using LCA as a pavement system metric both for accounting and process improvement purposes. Or, a strategic DOT goal to improve or communicate sustainability (however, the DOT chooses to define it) may favor the use of a rating system that takes a broad view of sustainability. Furthermore, it is also possible to target certain credits within a rating system for accomplishment based on agency or project goals (Muench, Armstrong, Allen 2012). In other words, rather than creating a new rating system from scratch to be used as an internal performance metric, an agency could use an existing one and target those credits that are consistent with its strategic sustainability goals.

Reasons to Measure Sustainability

The reasons to measure sustainability can be placed in three broad categories: accounting, decision support, and process improvement. Each of these is described in more detail below.

Accounting

"Accounting" refers to measurement for the sole purpose of quantifying. Usually this is in response to a reporting requirement, most often associated with GHG reporting and reduction limits. While initial cost has long been measured, there are currently no broad regulations within the U.S. to quantify sustainability. In Europe, quantification is more advanced with some owners requiring GHG or energy assessments, even for competing alternatives considered in design. In the U.S., it is likely that any future initiatives or mandates involving GHG emissions inventories will require measurement of GHG emissions at the national, state, agency, or project level. These initiatives/mandates can be broadly classified as:

- **National Environmental Policy Act (NEPA) requirements for large GHG emitters**. The draft guidance from the Council on Environmental Quality (CEQ) states: "…if a proposed action would be reasonably anticipated to cause direct emissions of 27,500 tons (25,000 mt) or more of CO_2e GHG emissions on an annual basis, agencies should consider this an indicator that a quantitative and qualitative assessment may be meaningful to decision makers and the public" (Sutley 2010). Generally, 27,500 tons (25,000 mt) is beyond what even a large paving project would generate. However, paving may play a smaller role in projects that meet or exceed the 27,500 tons (25,000 mt) criterion (Sutley 2010).
- **State GHG reduction mandates and reporting registries**. At least thirty states have some sort of official GHG reduction mandate, while forty-two have some form of reporting registry (i.e., they report GHG totals but not all are mandated to reduce them) (Center for Climate and Energy Solutions 2012). As state governments continue to flesh out these mandates and reporting requirements, they will have to take inventory of their GHG emissions at some level. While this may not initially involve pavements, their eventual inclusion cannot be discounted.
- **Cap-and-trade**. Various cap-and-trade initiatives are predicated on the ability to inventory GHG emissions. While a federal cap-and-trade program is not likely to be implemented in the near future, many agencies have entered into various cap-and-trade programs including the Western Climate Initiative (WCI), the Midwest Greenhouse Gas Reduction Accord (MGGRA), and Regional Greenhouse Gas Initiative (RGGI).

In general, these initiatives are at a high level, and it remains to be seen how their requirements will be interpreted to apply to pavement systems and the traffic which they support.

Decision Support

"Decision support" refers to measurement done to obtain quantities or qualities that can help in making organizational or project decisions. Results of multiple alternatives are often compared but may not be used to improve individual alternatives or processes. Decision-support tools can be mandated (e.g., many states require LCCA for pavement projects above a certain size) but many are not. Based on the language of the current U.S. transportation bill (Senate and House of

Representatives 2012), the use of LCCA may become even more prominent in the future. Pavement management systems (PMS) are an example of a decision-support tool that most states and large owner agencies possess. They measure pavement condition and track new construction, rehabilitation, preservation, and (in some cases) maintenance actions in an effort to identify appropriate rehabilitation/preservation/maintenance treatments and their timing in order to optimize pavement network condition. Decision support using LCA and sustainability rating systems is in its infancy in the U.S. transportation industry; there are a few systems publically available but their current use is, generally, experimental. However, it should be noted that the use of LCA (and its predecessors) for decision support in other industries has a history dating back to at least the 1960s.

Process Improvement

"Process improvement" refers to measurements that provide feedback data in support of refining and updating the overall methodology. Measurements can be compared to benchmarks or other indicators and then processes can be altered or modified to produce better results. Process improvement is one of the stated purposes of the FHWA's *Infrastructure Voluntary Evaluation Sustainability Tool* (INVEST) sustainability self-assessment tool (FHWA 2012) and the New York State DOT's *Green Leadership in Transportation Environmental Sustainability* (GreenLITES) program (NYSDOT 2012). Currently, process improvement as it relates to sustainability is not mandated and the use of measurement tools is minimal, but such use may be increasing.

Trade-off Considerations

Since sustainability is a broad systems characteristic encompassing virtually every impact a system has, most pavement features and qualities can be argued to support sustainability goals in one way or another. However, it is unlikely that all such features can be included in a pavement, either because some features support one sustainability objective but are in opposition to another, or because some features are mutually exclusive. For instance, an open-graded friction course (OGFC) may be desirable because it reduces tire-pavement noise and provides health benefits to the surrounding area (supports the social/equity component), but the same surface may also have a much shorter performance life (especially in the presence of studded tire wear), which would make its life-cycle cost substantially higher than a more traditional dense-graded AC surface (in opposition to the financial portion of the economy component). As another example, it may be desired to incorporate recycled materials in a rural paving project, but the nearest source of recycled material is 100 mi (161 km) away while an acceptable local extracted material is only 5 mi (8 km) away. In these instances, it is necessary to analyze the available options within the context of sustainability in order to make the best choice.

Essentially, this choice between multiple alternatives represents a consideration of "opportunity cost," the cost of an alternative that must be foregone in order to pursue a certain action (Investopedia 2012). In the previous example, if the local extracted material is selected in favor of the non-local recycled material, the difference in value between the two represents an opportunity cost. The difficulty is in determining the value of the alternatives in a sustainability context. In classic economics, value is usually expressed in monetary units (i.e., dollars). However, value in a sustainability context can have many different metrics expressed in many different units, some of which may be controversial or difficult to quantify. Some examples of sustainability value include life-cycle cost, GHG emissions, energy use, water/air quality, waste generation, scenic views quality, art, community context, history, habitat continuity, and performance life. Historically, the value of alternative pavement features has been overwhelmingly based on economics, often being based on initial construction cost alone. While important, initial cost represents an incomplete view of the overall costs and benefits of a particular feature. Even standard LCCA procedures tend to ignore benefits and costs that are not easily monetized.

Ultimately, this consideration of trade-offs is essentially a benefit/cost analysis done in a more holistic sense (i.e., considering more than just economics). This section describes considerations when contemplating trade-offs for pavement sustainability best practices. Or, put differently, this section describes a few key items to be considered when conducting a benefit/cost analysis of sustainable pavement features. Even if benefits and costs are difficult to quantify, it is important to use a consistent approach in analyzing trade-offs to avoid introducing unintended bias. In general, these considerations involve the following: priorities and values of the organization or project, performance, cost, impact magnitude and duration, and risk. None of these considerations is new, so this section amounts to a formal articulation of what they are. These basic trade-off considerations are referenced throughout this document.

Priorities and Values of the Organization or Project

Since sustainability is such a broad system concept, most pavement features support some component goals and may be in opposition to others. Thus, judgment on the sustainability value of a pavement feature depends on the relative value of sustainability components. Therefore, organization or project goals and priorities should be considered in evaluating trade-offs. Ideally these goals and priorities should indicate (1) which sustainability components an organization or project particularly values, (2) an order of precedence for these values, and (3) a plan to operationalize those values and precedence. If sustainability goals and priorities exist and are clearly articulated, the first order trade-off consideration is to favor the feature that best supports those values.

In some cases, LCA can be used to quantify and compare environmental impacts, while in other cases quantification is difficult, if not impossible. In these cases, it may be enough to determine the general duration of impact (that is, does it occur just during construction or is it over the entire life of the pavement) in order to make a decision.

Risk

All pavement sustainability choices involve an amount of risk. Generally, "risk" means that there is some uncertainty regarding the impact and cost of a selected alternative and such uncertainty leaves open the possibility of less desirable outcomes than predicted on average. For instance, a composite pavement may be selected as the preferred alternative because it results in the lowest life-cycle cost among alternatives considered. However, if inadequate bonding is developed between the surface and underlying layers, it may be that performance life is substantially reduced, resulting in a much higher life-cycle cost. Metrics that provide a probabilistic-based analysis (e.g., *RealCost* [FHWA 2011], *Construction Analysis for Pavement Rehabilitation Strategies—CA4PRS* [Caltrans 2008]) can help quantify risk due to uncertainty. Some metrics, like LCA, are only now beginning to incorporate uncertainty into their analysis.

Summary

This chapter provides a general overview of sustainability concepts and describes how they relate to pavements. This includes a basic definition of sustainability and a discussion of why sustainability essentially means "consider everything," yet also explains how its application must fall within the priorities and goals established by the organization. The role that pavements play in sustainability is described in terms of a common proxy (GHG emissions), and the key components of the pavement life cycle (materials production, pavement design, construction, use, maintenance and rehabilitation, and end-of-life) are also presented. The chapter concludes with summary of current methods for assessing sustainability and a general framework for considering potential issues and trade-offs.

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CHAPTER 3. MATERIALS CONSIDERATIONS TO IMPROVE PAVEMENT SUSTAINABILITY

Introduction

This chapter reviews materials used for paving applications, and how these materials affect the overall sustainability of the pavement system. Included in this review are aggregates, asphalt materials, cementitious materials, and other materials that are commonly used in pavement construction. Recycled materials are introduced, with more detailed information provided in chapter 8. Some construction quality considerations are also introduced, but these are discussed in more detail in chapter 5.

The impacts of material acquisition, processing, and transportation are discussed and presented in the context of how they influence pavement life. The scope of this chapter is from the extraction of materials to the point where materials begin final transportation to the construction site, either from the final processing plant (e.g., the stockpile for aggregates being used for base or subbase construction) or from the exit gate of the mixing plant (in the case of asphalt or hydraulic cement concrete production). In the latter case, it includes the mixture design and proportioning, as well as the plant operations to the point where the material is placed in trucks for transportation to the pavement grade. The disposition of the materials once they leave the plant is considered in chapter 5.

Materials and Consideration of the Life Cycle

Pavement materials should be assessed from a life-cycle perspective to determine the role they play in contributing to the sustainability of a pavement system. A life-cycle perspective allows decision makers to examine potential economic, environmental, and social impacts that may occur throughout the life cycle, and also to evaluate potential trade-offs. Some typical questions that arise with regards to pavement materials and overall decision making include:

- What are the sustainability goals of the organization specifying the materials, and are they compatible such that a clear set of criteria can be used when making materials decisions?
- For a selected life-cycle time period, what is the total life-cycle impact resulting from using a paving material only once versus using it multiple times?
- If a recycled, co-product, or waste material (RCWM) is used in a pavement construction project:
  - Does the RCWM result in equivalent structural or durability behavior as the material being replaced such that performance is not compromised? Does sufficient knowledge regarding performance exist that this question can be answered with confidence?
  - Does the RCWM have to be processed or transported long distances such that the impact on sustainability of the processing or transportation is greater than the benefits to sustainability of using it?
  - Does the inclusion of the RCWM make the resulting material difficult to recycle in the future?

Recycled, Co-Product, or Waste Materials – What's the Difference?

– Recycled materials are obtained from an old pavement and are included in materials to be used in the new pavement. Common recycled materials include reclaimed asphalt pavement or recycled concrete pavement. Depending on the regional market, these materials would be "waste" if not recycled, ending up in a landfill. Allocation of environmental impact between the manufacture of the original material and its reuse in the new material is based on the processing needed to make this material suitable for use in the new pavement. The demolition of the existing pavement and its transportation to a processing plant is allocated to the old pavement.

– Co-products are derived as part of another process—often industrial but possibly agricultural—that brings value to the overall process. For pavement applications, some of the most common co-products result from the production of pig iron for steel making, including slag cement and air-cooled iron blast furnace slag aggregate. Allocation for co-products is based on some agreed upon approach, but most often is based on economic worth of the various co-products.

– Wastes are materials that normally would be sent to a landfill, for which the cost of transport and processing is the only source of economic value. If the material has value beyond this, it is no longer considered a waste, but instead a co-product. Recycled asphalt shingles is an example of one such waste material as long as the economics stay consistent with the above definition. The classification of fly ash is more complex, as in some regional markets it would fit the definition of waste whereas in other markets it is clearly a co-product because it has economic value beyond the cost of transport and disposal.

- Does the constructability of a particular material increase the variability of performance in the field and, if so, does it increase the risk that it must be replaced more frequently?
- Does specifying a longer lasting material offset the impact of longer transportation distances or higher production-related impacts?
- Are specifications that limit the use of lower impact materials effective in reducing the risk of poor performance, or do they prevent the opportunity to improve the overall sustainability of a pavement project?
- Is the pavement designed to make the best use of lower impact materials without compromising performance?
- Can the impacts of transporting materials be reduced by improving logistics and through greater permitting of local materials? Can transportation impacts also be reduced by targeting the use of higher grade materials in the wearing course and lower quality local materials in the other layers?

These are just a few of the questions that transportation professionals often face when making material choices to improve the overall sustainability of a pavement over the life cycle. Others will be apparent in the discussions presented in this chapter.

Chapter Overview

The primary materials used in pavement applications include aggregates, asphalt materials and mixtures, hydraulic cement materials, and other assorted materials (e.g., steel, fibers). Each of these materials is addressed in this chapter as a separate section, with parallel sections introducing the material, describing the issues associated with its use, outlining strategies for improving its sustainability, and describing future directions and emerging technologies. Again, the focus is on aspects of the material processing and production, and includes consideration of RCWM materials.

Aggregate Materials

Introduction

Major Issues:

- ✓ *Environmental and social implications of aggregate acquisition and transportation.*
- ✓ *Special concerns regarding aggregate processing.*
- ✓ *Implications of aggregate durability.*
- ✓ *The utilization and performance of RCWMs as aggregates.*

Aggregates make up the largest share of the mass and volume in a pavement structure, whether used without a binding material (e.g., unbound subbase or base material), or as part of an asphalt or hydraulic cementitious bound layer. Although aggregates are relatively low cost and have a low environmental impact per unit mass relative to other materials that are used in pavements, they can have a significant impact on pavement sustainability because they are consumed in such large quantities. The U.S. Geological Survey (USGS 2013a) terminologies for different sources of aggregates used in pavements are *crushed stone* and *construction sands and gravels*. The majority of crushed stone and construction sands and gravels produced in the U.S. are used for roads. Crushed stone is defined as aggregate taken from hard rock quarries (often by blasting) and then processed through crushing to desired sizes. Groundwater may need to be pumped off depending on the depth of the quarry and the level of the water table, which can affect water tables in the surrounding areas. The biodiversity of a quarry site can be improved from pre-quarry to after-quarry use when proper remediation or restoration efforts are put in place.

Construction sands and gravels are predominantly mined from alluvial sources, usually by scraping or bucketing directly from the deposits. Some alluvial sources are in existing waterways, such as rivers and lakes, in which case removal of the sand and gravel can affect water quality and change stream flow patterns (speed, volume, and connectedness of channels). This, in turn, can affect aquatic habitat and can also change scour and the sediment-carrying capacity of streams. Other alluvial sources are from historical flood plains that do not currently hold water. In either case, large quantities of material are permanently removed, leaving deep pits across large areas of land that require remediation either to restore stream flow characteristics or to make dry land pits suitable for other purposes. Sands and gravels are often, but not always, processed through crushing to obtain the desired sizes and surface textures for road base and for mixing with asphalt or hydraulic cement.

Aggregates from both sources (hard rock quarries and alluvial deposits) must also be transported within the site and mechanically sorted by particle size by sieving, both of which are processes that consume energy. Aggregates are categorized by particle size as being coarse or fine. Typically, coarse aggregates are those retained on the No. 4 (4.26 mm) sieve, and fine aggregates are those that pass that same sieve. For unbound bases and subbases, material passing the No. 200 (0.075 mm) sieve is often referred to as *fines* whereas in asphalt mixture production those materials are most commonly referred to as *dust* or as *filler*. For concrete production, it is desirable to eliminate aggregates smaller than sand size from the gradation. This often requires washing the aggregates, which can consume significant quantities of water and affect water quality.

Aggregate Usage and Economics

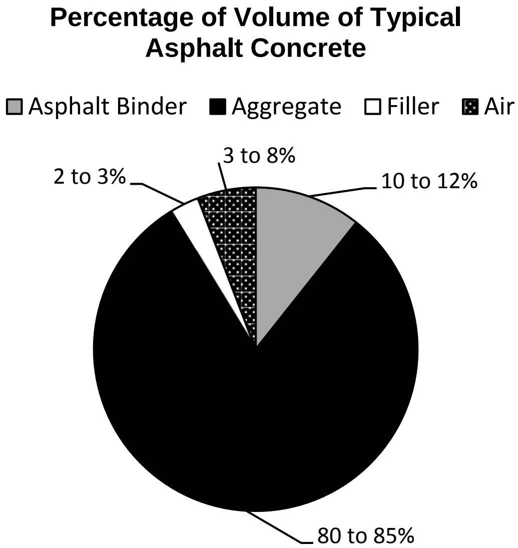
In the U.S. in 2012, approximately 1,324 million tons (1,200 million mt) of crushed stone worth approximately $12 billion was produced by 1,550 companies operating 4,000 quarries, 91 underground mines, and 210 sales/distribution yards in all 50 states. Of the total crushed stone produced in 2012, about 69 percent was limestone and dolomite, 14 percent granite, 7 percent traprock, 5 percent miscellaneous stone, and 4 percent sandstone and quartzite (USGS 2013a). Limestone is also used in the manufacture of most hydraulic cements including portland cement as well as being used as the aggregate in concrete and asphalt mixtures and for base and subbase layers. Granite and traprock (such as basalt) are used extensively as aggregate in both concrete and asphalt mixtures. Of the portion of total crushed stone production reported by use in 2012, 82 percent was used as a construction material, mostly for road construction and maintenance and 10 percent, for cement manufacturing (USGS 2013a).

In the U.S., approximately 927 million tons (840 million mt) of construction sand and gravel worth $6.4 billion was produced in 2012 by an estimated 4,000 companies from about 6,400 operations in 50 states (USGS 2013a). It is estimated that about 43 percent of construction sand and gravel was used as concrete aggregates, 26 percent for road base and coverings and road stabilization; 12 percent as construction fill; and 12 percent as asphalt concrete aggregates and in other asphalt-aggregate products (USGS 2013a).

As shown in figure 3-1, aggregates account for 80 to 85 percent by volume of typical asphalt concrete and 62 to 68 percent by volume of hydraulic cement concrete (Tayabji, Smith, and Van Dam 2010).

About 42 percent of the aggregates consumed by weight in the U.S. have been processed through crushing (Moray et al. 2006). These are mainly used in highway applications. As shown in figure 3-2, crushed aggregates, whether from crushed stone (hard rock mining) or construction sand and gravel (alluvial mining), are more angular than aggregates obtained from natural sand and gravel deposits. Crushed faces on aggregates are required for use in unbound aggregate base courses and asphalt mixtures as they interlock and provide stability to the layer under loading. They are also used for higher strength concrete mixtures as the increased roughened surface area provides enhanced bonding of the hydrated cement paste to the aggregate. In concrete mixtures, uncrushed rounded sand and gravel often provides better mixture workability, and is acceptable for use in concrete provided that the required strength and other specified property requirements are met.

In general, processing to achieve crushed aggregates consumes more energy and releases more GHGs during extraction and production than unprocessed sand and gravel aggregates. This is because manufacturing crushed stone requires drilling, blasting, and crushing, while production of unprocessed sands and gravels does not. Energy consumption and the release of GHGs for construction sands and gravels that are processed through crushing falls between that for crushed stone and unprocessed construction sands and gravels.



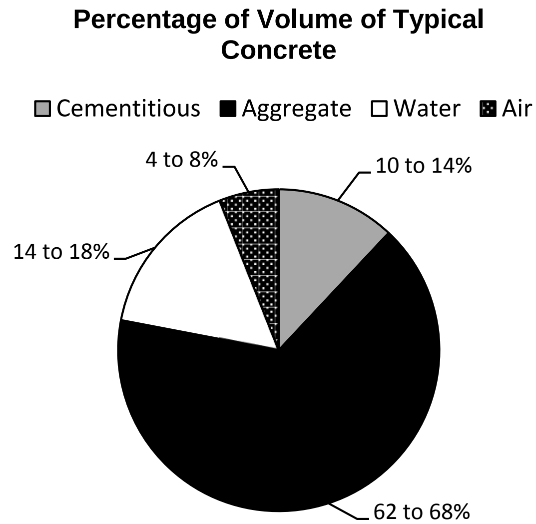


Figure 3-1. Typical volumes of aggregate in dense-graded asphalt concrete and in dense-graded hydraulic cement concrete (asphalt concrete: summary of mixture designs by authors; concrete: Tayabji, Smith, and Van Dam 2010). (Note: Aggregate for dense-graded asphalt concrete includes all sizes, whereas aggregate for concrete typically excludes sizes smaller than sand.)

Figure 3-2. Coarse aggregates: rounded gravel (left) and crushed stone (right) (Kosmatka and Wilson 2011).

Another group of aggregates that are used in highway construction are manufactured aggregates. Manufactured aggregates are those that are created specifically to possess a unique property (such as expanded shale and clay to create lightweight aggregates), or are a co-product of another process (such as crusher fines, foundry sands, or slag aggregates). Manufactured lightweight aggregates are rarely used in pavements, but are occasionally used in bridge structures. An emerging application of lightweight aggregates is to provide a source of internal moisture for curing concrete (ACI 2013). In that application, part of the natural sand is replaced with fine saturated lightweight aggregate (SLWA) to enhance strength gain and minimize early-age cracking of concrete (Bentz and Snyder 1999; Henkensiefken et al. 2009).

From a sustainability perspective, it is convenient to combine manufactured aggregates with recycled materials into the RCWMs category that was defined earlier. Thus, the following aggregates are classified as RCWMs:

- Reclaimed asphalt pavement (RAP) – RAP is most often produced when existing asphalt concrete layers are cold milled from an existing asphalt pavement as part of a rehabilitation or maintenance overlay, and the removed materials stockpiled for use in a new asphalt pavement, base, or subbase. While the predominant use is in new asphalt pavement, RAP is commonly used in aggregate bases, and coarse fractionated RAP is being used as aggregate in new concrete. More details on the use of RAP are provided later in this chapter and in chapter 8.
- Recycled concrete aggregate (RCA) – RCA is created when concrete is purposefully crushed to create aggregates for use in subbase, base, or paving (asphalt or concrete) applications. RCA often contains previously unhydrated cement that produces increased stiffness in bases/subbases when mixed with compaction water, creating a material with superior properties compared with virgin aggregates (Chai, Monismith, and Harvey 2009). When used as base or subbase, both the coarse and fine RCA are often used. In new concrete, it is most common to use only the coarse fraction of the RCA as the fines significantly increase water demand and also have a disproportionately high concentration of chlorides if recycled from pavements subjected to chemical deicing. RCA is discussed in greater detail in chapter 8.
- Recycled asphalt shingles (RAS) – Although predominately used as a source of reclaimed binder, RAS also provides fine aggregate for use in new asphalt concrete mixtures. RAS is discussed in detail later in this chapter.
- Air-cooled blast furnace slag (ACBFS) – ACBFS is an industrial co-product from iron blast furnaces in which pig iron is extracted from iron ore and the remaining molten material (slag) is directed into pits where it is allowed to cool in air. Once cooled, this material is crushed and can be used as aggregate for subbase and base applications, in asphalt concrete, and in concrete. Two recent publications provide more details on the use of ACBFS as an aggregate material in concrete (Morian, Van Dam, and Perera 2012; Smith, Morian, and Van Dam 2012).
- Steel furnace slag (SFS) – SFS is a co-product of the manufacturing of steel. The properties of the SFS, and thus the suitability for it to be used in pavement applications, are largely controlled by the method of processing. While most SFS can readily be used in asphalt pavements, some SFS is not considered suitable for use in concrete as it may lead to undesirable expansion and deterioration. Further, the expansion potential of some SFS has resulted in damaging expansion of unbound base or subbase material. As a result, SFS must be tested and its properties understood prior to use in a pavement structure to ensure that damaging expansion will not occur (Chesner, Collins, and MacKay 1998).
- Foundry sand – Waste foundry sand is generated by the ferrous and nonferrous metal casting industries. It can be used as a partial replacement of fine aggregate in concrete, in asphalt concrete mixtures, and as engineered fill material. As a waste material generated through an industrial process, the impact on mixture performance must be fully studied, as must the potential for leaching of heavy metals.

Regardless of the aggregate grouping, the extraction (e.g., mining, dredging, milling), processing (crushing and sieving), and transport of aggregates consumes energy and generates emissions from the fuel consumed by equipment and vehicles, and often from the electrical grid. Furthermore, fugitive dust is produced and water resources are utilized and impacted. Figure 3-3 summarizes the environmental burdens of mining and processing crushed aggregates and natural aggregates from a number of cited sources. Energy consumption and GHG emissions (in terms of Global Warming Potential [GWP]) included in the figure are calculated based on the lower heating values of consumed fuels and the electrical grid mix of the specified region (CA – Canada; SE – Sweden; CH – Switzerland; FI – Finland, US – United States) as identified by different life cycle inventories (Ecoinvent 2011; Stripple 1998; Häkkinen and Mäkelä 1996; Athena 2006; Marceau, Nisbet, and VanGeem 2007). An examination of each inventory data source indicates that the production of crushed stone consumes more primary energy (meaning the total energy burden including the production of energy resources) than the production of gravels and sands. That energy use will increase as the amount of crushing of the alluvial gravels and sands is increased to meet tighter material specifications for crushed faces on the aggregate, which improves the performance of asphalt materials and aggregate base materials.

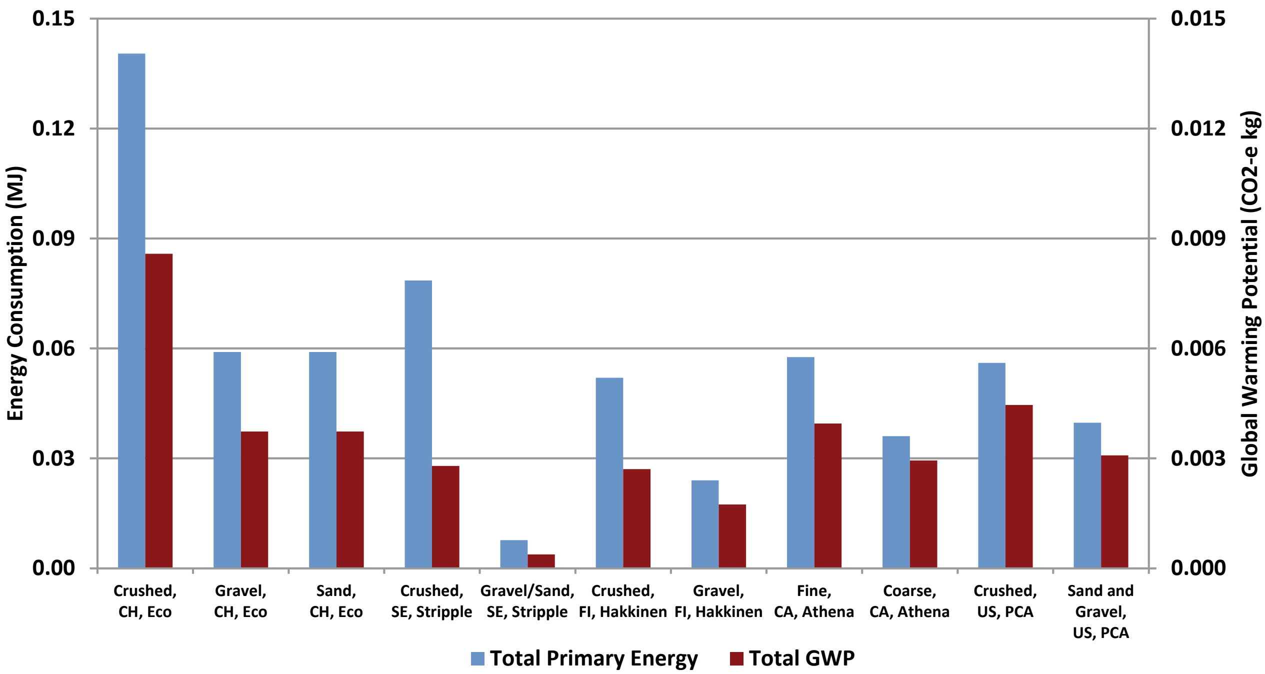


Figure 3-3. Primary energy and global warming potential from aggregate production per kg, at quarry (adapted from Wang et al. 2012). (Notes: 1. Energy consumption shown here excludes the production of capital goods such as construction of dams, power plants and transmission lines; 2. CO_2e per MJ is different for each case, depending on the electrical power production mix and fuels consumed).

The environmental burden of energy consumption depends largely on the source of the energy (e.g., coal, oil, gas, hydro, nuclear, renewables). Energy consumed in the production of aggregates includes transportation within the quarry and processing plant using earth moving equipment and trucks that are primarily powered by petroleum products, and conveyors powered by electricity. Another major component is the crushing and sorting equipment, which are typically powered by electricity. Electricity is usually drawn from the regional grid although in some cases the electricity may be produced on site through fossil fuel powered generators. As fuels that power electrical grids vary considerably by region and country, energy intensity, environmental emissions, and water use will vary as well. The regional electricity grid can affect the life-cycle impacts of aggregate production, or any other product, and must be considered when calculating or interpreting life-cycle impacts or comparing sources of materials.

Accounting for water consumption for electricity generation is an important topic and not always a straightforward issue. Energy produced in power plants by thermoelectric systems evaporate water during the cooling of the condenser water and hydroelectric plants evaporate water off the surface of the reservoirs (Torcellini, Long, and Judkoff 2003). There are differences in modeling storage water for hydroelectric facilities, turbine, and cooling water; a specific example is the net water consumption at hydroelectric facilities. This consumption is primarily related to the evaporation rate from the associated reservoir. This rate, which is a function of surface area, local climate, and other factors, is a challenging value to ascertain. Not only is the science complex and evolving, but is also highly variable between locations. These complexities are apparent when comparing different life-cycle inventory (LCI) datasets for hydropower (e.g., Ecoinvent, GaBi).

Another major source of environmental burden associated with aggregate is transportation. Aggregate must be transported from the source to the job site for unbound bases and subbases, and transported to the mixing plant for asphalt bound materials and hydraulic cement concrete (if the plant is not located at the quarry) and then to the project site. Transport-related impacts primarily involve the burning of petroleum-based fuels in trucks or other transport vehicles. The energy use and GHG emissions from transport can be larger than those from mining and processing, especially if trucks are used instead of more fuel efficient transportation modes such as rail or barges. Table 3-1 shows the relative fuel efficiency for the three primary modes of aggregate transport: truck, rail and barge. The values shown in the table are gross estimates that provide a first order comparison; actual fuel use will vary based on the specific mode technology used, load magnitude, percent of empty back haul, and topography.

Table 3-1. Summary of estimated national average freight movement fuel efficiency[1] (diesel) of freight transportation modes (2009 data) (Kruse, Protopapas, and Olson 2012).

Mode	Ton-Miles/Gallon
Trucks[2]	150
Rail	478
Inland towing	616

Notes:

1. This is gross fuel use, not life-cycle fuel use.
2. Truck load assumed to be 25 tons (22.6 mt) on a 40 ton (36.28 mt) gross vehicle weight truck, loaded one way.

Other environmental issues arising from aggregate mining, processing, and transportation include dust pollution, groundwater use, noise, pavement damage and traffic safety issues on roads leading to and from the source, and quality of life issues for residents and plant/wildlife subjected to those impacts. For these reasons, it can be a long and difficult process to obtain permits for aggregate quarries and pits, sometimes taking 10 years or more.

Because of these challenges, new aggregate quarries in some areas are located further away from the urbanized areas where aggregates are most often needed, increasing the environmental burden of aggregate transport to the main locations of consumption. In some areas, suburban sprawl has occurred on prime aggregate sources making it even more difficult to get permits, or the encroaching development results in reduced operating hours and other restrictions on existing quarry operations. For example, the California Geological Society (CGS 2012) has documented the anticipated scarcity of aggregate supplies in California over the next 50 years. Some urban areas that have river, lake, or sea access (such as Detroit, the San Francisco Bay Area, Chicago, Los Angeles) overcome this problem by importing aggregate to urban processing plants using low-impact marine transportation, sometimes from foreign countries over very long distances.

Strategies for Improving Sustainability

Some general approaches to improving pavement sustainability with regard to aggregate production, and the trade-offs that should be considered are summarized in table 3-2. A brief discussion of some of the major strategies to address these issues is summarized next.

Strategy: Reduce the Amount of Virgin Aggregate Used

There are two approaches that can be utilized to achieve Strategy No.1. The first is to increase the volume of recycled material used as aggregate. Pavement recycling is discussed in detail in chapter 8, but it is noted again here that a wide variety of RCWMs (e.g., RAP and RCA) can be effectively used as aggregate in pavements. The use of these materials often requires additional knowledge and care in processing, handling, and proportioning of the aggregate to ensure performance. Although it is attractive to introduce RCWMs into a paving project as a "sustainable" aggregate solution, this may lead to reduced sustainability if done without consideration of the effects that those materials have on the performance of the pavement. Thus, the use of a given RCWM for a given application must be carefully considered to achieve a balance between the following:

- Availability – Is the RCWM locally available compared to the natural aggregate being replaced? In many cases suitable RCWMs are readily available and are less expensive or similarly priced. But in those cases where a local source of the RCWM is not available, it may require long distance transportation that may result in increased cost and environmental damage. Thus, local availability must be considered before requiring the use of a certain percentage of RCWMs.

Table 3-2. Approaches for improving aggregate production for pavement sustainability.

Aggregate Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce the Amount of Virgin Aggregate Used	Use more aggregates derived from RCWM sources.	Can potentially reduce cost, and preserve scarce or difficult to permit virgin sources. May increase cost depending upon availability, transportation, or processing required; reduce ability to recycle in the future; durability; special pollution problems (pH, toxicity, contaminants).	Dependent on characteristics of RCWM, considering transportation, processing, ability to recycle multiple times, special pollution problems.	Preserves virgin sources. Can reduce need for new sources and associated impacts. Reduces need for new landfills. Potential for negative impacts depending upon transportation, processing requirements.
	Use more durable aggregate, maximizing pavement life.	May increase initial cost, decrease life cycle cost.	Dependent upon transportation distance if not locally available.	Primarily dependent upon transportation.
Reduce the Impact of Virgin Aggregate Acquisition and Processing	Review environmental impact and remediation plans of different aggregate sources when permitting (handled via the NEPA guidelines or equivalent environmental impact review [EIR] and permit process in many states).	Dependent upon requirements imposed by permit. Most permit processes do not consider impacts of locating quarries outside of the jurisdictional area and importing the aggregate (transfer of impacts).	More sustainable features for quarry may come from permitting process.	More sustainable features for quarry may come from permitting process.
	Implement processing and mining operations using less or lower impact energy sources and less water.	Will often result in initial cost increase due to changeover and life cycle cost decrease due to greater energy efficiency.	Will generally reduce environmental impact.	Will often reduce societal impact.
Reduce the Impact of Aggregate Transportation	Use locally available materials or those using a low impact mode for transportation (next item).	Will often reduce initial cost, may increase life cycle cost if there are significant differences in durability.	Will often reduce environmental impact.	May increase impact for those near local source production and transportation locations.
	Minimize transportation impact by maximizing use of marine/barge and rail transport and minimizing truck transport.	Will often reduce cost.	Will usually reduce environmental impact.	Will usually reduce societal impact, focusing it on marine and rail routes reducing noise, safety issues compared with road transport.
	Facilitate permitting of aggregate sources and processing sites near major use areas.	Will generally reduce cost due to reduced transportation cost.	Will usually reduce environmental burden due to reduction in truck transportation.	Will increase impact on those living near mining or processing sites.

- Experience – Is the local contracting community experienced in using RCWMs in the application and volumes that are being considered? It is well known that many RCWMs act differently during construction than natural aggregates, depending on the use and application. For example, if coarse aggregate RCA is to be used as a replacement for natural coarse aggregate in concrete, the RCA stockpile must be kept wet during mixture batching (ACPA 2009). This is not a common practice in some locales and omission of this important step can lead to mixing problems and performance issues. Similarly, RAP can be added to asphalt concrete mixtures at much higher levels than most current practices allow, but additional care must be taken throughout the entire mixture design and construction process to minimize durability and workability difficulties, such as processing to reduce variability within the stockpile, and screening into separate size graded or "fractionated" stockpiles. Providing additional information, training, and support to the contracting community may be required to develop local expertise on the use of RCWMs for different applications.
- Performance – Although the potential exists for the volume of RCWMs in a given application to be increased, there is also an increased risk that pavement performance will suffer if care is not taken to understand the impacts of increased RCWM aggregate volume on mixture performance. For example, in recent years as technology and understanding have improved, the maximum amount of RAP used in asphalt concrete mixtures has increased well beyond what had traditionally been specified. Yet there is a point beyond which increased RAP volume may have a negative impact on the long-term performance of the pavement, perhaps stiffening the mixture and adding a source of variability that can be difficult to manage. A good understanding of the material and the use of mechanistic-empirical design and appropriate laboratory testing and specifications is needed to design pavement structures without increasing risk. In addition, the use and application must also be considered, as "too much" RAP may create a mixture that is too stiff and brittle for a thin overlay surface mix, yet the same percentage of RAP might be much less than can be used for thick structural layers located below the surface where the increased stiffness is needed to reduce bottom-up tensile stresses (see chapter 4 for more information).

Illinois Tollway's Experience with RCWMs

The Illinois Tollway System is comprised of four toll roads including the Tri-State (I-94/I-294/I-80), Jane Addams Memorial (I-90/I-39), Reagan Memorial (I-88), and Veterans Memorial (I-355), collectively routes carrying more than 1.4 million vehicles per day and connecting Northern Illinois, Wisconsin, and Indiana. The Tollway has been enhancing the transportation infrastructure of Chicago Metropolitan area through major programs such as Congestion Relief (2004-2016) and Move Illinois (2012-2026). The major objectives of these programs are to enhance regional mobility, save drivers' time and money, and create jobs while adopting materials and construction sustainability plans. The Tollway requires 100 percent recycling of concrete and asphalt pavements to be reused in new pavements. The levels of asphalt binder replacement (ABR) in asphalt mixtures are typically 40-60 percent. High levels of ABR are achieved by Tollway contractors due to good construction practices such as RAP fractionation, inclusion of RAS, and utilization of the fine portion of fractionated RAP. WMA has been used in all large volume asphalt paving and overlay applications including warm mix stone matrix asphalt (WMSMA). The Tollway has recently implemented two-lift or composite concrete pavements. Large volumes of two-lift concrete, as high as 3,000,000 yd^2, are expected to be used on I-90 reconstruction over the next 4 years starting from 2014, which will allow for high levels of RCWM use in the non-exposed lower lift.

> Improvements in understanding and technology continue to push the limit on RAP replacement levels, but additional research is required to provide better design and construction information for wide-scale adoption of elevated RCWM replacement levels.

The increased use of RCWMs as aggregate for bases and subbases and in asphalt concrete and concrete mixtures offers a significant opportunity to increase the overall sustainability of pavements. The key to effectively implementing this approach is increased understanding and improved technology. Understanding is needed to appreciate how the inclusion of higher volumes of RCWMs will impact constructability and long-term performance. Improvements in technology will help address current limitations as well as provide better understanding of how these materials perform.

A second approach that can be employed to reduce the amount of aggregate used over the life cycle is to improve aggregate durability. Durability is not an intrinsic material property of the aggregate, but instead reflects the ability of the material to maintain its integrity when exposed to service conditions. Aggregates can degrade due to physical processes (e.g., wetting and drying, freezing and thawing) or chemical processes (e.g., alkali-silica reactivity [ASR] in cementitious materials) or may just interact poorly with the binding agent (e.g., moisture susceptibility in asphalt mixtures). Premature pavement failure due to durability issues can have significant environmental, economic, and social costs.

A suite of laboratory tests are used to assess the durability of aggregates for various applications. Some common tests include:

- AASHTO T 104/ASTM C88, *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate* – This test is a surrogate for general aggregate soundness.
- AASHTO T 161/ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* – This test assesses the aggregates' resistance to freezing and thawing.
- AASHTO T 303/ASTM C1260, *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)* – This test, along with ASTM C1293, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*, assesses the aggregates resistance to ASR.
- ASTM D4792, *Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions* - This test is used as a measurement of durability for steel slag.
- AASHTO T 283/ASTM D4867, *Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures* – This test method evaluates an asphalt mixture's susceptibility to moisture damage.

There are many other tests for various applications. Some are used exclusively by a local or statewide transportation agency whereas others are documented in national standards. The key is recognizing that the durability of the aggregate has a big impact on the future performance of the pavement and that adequate testing of aggregates is needed in order to avoid unanticipated failures.

In addition, there are standard practice documents to help guide pavement practitioners through the process of selecting durable aggregates. For example, AASHTP PP 65-11, *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*, can be used to guide a practitioner through the recommended testing sequence and to develop a reasonable ASR mitigation strategy for a given pavement project.

As high-quality, durable aggregates become increasingly scarce, it is important to require only that level of durability that is needed for the specific application. Requiring “premium” aggregates for every application is not prudent, but instead is wasteful and contributes to the scarcity of those durable aggregates that are needed for the most severe environment, contributing to associated high economic and environmental costs. With the use of appropriate specifications, pavement durability can be ensured in a cost effective and more sustainable manner.

Strategy: Reduce Impact of Virgin Aggregate Acquisition and Processing

The first step in reducing the impact of virgin aggregate acquisition is to review environmental impact and remediation plans of different aggregate sources when issuing permits. This is typically conducted under NEPA guidelines or equivalent environmental impact review (EIR) and permit process conducted in many states. Most permit processes do not consider the potential for increasing the environmental impacts of locating quarries outside of the jurisdictional area caused by the need to transport aggregate over longer distances. A permitting process that establishes a broader analysis has the potential to reduce the likelihood of unintended consequences of transferring impact and therefore may improve the overall sustainability of aggregate acquisition.

Aggregates must uniformly possess the size and properties needed to ensure performance within the pavement structure. Uniformity is controlled by the parent material, the extraction operation, transportation, and handling during construction. Other attributes of the aggregate can impact the required processing energy and emissions, including the type of equipment used and aggregate hardness. In particular, the type and size of the crusher has a large impact on the size and shape of the aggregate particles. Efforts must be exerted to optimize the crushing operations to create aggregates possessing the size and shape needed for the application while minimizing waste by avoiding the production of an inordinate amount of fines (known as crusher fines). Many aggregate sources require washing to be suitable for use in some applications and thus issues of water use, reuse, and quality must be addressed. Noise and dust from aggregate processing also have environmental and social impacts.

Strategy No: Reduce Impact of Aggregate Transportation

High-quality aggregates often must be transported over long distances to meet localized demands. In some cases, these aggregates are being imported hundreds and even thousands of miles from other states and even from other countries (e.g., Mexico and Canada on the west coast, Bermuda on the east coast, Central America in the Gulf region). This can have a significant economic and environmental impact, especially if the major mode of transportation is by truck. Additionally, as previously mentioned, the expansion of existing aggregate pits and quarries and the development of new ones are becoming increasingly difficult, particularly in environmentally sensitive areas or in the vicinity of human habitation. Priorities for protecting local habitats and local communities must be weighed against the disruption of habitat and communities elsewhere, along with increased environmental impacts associated with long-distance transport.

Approaches to reduce the impact of aggregate transportation include increased use of locally available materials. This includes both natural sources of aggregates as well as the use of locally available RCWMs including RCA, RAP, and ACBFS. A key element of this approach is to ensure that the aggregate meets the durability requirements specifically for the application. For example, aggregates used in lower layers of a pavement—whether an asphalt mixture (e.g., base and binder layers) or concrete (the lower lift in a two-lift concrete pavement)—do not need to possess the same resistance to wear and polishing as those used in the surface layer. This consideration can be used to reduce the need to import wear resistant aggregates from greater distances at a higher cost.

Another approach is to minimize transportation impact by maximizing the use of marine/barge and rail transport and minimizing truck transport. As indicated previously in table 3-1, truck transport is significantly less efficient compared to marine/barge and rail transport. Facilities have been established in a number of urban centers that have marine access to specifically handle and stockpile aggregates, thus supplying the urban market. Further, continued growth in rail facilities will result in increased efficiency and reduced cost and environmental burden.

The final approach listed is to facilitate permitting of new aggregate sources and processing sites near major use areas. This approach will result in lowering the impact of aggregate transport, with the trade-off of potentially operating aggregate sources within more populated areas thus increasing negative social impact. The use of advanced aggregate acquisition and processing strategies can minimize this impact, but cannot completely alleviate it.

Issues/Future Directions/Emerging Technologies

Issues, future directions, and emerging technologies for enhanced sustainability of aggregates in transportation include:

- Increased shipping of aggregates by truck from long distances increases emissions, energy use, and noise, whereas local quarrying of aggregates has implications for land use, noise, dust, and other factors. As local aggregate sources are exhausted and the development of new sources stymied by community opposition, pressure will be exerted to use aggregates with less desirable characteristics. This could affect the long-term performance of pavements.
- Increasing pressure to use higher volumes of RCWMs will likely renew pressure to make complete use of <u>all</u> materials from a construction site (e.g., current practice often is to waste crushed concrete fines, but their use may be highly encouraged in the future). Further, pressure to use non-conventional RCWMs (such as steel slag aggregate or recycled glass, for example) may also increase. If done without sufficient research, the increased use of RCWMs may compromise pavement performance unless it is accommodated in the design stage and utilizes effective construction practices.
- As readily available sources of aggregates of the highest quality become exhausted, the use of "marginal" aggregates will increase. In many cases, these aggregates can be used without negatively affecting pavement life. Yet if such aggregates are used inappropriately, premature pavement failures will likely occur.

- Specialty aggregates are at times needed to fulfill a specific need driven by a sustainability goal. For example, highly durable aggregates will be needed on an exposed aggregate surface, or a light-colored aggregate may be specified to increase surface reflectivity to reduce lighting requirements. In addition, other aggregates might be sought to improve the quality of the pavement material such as saturated, lightweight fine aggregate added to cementitious mixtures to enhance curing.

Asphalt Materials and Mixtures

This section reviews the manufacture and transportation of asphalt materials. It summarizes generic asphalt mixture types and provides a brief overview of their uses, design, and plant operations. Sources of environmental impact are identified in the exploration, extraction, and transport of petroleum, the refining of petroleum into asphalt binder, the modification of the binder, the transport of all materials to the plant, and the combining of the materials at the plant where asphalt mixtures are made. Discussions of mixture design, proportioning, and plant operations are also included, while specific construction considerations are presented in chapter 5 (except as it is affected by materials selection and mixture proportions).

Long-term binder availability and sources of cost variability are also discussed in this section. Introduction of recent innovations that are changing the face of the asphalt paving industry are presented, including WMA and high binder replacement mixtures using RAP and RAS.

Asphalt Materials Usage and Economics

The U.S. used approximately 130 million barrels (23 million tons [21 million mt]) of asphalt binder and road oil in 2011, worth $7.7 billion, according to the US Energy Information Administration. In the recent peak years of 1999 and 2005, nearly 200 million barrels were consumed (EIA 2011). According to the Asphalt Institute, approximately 83 percent of asphalt binder used in the U.S. in 2011 was used for paving purposes (Grass 2012). In the U.S., more than 92 percent of all paved roads and highways are surfaced with asphalt products. The U.S. has about 4,000 plants producing asphalt mixtures with total production of about 452 million tons (410 million mt) in 2007 (NAPA/EAPA 2012) and about 396 million tons (359 million mt) in 2010 (Hansen and Newcomb 2011). The value of asphalt paving mixtures produced in the U.S. was estimated at $11.5 billion in 2007 (U.S. Census Bureau 2007a).

Introduction

Asphalt materials, are sticky, black, highly viscous liquids or semisolids that consist of the heavier and more polar molecules that are present in many crude petroleum sources (AI 2007). Asphalt materials may be found in natural deposits where geological conditions have left primarily asphalt-type material mixed with fine dust material, such as Trinidad Lake (Trinidad, West Indies) and La Brea (Los Angeles), or distributed in rock formations, such as in west Texas. Some forms of these natural asphalt material deposits may be used directly in pavement construction and maintenance.

However, the vast majority of asphalt material used for pavement comes from petroleum refineries that produce gasoline, kerosene, diesel, and lubricating oils, among other products. Petroleum residues from the distillation of crude oils are the starting materials for asphalt material production. Of the multitude of crude oils commercially available, only a limited number are considered suitable for producing asphalt materials of the required quality in commercial quantities. In general, heavy (specific gravity >0.9) crude oils are used to produce asphalt materials of the required quality. These types of crude oil tend to contain high sulfur contents (>1 percent by mass). Asphalt residues, as a fraction of suitable crude oils, typically range between 20 to 50 percent by mass, and a smaller percentage by volume because of the heavier specific gravity of asphalt materials compared to other materials made from crude oil (Asphalt Institute and Eurobitume 2011).

Major Issues:

- ✓ *Continued increase in price of petroleum, and thus asphalt, which is a finite resource.*
- ✓ *Appropriate use of polymer, rubber, and other types of binder modifiers.*
- ✓ *Depletion of high-quality aggregates needed for some type of mixtures.*
- ✓ *Specialization of mixtures for safety, noise, and structural considerations and their environmental and cost implications.*
- ✓ *Use of RAP and other RCWMs including asphalt shingles, recycled tire rubber, and sulfur.*
- ✓ *Environmental, social, and cost implications of mixture design and durability.*
- ✓ *Future binder availability and alternatives.*

Asphalt material is typically produced by removing the lighter hydrocarbon molecules through a combination of vacuum and heat, or by mixing with a solvent such as propane. The source of crude oil can have a significant effect on the energy and environmental impact of a specific asphalt material as the processes needed to extract, process, transport, and refine it to produce asphalt material and other products will vary with the source.

Confusion sometimes arises in the terminology used to describe asphalt paving products. In North America, *asphalt* is taken to be the material refined from petroleum that is then combined with other materials to create products having a variety of names (e.g., asphalt concrete, hot-mix asphalt, warm-mix asphalt). In other countries, the petroleum-derived product is referred to as *bitumen*, and the term *asphalt* refers specifically to certain types of mixtures of bitumen and aggregate. Additionally, the word *tar* is sometimes incorrectly used as a colloquialism to refer to asphalt. Actually, *tar* is a specific material made from destructive heating of organic materials in a process called pyrolysis, and when produced from pyrolysis of coal or petroleum the resulting tar may have negative environmental impacts associated with its use (Mahler and Metre 2011; EPA 2008). Tar mixtures were used for a small portion of the paving done in the United States up until the 1970s and in other countries (NAPA/ EAPA 2012). Tar was attractive as a paving material because it is not soluble in petroleum-derived fuels or lubricants and thus will not degrade in parking or service areas where it may be exposed to fuel or lubricant leaks or spills. As a result, it is still sometimes used as a surface sealant for asphalt parking lots and driveways, even though there are environmental and human health concerns associated with its use because of the carcinogenic nature of coal-derived tars.

Asphalt Binders

In a complex refinery, a broad range of petroleum products is produced, with asphalt material being a minor product compared to the more valuable transport fuels (Bernard, Blomberg, and Southern 2012). Plant design and operations vary for each refinery based on the markets for each product, the characteristics of the crude sources, and prevailing environmental and other regulations. Different processes, such as vacuum/steam or solvent deasphalting, can be used to break the hydrocarbons in crude oil into different products, with each having different environmental and energy impacts. Crude sources can have different composition depending on their location and to a lesser extent on the method of retrieval; this determines which crudes can be recovered economically (e.g., primary, secondary or tertiary recovery from wells, surface deposits, oil sands, hydraulic fracturing), but can also vary with time, depending on market prices for products and the availability and cost of different types of crudes. "Light" and "sweet" crudes, meaning respectively those with less asphalt material and less sulfur, command higher prices because they produce more transport fuels and are generally less costly to refine. In assessing the contribution of refinery operations to the energy and emission of asphalt production, storage of asphalt should also be considered, since asphalt must often be kept at a constant high temperature by heating to pump it through the refinery, in and out of storage tanks, and while in truck or rail transport. This is particularly important in cold climates. Blending of different grades of asphalt to meet specifications, and the production, milling, and blending of polymers, rubber, and other asphalt modifiers also consume energy and produce emissions.

Not all petroleum refineries produce asphalt. Since 1980, the refining industry's emphasis has shifted from growth of operable crude oil distillation capacity to investment in downstream (secondary) processing units, thereby increasing the overall level of refinery complexity (Lidderdale, Masterson and Dazzo 1995). Secondary processing units, such as use of delayed cokers, catalytic crackers, and hydrocrackers, are used to break the portion of the oil that would otherwise be used for asphalt to improve the yields of lighter products. As of January 2013, 56 of 131 oil refineries in the U.S. produced asphalt (EIA 2013).

Asphalt Paving Materials

Asphalt is produced in different forms for use in pavements, which mostly have to do with how the viscosity of the asphalt is reduced (i.e., made more flowable) for construction so that it can coat aggregates or be sprayed onto the surface before reverting to a more viscous or semisolid state prior to opening to traffic. A schematic illustrating the production of asphalt cement is shown in figure 3-4.

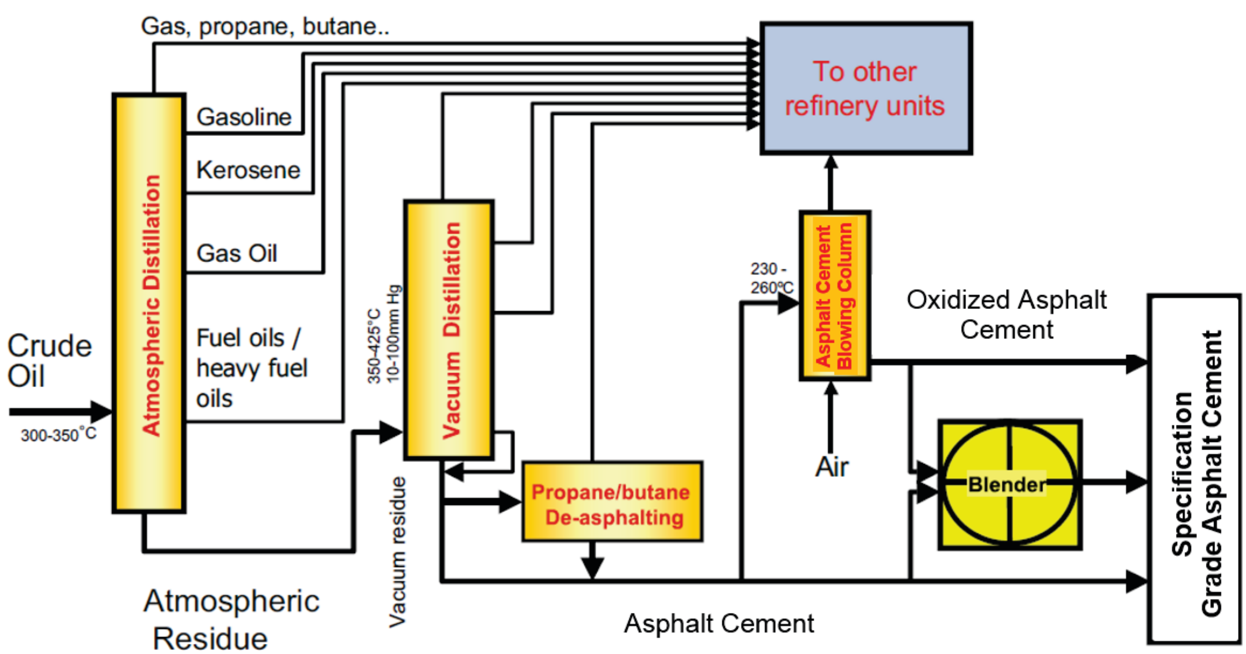


Figure 3-4. Schematics illustrating straight-run distillation of asphalt within a complex refinery (Asphalt Institute and Eurobitume 2011).

The following defines some basic terminology as applies to asphalt paving materials (note that most asphalt and asphalt-aggregate materials have a number of nearly synonymous terms and nomenclatures, varying by specifying agency and sometimes changing over time) (AI 2007):

- *Asphalt cement*, also referred to as *neat asphalt*, *asphalt, or asphalt binder*, is the portion of the crude oil that is used directly in paving. In this form, it is made flowable by heating and then reverts to a semisolid state as it cools. *Asphalt cement* is used as the binder in *hot-mix asphalt*, *warm-mix asphalt*, *open-graded asphalt, stone mastic asphalt*, *chip seals* and as a *tack coat*. It is the asphalt material used to produce *asphalt emulsion, polymer-modified asphalt, rubberized asphalt*, and *asphalt cutback*.

- *Asphalt emulsion* is made by shearing asphalt into microscopic droplets (0.5 to 10 microns) which are mixed with water (typically in ratios between 40:60 and 60:40 asphalt:water) and an emulsifying agent (very small percentages) that keeps the drops in suspension in the water. The asphalt reverts to the semisolid state when the emulsifying agent is neutralized or "breaks," allowing the particles to join together, which is followed by evaporation of the water. Asphalt emulsions are used extensively for surface treatments such as *fog seals* (emulsion and other hydrocarbons), *sand seals* (emulsion and fine aggregate), *microsurfacings* (emulsion, water, fine aggregate, mineral filler, other additives) and *slurry seals* (emulsion, fine aggregate and cement). *Polymer-modified asphalt* and *rubberized asphalt emulsions* are also used for these and other applications. Asphalt emulsion can be mixed with aggregate at an asphalt mixing plant to create *cold-mix asphalt* or in situ for *cold in-place recycling* (CIR).

- *Asphalt cutback* is made when asphalt cement is dissolved in a petroleum-based solvent. Solvents include gasoline or naphtha (rapid curing cutback), kerosene (medium curing cutback) or low-volatility oils (slow curing cutback). These materials are liquid at ambient temperatures with the asphalt cement being reconstituted as the solvent volatilizes after the cutback is spray applied or mixed with aggregates. The modern use of asphalt cutbacks has been curtailed as they produce significant volatile organic carbon (VOC) air emissions, but they are still used in some locales, especially during cooler temperatures or in wetter climates when asphalt emulsions become ineffective. Asphalt cutback can be mixed with aggregate at an asphalt mixing plant to create *cold-mix asphalt* or in situ for *CIR*.

- *Hot-mix asphalt* is produced when heated asphalt cement is mixed with heated, dense-graded aggregates in a plant to achieve a mixture at temperatures of approximately 275 °F to 329 °F (135 °C to 165 °C). HMA is often used as the main structural layer as well as the surface layer in many kinds of asphalt, composite, and semi-rigid pavements.

- *Warm-mix asphalt* represents a broad range of technologies used with asphalt concrete that allow the mixture to stay workable and compactable at lower temperatures. WMA can be used to reduce the mixing temperature and facilitates paving in cooler weather, and also allows longer transportation distances. Utilization of WMA technology can reduce compaction temperatures by approximately 25 to 80 °F (14 to 25 °C) (PAPA 2011). The amount of reduction depends on the WMA technology used and the characteristics of the mix, plant, climate, lift thicknesses, and hauling distance.

- *Open-graded asphalt* is made when asphalt cement is mixed in a plant with the aggregate gradation missing portions of the smaller-sized particles. Open-graded asphalt placed as a thin surface course on top of a traditional asphalt concrete improves surface friction and reduces tire-pavement noise. Open-graded asphalt can also be used to create a permeable base if used below an impervious surface layer or it can be used as the full depth of the paved surface as part of a pervious pavement system.

- *Stone mastic asphalt* (SMA) is created when asphalt cement is mixed with gap-graded aggregates. SMAs are used almost exclusively as surface courses as they are highly resistance to pavement deformation (rutting) in the wheelpaths and top-down cracking.
- A *tack coat* is an asphalt cement, asphalt emulsion, or asphalt cutback sprayed onto a paved surface to assist in bonding asphalt concrete layers together during construction.
- A *prime coat* is used to waterproof and bind together aggregate base surfaces. Sometimes prime coats are made with asphalt emulsions having up to 30 percent slow curing solvent to keep the asphalt liquid longer. Slow curing cutbacks are also used as *prime coats*.
- *Chip seals* are created when an asphalt cement, asphalt emulsion, or asphalt cutback is sprayed onto a granular base or onto an existing pavement surface and followed with the application and embedment of single-size aggregate “chips.” *Rubberized asphalt* is also used for *chip seals*.
- *Crumb rubber modifier* (CRM) is created by grinding recycled tire rubber after stripping out steel reinforcement. CRM can be mixed with asphalt cement, natural rubber, and other ingredients to produce *rubberized asphalt* (ASTM specifies that rubberized asphalt has a minimum 15 percent recycled rubber by mass; AASHTO does not currently have a specification but is working on developing one [RAF 2013]). Rubberized asphalt is used in different types of asphalt-aggregate mixtures for structural and surface layers, and for chip seals. CRM is also used with polymers in *terminal blend rubberized asphalt*, although with no required minimum CRM content and more finely ground particles (Hicks, Cheng, and Duffy 2010).
- *Polymer-modified asphalt* (PMA) is created when, asphalt cement is mixed with a number of different polymers to produce a binder with the properties needed for different applications, most typically with enhanced high temperature performance characteristics.

Co-Product Treatment for Asphalt Materials

Asphalt is one of many co-products produced in oil refineries. Because of the importance of refinery products on the environment and economy, many of these products have been studied using LCA. Each study has had to select a co-product treatment approach. Nearly all rely on allocation, although some have combined subdivision methods with allocation by distinguishing processes within the refinery that can be attributed to particular products while relying on allocation by energy or mass to partition oil extraction and transport impacts and other processes that cannot be reasonably partitioned. Since different refinery products have different fuel contents, weights, or economic values, the method of allocation can have a significant effect on the calculated impact. Different allocations can be applied to different steps in the asphalt production. The extraction and transport of the crude to the refinery is similar for all the products obtained from the crude. At the refinery level, depending on the refinery setup, some processes may be common to some products while other processes are unique to a single product.

Most LCA studies use mass allocation. To help understand the impact, sensitivity analyses are often performed in LCA using alternative allocation methods. Wang, Lee, and Molburg (2004) suggest that the different approaches for allocation for different refinery products can lead to differences in assigned environmental impacts of up to 25 percent. A more recent LCI considering a typical set of crude sources in Northern European refineries has been prepared by Eurobitume for conventional asphalt binders. A hybrid approach using allocation based on mass for parts of the process and economic value for other parts was used to determine the environmental impacts for the cradle-to-gate inventory (Eurobitume 2012; Bernard, Blomberg, and Southern 2012).

Polymer-modified asphalt are used in different types of asphalt-aggregate mixtures for structural and surface layers, and for chip seals. As mentioned, CRM is also used with polymers in *terminal blend rubberized asphalt* (Hicks, Cheng, and Duffy 2010).

- *Cold-mix asphalt* used as a storable patching material most often uses cutback asphalt and/or asphalt emulsion mixed with aggregate and/or RAP.
- *Cold in-place recycling and full-depth reclamation* produce materials that involve mixing RAP that is created in-place with various materials, including asphalt emulsion, foamed asphalt, cement, lime, and other cementitious materials. These treatments are discussed in more detail in chapters 7 and 8.

Mixture Design of Asphalt Concrete

Mixture design for asphalt concrete generally requires the following steps:

- Identification of the function of the pavement layer (e.g., surface drainage layer, surface layer, structural layer, fatigue resistant bottom layer, subsurface drainage layer, base for concrete or asphalt pavement), and selection of appropriate mixture type (e.g., dense-graded asphalt concrete, SMA, open-graded asphalt concrete, rich-bottom asphalt concrete). A decision on whether to use a WMA technology is often also made at this juncture. Open-graded asphalt mixtures used for thin permeable layers on pavement for high-speed traffic are also used as the surface layers for fully permeable asphalt pavements (NAPA 2008).
- Identification of the asphalt material to be used appropriate to the mixture type (conventional, polymer-modified, rubberized, terminal blend rubberized) and the selection of the grade of asphalt. Most paving asphalt used in the U.S. is specified in terms of its Performance Grade (PG), which considers workability, the high-temperature properties important for rutting, and the low-temperature properties important for low-temperature cracking as the binder ages.
- Identification of the aggregate sources having specified properties for the application and testing of volumetric properties to determine the aggregate gradation.
- Selection of the final binder content based on relationships between the binder content and other mixture proportions. These include the risks of too much binder, such as rutting and shoving, which are predominately an issue in the first few years of service before the asphalt stiffens as it ages. Also considered are the risks of too little binder, which include early cracking, raveling, water damage, and inadequate compaction, all of which have additional negative impacts that affect the long-term performance of the mixture.
- Consideration of the amount of RAP or RAS included in the mixture, as these affect the properties of the blended asphalt binder (composed of virgin and recycled binder), the aggregate characteristics and gradation, and the volumetric proportions associated with performance.
- On some projects where the risks warrant additional cost and time, advanced materials characterization is performed on the draft final mixture design to help determine whether it meets the requirements for the project (called *performance-related testing*). The properties measured in many of these tests, such as the complex modulus, can also be

used as inputs to mechanistic-empirical pavement design methods, which are discussed in more detail in chapter 4.

Two strategies for reducing the environmental impacts of asphalt mixtures are to:

1. Increase their performance and therefore increase the time between future maintenance and rehabilitation treatments.
2. Decrease the negative impact of materials in the mixture by reducing the amount of virgin asphalt binder and aggregate through the use of recycled materials such as RAP, RAS, and recycled tire rubber, by minimizing or eliminating those additives that may increase the impact of material production (polymers, virgin rubber, or chemical WMA additives[1], for example), and by changing specifications to permit increased use of locally available but lower quality aggregates. Inherent in the use of these approaches is that overall pavement performance is not reduced or compromised.

These two strategies may contradict each other, with one calling for enhanced durability and the other for the use of potentially less durable materials, and therefore must be balanced. Solutions that are able to achieve both longer life and a reduction in the amount of virgin materials offer the most promise for improving sustainability.

One type of distress that can substantially shorten the life of asphalt pavements is moisture damage, which is amplified when water is able to penetrate the asphalt pavement matrix. Certain types of aggregates carry a much greater risk of moisture damage than others. Lime and liquid anti-strip chemicals are two additives that can reduce the susceptibility of mixtures to moisture damage. Lime is typically added at about 1 percent by weight of mixture (~37.3 lb/yd^3 [22 kg/m^3]), whereas liquid anti-strip agents are typically added at about 1 percent by weight of asphalt cement (~0.24 gal/yd^3 [1.2 l/m^3]). Each additive has its own particular economic and environmental impacts. Lime, for example, has a relatively high GHG emissions footprint as its production requires calcination of calcium carbonate, which uses heat to liberate fossil carbon dioxide, leaving calcium oxide. Liquid anti-strip additives are made from a variety of chemicals, each of which has its own impact on the environmental impact of the mixture.

Mixture Design of Other Asphalt Road Materials

The design of materials for full-depth reclamation (FDR, as well as other forms of in-place recycling), chip seals, and other road materials containing asphalt follow a similar process as that described for asphalt concrete above: identification of the function of the material; review of alternative aggregates, asphalt binder, and other materials to be included in the mixture; selection of final materials based on the existing structure, climate, traffic, and applicable specifications; and optimization of the proportions. For example, chip seals will include consideration of aggregate size, shape, gradation and mechanical durability, determination of whether to use sprayed asphalt or an emulsion and whether it will include polymers or rubber, and selection of the final application rates for the asphalt and aggregate. For full-depth reclamation, the mixture design will include characterization of the in-place materials, selection of stabilization materials

[1] Note that there are a number of WMA technologies that have very different environmental impacts. Those based on chemical additives often have a greater benefit in maintaining compactability at lower temperatures than those based on mechanical water foaming, but chemical additives may also have a higher environmental impact during their production. However, most chemical WMA additives are used in very small amounts, typically 1 percent by weight of asphalt cement (~0.24 gal/yd^3 [1.2 l/m^3]), and thus the overall environmental impact is thought to be small.

Full-Depth Reclamation with Foamed Asphalt

The process of full-depth reclamation (FDR) involves the pulverization of the existing asphalt surface and the recyclable (unbound or chemically stabilized aggregate) underlying materials, to a maximum depth of 12 to 18 in (305 to 457 mm) depending on available compaction equipment and subgrade support, while simultaneously mixing it with a binding material, or less frequently compacting it without stabilization as aggregate base. Binding materials can include a combination of foamed asphalt, cement filler, and water, cement and water, emulsified asphalt, or other cementitious materials. The mixture is graded, compacted, and overlaid after recycling. One type of full-depth reclamation is with foamed asphalt (FDR-FA), which is created when cold water, along with compressed air, is injected into hot asphalt in a specially designed chamber. The water becomes steam when it undergoes the sudden increase in temperature, which becomes trapped in tiny asphalt binder bubbles. This results in a thin-film, high-volume asphalt foam with reduced viscosity and increased coating potential. The foaming state is temporary, and within a few minutes the asphalt binder will assume its original properties. Foamed asphalt has been used effectively as a stabilizing agent in full-depth reclamation (source: http://www.pavementinteractive.org/). FDR-FA has sustainability benefits for lower volume roads (AADT <20,000) including (Caltrans 2012; Fu 2010):

- *Reduced life-cycle costs due to longer service life.*
- *Lower environmental impact due to reduced use of virgin aggregates and reduced landfill usage.*
- *Increased structural capacity.*
- *Reduced use-phase costs through expedited construction and simplified staging.*

Caltrans (2012) and Jones, Harvey, and Halles (2008) provide further details on this topic.

(as appropriate), such as cement, foamed asphalt (typically with a small amount of cement as well) or asphalt emulsion (conventional and fast curing), and final proportions to achieve desired properties that can be tested in the laboratory. FDR is most commonly used on low- to medium-volume routes, but has been used on some high-volume routes such as I-80 in California (over a cement-treated base) and I-81 in Virginia.

The same approach should be used when designing these materials, attempting to find the balance between specifying the use of higher quality materials (which often have higher initial cost and environmental impact) and the use of lower quality, lower cost materials (with a lower environmental impact but potential performance reductions). Thus, the entire life cycle must be considered, not only from an economic perspective but also from an environmental perspective. The ideal solution will be a function of the materials, traffic, climate, and construction processes.

Mechanistic-empirical (ME) design procedures can be used to calculate the anticipated effects of material choices on pavement performance, given detailed material properties, pavement structure information, traffic loadings, and climatic factors. It can therefore be used to investigate the trade-offs due to changes in material that affect the material properties and to see how those changes affect the structural capacity of the pavement over time. If LCA is combined with ME design, together they can be used to calculate the net environmental impact of changing materials properties and performance over the life cycle. Chapter 4 includes more discussion on the use of ME design, and how materials properties are considered in the structural design of pavements.

Warm-Mix Asphalt Technologies

Almost without exception, increasing the density and decreasing the variability of asphalt materials will improve performance. WMA is a relatively new technology being used to increase overall density and lower variability of density, and offering the possibility of lower production temperatures and less initial environmental impact of materials production and construction.

As discussed in chapter 5, increased asphalt concrete density is a result of good specifications and the effective quality assurance (QA) practices regarding compaction that are well known in the industry. This requires attention from both the owner and the contractor. Improved compaction requires no additional materials, and usually requires no additional equipment usage, but rather careful attention to details and effective management of the factors controlling success. Unlike changing mixture design parameters (e.g., changing the binder content in an asphalt concrete material, using a softer binder to improve reflection cracking resistance in an asphalt concrete material, or increasing the cement content of a FDR material), increasing the density of a material by compaction will improve both the rutting and cracking resistance. Further discussion of compaction and other construction operations is included in chapter 5.

As previously described, WMA technologies are used with asphalt concrete to allow the mixture to stay workable/compactable at lower temperatures. WMA may be used for a number of reasons, including reducing mixing temperature, facilitating paving in cooler weather, or allowing longer transportation distances (or combinations of all three).

Most asphalt mixing plants in the U.S. have shifted from diesel or other fuel oil and are now fueled by natural gas, which is primarily used for heating aggregate and asphalt for mixing, and secondarily for drying aggregate (EPA 2000; Cleaver 2011; Carbon Trust 2010). In recent years, a number of asphalt mixing plants have begun burning recycled motor oil as a fuel for mixing and drying, which disposes of this otherwise hazardous material in a safe manner while at the same time offsetting the use of other fossil fuels (EPA 2012). WMA can be used to significantly reduce mixing temperatures, with the amount of reduction depending on the WMA technology used and the characteristics of the mixture, plant, climate, lift thicknesses, and hauling distance (D'Angelo et al. 2008). WMA technologies will reduce the environmental impact of asphalt mixture preparation and paving if they are used to reduce mixing temperature, thus decreasing the fuel consumed to heat the asphalt mixture. The total environmental impact of the use of WMA will depend on the technology used as technologies that use waxes or polymers have associated environmental impact of the additive itself that must be considered, but are also generally more effective than mechanical foaming WMA technologies. Keeping aggregate and RAP sources dry also helps to reduce the energy needed to dry aggregates (Cleaver 2011; Carbon Trust 2010).

The estimated total amount of WMA in the U.S. has grown rapidly over the past several years as shown in figure 3-5. This increase in use reflects the key advantages of using WMA: reducing the fuel used to heat the mixture at the plant, improved mixture compactability, and increased flexibility during the construction phase allowing longer haul distances and extending the paving temperature range.

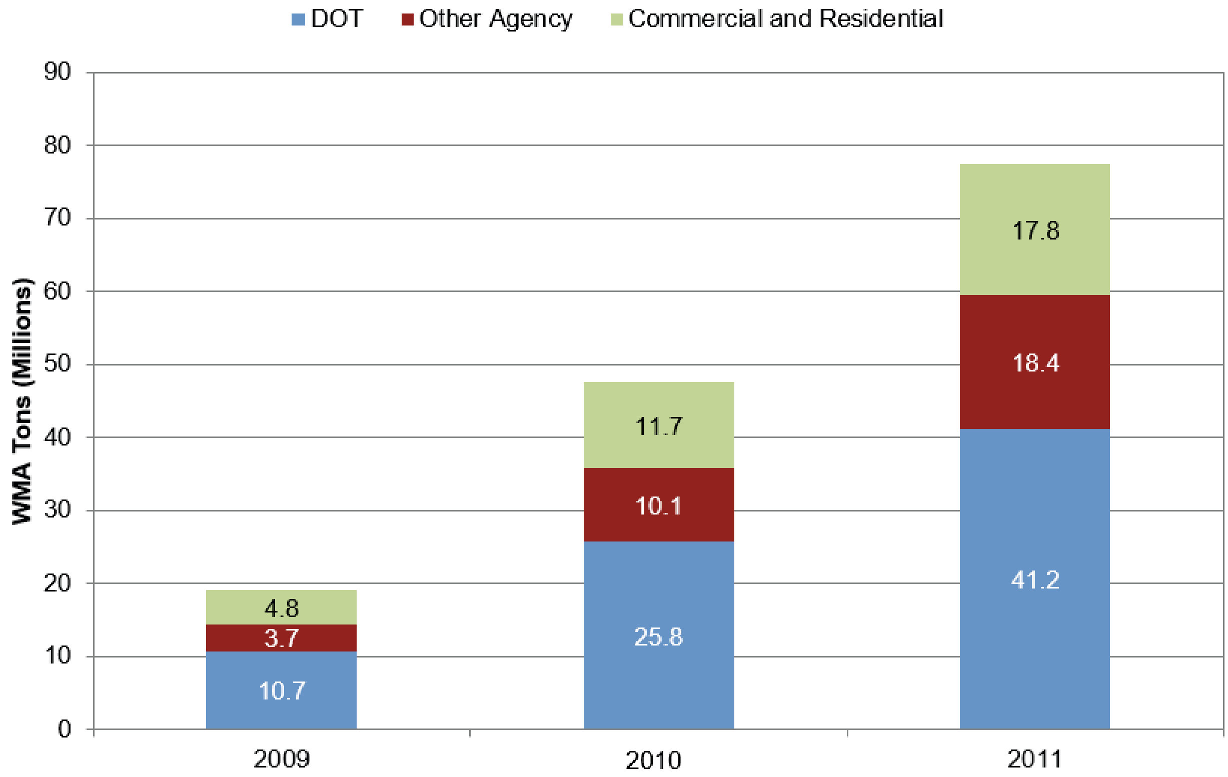


Figure 3-5. Estimated tons of WMA usage by industry sector 2009-2011 (Hansen and Copeland 2013).

WMA technologies are generally grouped into three families: chemical admixtures, chemical foaming agents, and mechanical foaming, the latter of which is most commonly used in the U.S. (Hansen and Newcomb 2011). Chemical admixtures can further be divided into those that change the melting point of asphalt and those that change the coating characteristic of the asphalt. Chemical foaming agents add a chemical that does not change volume as it releases water into the mix. Mechanical foaming of the asphalt cement is accomplished either before the cement is added to the aggregate in a special foaming chamber or after by introducing moisture in the fine aggregates. All of these technologies allow the aggregate particles to orient themselves at lower than normal temperatures while being compacted. The reduction in mixing temperature at the plant depends on the WMA technology used, the materials, the haul distance, and the weather. Current research suggests that WMA does not significantly affect the long-term performance of the pavement, provided all other aspects of mixing and compaction are done appropriately. If asphalt mixing plants are adjusted to use WMA technologies by reducing mixing temperatures, then WMA can potentially reduce energy use. Because good asphalt compaction has such a significant effect on performance, it is possible that the major benefit of WMA is as a compaction aid resulting in increased pavement longevity with longer times between maintenance and rehabilitation activities.

Research regarding environmental benefits for different situations is ongoing. LCIs of WMA chemicals, which would permit consideration of the environmental impacts of their production in an LCA, have not been published to date. Mechanical foaming only uses relatively small amounts of water and involves the initial installation of foaming equipment, which should have minimal environmental impact.

Over the years, there have been a number of studies looking at air emissions and exposure of construction workers to asphalt concrete materials (see, for example, NAPA/EAPA 2012). While WMA technologies are used to reduce the mixing and compaction temperatures of asphalt mixtures, they can also reduce the emissions associated with the hot material that sometimes cause short-term worker irritation during mixing and laydown (there are very few emissions released after initial compaction) (Farshidi et al. 2011). This is especially helpful for rubberized mixtures that otherwise can sometimes generate enough fumes that workers require respirators when paving (Farshidi et al. 2011). Worker exposure and leachate into water are issues to consider when adding any material other than conventionally refined asphalt and aggregate to asphalt concrete.

Although it is far more difficult to document, and less conspicuous than introducing a new material, increasing the density and decreasing the variability of asphalt concrete offers opportunities for significant improvements in performance and consequent environmental benefits. The benefits include less use of currently used materials, which may be amplified in high-traffic situations. Implementation of good QA practices requires investments in human capital and organization, which may pose a particular challenge for smaller contractors and local governments where specialized pavement expertise for effective QA is less available. Moreover, the benefits that come from these investments may be difficult to communicate.

Highest Use for Recycled Materials: Core Concepts

Recycling of used materials can be a good strategy to reduce the need for new materials. Examples are the use of RAP in new asphalt pavement or RCA in new concrete pavement. But it extends beyond aggregates. Depending on the material, secondary uses can include the use as fuel (for example rubber tires), feedstock (for example RAS to displace asphalt binder), or material resource (for example RAP or RCA). In addition to that, the material can be used in the original function (aggregate in asphalt mixture), or in a different function (aggregate in the base). When considering sustainability, the question comes up: what is the highest use for recycled material?

The first step to realize is that defining the highest use is a project-based (or at most a regional) decision. The second step is to make sure that whatever use is intended, it has to perform from a technical perspective. If adjustments need to be made, for example to a mix design, then those adjustments need to be taken into account when making this decision. The next step is to look at other relevant sustainability parameters through an LCCA approach, an LCA approach, and a rating systems approach. The highest use can be synergetic between these three systems, but sometimes it is not. This is what is referred to as trade-offs. Another consideration in defining the highest use is the starting point at which whatever decision is made, and that it should always be made with a life cycle perspective. Not setting appropriate systems boundaries and leaving out life-cycle phases can lead to missing important trade-offs. The implementation approach is presented in a sidebar discussion in chapter 8.

Recycling and Asphalt Road Materials

RAP is an important source of aggregate and asphalt binder for asphalt paving projects. RAP can be used as a replacement for virgin aggregate base, which does not take full advantage of the potential contribution of the asphalt coating the aggregate as a binder. In general, recycled materials should be used for the "highest use," which would be first as replacement for virgin asphalt and aggregate in new asphalt concrete, followed by use in recycled cold-mix materials, followed by use as aggregate base or aggregate in concrete. The asphalt binder in asphalt concrete carries much of the total environmental impact of the mixture because of the impact of petroleum acquisition and refining. Use of RAP in asphalt concrete replaces not only virgin aggregate, but the RAP binder is reused as binder, at least in part, thereby reducing the amount of virgin binder needed in the new asphalt concrete. Thus, RAP use in new asphalt concrete reduces the need for virgin asphalt and aggregate, both non-renewable and finite materials, making asphalt concrete the highest use (i.e., its use displaces consumption of high impact and non-renewable materials) for this material.

The amount of RAP used in asphalt mixtures was 66.7 million tons (60.5 million mt) in 2011, a 19 percent increase over 2009 (56 million tons [50.1 million mt]) and about a 7 percent increase over 2010 (62.1 million tons [56.3 million mt]). Assuming 5 percent liquid asphalt in RAP, this represents approximately 3.6 million tons (3.3 million mt), of virgin asphalt binder conserved, or about 12 percent of the total binder used in 2011 (Hansen and Copeland 2013).

Looking at U.S. data from 2011 (see figure 3-6), approximately 87 million tons (79 million mt) of RAP that was milled from existing pavements was run through asphalt mixing plants that year, with approximately 74 million tons (67 million mt) of the 81 million tons (73 million mt) of RAP (92 percent) recycled into new asphalt concrete materials. For the years 2009 through 2011, RAP that was not recycled into asphalt concrete was used for aggregate base (less than 10 percent annually) and cold mix (less than 3 percent annually). Less than 0.1 percent landfilled (Hansen and Copeland 2013). These figures do not consider asphalt pavement recycled in place.

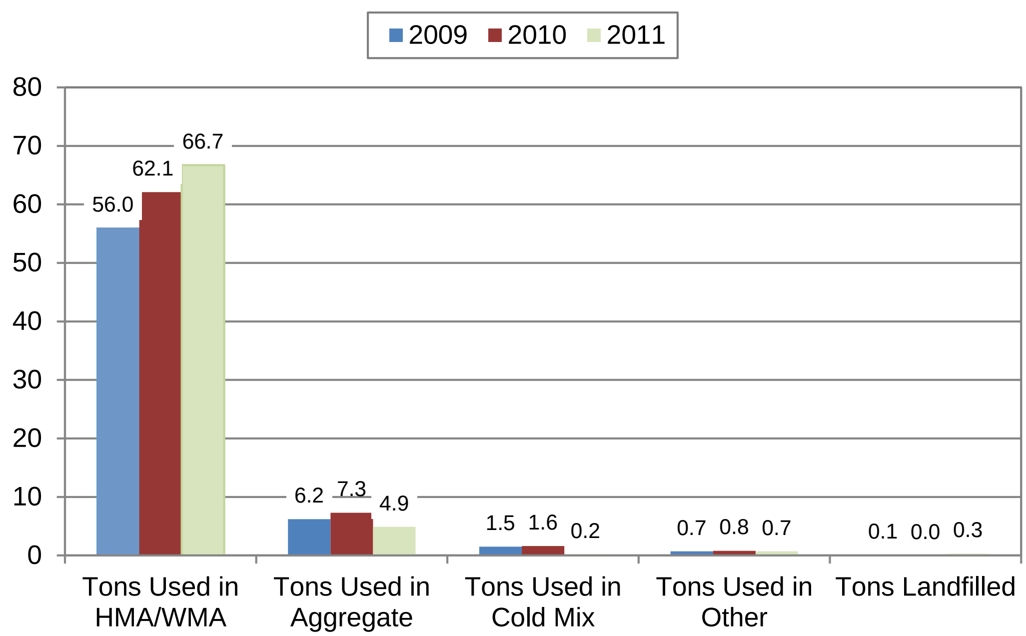


Figure 3-6. RAP use in the U.S., 2009 through 2011 (adapted from Hansen and Copeland 2013).

The characteristics and quality of the aggregate and asphalt in the RAP are dependent on the quality of the original materials, any additional patching or other maintenance materials recovered during milling, and any additional processing that occurs during and after milling and reuse. The effects of moisture-sensitive aggregate, rubber, polymers, or other ingredients in the milled material have not been the subject of intensive research. The variability of the characteristics and quality are dependent on the variability in the milled material, and the amount of crushing, sizing, and reblending that is done to homogenize the material at the plant.

The asphalt binder in RAP, called the residual binder, is generally stiffer and more brittle than virgin asphalt because it has been oxidized through previous heating in the mixer and its atmospheric exposure during service. The latter is particularly true for RAP recovered from older pavements, for RAP in hotter climates, and for RAP obtained from layers near the surface where some of the lighter molecules may have volatilized. The aged residual asphalt binder will stiffen the new mixture, generally improving rutting resistance but potentially increasing the tendency for top-down cracking when used in surface mixtures unless it is well managed through specifications. The stiffer, aged residual binder in RAP can help reduce bending and tensile strains that contribute to bottom-up cracking when used in thicker layers below the surface.

The degree to which the residual binder on the RAP particles blends with virgin asphalt has an important effect on the properties of the new mixture and its performance. The amount of blending is dependent on the properties of the new asphalt, how long and at what temperatures the RAP is heated during its processing, the mixing time, and whether softening agents are added. For example, there is very little blending in cold-mix recycling technologies. The amount of blending that actually occurs in asphalt concrete, its effect on the mixture properties, and how much of the asphalt in the RAP can be considered as replacement of virgin asphalt is a subject of research at this time.

The ability to control particle size and avoid segregation during mixing with virgin materials in an asphalt plant is largely dependent on whether the RAP is sized, or fractionated, and binned into different consistent size gradations (Bonaquist 2011; Christensen and Bonaquist 2006). Controlling particle size is more difficult during in-place mixing processes.

RAP has been used for up to 50 percent replacement of virgin materials in dense-graded asphalt concrete. However, where mixture performance is most critical, such as in asphalt surface layers, the level of replacement is often lower. Many agencies place limits on how much RAP can be used for different applications, depending on their assessment of risk. In general, replacement at up to 15 percent is considered to have minimal effects on properties. Most state highway agencies allow up to 15 or 30 percent replacement for structural layers, and some also allow those amounts for surface layers. The average RAP content in asphalt concrete mixtures in the U.S. in 2009/10 was about 13 percent for state DOT mixtures, 15 percent for other agency mixtures, and 18 percent for commercial and residential paving mixtures (Hansen and Newcomb 2011). Since most asphalt used in asphalt concrete is specified in terms of its PG grade (which accounts for the binder's contribution to rutting, thermal cracking, and fatigue cracking), the method of estimating these properties for the blended (or partially blended) residual and virgin binder is critical.

Increasing the amount of virgin binder replaced through mobilization of the residual binder as part of the new blended binder greatly reduces the environmental impact of the mixture. These benefits are offset somewhat by the additional energy needed to heat the virgin aggregate in the blended mixture to higher than normal temperatures for mixing, because the RAP cannot be heated to normal mixing temperatures without burning the residual asphalt. Instead, for RAP contents up to about 35 percent, the virgin aggregate must be heated to temperatures of 420 °F to 500 °F (215 °C to 260 °C) compared to 275 °F to 330 °F (135 °C to 165 °C) for a mixture made entirely with virgin materials (Kandhal and Mallick 1997; AI 2013). For higher RAP contents it is necessary to ensure that the RAP is dry (stockpiles should be covered) to avoid heat loss in removing water from RAP. Transportation of RAP for use in locations where it is not readily available must also be considered when evaluating energy and environmental impacts because long haul distances by truck have significant cost and environmental impacts.

Use of CRM in Asphalt Binders

The inclusion of CRM from recycled tires in asphalt binders, primarily as rubberized asphalt, has been the subject of extensive research starting in the 1980s. It is used extensively by a few states, primarily in gap-graded and open-graded asphalt concrete and rubberized chip seals. Rubberized asphalt includes at least 15 percent recycled tire rubber. Accelerated pavement testing has demonstrated that a rubber-modified asphalt mix on top of a dense-graded mix can delay or arrest further propagation of bottom up cracks through the rubber modified mix to the surface (Gibson et al. 2012; Jones, Harvey, and Monismith 2008). Field studies in California indicate that rubberized open-graded asphalt mixtures have superior performance to open-graded mixtures with conventional binders in terms of raveling, cracking, and noise (Rezaie, Harvey, and Lu 2012). These mixtures have higher binder contents and are mixed at temperatures that are approximately 18 to 36 °F (10 to 20 °C) higher than conventional binders, both of which increase their environmental impact per unit volume (Bearden and Le 2011). The net effect with the thickness reduction and performance can be calculated through an LCA. An LCA that considered GHG and energy use in one case study demonstrated that full thickness of asphalt concrete and half thickness of gap-graded rubberized asphalt concrete in a thin overlay with similar expected performance had nearly the same materials production impacts, but the half thickness rubberized mix had a lower construction phase impact due to the reduced mass of material that had to be transported to the site (Wang et al. 2012). Similar calculations can be made for terminal blended rubberized asphalt, which is used in some asphalt concrete mixtures and in chip seals. The future effects of increasing quantities of rubberized asphalt in RAP stockpiles on mixture design and performance have not yet been investigated by researchers. Methods need to be developed to determine how much rubberized material exists in a given RAP stockpile as well as understanding of how this material will affect the properties of the new asphalt mixture.

As is discussed in more detail in chapter 7, most in-place recycling is done “cold” or “warm.” CIR consists of milling the top 3 inches (76 mm) of the existing pavement, mixing with asphalt emulsion or cutback and asphalt cement, placement and compaction of the mix, followed by a thin asphalt overlay or surface treatment. It is used in lieu of milling and replacement with asphalt concrete. CIR reduces the thickness of the asphalt concrete overlay needed (or may eliminate it altogether) to obtain the desired life.

Full-depth reclamation, which is discussed in detail in chapter 8, is used for badly cracked asphalt pavement where overlays and surface treatments will not provide much additional life. It consists of pulverizing all of the existing asphalt and part of the aggregate or treated base and subbase beneath it up to depths of approximately 18 inches (457 mm), compaction, and then the placement of an asphalt overlay. FDR can use the pulverized material as an untreated aggregate base, or more commonly, a stabilizer (e.g., small amounts of cement, asphalt emulsion with some cement, or foamed asphalt with some cement) is introduced during the pulverization process. The stabilized FDR eliminates reflection cracking, reducing the thickness of the asphalt overlay needed, and can potentially provide a long life stabilized base with no need for new aggregate (see chapter 8 for more details on FDR).

Hot in-place recycling (HIR) is sometimes performed on existing asphalt pavements, where about 2 inches (51 mm) of the existing pavement is heated, milled, mixed with virgin materials, placed and compacted, all in one pass of an equipment train. Chapter 7 provides more information on HIR.

RAS, obtained from the roofing industry, is another source of recycled asphalt for asphalt concrete. On average, RAS contains about 20 percent asphalt binder by mass compared with about 5 percent for RAP, along with aggregates, mineral filler, and fibers. Approximately 1.3 million tons (1.2 million mt) of RAS were used in asphalt concrete in 2011 (Hansen and

Newcomb 2011), with RAS usage in 2011 replacing about 0.42 million tons (0.38 million mt) of asphalt. To create RAS, shingles are shredded and sorted for use. If shingles were obtained postconsumer (i.e., as part of a roof tear off and replacement), additional sorting is necessary to remove nails and other impurities. Typical use is limited to about 5 percent by mass of the total mixture because of potential for variability, the higher stiffness of roofing asphalt compared to asphalt used for pavements, and the degree to which RAS blends with virgin and residual RAP asphalt. A number of high profile projects have been constructed with mixtures containing both RAS and RAP, including an overlay of Michigan Avenue in Chicago (Illinois Interchange 2012). RAS/RAP mixtures are also being used by the Illinois Tollway to lower costs and reduce the environmental impacts of pavement materials. The EPA (2013a) recently performed a limited LCI and LCA on the use of RAS, evaluating only GHG emissions, and concluded that there are environmental benefits to the use of recycled asphalt shingles in asphalt production for use in road construction, and that the addition of RAS to pavement mixtures containing RAP helps further increase environmental reductions relative to the baseline of using virgin asphalt.

Various polymers are used to improve the viscoelastic properties of asphalt binders, improving the rutting and cracking performance of pavements. Polymer addition is typically 3 percent by weight of asphalt cement (about 0.70 gal/yd^3 [3.5 l/m^3]). Polymers used to modify asphalt are primarily derived from petroleum, and there are a number of different polymers each used for specific purposes. The use of polymer-modified asphalt can improve the performance of pavements, but the manufacturing of these polymers can also increase the environmental impact of the asphalt binder in the mixture, a fact that must be considered when evaluating environmental impacts.

Polyphosphoric acid (PPA) is a polymer of orthophosphoric acid (H_3PO_4). Experience has shown that PPA increases the high temperature stiffness of an asphalt binder to reduce rutting with only minor effects on the intermediate and low temperature properties, and it is typically used as an alternative to polymers for this purpose. Some highway agencies have no restrictions on the use of PPA as an asphalt modifier, while others have restrictions on its use. Work by the FHWA has clearly demonstrated that the increase in binder stiffness from the addition of PPA is crude-source dependent, with anywhere from 0.5 to over 3 percent needed to increase the high temperature binder grade (FHWA 2012a). Other laboratory testing has indicated that there may be some interactions with hydrated lime and an increased potential for moisture damage when more than 1 to 1.5 percent by mass of binder is used. LCI data are available for PPA to evaluate its environmental impact when included in asphalt materials (FHWA 2012a).

In addition to tire rubber (see CRM sidebar), other RCWMs have been recycled into asphalt concrete mixtures, including glass as a replacement for aggregate, slag from metallurgical processing, foundry sands, and recovered sulfur as an asphalt binder modifier. Before utilizing these or other RCWMs, a thorough review of the available information on the RCWM in question should be performed, and an LCI should be used to evaluate potential environmental impacts over the life cycle (this should include an assessment of leachate and volatilization potential as well as worker health and safety). Furthermore, the impact of RCWM use on pavement performance must be considered. One particular issue that should be considered is whether the inclusion of the RCWM places any constraints on the future recycling of the mixture. Even if an RCWM is used in a mixture, aggregate and asphalt will still be the primary materials, and the influence of the additional materials on their repeated recyclability may not be considered in the literature and can only be considered in an LCI if the information is available.

Assessment and Minimization of Environmental Impacts of Asphalt Road Materials

As previously indicated, different asphalt materials and mixtures have different environmental impacts. With regards to binders, the crude source, refining, transport, and the type of binder (asphalt cement, cutbacks, emulsions) all influence the environmental impacts (energy, GHG, air pollution, and so on). The amounts and methods of inclusion of rubber, polymers, PPA, solvents, emulsifying agents, and other binder modify agents will also change the impacts, generally increasing the impact in the materials production stage of the life cycle on a per mass basis.

The type of mixture (e.g., HMA or WMA, dense graded or open graded) and how it is placed (e.g., with a paver or applied as a surface treatment) also affect its environmental impact. Additionally, the type and amount of RCWM that is used, whether RAP, CRM, RAS, or any number of other materials, will likely influence the environmental impact either adversely or positively. An overriding concern is how the performance of the pavement is influenced by changes in the mixture, because a reduction in pavement performance can counteract any environmental benefit that was gained during the materials selection and construction phases. Thus, the overall pavement life cycle must be considered in order to help resolve some of the complexity in the decision-making process.

Other Asphalt Road Material Considerations

Where local or area urban heat islands are an issue (see chapter 6 for details), the solar reflectivity, heat capacity, heat conductivity, and permeability of the pavement may play a role. Ongoing research is being conducted to determine the importance of these characteristics and this phenomenon in different contexts. New asphalt concrete typically has low solar reflectivity, or albedo, on the order of about 5 percent, which means 95 percent of the incident solar radiation is absorbed. However, it tends to become more reflective over time as the asphalt oxidizes and as traffic or other abrasive actions wear the asphalt film off of the surface aggregates, at which point the reflectivity becomes more a function of the color of the aggregate.

Slurry seals are expected to exhibit reflectivity levels similar to the asphalt binder used, although there are little data available. The reflectivity of chip seals is largely dependent on the reflectivity of the aggregate used for the chips. Chips that are precoated with asphalt will have reflectivity similar to that of asphalt concrete materials, with the same type of increase in reflectivity occurring over time. Fog seals and other treatments that place fresh asphalt on the surface will tend to reduce reflectivity for a short period of time. The aggregate mineralogy, and the permeability of the pavement material, will affect the heat capacity and thermal conductivity that can have a significant effect on pavement temperatures, although less so than reflectivity (Li et al. 2013; Stempihar et al. 2012).

Treatments are available for asphalt concrete that can make it more reflective to solar radiation (Tran et al. 2009). Information regarding the environmental impacts of producing those treatments, and their potential effects on performance and future recycling, is not available in the literature. However, if the temperatures in the upper 4 inches (102 mm) of asphalt concrete layers is reduced, the risk of rutting is also reduced, particularly where heavy trucks move at slow speeds in hot climates. Light colored chip seals or other surface treatments that can reduce pavement temperature may help reduce that risk (Pomerantz, Akbari, and Harvey 2000).

Photocatalytic coatings primarily based on titanium dioxide have been developed for asphalt pavements to react with chemicals in the ambient air contributing to air pollution (Dylla et al. 2013; Brovelli and Crispino 2013).

Most pavement materials, including rubberized and polymer-modified asphalt mixtures, have been found to produce no leaching of pollutants into water that exceeds regulatory requirements, even when used with open-graded mixtures and after simulated aging (Kayhanian et al. 2009). Open-graded asphalt materials can potentially be used on pavement surfaces to trap pollutants from vehicles and airborne deposition that might otherwise be carried off the roadway into receiving waters or stormwater systems by rainfall.

Substitutes for Petroleum Asphalt

Petroleum typically contains between 0 and 3 percent sulfur, with the sulfur being removed during processing of "sour" crudes, resulting in an abundance of sulfur. The last decade has also seen a rise in the available sulfur on the market due to the increased use of acid gas wells to produce liquefied natural gas (LNG); sulfur levels can be as high as 35 percent (weight of material) taken from these natural gas wells. Because of this abundance of elemental sulfur, there has been considerable interest in using sulfur as a binder extender. Work on this was first performed in the late 1970s and early 1980s, but interest dropped due to cost and technical/safety reasons (FHWA 2012b). More recently, a new technology, known as Sulfur Extended Asphalt Modifier (SEAM) and recently renamed Shell Thiopave®, has been developed that is intended to function as both a binder extender and an asphalt mixture modifier (Tayabji, Smith, and Van Dam 2010). However, even though Thiopave pellets contain some additives designed to reduce odor and fumes during mixing, temperature control of the mixture and good ventilation practices are still required. Asphalt concrete mixtures produced with Thiopave must be mixed above a temperature of 248 °F (120 °C) for the sulfur pellets to melt and be dispersed throughout the asphalt mixture, but the temperature must remain below 293 °F (145 °C) to avoid the potential for emission generation that can be harmful to both workers and equipment. Furthermore, the location of Thiopave mixtures must be tracked in the field so that it can be properly handled and engineered if it is recycled as RAP into new asphalt concrete materials because of possible worker safety and equipment damage issues.

Research work is underway in the U.S. and other countries evaluating the replacement of petroleum-based asphalt with "bio-binders," which are made from biomass such as tree, plant, and animal waste (TRB 2012). Bio-binders exhibit similar properties to asphalt, such as the ability to flow when heated so they can coat aggregate or be sprayed, and the ability to withstand large strains without cracking. Examples include binders derived from corn stover, the non-food portion of corn (Metwally 2010), swine waste (Fini et al. 2011), algae (TRB 2012), and vegetable oil. One issue is the desire not to use biomass that would otherwise be useful as human or animal food.

Land-produced plant biomass is typically 80 percent cellulose and 20 percent lignin, and lignin can be a source of polymers for use in asphalt. Cellulose is a dense polymer chain of sugar molecules, and lignin is composed primarily of phenolic compounds in a hard, polymer-like structure. Three different types of processes are being evaluated to convert cellulose containing biomass to liquid fuels (King and King 2009):

- Fermentation, in which enzymes convert the biomass to energy, leaving lignins that would need to be further modified to function as paving binder.
- Fast pyrolysis, in which biomass is heated to very high temperatures in the absence of oxygen, breaking down the cellulose and lignin into smaller molecules that might then be processed into liquid fuels and possibly asphalt.
- Gasification, in which biomass is converted to combustible gases using newly developed processes similar to coal gasification technology.

Currently, there are some bio-binder products available on the market, although none have replaced a significant amount of paving asphalt in pavements built for state DOTs. No LCA publication was found in the literature on any of these bio-binders that considers the net life-cycle effects of the materials production, construction, use, and end-of-life phases.

Strategies for Improving Sustainability

Some general approaches to improve sustainability with regard to asphalt materials (and the trade-offs that should be considered) are summarized in table 3-3. It is noted that very little quantitative analysis of the net effects of these possible sustainability-improving practices has been evaluated using LCA procedures that would consider the materials production, construction, use, and end-of-life phases. A brief discussion of the identified strategies is provided below, and it is noted that many of these strategies reduce life-cycle costs as well as environmental impacts while enhancing overall social good.

Strategy: Reduce Amount of Virgin Asphalt Binder and Virgin Aggregate in Asphalt Concrete by Plant Recycling

The extraction and production of virgin asphalt binder from petroleum, a finite resource, is one of the major sources of environmental impact for asphalt concrete. The technology for performing mixture designs with increased percentages of reclaimed asphalt materials, such as RAP and RAS, and the use of binders modified with CRM from waste tires, is rapidly improving as is the design technology for using these mixtures in a manner that does not compromise the performance of the pavement.

Strategy: Reduce Energy Needed and Emissions from Mixing Asphalt Concrete

Use of warm-mix technology can potentially reduce the energy needed to produce asphalt concrete, and can also reduce the emissions. However, this does depend on the type of WMA technology employed and how it is used. The environmental impact of producing alternative WMA technologies has not been clearly established. Changing the fuel used in production (e.g., from diesel to natural gas) will reduce emissions, but with the potential for slight additional cost. The use of newer, more efficient asphalt mixing plants will reduce energy consumption and emissions, allow a greater percent incorporation of RAP and RAS, and many newer plants are equipped with WMA foaming technologies. This will result in overall cost and emission reductions, although requiring additional capital investment.

Table 3-3. Approaches for improving pavement sustainability with regard to asphalt materials production.

Asphalt Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Virgin Binder Content in Asphalt Concrete	Use greater quantities of RAP if same or better performance can be realized.	Reduces cost of asphalt concrete if RAP available.	Dependent on performance, energy costs of mixing, transportation.	Extends life of petroleum resources. Reduced need for landfill.
	Use rubberized asphalt for asphalt concrete.	Some increase in initial cost, impact of mixture design higher, potential payback in less material for thin overlays, increased life.	Reduces impacts by decreasing amount of materials needed over time horizon.	Reduced exposure of public to accidents in work zones.
	Use RAS as partial replacement for asphalt binder if same or better performance can be realized.	Reduces cost of asphalt concrete if RAS available.		Extends life of petroleum resources. Reduced need for landfill.
	Use bio-binders.	Impacts and trade-offs unknown.	Impacts and trade-offs unknown.	Impacts and trade-offs unknown.
	Use sulfur-modified asphalt.	Not well quantified.	Potential difficulty in future recycling.	Risks for worker health.
Reduce Virgin Aggregate Content in Asphalt Concrete	Use greater quantities of RAP if the same or better performance can be realized.	Reduced cost of asphalt concrete if RAP available.	Dependent on performance, energy costs of mixing, transportation.	Extends life of aggregate resources. Reduced need for landfill.
Reduce Energy Consumed and Emissions Generated to Produce Asphalt Concrete	Use WMA to reduce mixing temperatures.	Zero to small increase in cost.	Reduced energy and GHG to make asphalt concrete. Impact of producing WMA additives needs to be considered.	Reduced worker exposure to fumes.
	Change fuel used for heating to reduce emissions, such as natural gas.	May increase cost.	Reduced emissions to make asphalt concrete.	Reduced worker exposure to fumes.
Reduce Energy Consumed and Emissions Generated to Produce Asphalt Concrete	Employ new, more efficient plant designs to reduce energy consumption and increase the percent RAP and RAS used	Increased capital cost to upgrade existing facilities. Reduced operating cost due to decreased energy consumption as well as increased use of RAP and RAS.	Reduce emissions to make asphalt concrete through reduced fuel consumption and higher percentage use of RAP and RAS	More efficient utilization of recovered materials such as RAP and RAS
Extend Lives of Asphalt Concrete Materials	Increase compaction specifications, no trade-offs.	Some increase in initial cost for extra contractor effort and inspection, large payback in increased life.	Reduces impacts by decreasing amount of materials needed over time horizon.	Reduced exposure of public to accidents in work zones.
	Use WMA to obtain better compaction.	Zero to small increase in cost, payback in increased life.	Reduces impacts by decreasing amount of materials needed over pavement life cycle. WMA additives needs to be considered.	Reduced exposure of public to accidents in work zones
	Improved mixture designs.	Some cost for new equipment, training, payback from longer lives.	Reduces impacts by decreasing amount of materials needed over life cycle.	Reduced exposure of public to accidents in work zones.
	Use polymers.	Some increase in initial cost, impact of polymer production, potential payback in increased life.	Reduces impacts by decreasing amount of materials needed over life cycle. Impact of producing polymer additives needs to be considered.	Reduced exposure of public to accidents in work zones. Increased exposure of workers to fumes.
	Use rubberized asphalt.	Some increase in initial cost, impact of mixture design higher, potential payback in less material for thin overlays, increased life.	Reduces impacts by decreasing amount of materials needed over time horizon.	Reduced exposure of public to accidents in work zones. Increased exposure of workers to fumes.

Table 3-3. Approaches for improving pavement sustainability with regard to asphalt materials production (continued).

Asphalt Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Extend Lives of Asphalt Concrete Materials	Use lime or liquid anti-strip to decrease risk of early failure due to moisture damage.	Slight increase in initial cost, payback from extended life where warranted.	Initial impact from manufacture of materials, potential payback if life would otherwise be shortened.	Increased worker exposure to lime or chemicals.
Reduce Materials Transportation Impacts	Use more locally available materials.	Lower initial cost. Potential for greater life cycle cost if perform is compromised. May have shorter lives if performance-related properties are poorer.	Reduces impacts of transportation of materials, particularly important if trucks would be used. May have shorter lives if performance-related properties are poorer.	Reduced exposure of public to trucking.
Extend Lives of Seal Coats	Use rubber or polymer binders.	Some increase in initial cost, impact of binder production higher, potential payback from increased life.	Increased impact due to production of polymers. Potential payback from improved life.	Polymers made from finite petroleum resources.
Reduce Need for Virgin Materials and Transportation	Use in-place recycling (full-depth reclamation, partial-depth recycling). May have high construction variability.	Can potentially reduce initial cost by reducing transportation of virgin materials and permitting thinner overlays, and may extend life where appropriately selected and designed. May have high construction variability.	Can reduce use of virgin materials depending on life. Can reduce transportation of materials. Energy savings dependent on technology and life. May have high construction variability.	Fewer heavy trucks on the road hauling materials.
Increase Pavement Albedo where Warranted (See Chapter 6)	Use lighter colored aggregates, place light colored chip seals, other reflective surface treatments.	Cost may be greater if reflective treatment not otherwise needed. Can potentially reduce risk of rutting of asphalt concrete. More materials used if additional coating applied that is not otherwise needed.	Needs to be evaluated on a case by case basis (see Chapter 6). If warranted, specific impacts that are positively impacted must be noted. Unintended consequences should also be examined.	Needs to be evaluated on a case by case basis (see Chapter 6). If warranted, specific impacts that are positively impacted must be noted. Unintended consequences should also be examined.

Strategy: Extend Life of Asphalt Concrete Materials

All things being equal, extending the life of asphalt concrete and seal coats reduces environmental impacts over the pavement life cycle. Effective mixture design and a high degree of construction compaction are strategies that are known to extend life, typically with few trade-offs. Dense-graded asphalt concrete can usually be compacted to 2 percent air voids without risk of rutting, and good compaction can be made easier to achieve with the aid of warm-mix technology. Rubber and polymers can be used in mixture designs for specific applications to increase life, but these may potentially carry some additional environmental impact from a materials production standpoint. They also typically have additional initial cost, which can be offset if they permit a reduction in pavement thickness. They may also negatively affect the ability to fully utilize RAP containing the additives in future asphalt concrete. As such, these materials should be used where they provide significant increases in performance. Reducing the risk of moisture damage in asphalt concrete through additives can also increase life, although the net environmental impacts of the additives have not been investigated through an LCA.

Strategy: Reduce Need for Virgin Materials and Transportation through In-Place Recycling

Recycling and reclamation can result in substantial cost savings and environmental impact reductions over the use of new materials when the technology (partial-depth recycling, full-depth reclamation) is properly selected, designed, and constructed. The cost and impact reductions can come from less use of new materials and reduced haulage. The life of the material must be considered when selecting strategies, since improvements in manufacture and construction can be offset by reduced life. Recycled materials have proven to be at least equal to new materials in quality, when properly engineered. FDR can be used to improve pavement cross-sectional geometrics and in some cases the traffic disruption is lessened compared to other rehabilitation techniques. Kandhal and Mallick (1997) provide additional information on recycling.

Strategy: Develop Alternatives to Petroleum-Based Binders

Work is under way to develop alternative binders, particularly bio-binders that have reduced environmental impacts compared to those derived from petroleum. However, the environmental impacts of these materials have not yet been evaluated using LCA, nor have their long-term performance capabilities been demonstrated.

Future Directions/Emerging Technologies

A number of strategies for reducing impacts from asphalt binders, modifiers, additives, and aggregate have been presented. Some future directions and emerging technologies that should be monitored and implemented, when and where beneficial, are:

- A reduction in material quantities through improvements in mixture design, construction practices, and, in some cases, new materials such as WMA or, where traffic, climate and existing condition warrant, inclusion of polymers, rubber, and other modifiers.
- Greater use of RCWMs, including RAP, RAS, and others, to reduce the mining, extraction, manufacture, and transport of non-renewable virgin materials, provided that performance is not compromised. For individual projects, this requires analysis of whether suitable RCWMs are locally available because long transportation distances may reduce the energy and environmental benefits of using RCWMs.
- Greater use of locally available pavement materials provided that those benefits are not offset by reduced performance. For asphalt materials, locally available aggregates are the primary consideration.
- Development of alternatives, namely bio-based alternatives, to nonrenewable feedstocks such as petroleum. The environmental, economic, and societal impacts of producing these alternatives will need to be evaluated to determine their overall feasibility.

Hydraulic Cement Materials

This section reviews the manufacture of HCC mixtures, including material acquisition, processing, transportation, and processing at a concrete plant. As aggregates were discussed at the beginning of this chapter, the focus of this section is on cementitious binders and additives, and how these combined with aggregates can be used to improve the sustainability of pavements. Economic and environmental impacts occur throughout all life-cycle phases, with this section focused on those directly related to the materials including cementitious materials, mixture design, proportioning, and mixing. Topics include energy consumption, emissions, calcination, resource consumption, and water use. Recent innovations are discussed including mixtures with high contents of supplementary cementitious materials (SCMs), portland limestone and other blended cements, high-efficiency cement manufacturing plants, and concrete plant operations. Materials transport from the plant and construction are discussed separately in chapter 5.

Major Issues:

- ✓ *The relatively high non-renewable energy consumption and GHG emissions inherent in the portland cement manufacturing.*
- ✓ *The non-renewable energy consumption and GHG emissions associated with the production of traditional paving concrete.*
- ✓ *Water use associated with concrete production.*
- ✓ *Increasing the use of RCWMs as aggregates without compromising performance.*
- ✓ *Ensuring concrete durability.*

Introduction

In its simplest form, HCC is a mixture of coarse and fine aggregate bound together with "glue" that is created when water is mixed with hydraulic cement. Air is present in the mixture, either being entrapped or purposefully entrained as microscopic air bubbles. Figure 3-7 presents the components and their typical volumetric distribution in dense-graded HCC.

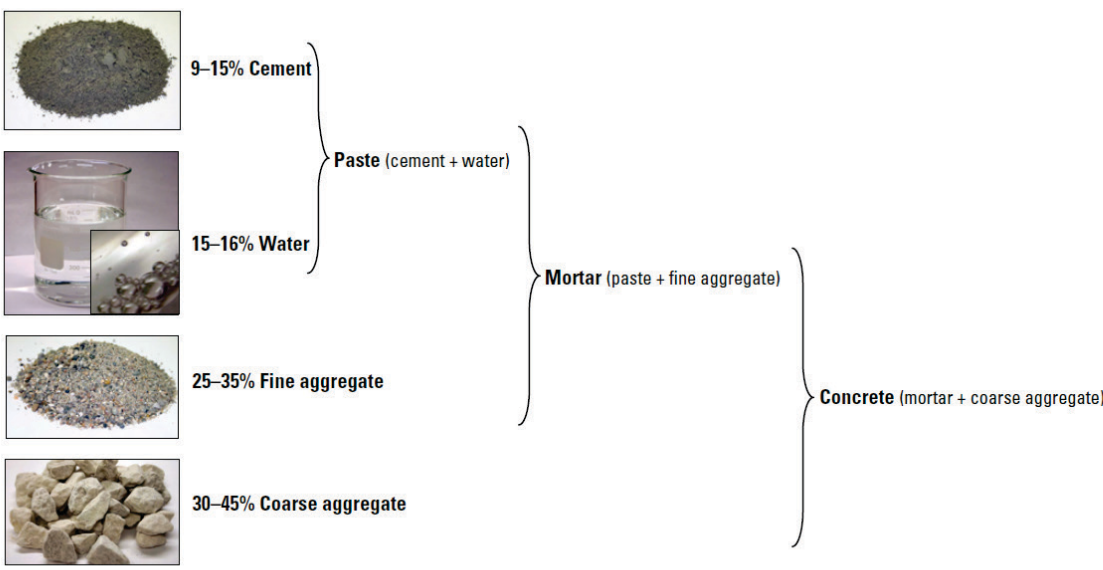


Figure 3-7. Typical volumetric distribution of hydraulic paste (cement, water, air) and aggregates in paving concrete (Taylor et al. 2006).

The hydraulic cement used today is most commonly a blend of portland cement (AASHTO M 85/ASTM C150), SCMs, and ground limestone. Furthermore, chemical admixtures are almost always employed to modify the behavior of the fresh and hardened HCC, making it easier to place, enhancing its strength, and making it more durable. In addition, the aggregates are often graded to possess a more optimized size distribution to create a mixture with a reduced cementitious content, improved workability, and enhanced long-term performance.

Portland Cement

Following water, HCC is humankind's most commonly used material, with roughly 1 yd^3 (0.76 m^3) of it produced annually for every person on the planet. As such, the economic, environmental, and societal impacts of HCC are huge. Furthermore, the cost and environmental impact of HCC is largely dependent on the cement (much of this section will generally refer to portland cement instead of hydraulic cement since it is by far the mostly commonly used type). This is illustrated in table 3-4, which shows that the production of portland cement consumes 74 percent of the energy and produces 81 percent of the GHG emissions associated with the cement and concrete industry in the U.S. (Choate 2003).

Table 3-4. Annual energy and CO_2 emissions associated with U.S. cement manufacturing and concrete production (Choate 2003).

	On-site Energy 10^6 kJoules	**On-site Energy %**	**CO_2 Emissions 10^6 tonne**	**CO_2 Emissions %**
Raw Materials – Quarrying and Crushing				
Cement Materials	3,817	0.7%	0.36	0.3%
Concrete Materials	14,287	2.6%	1.28	1.2%
Cement Manufacturing				
Raw Grinding	8,346	1.5%	1.50	1.4%
Kiln: fuels	410,464	74.0%	38.47	36.8%
Reactions			48.35	46.3%
Finish Milling	24,057	4.3%	4.32	4.1%
Concrete Production				
Blending, Mixing	31,444	5.7%	5.65	5.4%
Transportation	61,933	11.2%	4.53	4.3%
Total	**554,409**	**100%**	**104.50**	**100%**

Source: Energy and Emission Reduction Opportunities from the Cement Industry, U.S. Department of Energy.

Portland cement is manufactured by pyroprocessing raw materials, dominated by limestone, in a rotary cement kiln at high temperatures (2460 to 2640 °F [1348 to 1448 °C]). This alters the mineralogy of the raw materials, creating small, dark nodules referred to as cement "clinker" composed of reactive cementitious phases (Kosmatka and Wilson 2011). Although the consumption of fuel (which will differ regionally, consisting of pulverized coal, natural gas, used tires, waste industrial oils and solvents, and, in some cases, biomass) is responsible for a portion of the GHG emissions, over half of the GHG emissions in clinker production are released due to the decomposition of limestone ($CaCO_3$) into lime (CaO) and carbon dioxide (CO_2) (EPA 2013b; Van Dam et al. 2012).

Hydraulic Cement Materials Usage and Economics

The U.S. used approximately 79 million tons (72 million mt) of hydraulic cement in 2011, worth about $6.5 billion, according to the U.S. Geological Survey (USGS 2013b). In the recent peak year of 2005, approximately 111 million tons (122 million mt) of cement were consumed (USGS 2013b). Calcium sulfoaluminate and other non-portland hydraulic cements used are included in these figures, but only account for about 0.03 percent of cement used. According to the USGS, approximately 5 percent of cement used in the U.S. in 2011 was used for road paving purposes (USGS 2013b). In the U.S., about 8 percent of all paved roads and highways are surfaced with concrete. The U.S. has about 5,500 ready mixed concrete plants in 2011 (U.S. Census Bureau 2013), many of which produce concrete for paving. The value of ready mixed concrete produced in the U.S. was estimated at $34.7 billion in 2007 (U.S. Census Bureau 2007b), which suggests that the value of concrete used for road paving was about $1.7 billion based on 5 percent of cement used.

Even though cement kiln efficiency has improved markedly over the last two decades—significantly reducing the energy needed for pyroprocessing and the associated emissions—the calcination reaction is an unavoidable occurrence in creating portland cement and thus the CO_2 liberated from this reaction cannot be eliminated. Approximately 0.8 to 1.0 tons (0.7 to 0.9 mt) of CO_2 are produced per ton of cement manufactured in the U.S. (Van Dam et al. 2012). Furthermore, cement production is responsible for approximately 31.6 Tg CO_2e, or just under 0.5 percent of the U.S. total GHG emissions of 6,702 Tg CO_2e in 2011 (EPA 2013b). This is a dramatic reduction in GHG emissions from the peak that occurred in 2005 when 45.2 Tg CO_2e were associated with cement production, largely due to the economic downturn and resultant reduction in demand for cement that began in 2008.

As previously described, portland cement clinker is manufactured through pyroprocessing in large rotary kilns. Older technology is referred to as "wet process" in which the raw materials were ground wet, and then stored, proportioned, and fed into the kiln as a slurry. Modern cement kiln technology has reduced the energy needed to evaporate the water used in grinding through dry-process grinding and material handling. A schematic of a modern dry-process plant is shown in figure 3-8. This figure shows a general process design, but in truth every plant is unique, with modern plants incorporating new technologies to increase efficiency and reduce waste/emissions. A modern cement plant can take over a decade to permit and build at a cost of over $1 billion, and is much more efficient than plants that were prevalent two decades ago. Prior to the economic downturn in 2008, the U.S. cement industry continued to use a number of the wet-process plants, but today these are no longer operational. The following discussion focuses on the production of cement and enhancements that have occurred over time.

The first step in manufacturing cement is to mine and process the raw materials necessary. The single largest need is for calcium, which is predominately obtained from limestone (calcium carbonate). As a result, cement plants are often located near an abundant source of limestone. Silica and alumina are most often provided by natural materials such as clay or shale, although to create the desired proportions of calcium, silica, alumina, and iron, other materials are often blended in including fly ash or iron blast-furnace slag. This basic process has not changed much over the decades, although more efficient mining equipment and crushers have been employed.

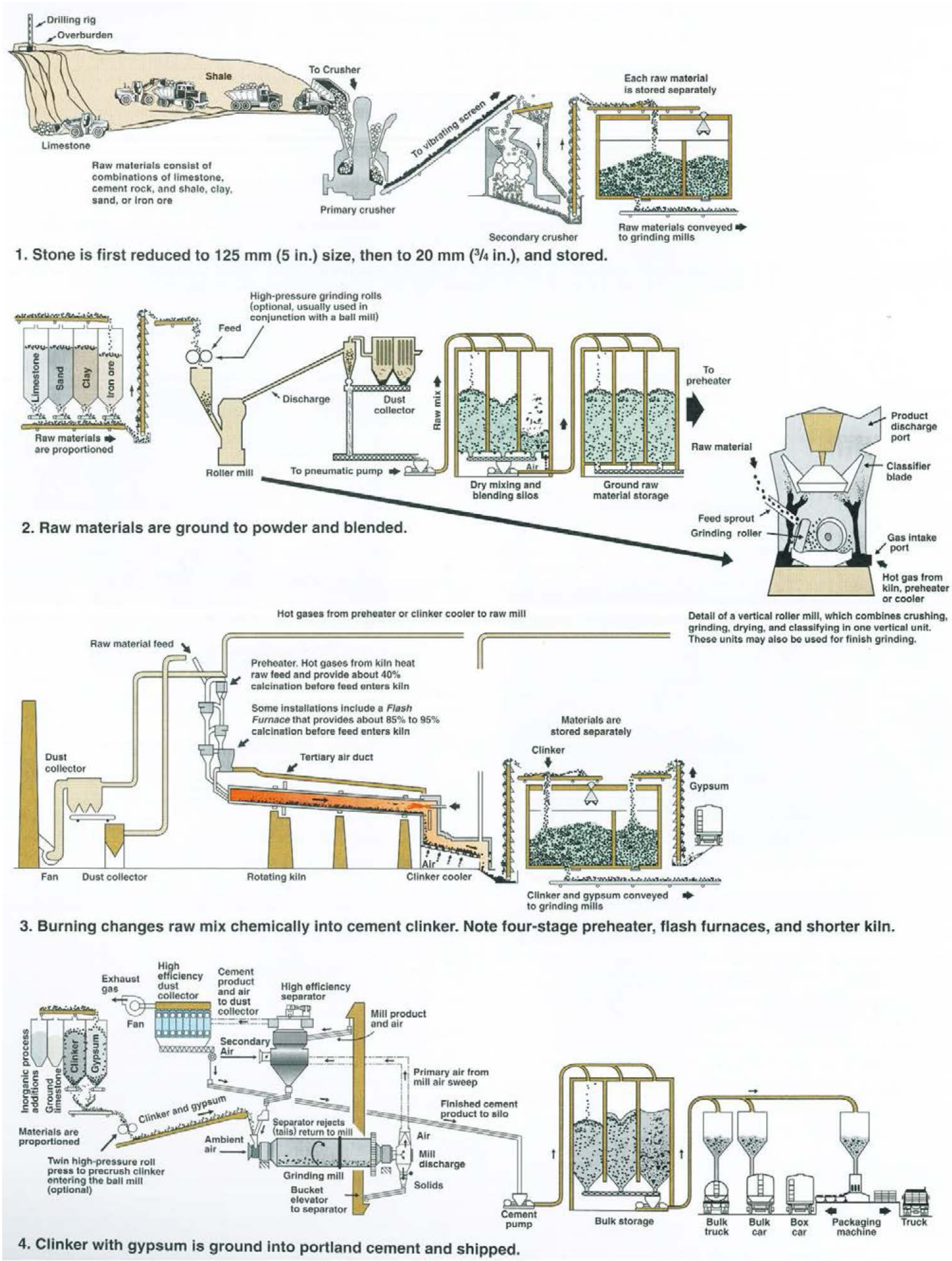


Figure 3-8. Steps in the modern dry-process manufacture of portland cement (Kosmatka and Wilson 2011).

As illustrated in figure 3-8, these mined raw materials are sized (crushed if needed) and stored, then finely ground prior to burning in a rotary kiln. Improvements in technology at this stage have resulted in significant increases in processing efficiency over the last few decades, with the biggest change occurring by moving from wet processing to dry processing. As the name implies, in wet processing water is used in a grinding mill to create slurry that is then fed into the rotary kiln. This requires a very long kiln, as the first stage in the burning process is to dry the slurried kiln feed, a process that is very energy (and therefore emissions) intensive. In older dry process facilities, grinding mills and air separators are used to create powder that is then fed into a shorter kiln. Although grinding energy is increased, the net energy savings relative to wet process technology is significant. In modern cement plants, as illustrated in figure 3-8, the older grinding mills and air separators are replaced with much more efficient roller mills that combine crushing, grinding, drying, and classifying into a single vertical unit.

Additional efficiencies have been incorporated into the burning process, most focusing on recirculating hot exhaust gases and using them to dry, heat, and initiate the calcination of raw materials before they enter the kiln. As shown in figure 3-8, hot gases from the kiln already begin the drying process in the vertical roller mills. The raw materials in a modern plant are then fed through a series of vertical heat exchange devices known as preheater cyclones and precalciner vessels. The most modern cement plants will have flash furnaces installed at which point 85 to 95 percent of the calcination occurs before the raw feed even enters the kiln (Kosmatka and Wilson 2011). Such cement plants have very short kilns, further improving efficiency.

In the kiln, the raw materials are heated until “clinkering” occurs in which the primary cement phases are formed. Upon cooling, the greyish black pellets that emerge are called clinker. As shown in figure 3-8, the cooled clinker is combined with calcium sulfate (gypsum), which is added to control the time of setting, and is then ground in a grinding mill. Many improvements in efficiency have occurred during this step as well, including the use of more efficient grinding mills, high efficiency separators, and high efficiency dust collection. After grinding, the grey powder is now “portland” cement, which will be stored for shipping in bulk or bagged form.

Today, portland cement sold in the U.S. under AASHTO M 85 almost always contains ingredients beyond ground clinker and gypsum. For one, the specification allows up to 5 percent limestone to be interground with the clinker, although the practical limit is somewhere around 3.5 percent in order to meet other specification requirements. Furthermore, up to 5 percent inorganic processing additions may also be added, the most common being slag cement. And finally, 1 percent organic processing addition may also be added. As these additions have a lower environmental impact (e.g., lower GHG emissions, embodied energy) than portland cement, the addition of each has the potential to lower the energy consumed and emissions generated to manufacture a unit mass of portland cement.

Innovations at cement plants continue to improve efficiency and thus lower energy consumption and emissions. Some plants rely on renewable energy to provide their electrical needs, including electricity produced by wind and solar. Additionally, coal is increasingly being replaced as a fuel, with some plants switching to natural gas or a combination of biomass fuel and waste fuels, such as worn-out tires, solvents, and waste oil (Kosmatka and Wilson 2011). Many plants also use highly efficient modes of transportation, shipping cement in bulk either by rail or barge. The main driver for most of these changes is economics, but regulatory changes and the need to be more “sustainable” has motivated the cement manufacturing industry to minimize waste and reduce emissions, with the overall effect being an increase in efficiency.

Nevertheless, increasing levels of efficiency do not reduce the CO_2 released in the calcination process, which as shown in table 3-4 is roughly 46 percent of all CO_2 released in the production of concrete (Choate 2003). As mentioned earlier, this CO_2 cannot be reduced through improved efficiency or renewable fuels. The only solution for reducing calcination CO_2 is to reduce the amount of portland cement clinker consumed over the life cycle of the pavement. A recent LCI on the manufacturing of portland cement in the U.S. is available (Marceau, Nisbet, and VanGeem 2007).

Supplementary Cementitious Materials

SCMs are materials that when blended with portland cement contribute to the properties of concrete through hydraulic or pozzolanic activity, or both (Kosmatka and Wilson 2011). Hydraulic activity occurs when the material chemically reacts with water, forming cementitious hydration products. Pozzolanic activity occurs in the presence of water when reactive siliceous or aluminosiliceous material reacts with calcium hydroxide (a reaction product from the hydration of portland cement) forming calcium silicate hydrate and other cementitious compounds. Calcium silicate hydrate is a more desirable hydration product than calcium hydroxide and the pozzolanic reaction is considered to have a positive impact on the long-term properties of the hardened concrete.

SCMs can be mixed into the cement by the cement manufacturer and sold as blended cement under AASHTO M 240 or added at the concrete plant by the concrete producer. SCMs that are commonly used in paving concrete include fly ash (specified under AASHTO M 295) and slag cement (specified under AASHTO M 302). Far less commonly used SCMs are natural pozzolans (also specified under AASHTO M 295) and possibly small amounts of silica fume (specified under AASHTO M 307).

Alternative Fuels for Cement Kilns

As part of their effort to reduce their GHG footprint, the cement industry continues to seek alternative fuels to burn in cement kilns as an alternative to the use of fossil fuels such as coal, petroleum coke (produced when asphalt is processed to make lighter products), and natural gas. The most common alternative fuel is derived from waste tires, which pound for pound have more fuel value than coal, and can also result in lower emissions (PCA 2011). Other waste-derived alternative fuels include paper, packaging, plastics, saw dust, and solvents that, because of the extremely high temperatures that exist in a cement kiln (well above 3000 °F [1650 °C]), burn quickly and with extreme efficiency (PCA 2011). This perspective is echoed by the Cement Kiln Recycling Coalition (CKRC 2013), which states that alternative fuels for cement kilns can be produced from paint solvents, discarded paints and coatings, inks and ink solvents, various resins and organic sludges, petroleum refining by-products, as well as scrap tires and many other materials. In 2010, over 68 percent of U.S. and Canadian cement plants reported using one or more waste fuels, providing 13 percent of the energy demand at cement plants (PCA 2011).

The sustainability benefits of using these types of alternative fuels are great as materials that would otherwise need to be treated as hazardous waste are handled and used in a safe and beneficial manner. This reduces the need for landfills for hazardous waste as well as the amount of fossil fuel consumed in cement production, thus conserving fossil fuel and reducing GHG emissions. In addition to waste-derived alternative fuels, considerable interest exists to utilize biofuels in cement production. In one investigation, the main biofuel used was sorghum, which was complemented by maize (varieties of corn that don't go to seed), perl millet, switchgrass and oat hulls (Norris 2011). The investigation showed enough promise that it was thought that biofuels could be used to completely replace coal by 2020. In another investigation, a cement plant has employed a novel approach to use the carbon dioxide-rich exhaust gases from the cement kiln to accelerate the growth of algae, which in turn is dewatered and burned as fuel in the kiln (Tree Hugger 2013).

Table 3-5 summarizes properties of these common SCMs, noting that calcined clay, shale, and metakaolin are classified as natural pozzolans. Tables 3-6 and 3-7 summarize how each SCM impacts the behavior of fresh and hardened concrete, respectively. Brief descriptions of some of the primary SCMs are provided in the following sections.

Table 3-5. Chemical composition and select properties of common SCMs (Taylor et al. 2006; Kosmatka, Kerkoff, and Panarese 2002).

Component	Type I Cement	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Metakaolin
Silica (SiO_2),%	22.00	52.00	35.00	35.00	90.00	53.00
Alumina (Al_2O_2),%	5.00	23.00	18.00	12.00	0.40	43.00
Iron oxide (Fe_2O_2)%	3.50	11.00	6.00	1.00	0.40	0.50
Calcium oxide (CaO),%	65.00	5.00	21.00	40.00	1.60	0.10
Sulfate (SO_4),%	1.00	0.80	4.10	9.00	0.40	0.10
Sodium oxide (Na_2O),%	0.20	1.00	5.80	0.30	0.50	0.05
Potassium oxide (K_2O),%	1.00	2.00	0.70	0.40	2.20	0.40
Total eq. alkali (as Na_20),%	0.77	2.20	6.30	0.60	1.90	0.30
Loss on ignition,%	0.20	2.80	0.50	1.00	3.00	0.70
Blaine fineness, m^2/kg	350.00	420.00	420.00	400.00	20,000.00	19,000.00
Relative density	3.15	2.38	2.65	2.94	2.40	2.50

Table 3-6. Effects of SCMs on the properties of fresh concrete (Taylor et al. 2006).

Property	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Calcined Shale	Calcined Clay	Metakaolin
Water Requirements	↓↓	↓↓	↓	↑↑	↔	↔	↑
Workability	↑	↑	↑	↓↓	↑	↑	↓
Bleeding and segregation	↓	↓	↕	↓↓	↔	↔	↓
Air Content	↓↓	↓	↓	↓↓	↔	↔	↓
Heat of Hydration	↓	↕	↓	↔	↓	↓	↓
Setting Time	↑	↕	↑	↔	↑	↑	↔
Finishability	↑	↑	↑	↔	↑	↑	↑
Pumpability	↑	↑	↑	↑	↑	↑	↑
Plastic Shrinkage Cracking	↔	↔	↔	↑	↔	↔	↔

Table 3-7. Effects of SCMs on the properties of hardened concrete (Taylor et al. 2006).

Property	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Calcined Shale	Calcined Clay	Metakaolin
Early strength	↓	↔	↓		↓	↓	
Long-term strength	↑	↑	↑	↑↑	↑	↑	↑↑
Permeability	↓	↓	↓	↓↓	↓	↓	↓↓
Chloride ingress	↓	↓	↓	↓↓	↓	↓	↓↓
ASR	↓↓	↕	↓↓	↓	↓	↓	↓
Sulfate resistance	↑↑	↕	↑↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage	↔	↔	↔	↔	↔	↔	↔

Sources: Thomas and Wilson (2002); Kosmatka, Kerkoff, and Panarese (2002)

Key:

↓	reduced	↑↑	significantly increased
↓↓	significantly reduced	↔	no significant change
↑	increased	↕	effect varies

Fly ash is collected from the flue gases of coal-fired power plants. As pulverized coal is combusted, mineral impurities are carried away in the flue gases, solidifying into spherical glassy particles as they cool. These are collected by electrostatic precipitators or bag filters as particles roughly the same size as cement. In 2011, approximately 59 million tons (54 million mt) of fly ash were produced in the U.S., of which 38 percent was beneficially used with 13 million tons (12 million mt) used in concrete/concrete products or in blended cement/raw feed for clinker (ACAA 2013a). As shown in figure 3-9, this is a decrease in both peak fly ash production (which was approximately 78 million tons [71 million mt] in 2002) and utilization rate (approximately 45 percent in 2006) (ACAA 2013b). The main reason for the decrease in fly ash production and utilization was the economic slowdown in the U.S. beginning in 2006. Other pressures exist that may reduce fly ash availability in the future, including increased reliance on natural gas instead of coal for electrical production as well as increasing environmental pressures to reduce emissions from power plants.

Fly ash varies in composition and mineralogy as a result of the source of coal, how it is burned, and how the ash cools. Under AASHTO M 295, it is classified as either a Class C fly ash or a Class F fly ash. A summary of how the different fly ashes behave in concrete, based on tables 3-6 and 3-7, is as follows:

- As seen in table 3-5, in general, Class C fly ash has higher calcium oxide content than Class F fly ash and thus has both hydraulic cementitious and pozzolanic characteristics; Class F fly ash, on the other hand, has less calcium oxide and is therefore more pozzolanic.

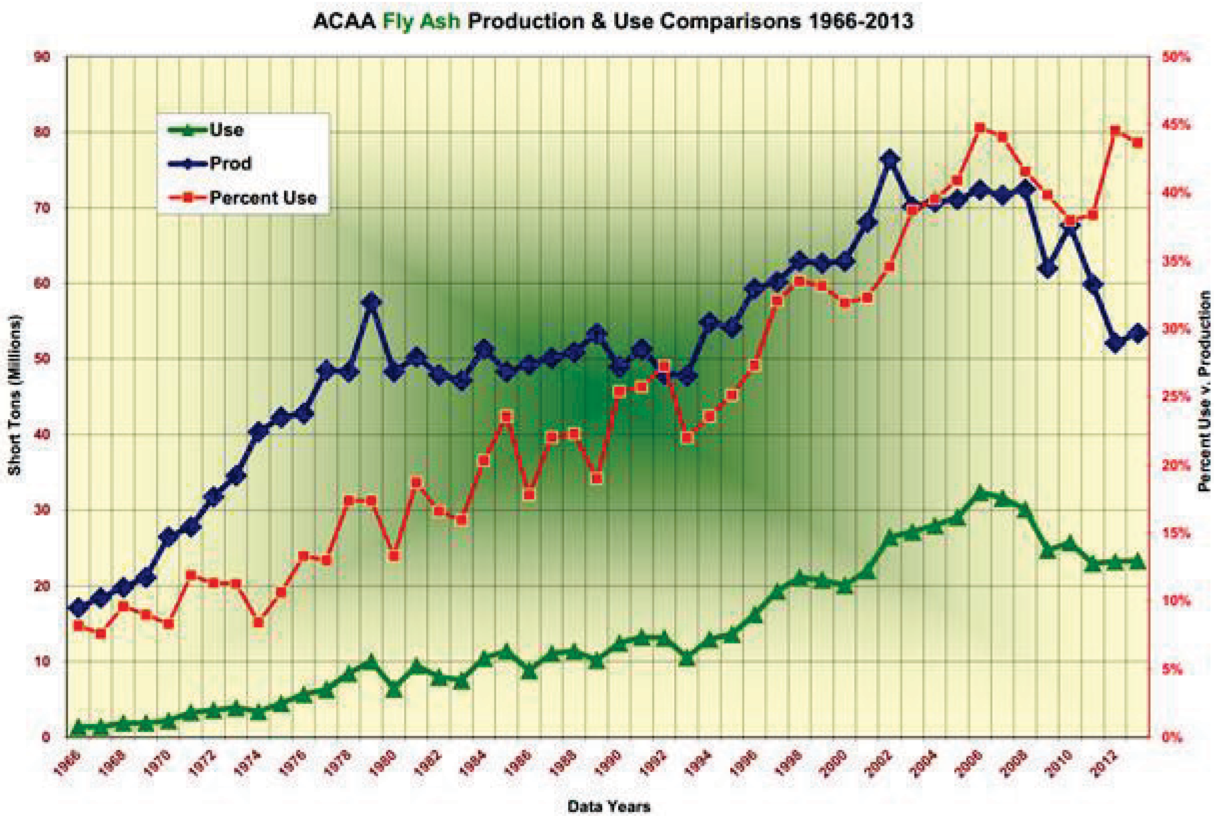


Figure 3-9. U.S. fly ash production, use (U.S. short tons), and utilization rate from 1966 to 2013 (ACAA 2013b). (Note: 1 short ton = 0.907 metric ton)

- Class C fly ash is typically dosed at 15 to 40 percent by mass of the total cementitious materials used whereas Class F fly ash is typically dosed at 15 to 25 percent for pavement applications (Taylor et al. 2006).
- The spherical nature of the fly ash particles improves the workability and cohesiveness of concrete paving mixtures while reducing water demand. Furthermore, the lower density of fly ash versus portland cement means that for a given mass there is more volume in the paste. This improves cohesiveness and workability and also reduces bleeding.
- The presence of fly ash can negatively impact the ability to entrain air in the concrete, primarily due to carbon impurities that may be present. The limits on loss on ignition is an attempt to control the amount of carbon. A newly released NCHRP study provides methods to evaluate a given fly ash's impact on air entrainment (Sutter, Hooton, and Schlorholtz 2013).
- Class C fly ash may affect early setting and the heat of hydration whereas Class F fly ash almost always delays setting while reducing the heat of hydration. In concrete made with Class F fly ash, the delay in setting and early strength gain increase with increasing dosage and may impact the constructability of the pavement, especially in cooler weather.
- Early strength gain is rarely affected by Class C fly ash but almost always slowed when Class F fly ash is used. On the other hand, all fly ash tends to improve long-term strength and reduce permeability (which increases durability).

- The pozzolanic reaction helps mitigate ASR and sulfate attack. Thus, in general, concrete made with Class F fly ash will have improved chemical durability over concrete made with pure portland cement or Class C fly ash. In some cases and in some dosages, concrete containing Class C fly ash can actually have poorer durability than would be incurred in concrete made with a pure portland cement.

As an industrial co-product or waste material, the composition, reactivity, and properties of fly ash are highly variable. This variability can be extreme for fly ashes from different sources, but is also true for fly ash produced at the same electrical plant because coal sources, burning techniques, and environmental technologies are changing rapidly. As a result, rigorous testing of fly ash must be conducted on a frequent basis to ensure its continued suitability for use in concrete. NCHRP Report 749 provides guidance on the testing of fly ash for highway structures (Sutter, Hooton, and Schlorholtz 2013).

Slag cement is an industrial co-product from iron blast furnaces in which pig iron is extracted from iron ore. The remaining molten material (slag) is directed into a granulator that quenches the material using water to form glassy, sand-like particles. These are then ground to similar size, or slightly finer, than portland cement. Although the chemical composition is identical to that of air-cooled blast furnace slag, the rapid cooling through quenching does not allow chemically stable crystalline minerals to form. Instead, the amorphous oxides of calcium, aluminum, magnesium, and iron (the typical composition is shown in table 3-5) are reactive, either slowly in the presence of water alone or more vigorously when activated in water in the presence of sodium hydroxide or calcium hydroxide. The latter is the condition present in the pore solution of hydrating portland cement, and thus the two react in a complementary manner.

Co-Product Treatment for SCMs

There is debate on how to allocate environmental impacts for high value SCMs, such as fly ash and slag cement. In the past these materials were considered wastes from industrial processes (coal-powered electricity generating fly ash, and steel production generating blast furnace slag). The current practice in the U.S. is to consider fly ash a waste material diverted from a landfill for beneficial use, meaning that none of the environmental impact associated with electricity generation is typically assigned to the fly ash. As long as the cost of transport and processing of the fly ash is the only source of economic value, a waste classification is appropriate. However, once the fly ash has value beyond this, it should no longer be considered waste, but instead a co-product. Already in some markets fly ashes are in high demand and economically valuable, meaning they are no longer waste flows. In these cases, it is appropriate to allocate some of the environmental burden associated with coal-fired power plants to fly ash. The most common means to accomplish this is through economic worth of the co-products. LCAs in some regions (e.g., Europe) show that the economic worth of fly ash compared to electricity generation is small and hence the assigned environmental impacts are also small. The same practices can be applied to slag cement as a co-product in steel production. It is noted that different allocation methods can lead to differences in assigned environmental impacts. There are also other motivations for industries to seek classification as waste or co-product. For example, in Europe fly ash producers often do not want classification as "waste" because that requires a much more difficult regulatory environment for handling, storing, and transporting the material. Chen et al. (2010) considered different allocation methods for slag cement and fly ash used in Europe, arguing that demand for these products outpaced production and thus their designation as a waste may not be appropriate. Allocation based on economic value as compared to allocation by mass leads to significantly lower environmental flows attributable to both SCMs, and seems to better reflect the purpose of the industries that produce the SCMs – production of steel or electricity.

As shown in figure 3-10, slag cement use dropped with the economic downturn beginning in 2007. The Slag Cement Association (SCA) reported an 11 percent drop in 2009, although there was an even greater drop in the use of portland cement suggesting that slag cement was gaining popularity even as portland cement use fell. Overall trends appear to show some increases in slag production as the economy improves, but a long-term trend of decreased availability due to the closure of a number of U.S. blast furnaces and a lack of construction of new furnaces is expected. As of 2011, there were only four granulators installed at active blast furnaces in the U.S. (USGS 2013a).

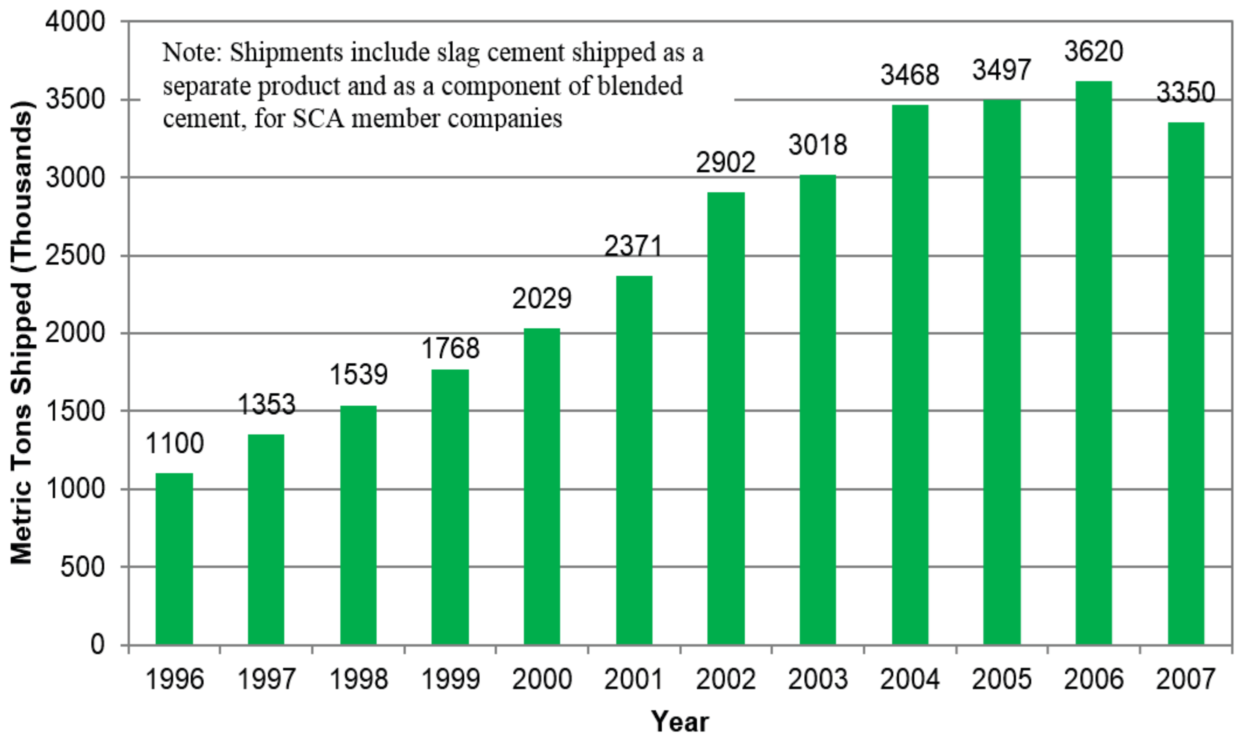


Figure 3-10. U.S. slag cement shipments from 1996 to 2007 (adapted from SCA 2007).

Slag cement is an attractive SCM for a number of reasons. For one, the typical dosage of slag cement is usually in the range of 25 to 35 percent of the total cementitious materials for paving concrete, although it can be used in even higher amounts (ACPA 2003). Furthermore, slag cement creates very light colored concrete that some find aesthetically pleasing and has a high albedo that may help reduce the urban heat island effect where this is important (this is discussed in chapter 6). Some additional commentary on slag cement and paving concrete constructed with it include:

- Although slag cement particles are angular, it has a lower specific gravity than portland cement, meaning that a greater volume of slag cement is used to replace the same mass of portland cement; this results in reduced water demand and improved workability.
- Slag cement can reduce air entraining efficiency so this must be carefully controlled.
- Slag cement can reduce the heat of hydration, which can be effectively used to reduce built-in curl and cracking if the specific concrete heat of hydration is measured. On the other hand, the lower heat of hydration can result in increased setting times, particularly

during cold weather placements. A rule of thumb is that the set time is delayed 30 minutes for every 10 percent slag cement replacement of portland cement (ACPA 2003).

- Early strength gain is generally retarded when slag cement is used, but the long-term strength is increased.
- Permeability and chloride ion ingress are reduced when slag cement is used, and slag cement can be used to effectively mitigate ASR and sulfate attack.

As an industrial co-product material, slag cement will vary from source to source, but variability within a given source is usually very low. Often the properties of the slag cement are altered slightly depending on the fineness of the grind, with more finely ground slag cement being more reactive. An LCI for slag cement has been published (Prusinski, Marceau, VanGeem 2004).

Other SCMs, including silica fume and natural pozzolans, are rarely used in concrete paving. Silica fume, an ultrafine non-crystalline silica co-product of the production of silicon metals and ferrosilicon alloys, is a highly reactive pozzolan often used in high-performance and ultra-high-performance concrete (UHPC). It is difficult to work with and is significantly higher in cost than portland cement and thus its use is often restricted to applications such as bridge decks that demand high strengths and a highly impervious matrix.

Natural pozzolans represent a family of SCMs produced from natural mineral deposits or biomass. Some of these minerals, such as volcanic ash, are similar to what were used in ancient Rome to construct the Pantheon and aqueducts and can be used with only minimal processing, whereas others require calcination through heat treatment. More recently, there have been efforts to derive commercially viable natural pozzolans from biomass such as rice husks, but this effort has not yet been commercially successful in the U.S., primarily because of difficulties in controlling burning processes to produce consistently high quality pozzolans. Abundant supplies of natural pozzolans are available in many parts of the world where volcanic activity is common, including parts of Europe, Central America, and Africa. In the U.S., interest in natural pozzolans is increasing due to some rising uncertainty regarding the supplies of fly ash and slag cement.

Blended Cements

Blended cement is produced and sold by cement manufacturers that intergrind or blend portland cement with fly ash, natural pozzolans, slag cement, limestone, or a combination. The blended cement can be a binary system, made with portland cement and one other material, or a ternary combination of portland cement and two other materials as specified under AASHTO M 240, *Standard Specification for Blended Hydraulic Cements*. These materials are classified as follows:

- Type IP(X) – The "P" indicates that this is portland-pozzolan cement in which "X" denotes the targeted percentage of pozzolan expressed as a whole number by mass of the final blended cement. Thus, a Type IP(20) is a blended portland-pozzolan cement that contains 20 percent pozzolan. The range of X allowed is up to 40 percent by mass of the blended cement.
- Type IS(X) – The "S" indicates that this is portland-slag cement in which "X" denotes the targeted percentage of slag cement expressed as a whole number by mass of the final blended cement. Thus, a Type IS(35) is blended portland-slag cement that contains 35 percent slag cement. The range of X allowed is up to 95 percent by mass of the blended cement.

- Type IL(X) – The “L” indicates that this is portland-limestone cement in which “X” denotes the targeted percentage of limestone expressed as a whole number by mass of the final blended cement. The limestone can constitute up to 15 percent by mass of the blended cement.
- Type IT(AX)(BY) – The “T” indicates that this is ternary blended cement in which the “A” refers to the type of pozzolan, slag, or limestone (either “P” for pozzolan, “S” for slag cement, or “L” for limestone) that is present in the larger amount by mass and the “B” refers to the additional material, either “P” for pozzolan, “S” for slag cement, or “L” for limestone that is present in the lesser amount. The “X” and “Y” refer to targeted percentage of mass for constituent “A” and “B” respectively. For example, a material designated as Type IT(S25)(P15) contains 60 percent portland cement, 25 percent slag cement, and 15 percent pozzolan. Two different pozzolans can also be blended together to create a Type IT(PX)(PY).

Typical portland cement replacement rates for blended cements are 10 to 12 percent for Type IL, 15 to 25 percent for Type IP, and 30 to 50 percent for Type IS (based on Van Dam and Smith 2011). The composition of a Type IT can vary significantly depending on the characteristics of the specific SCMs.

In addition to the above designations, blended cements can be further labeled with the following suffixes:

- “A” to indicate air-entrained material.
- “MS” or “HS” to indicate moderate or high sulfate resistance.
- “MH” or “LH” to indicate moderate or low heat of hydration.
- “R” to indicate resistance to alkali-silica reactivity (note this was added in 2014).

The most recent addition to AASHTO M 240 is the Type IL portland-limestone cements that were added in 2012. This followed the allowance of intergrinding portland cement clinker with up to 5 percent limestone that has been allowed in AASHTO M 85 since 2007. Portland-limestone cements have been used in Europe for over 25 years (with the most popular type of cement used in Europe containing up to 20 percent limestone), and Canada approved the use of portland-limestone cements containing up to 15 percent limestone in 2009. In the latter case, the 15 percent limit is in place to ensure the portland-limestone cement performs similarly to conventional portland cement and blended cements. At that replacement level, it is estimated that the use of a portland-limestone cement reduces CO_2 emissions by up to 10 percent compared to conventional portland cement (CAC 2009).

Although it is more common in the U.S. for the concrete supplier to blend portland cement with SCMs at the concrete plant, when the pozzolan, slag cement, or limestone are interground or blended by the cement supplier under AASHTO M 240 there is a greater level of quality assurance over the final product with less potential for unforeseen interactions and incompatibilities (Taylor et al. 2006). In addition, the use of AASHTO M 240 blended cements helps to avoid the potential for proportioning mistakes that can occur in the field. One drawback, however, is the use of a blended cement limits the concrete supplier’s ability to adjust the SCM content in response to changing conditions (e.g., cooler weather).

Although all of these blended cements have been extensively evaluated in the laboratory, and early performance has also been assessed, continued monitoring and assessment of their long-term performance and characteristics for consideration in pavement design is needed.

Aggregates in Hydraulic Cement Concrete

Aggregates have been discussed earlier in this chapter, including the environmental impacts of mining and processing them for use in pavements. This section addresses attributes of aggregates as they have a direct impact on the sustainability of hydraulic cement paving concrete. These attributes include aggregate grading, durability, and the use of RCWMs.

Aggregate coefficient of thermal expansion (CTE) is an important property that is defined as the change in unit length per degree of temperature change. Since coarse aggregate makes up the bulk of the volume of concrete, the CTE of the coarse aggregate is the most influential factor in the CTE of the concrete. Aggregates with very high CTE require special consideration when used in concrete paving mixtures, particularly in climates with large diurnal and seasonal temperature changes. High CTE in concrete results in greater curling of the concrete under a thermal gradient, when the top and bottom of the slab are at different temperatures. This results in the development of higher tensile stresses that increase the potential for cracking in both jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP), and provides an increased potential for faulting and roughness in jointed designs that must be handled in the pavement structural design and construction specifications. AASHTO T 336 is the recommended test method for CTE of the concrete mixture (FHWA 2011). Greater discussion of the effects of concrete CTE is included in chapter 4.

Aggregate grading is an important step in establishing concrete mixture proportions as it has a profound effect on the amount of cementitious material needed to obtain the desired fresh and hardened properties for paving concrete. There are multiple approaches used to establish mixture proportions to achieve the proper balance of workability, strength, volumetric stability, and durability in the most cost effective and environmentally benign manner possible. Trade-offs often exist when attempting to optimize any one or two of these criteria at the expense of another. For example, reductions in the water-cementitious materials ratio (*w/cm*) generally decreases paste permeability and increases paste density, thereby increasing both strength and durability; however, workability will likely suffer if other adjustments are not made at the same time (e.g., changes in aggregate gradation or particle shape or the inclusion of chemical or mineral admixtures).

A properly proportioned concrete paving mixture will often have an "optimized" aggregate grading (sometimes referred to as a well-graded mixture), in which multiple aggregate particle sizes are represented. This allows for a reduction in cementitious material content (making good use of fly ash, slag cement, and limestone replacement of portland cement) while achieving the required fresh (workability, finishability, and so on) and hardened (strength and durability) properties. Aggregate grading optimization has many different forms and there is not a single method that must be followed to achieve it. Pioneering work by Shilstone (1990), modified by others, provides good guidance but other approaches exist that work equally well. At its core, aggregate optimization is an empirical exercise that not only is affected by the aggregate particle sizes, but also the particle shape, texture, and specific gravities. When done correctly, aggregate grading optimization maximizes the aggregate volume through careful consideration of the particle size distribution. Today it is common to find highly workable, strong, and durable concrete paving mixtures with total cementitious materials contents of 540 lbs/yd^3 (320 kg/m^3) or less, resulting in both economic and environmental savings compared to previous practices.

Aggregate durability has been discussed earlier in this chapter, but its importance to the overall durability of concrete and on the longevity of the pavement cannot be overemphasized. Fundamentally, durability reflects the ability of a material to maintain its integrity in the environment it serves, and a concrete pavement that fails prematurely due to poor durability is not considered sustainable. It is therefore critical that aggregates used in concrete meet all the requirements of AASHTO M 6, *Standard Specification for Fine Aggregate for Portland Cement Concrete* and M 80, *Standard Specification for Coarse Aggregate for Portland Cement Concrete*. In addition, the aggregate should meet the following durability requirements:

- Freeze-thaw durability – Certain coarse aggregates are susceptible to damage if subjected to cyclic freezing and thawing in a saturated state. Aggregates are most often tested for freeze-thaw durability using ASTM C666.
- ASR – ASR has affected countless pavements throughout the U.S. resulting in early loss of service life. The FHWA maintains a web-based ASR reference center (http://www.fhwa.dot.gov/pavement/concrete/asr.cfm) to provide the latest information on ASR to the pavement community and AASHTO recently published a provisional protocol PP65-11, *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction* that should be used to screen aggregates to be used in paving concrete. The use of SCMs such as Class F fly ash or slag cement are the most common mitigation strategies employed if susceptible aggregates are to be used.

As discussed previously under the aggregates section of this chapter, the use of RCWMs continues to increase for economic and environmental reasons. Specific issues regarding the use of RCWMs as aggregate in paving concrete are as follows:

- Recycled concrete aggregate – Specific caution needs to be exercised when using RCA as aggregate in new concrete. For one, it is most common to use only the coarse fraction of the RCA because the fine fraction has high water demand that affects workability and may have high chloride contents if deicers have been used. Furthermore, it is critical that the aggregate stockpile is watered prior to batching. There are several recent publications that provide excellent guidance on the use of RCA as aggregate in paving concrete (ACPA 2009; Van Dam et al. 2011).
- Reclaimed asphalt pavement – RAP is a commonly recycled material produced when an existing asphalt concrete pavement is cold milled as part of a pavement rehabilitation or reconstruction. The preferred higher use of RAP is in new asphalt concrete as it makes maximum use of the binder as well as the aggregate. In some markets, such as the Chicago area, there is a large surplus of coarse "fractionated" (material retained on larger sized sieves) RAP and it is being used as aggregate in new paving concrete by some entities such as the Illinois Tollway Authority. In these instances, care should be exercised to ensure the presence of the RAP will not negatively impact the fresh and hardened properties of the concrete.
- Air-cooled blast furnace slag – ACBFS continues to be used as a coarse aggregate in paving concrete. However, there are pavement design, concrete mixture, and construction considerations that must be followed in order for the material to be used most effectively in this application (Morian, Van Dam, and Perera 2012; Smith, Morian, and Van Dam 2012).

Water Sources

Water is used in the concrete production process not only in the preparation of the concrete mixtures, but also in the cleaning of trucks and equipment. Decisions regarding concrete mixing water must consider three criteria (Van Dam et al. 2012):

1. Quality (e.g., the water must be free of organic materials that may adversely affect strength and durability of the concrete);
2. Impact on the environment (e.g., depletion of local water resources, such as wells, streams and ponds, or energy required for potable water distribution systems and the infrastructure required for delivery of that water); and
3. Economic factors.

Technologies for using increasing amounts of "grey water" (that obtained from washing concrete production equipment and trucks) are rapidly becoming more common and accepted. Figure 3-11 presents a schematic for recycling concrete wash water into concrete mixture water, while table 3-8 presents typical limits on chlorides, solids, and other potentially harmful contaminants in recycled water. Table 3-9 shows some of the impacts the use of recycled water can have on concrete properties, with the primary concern being high solids content.

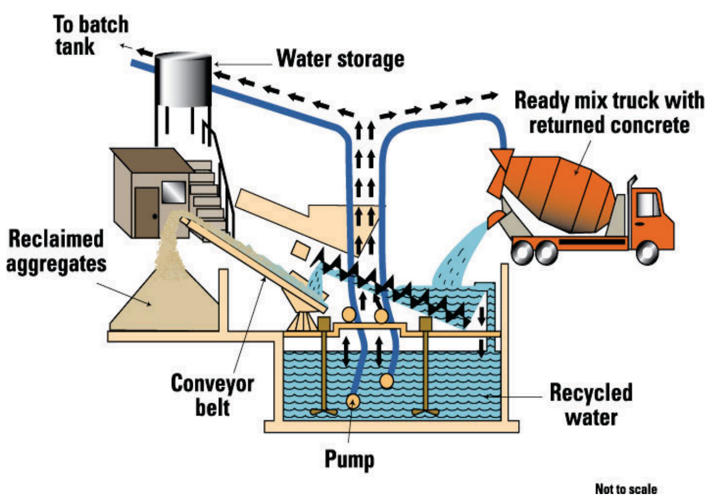


Figure 3-11. Schematic of mixer truck washout water recycling for concrete batch plant mix water (Taylor et al. 2006).

Table 3-8. Harmful contaminants, tests methods and limits for grey water to be used in concrete mixtures (Taylor et al. 2006).

Maximum Conc. In Combined Water	Limits, ppm	Test Method
Chloride as Cl^- Prestressed Other Reinforced Concrete	 500 1000	ASTM C 114
Sulfate as SO_4	3000	ASTM C 114
Alkalis as (Na_2O +0.658 K_2O)	600	ASTM C 114
Total Solids by Mass	50,000	ASTM C 1603

Table 3-9. Effect of recycled water on concrete properties (Taylor et al. 2006).

Recycled Water with	Water Demand	Setting Time	Compressive Strength	Permeability	Freeze-thaw Resistance
Solid contents within ASTM C94 limits ($\leq$ 8.9 kg/m^3 or $\leq$15 lb/yd^3)	↔	↔	↔	↔	↔
High solid contents (> 8.9 kg/m^3 or >15 lb/yd^3)	↑	↓	↓**	↑**	↔
High solid contents and treated with hydration stabilizing admixture	↔	↔	↔	no data	no data

Source: After Lobo and Mullings (2003)
* Compared to reference concrete with tap water.
** Strength and permeability effects were related to increased mixing water content.
Key: ↓ decreased
↑ increased
↔ no trend

Chemical Admixtures

Chemical admixtures are added during batching to modify the fresh or hardened properties of concrete. These modifications can enhance sustainability by improving the workability of the concrete, reducing water demand, and improving durability. Modern paving concrete makes extensive use of chemical admixtures with the most common admixtures listed in table 3-10. An excellent description of the various chemical admixtures can be found in Kosmatka and Wilson (2011). A summary of the three most common classes of chemical admixtures used in pavements follows.

Table 3-10. Common chemical admixtures used in paving concrete (Taylor et al. 2006).

Class	Function
Air-entraining admixture (AEA)	To stabilize microscopic bubbles in concrete, which can provide freeze-thaw resistance and improve resistance to deicer salt scaling.
Water-reducing admixture (WRA)	To reduce the water demand by 5 to 10 percent, while maintaining slump characteristics.
Mid-range water reducing admixture (MRWRA)	To reduce the water demand by 6 to 12 percent, while maintaining slump and avoiding retardation.
High-range water reducing admixture (HRWRA)	To reduce the water demand by 12 to 30 percent, while maintaining slump.
Retarder	To decrease the rate of hydration of cement.
Accelerator	To increase the rate of hydration of cement.

Air entraining admixtures (AEAs), specified in accordance with AASHTO M 154, are used almost universally in modern paving concrete to enhance the freeze-thaw durability of the hydrated paste, but they also improve the workability of the concrete and reduce water demand, mixture segregation, and bleeding (Taylor et al. 2006). AEAs form microscopic spherical bubbles that should remain stable as the concrete hardens. It is essential that the bubbles are uniformly spaced and sufficiently close to protect the paste from damage during freezing and thawing. Figure 3-12 shows the air voids in a polished concrete sample viewed through a stereomicroscope.

Traditionally, AEAs were predominately based on salts of wood resins (Vinsol® resin) but modern AEAs are often derived from varied natural and synthetic sources. Because the chemistry of the AEA and interactions with other mixture constituents can impact its effectiveness, it is important to test the concrete during laboratory mixture proportioning through construction using the job mix formula (Taylor et al. 2006).

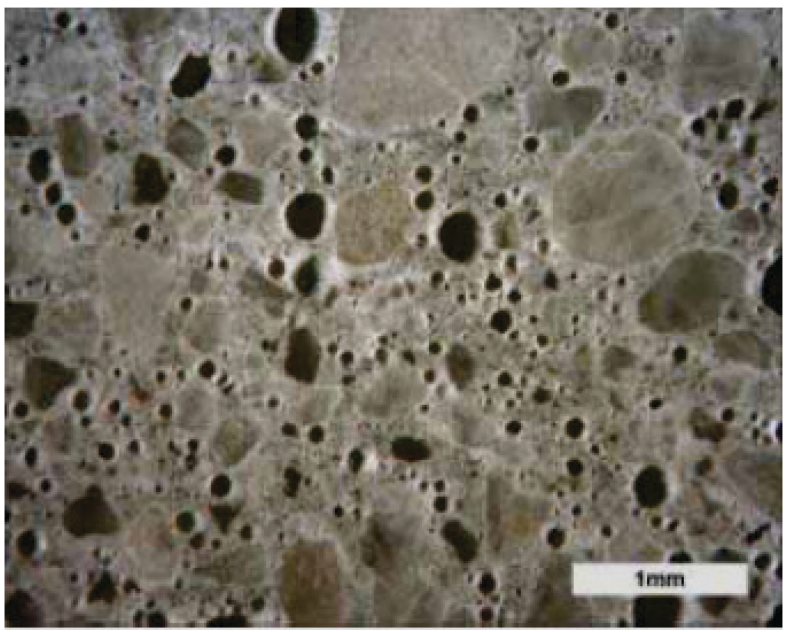


Figure 3-12. Polished slab of concrete viewed through stereomicroscope. Dark circles are entrained air voids distributed throughout the grey hydrated cement paste.

For the most part, testing of fresh concrete measures only the total air content in the concrete, but ideally what is desired is an indication of the size and distribution of those air voids in the concrete. The air-void analyzer (AVA) showed early promise in measuring the air-void system parameters in fresh concrete but it has not been found to be as effective when used with stiff, low slump paving concrete. Currently, the only way to ensure that the air-void system parameters meet the criteria for resistance to freeze-thaw damage is to cut and polish the hardened concrete and examine it with a stereomicroscope in accordance with ASTM C457. Automated methods based on digital image analysis are in use and being refined to make this process less onerous.

Water-reducing admixtures are divided into two classes, according to ASTM C494: water-reducing admixtures (WRA) and high-range water-reducing admixtures (HRWRA), although it is common to also include a mid-range water-reducing admixture (MRWRA) as previously listed in table 3-10. These admixtures function at the surface of the cement grains, causing grains to disperse and minimizing cement particle agglomeration. This makes the available water much more effective, and therefore reduces water demand.

For paving, it was very common in the past to use standard WRAs (based primarily on lignosulfonate chemistry) but this practice is slowly giving way to the increasing use of MRWRA based on the newer polycarboxylate chemistry. This chemistry is highly advantageous as it maintains its effectiveness for longer periods of time, but polycarboxylates are also known to entrain air and thus must be formulated for the application and tested for compatibility with the AEA to ensure that the entrained air-void system has the desired properties.

From a sustainability perspective, water-reducing admixtures have revolutionized concrete technology including concrete paving. A WRA will permit up to 12 percent water reduction while maintaining the desired level of workability (slump, cohesiveness, compactability, finishability). This allows for the mixing water to be reduced while holding the cementitious content constant, thus reducing the *w/cm*. All things equal, lowering the *w/cm* reduces the volume of pores in the hardened concrete, which in turn results in higher strength and lower permeability. Thus, water-reducing admixtures are considered an essential constituent in improving the sustainability of paving concrete as they increase concrete longevity, reduce water use, and allow for a reduction in cementitious materials.

Set-Modifying Admixtures are used to either accelerate (accelerators) or retard (retarders) the set time and early strength gain of concrete. Cement hydration is a chemical reaction that is sensitive to many factors, some of which are inherent in the mixture and others external to it. Externally, the biggest factor affecting set time is temperature, with cold temperatures slowing down the hydration process. To address this, accelerators are sometimes used during cold weather placements to "kick-start" the reactions so that the heat of hydration can be engaged to support continued reaction. This is especially true for high SCM mixtures that often have a lower heat of hydration. Accelerators are also often used in accelerated construction in which the pavement needs to be opened to traffic as soon as possible.

At the other extreme, higher temperatures may accelerate the hydration process, and the use of retarders may then be needed during hot weather conditions in an attempt to delay hydration. In addition, a long hauling distance may require that the concrete set be retarded to accommodate the time of transport.

In the long term, accelerated mixtures rarely achieve the same strength or as low a permeability as mixtures that were retarded. Thus, the need for early strength in some applications needs to be balanced against the potential for lower long-term strength and reduced durability over the life cycle.

Alternatively, proprietary non-portland cement-based systems are available that can achieve high-early strength and reportedly long-term performance, but these materials are more costly than portland cement-based systems and are often more difficult to work with. This restricts their use primarily to maintenance and rehabilitation applications. The environmental impacts of non-portland cements depend on the raw materials and processes used to produce them. For example, the GHG emissions from calcium sulfoaluminate (CSA) cement production can be significantly lower than for portland cement. This is true even though the mining of the primary raw ingredient in CSA, bauxite, produces more GHG than does the raw materials extraction for portland cement, because the bauxite does not undergo calcination (Quillen 2007). Other emissions may be higher for CSA than portland cement.

The **environmental impact of admixtures** must consider the impacts incurred in the production and transportation of the admixture to the concrete plant site. In general, the amount of admixture used is quite small, usually on the order of less than 0.25 gal of liquid admixture per yd^3 (1.23 l per m^3) of concrete. As a result, it is common for the environmental impact of chemical admixtures to not be included in an LCA as the impact of such small dosages of these admixtures was found to be insignificant in previous LCA studies. However, there are some types of admixtures that are rarely used in paving concrete, such as HRWRA, that when added at a much higher dose may contribute significantly to the environmental impact of the concrete mixture. For example, at least one study on concrete bridge decks has shown that admixtures can contribute a non-negligible fraction of material production energy and emissions when heavily dosed (Keoleian et al. 2005).

Mixture Proportioning and Plant Production

For slipform paving concrete, the general approach to mixture design is to economically create relatively stiff concrete mixtures (slumps typically in a range of 0.5 to 1.5 inches [13 to 38 mm]) with good cohesiveness and finishability. The specified air content will vary with the type of exposure the pavement will have to freeze-thaw cycling and deicers, but generally will lie in a specified range between 5.0 and 7.5 percent. The concrete strength is often assessed based on flexural strength, most often measured in third-point loading in accordance with AASHTO T 97, and exhibiting typical values between 600 and 800 lb/in^2 (4.2 and 5.5 MPa) at 28 days. There are many other factors that can be considered, any of which contribute to the overall sustainability of the concrete. Detailed information on concrete mixture design and proportioning for pavements can be found in Taylor et al. (2006). Other plant-prepared concrete mixtures that might be used on a pavement project include roller compacted concrete (RCC), cement-stabilized or cement-treated bases, or pervious concrete. Regardless of the mixture type, a similar approach is used for proportioning and production.

Mixture proportions are selected prior to construction to meet the various mixture design objectives, which may include economy, workability, strength, durability, and sustainability. There are many approaches to establishing the required proportions, but all involve working in the laboratory with the anticipated concrete constituents and batching and testing mixtures until the desired mixture design objectives are met in the laboratory. It is then essential that the concrete is tested in the field prior to full-scale production to ensure that the laboratory-derived proportions can be produced under field conditions using the assigned concrete plant and will yield the desired fresh and hardened properties.

Batching is the process of measuring quantities of concrete mixture ingredients, based on the proportions developed previously, and then introducing them into the mixer. Central batching of the mixture must be executed under tight control because the consistency of the mixture from batch-to-batch and day-to-day significantly affects the workability and finishability of the fresh concrete as well as the hardened concrete properties (strength and durability). Batch-to-batch consistency is absolutely essential to creating a good performing concrete pavement as non-uniform concrete can lead to variable quality that can adversely affect initial ride quality, surface texture, and ultimately performance and life.

Once the concrete is batched into the mixer, it must be thoroughly mixed to a uniform consistency. Not only must the mixing process thoroughly combine the cementitious materials, aggregates, and water, it is also an essential step in creating the entrained air-void system that protects the concrete paste against freeze-thaw damage. Properly mixed concrete should have essentially the same fresh and hardened properties throughout the entire batch, allowing for variability in the testing itself. This can be evaluated using AASHTO M 157.

Most concrete used in paving projects will be produced by a stationary central mixer, whether a permanent plant or a portable plant erected on site. There are many different types of stationary concrete mixers, with a tilt rotating drum mixer being the most common for paving concrete although non-tilting type, reversing drum, or horizontal shaft mixers are also used. Quality concrete can only be produced in a well-maintained plant, and thus worn, damaged, or coated blades must be replaced, repaired, or corrected. For a given concrete plant, the three most important factors are:

- Batch Size – Mixers should not be loaded above their rated mixing capacities.
- Sequencing – Mixture constituents must be added in a given sequence that must not vary batch to batch. In general, some of the water is added first, followed by coarse aggregate, sand, and then the cementitious materials. Approximately 10 percent of the water is held back to be added after all other materials are in the mixer. Admixtures in particular must be added in the same sequence each time.
- Mixing Time – The time of mixing is critical as inadequate mixing will result in non-uniformity and over mixing can negatively impact the entrained air-void system. Many specifications require a minimum mixing time of 1 minute plus 15 seconds for every cubic yard of concrete unless performance testing is conducted that demonstrates uniformity in a shorter period of time.

Once concrete is mixed in a stationary mixer, it is deposited in non-agitating trucks or into truck mixers that operate at “agitating speed” of 2 to 6 rpm to maintain homogeneity (Kosmatka and Wilson 2011). Truck mixers can also be used to finish the mixing process that was begun in the stationary mixer (referred to as shrink-mixed concrete).

In some cases, typically for smaller projects, when high-early-strength materials are being used in maintenance or rehabilitation, or when exceptionally long transit times exist, concrete constituent materials are batched dry and mixed in truck mixers. Typically 70 to 100 revolutions of the drum or blades at mixing speed (12 to 18 rpm) are used to produce the uniformity required, after which the speed is reduce to 2 to 6 rpm (agitating speed) to maintain homogeneity in transit and during delivery (Kosmatka and Wilson 2011). Overmixing can have negative effects on the fresh and hardened concrete properties and thus AASHTO M 157 limits the number of drum revolutions to 300 after water is added to the dry constituents.

There are also specialized mobile volumetric mixers that batch concrete by volume and continuously mix it using an auger system (Kosmatka and Wilson 2011). These types of mixers are typically used for small batches or with rapid-setting proprietary materials during concrete pavement maintenance and rehabilitation.

Factors that impact the quality assurance of mixture production include material handling and stockpiling operations (especially the use of techniques that prevent aggregate segregation and ensure consistent aggregate moisture conditions), the calibration and accuracy of batch scales and weigh hoppers, and ensuring adequate mixing time. It is particularly important that aggregate moisture contents be measured frequently and that mixture proportions are adjusted accordingly. In addition, mixer uniformity testing should be performed in accordance with ASTM C94 for each concrete plant/mixture combination to determine the minimum mixing time required to achieve uniform concrete. Taylor et al. (2006) and Kosmatka and Wilson (2011) provide excellent guidance on the required concrete plant operations necessary to produce consistent concrete for a paving operation.

Durability

A number of properties of the hardened concrete influence durability, including permeability, strength, air-void system characteristics, resistance to external chemical attack, and the physical and chemical stability of the aggregates. ACI 201.2R (ACI 2008) provides an excellent summary of physical and chemical mechanisms that can impact the durability of concrete and describes strategies to improve durability.

Sustainability dictates that the concrete used in paving be durable in the environment in which it serves. Concrete has a reputation as a long-lasting paving material, and there are many examples of concrete pavements remaining in service for 40 years or more (Tayabji and Lim 2006). As a result, it has become common practice for some highway agencies to design high-traffic-volume concrete pavements for services lives of 40 to 50 years. But for this practice to be sustainable, the concrete must possess the durability to withstand the environmental loading it will be subjected to over many decades of service. During laboratory mixture proportioning, testing must be conducted confirming that the proposed concrete mixture meets or exceeds the design requirements, and rigorous testing must be conducted during production to make sure that concrete as produced possesses the attributes to create a long-lasting concrete pavement.

The concrete design, proportioning, and production process must create a concrete paving mixture that economically meets all design strength, durability, and sustainability requirements over the pavement life cycle. Concrete with a low cementitious materials content (540 lbs/yd^3 [320 kg/m^3]), a high replacement of portland cement with high-quality SCMs (30 percent or greater), durable aggregates, a properly entrained air-void system, and a relatively low *w/cm* (based on mass, 0.40 to 0.45 is considered good for most applications) will have a relatively low GHG emissions footprint at production and is expected to have good long-term physical properties to provide excellent economic, environmental, and societal performance. However, there is no one “recipe” that will create “sustainable” paving concrete. Instead, the concrete technologist/producer needs to work within project constraints and the available materials to balance a number of discrete and competing variables to enhance sustainability moving forward.

Strategies for Improving Sustainability

Some general strategies for addressing the major issues described above are summarized in table 3-11, with greater elaboration provided below. Although some quantitative analysis of the net impacts of these practices to improve sustainability have been evaluated using LCA (particularly as relating to the use of SCMs to replace portland cement in concrete), more work needs to be done to consider the full materials production phase.

Table 3-11. Approaches for improving pavement sustainability with regard to concrete materials production.

Concrete Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Non-Renewable Energy Consumption and GHG Emissions in Cement Manufacturing	Improved cement plant efficiency through better energy harvesting and improved grinding	High capital cost but lower cost of manufacturing	Reduced energy consumption and GHG emissions	Less fuel consumed and emissions generated
	Utilization of renewable energy including wind and solar	High capital cost but lower cost of manufacturing	Reduced non-renewable energy consumption and GHG emissions	Less non-renewable fuel consumed and GHG generated
	Utilization of more efficient fossil fuels	Lowers manufacturing costs	Reduces emissions per unit of energy used	Cleaner burning fuel
	Utilization of waste fuels	Lowers manufacturing costs	Beneficial use of waste material	Reduces materials in landfills
	Utilization of biofuels	Reduces cost to cost neutral	Reduces GHG emissions	Reduces dependency on fossil fuels
	Minimize clinker content in portland cement through allowable limestone additions and inorganic processing additions	Reduces cost to cost neutral	Reduces GHG emissions and consumption on fuel	Reduces dependency on fossil fuels and lowers emissions
	Increase production of blended cements containing limestone or SCMs	Reduces cost	Significant reduction in energy consumption and GHG emissions. Redirects RCWMs from landfill	Reduces dependency on fossil fuels and less material sent to landfill
Reduce Energy Consumption and Emission in Concrete Production	Increase concrete mixing plant efficiency and reduce emissions	Increased capital cost but decrease production costs	Reduced emissions	Reduced local emissions including noise and particulate
	Utilization of renewable energy	Cost neutral to increase cost	Reduced emissions	Reduced emissions
	Use electrical energy from the grid	Depends on proximity to grid – should save cost	Reduced emission, better emission controls	Reduced local emissions
	Use less cement in concrete mixtures without compromising performance	Reduce cost of concrete	Reduced emissions and energy	Longer lasting pavements – less delays
	Use more blended cements without compromising performance	No impact on cost	Reduced emissions and energy	Longer lasting pavements – less delays
	Increase addition rate of SCMs at concrete plant without compromising performance	Reduce cost of concrete	Reduced emissions and energy	Longer lasting pavements – less delays
Reduce Water Use in HCC Production	Recycle washout water	Cost neutral to slightly added cost	Use less water resources	Improved water quality
	Recycle water used to process aggregates	Cost neutral to slightly added cost	Use less water resources	Improved water quality
Increase Use of RCWMS and Marginal Materials as Aggregate in Concrete	Change specifications to allow greater amounts of RCWMs to be used in concrete without compromising performance	Reduced cost	Less landfill material, less transportation	
	Use RCWMs and marginal aggregates in lower-lift of two-lift pavement	Cost neutral to slightly added initial cost; potential for reduced life cycle costs	Less landfill material, less transportation	
Improve the Durability of Concrete	Lower *w/cm* through admixture use	Cost neutral to slightly added cost	Longer lasting pavements	Less delays over life cycle
	Utilize an effective QA program throughout material production phase	Slightly added initial cost – save cost on litigations	Longer lasting pavements	Less delays over life cycle

Strategy: Reduce Non-Renewable Energy Consumption and GHG Emissions in Cement Manufacturing

There are two major approaches to implementing this strategy: reduce consumption of non-renewable energy in the manufacturing process and reduce the clinker content of the cement that is shipped. Regarding the first approach, the main obstacle to implementation is the need to invest capital to improve existing cement plants or construct new ones. Retrofitting new technology on older plants is not always possible and it can take over a decade and $1 billion to permit and construct a new cement plant. Yet innovations can result in significant improvement to existing plants, including increasing the use of renewable energy (e.g., wind, solar) to generate electricity and switching to alternative fuels in the kiln (such as natural gas, waste fuels such as used tires and solvents, and increased use of biofuels). Nevertheless, the "low hanging fruit" regarding improvements to existing facilities have already been picked and future enhancements will take greater investment. The capital to invest in such improvements will remain tight until the world market for cement improves.

The second approach to this strategy is to focus on diluting the clinker content of the cement that is shipped from the plant. The largest contributor to GHG emissions is tied to calcination of calcium carbonate, an inherent process essential to the manufacturing of portland cement. From a cement manufacturer's perspective, major reductions in GHG emissions can only occur by reducing the clinker content in the cement sold, both by increasing the percent of limestone and inorganic processing aids in AASHTO M 85 portland cement and through increased production of AASHTO M 240 blended cements containing limestone or SCMs (i.e., Type IL, Type IP, Type IS, and Type IT). As manufactured products, the quality assurance on blended cements is higher than what occurs when SCMs are added to the concrete mixture at the plant. However, the trade-off is reduced flexibility during concrete production that may require capital investment by the concrete producer to add one or more additional cement silos. Furthermore, stable sources of high quality SCMs are uncertain, which may result in shortages in the future.

Strategy: Reduce Energy Consumption and Emissions in Concrete Production

The concrete production process is complex, but efficiencies can be realized at almost every step. To help evaluate the overall efficiency of concrete production, the National Ready Mix Concrete Association (NRMCA) offers a Sustainable Concrete Plant Certification[2] that provides a quantitative, performance-based metric for concrete suppliers to demonstrate excellence in sustainable development. This certification includes reduced energy consumption, particulate and GHG emissions, water use, and groundwater and surface water contamination.

The efficiencies of concrete plants continue to improve, resulting in economic, environmental, and societal savings. The utilization of renewable energy, whether produced on site or purchased off the grid, will result in reduced consumption of energy produced by fossil fuels and a reduction in emissions. If electricity is not produced on site using renewable means (e.g., wind, solar), the concrete plant should draw from the electrical power grid if at all possible because this is more efficient than producing power with on-site generators. On-site production of power is the least attractive alternative as it is not only inefficient, but can have major local impacts regarding emissions and noise generation.

Although the strategies cited to reduce energy consumption in concrete production also reduce GHG emissions, additional strategies can be employed to further reduce GHG emissions

[2] http://www.nrmca.org/sustainability/Certification/PlantCertification.asp

associated with the production of concrete. These are centered on using less portland cement clinker per cubic yard of concrete, which can be accomplished through the following means:

- Use an optimized aggregate gradation. This is commonly the most effective way to reduce the required total cementitious materials content, but often requires one or more additional aggregate bins be added to a concrete plant that was originally set up to handle only coarse and fine aggregate. The concrete properly produced with an optimized gradation will have good uniformity, resist segregation, be readily consolidated and finished, and have excellent strength, shrinkage, and permeability characteristics.
- Use blended cements. Blended cements provide a means to significantly reduce GHG emissions by reducing the content of GHG-intensive portland cement used in the mixture. However, the use of blended cements will require concrete suppliers to have at least three cement silos: one for portland cement, one for blended cement, and one for an SCM. In this scenario, many suppliers would have to add an additional silo that would represent a significant capital investment.
- Increase the addition rate of SCMs at the concrete plant. SCMs added at the concrete plant can be used in lieu of blended cement or can be used in addition to a blended cement in a complementary fashion. There is a practical limitation to how much total replacement of portland cement with SCMs can be used, and depends on the required early strength, type of SCM, and ambient climatic conditions, among other factors. The importance of good mixture proportioning and testing, as well as good quality assurance during production, cannot be overemphasized; otherwise, pavement performance may be compromised.

Strategy: Reduce Water Use in HCC Production

Water is used in the production of concrete to support the chemical reactions that cause cement to harden and gain strength. A typical concrete made with 564 lbs of cement per yd^3 (335 kg of cement per m^3) of concrete and a *w/cm* of 0.50 will require 282 lbs of water per yd^3 (167 kg of water per m^3) of concrete. Through good mixture proportioning and the use of water-reducing admixtures, the cement content could easily be reduced to 520 lbs/yd^3 (308 kg/ m^3) and the *w/cm* could be reduced to 0.42, saving 64 lbs of water per yd^3 (38 kg of water per m^3) of concrete. Not only is water saved, but the GHG emissions are also reduced through the reduced quantities of cement.

Water consumption can also be reduced by recycling water used to process aggregates, including the water used for aggregate washing and for maintaining aggregate moisture, and in washing out trucks and equipment as illustrated previously in figure 3-11. This requires capital investment and space to establish an area to recycle water.

Strategy: Increase Use of RCWMs and Marginal Materials as Aggregate in Concrete

Of all the various strategies, this one requires the greatest care during mixture proportioning and production to ensure pavement performance is not compromised. RCA and ACBFS have both been successfully used as coarse aggregates in concrete pavement, yet both have also resulted in some notable failures. One problem is that concrete made with RCWM coarse aggregates often exhibits hardened properties that differ from concrete made with virgin aggregates and these differences may not be accounted for in the structural design of the pavement. Another potential issue is that RCA and ACBFS coarse aggregate must be kept wet when stockpiled prior to batching due to their high absorptivity. If batched dry, they will absorb a significant amount of the mixing water, which not only negatively affects workability but can also lead to early cracking. Guidance on using RCWMs as aggregates in paving concrete is available from several sources (e.g., ACPA 2009; Van Dam et al. 2011; Smith, Morian, and Van Dam 2012).

The use of "marginal" aggregates is something that is becoming a necessity as sources of good quality aggregates become exhausted. Many factors can make an aggregate marginal, including issues with cleanliness, freeze-thaw durability, wear resistance, or susceptibility to ASR, among other items. The key to the effective utilization of marginal aggregates is to understand what properties of the aggregate are in question and then implementing strategies to address those limitations, primarily through consideration of these properties in design. For example, if it is a matter of cleanliness, washing the aggregates may be all that is needed. If freeze-thaw durability is an issue and it is related to the size of the aggregate (larger sized aggregate particles are more susceptible to freeze-thaw damage, all other things equal), then the aggregate can be crushed more thoroughly to a smaller size and then blended with a larger-sized stone that possesses the required freeze-thaw durability. Aggregates that are susceptible to ASR can be used if an effective mitigation strategy is employed, such as the use of an appropriate SCM. Wear resistance can be addressed by using susceptible aggregates in lower depths within the concrete slab through the use of two-lift construction. In fact, two-lift construction is a very effective design that can be used to accommodate increasing levels of RCWMs in the lower lift and thus reduce the overall environmental impact of the pavement.

Overall, the success in using marginal aggregates depends on having the knowledge to mitigate the weakness in the aggregate and then employing the appropriate mitigation strategy is employed during production.

Strategy: Improve the Durability of Concrete

There are many examples around the U.S. where concrete roads built in the early 1900s are still in service today, and other examples of concrete roads that carried traffic for 30 to 40 years with little need of maintenance. At the same time, there are also many examples of concrete roads that have suffered serious damage within a decade of construction due to durability issues such as freeze-thaw damage or ASR. For example, a current issue in several Midwestern States is joint deterioration that is the result of freeze-thaw damage, apparently amplified by the use of liquid brine deicing agents (Taylor 2011). Since durability is not an intrinsic property of concrete, but instead reflects the concrete's ability to resist the environment in which it serves, there is no way to directly measure it. ACI 201.2R (ACI 2008) provides a good description of mechanisms that can affect concrete durability and how durability can be enhanced. In general, depending on the environment, durable concrete possesses the following characteristics:

- A relatively low *w/cm*, typically in a range of 0.40 to 0.45. This will reduce the permeability and increase the strength of the hardened concrete.
- A high quality SCM in sufficient quantity to reduce permeability and increase long-term strength. An SCM can also be used to mitigate ASR and sulfate attack, but its ability to do so must be verified through testing.
- An effective air-void system comprised of closely spaced, spherical microscopic air bubbles. These are essential to relieve pressure generated as the water freezes in the concrete pores, and are particularly critical in freeze-thaw environments where deicing chemicals are used.

- Aggregates that are both physically and chemical stable, and will not degrade or crack under service conditions. If ASR susceptible aggregates must be used, mitigation strategies in accordance with AASHTO PP 65-11 should be employed to minimize the risk of damage.

Additional features may be needed to ensure durability for a given situation. It is essential that an effective QA program be rigorously adhered to throughout concrete production and construction.

Future Issues/Emerging Technologies

There are a number of issues and emerging technologies that have the potential to affect the production and use of concrete materials in the near future. These include:

- The EPA released an amended air toxics rule for portland cement manufacturing that significantly restricts emissions (especially of mercury which comes from both the burning of coal and calcination of the calcium carbonate) by U.S. cement plants by September 2015[3]. The impact of this new rule is uncertain, but it is clear that it will result in lowering the environmental impact of cement production. Switching to alternative fuel sources can address some of the issues related to mercury released during coal combustion, but mercury released during calcination of the calcium carbonate will result in increased capital cost for some cement plants to install mercury capture equipment and the likely closing of others where it is not economically viable.
- If fly ash becomes scarce, the market share of slag cement would be expected to increase. As U.S. slag production is expected to remain relatively constant, the long-term growth in the supply of slag cement is likely to hinge on imports, either of ground or unground material (USGS 2013b). The environmental impact of

Portland Limestone Cements (PLC)

One way to reduce the environmental footprint of cementitious binders is through the use of AASHTO M240 (ASTM C595) Type IL portland-limestone cements, which allows up to 15 percent limestone to be interground with portland cement clinker. The 15 percent limit is in place to ensure the PLC performs similarly to conventional portland cement and blended cements. At this replacement level, it is estimated that the use of portland-limestone cement reduces CO_2 emissions by up to 10 percent compared to conventional portland cement (CAC 2009).

Although the major motivation to use Type IL cement is to reduce CO_2 emissions, there are other advantages. Limestone is softer than clinker and thus when the two are interground the limestone particles are finer than the clinker particles resulting in improved particle packing. The fine limestone particles act as dispersed nucleation sites for the formation of hydration products that result in a dense microstructure as hydration proceeds. And finally, the limestone reacts with the aluminate phases present in portland cement and many SCMs to create carboaluminate phases (Matschei, Lothenbach, and Glasser 2007). Further advantages can be achieved when an SCM (e.g., fly ash, slag cement) is combined with a Type IL cement. Thus, in an AASHTO M240 Type IT blended ternary cement, cement manufacturers can optimize the chemical and physical properties of the portland cement, limestone, and the SCM to achieve equivalent or even improved performance to that obtained using conventional portland cement. Several North American field studies have demonstrated that Type IL cements can be used similarly to AASHTO M85 and other M240 cements in the construction of concrete pavements (Thomas et al. 2010; Van Dam, Smartz, and Laker 2010). It is cautioned that long-term pavement performance data are not yet available for concrete pavements made with Type IL cements.

[3] http://www.epa.gov/airquality/cement/pdfs/20121220_port_cement_fin_fs.pdf

importation will be closely linked to the mode of transportation, with transport by barge/ship having significantly lower impact than by truck (see table 3-1).

- One innovation is the high-volume SCM/portland limestone cement mixtures that are becoming more common. As state highway agencies accept this technology, it has the potential to significantly lower the GHG emissions associated with paving concrete.
- Photocatalytic cement is another innovation that potentially offers an opportunity to create a highly reflective surface that remains clean while treating air pollution through a photocatalytic reaction involving nanoparticles of titanium dioxide (TiO2). The reactions result in a chemical reduction of nitrous oxides (NOx), which prevents the formation of ozone and associated smog. In addition to this pollution-reducing quality, these cements are often very lightly colored and have very high albedo (reflectance) properties, which can result in a lowering of pavement and near surface temperatures (see chapter 6) while providing an aesthetically pleasing appearance due to their self-cleaning properties. The environmental benefits of photocatalytic cements have been documented in laboratories and on paving projects throughout Europe (Guerrini et al. 2012; Beeldens 2012), where more than 2.4 million yd2 (2 million m^2) of photocatalytic surfaces have been constructed, with horizontal surface applications like pavements (including both paving block and single-lift concrete pavement) comprising about half of that total. Reductions in NO_x have been reported to be as high as 60 percent, depending upon local environmental conditions and the technique for dispersing the TiO_2 in the concrete (Beeldens 2012). Pavement uses of photocatalytic cements in the U.S. have included paving blocks, porous concrete, and slurry-infiltrated asphalt pavement (Guerrini et al. 2012). One acclaimed project is the reconstruction of Cermak Road in Chicago, where pervious pavers with a photocatalytic surface have been employed (Oberman 2013). An effort to implement this technology featuring its use in the top layer of a two-lift concrete pavement project constructed on Route 141 near St. Louis, Missouri in 2010 was not as successful as hoped, demonstrating the need for continued research on this technology to determine the best avenue for implementation.
- Low carbon and carbon sequestering cementitious systems are emerging including geopolymers (Van Dam 2010) and alkali-activated fly ash (Hicks, Cheng, and Duffy 2010). Work continues on a number of other cementitious systems that have the potential to actually sequester carbon dioxide as they harden, lowering the carbon footprint of concrete mixtures. However, at the current time none of these systems is currently viewed as economically viable for large-scale adoption.

Other Concrete Mixtures

The preceding discussion focused almost exclusively on paving grade concrete, which is most often placed with a slipform paver or in fixed-form construction. Other types of plant-mixed concrete used in pavement applications include:

- Roller-compacted concrete (RCC) – RCC consists of the same basic ingredients as conventional paving grade concrete and obtains the same basic strength properties, but is a much stiffer mixture that is placed and compacted similar to asphalt concrete. The biggest difference is in the mixture proportions, in which RCC has a higher percentage of fine aggregate allowing tight packing and consolidation. For pavements, RCC has traditionally been used for industrial and heavy-duty parking and storage applications, but lately it is seeing more use for streets and highway shoulders. Detailed information on RCC for pavement applications is available from Harrington et al. (2010).

- Lean concrete and cement-treated base (CTB) course – There are multiple variations of cement-stabilized and cement-treated base courses consisting of aggregate, cement (also made with SCMs), and water. They can be made in a concrete plant or mixed on grade. A lean concrete base is, as the name implies, similar to a traditional concrete but has less total cementitious materials content (typically between 200 and 350 lbs/yd^3 [99 and 174 kg/m^3]) and develops 28-day compressive strengths between 750 and 1500 lbf/in^2 (5.2 and 10.3 MPa). If still less cementitious materials are used, the material is referred to as cement-treated, which typically achieves a 28-day compressive strength of just around 750 lbf/in^2 (5.2 MPa) (Smith and Hall 2001). CTBs can be made to be permeable, allowing infiltrating water to flow through the base to the drainage system.
- Pervious concrete – Pervious concrete pavements have a high degree of porosity allowing precipitation to flow through the voids in the concrete surface, helping to recharge groundwater while reducing stormwater runoff. Pervious concrete mixtures are carefully controlled, containing little to no sand that results in the inherent porosity (15 to 25 percent) needed to allow moisture flow through the material. Some pervious concrete mixtures being used have much smaller maximum aggregates sizes, but have similar permeability to that of “traditional” pervious concrete mixtures. Pervious concrete is most often used in parking areas, shoulders, or for low-volume roads. Information on pervious concrete can be found in a recent FHWA Tech Brief (Smith and Krstulovich 2012).

Other Materials

This section briefly reviews the manufacture of other common materials used in pavements, including steel, soil stabilizers and geosynthetic materials. Sources of environmental impact are identified in the acquisition, manufacturing, and transport of these materials to the site. Topics include energy and emissions generated.

Steel

Most concrete pavements constructed today are either JPCP or CRCP. JPCP is the most common type, and are built without steel reinforcement in the central portions of the slab, but may contain embedded steel in the form of smooth, round dowel bars at the transverse joints or deformed tie bars at the longitudinal joints. CRCP designs are constructed by several highway agencies, often in high-volume urban corridors. These designs contain a significant amount of continuous longitudinal steel, perhaps up to 100 to 120 tons (90.7 to 108.8 mt) per lane-mile (Tayabji, Smith, and Van Dam 2010).

Traditional steel manufacturing is a high environmental impact activity, involving the extraction of iron ore, limestone, and coal; making of coke; smelting the ore to create pig iron in a blast furnace; and then making steel through alloying with carbon and other elements in a steel furnace. Improvements in technology have increased the efficiency of the process, but there are still unavoidable impacts from the production system, which requires high temperatures and thus combustion of fuels, and the release of additional CO_2 emissions as the limestone undergoes calcination during the reduction of iron ore to pig iron. Secondary (recycled) steel production in electric arc furnaces has fewer environmental impacts; this is important because structural steel is estimated to have a recycled content of greater than 90 percent, and much of the reinforcing steel used in the U.S. is recycled (AISC 2013).

Reinforcing Fibers

It is becoming more common for fibers to be used in concrete in certain pavement applications (most notably thin overlays) to overcome the quasi-brittle nature of concrete and its relative weakness in tension/flexure. Common fibers are composed of various materials including organic matter (i.e., cellulose), polymers (i.e., polypropylene, polyester, nylon), glass, and steel. The ability to modify the behavior of concrete is heavily influenced by the fiber material, shape, and volume fraction. In general, low-strength, low-modulus fibers such as polypropylene microfibers added in low volume show some ability to reduce plastic shrinkage cracking in concrete but little ability to affect the mechanical properties of hardened concrete. On the other hand, the use of high-strength, high-modulus fibers at relatively high volumes significantly increases the modulus of rupture, fracture toughness, and impact resistance of the hardened concrete.

The addition of fibers to concrete changes its workability, and as the fiber stiffness, length, thickness, and volume fraction increase, so do difficulties in placing and finishing. The trade-off is to find a fiber type (material and size) and volume that provides the desired enhancement to the concrete's mechanical properties without compromising workability beyond the point where the pavement cannot be placed and finished. Today, synthetic macrofibers (1.5 to 2 inches [38 to 51 mm] long with an aspect ratio of 75) are filling this niche for pavement applications, typically being composed of high-strength, high-modulus polymers and dosed at a rate between 3 to 7.5 lbs/yd^3 (1.8 to 4.5 kg/m^3).

The sustainability benefits derived from fiber reinforcement can be ascertained by considering the environmental impact of fiber production and balancing it with anticipated improvements in pavement performance or reductions in slab thickness. As with many additives, the mass of fibers added to concrete is relatively small (around 0.1 percent by mass) and thus the impact is likely below the cutoff for consideration in an LCA. Nevertheless, this should be demonstrated by considering the manufacturing process for the particular fiber under consideration and the anticipated dosage.

Interlocking Concrete Pavers

Interlocking concrete pavers are precast concrete manufactured in central plants. They can be used to create both impermeable and permeable pavements, typically where vehicles are traveling at lower speeds. Permeable pavers have laying patterns that create gaps between them that are filled with permeable aggregate that allows water to pass through the surface (Smith 2011). Concrete grid pavements consist of larger units with surface openings typically filled with soil and grass (ICPI 2013). Interlocking concrete pavers can be manufactured with two layers of concrete where the top layer is made with photocatalytic cement. Pavers are often used in urban areas for traffic calming and aesthetics, and their easy removal and reinstatement provides ready utility access. Pavers have also been used extensively in port areas carrying extremely heavy wheel loads.

Sustainability issues for the production of pavers are similar to those for other concrete materials, since they share many of the same mixture ingredients and processes. But they provide aesthetic appeal, are readily repairable, can be used to create permeable surfaces, and can be highly reflective, all features that give them strong applicability to urban markets.

Geosynthetics

Geosynthetic materials take many forms that are used for a number of pavement applications, primarily with asphalt-surfaced structures. These include:

- Non-woven geotextiles or geosynthetic fabrics are used to reduce infiltration of fine and plastic soils particles from the subgrade into non-plastic base and subbase layers. This is particularly critical when the base or subbase layer is being used as a drainage layer, in which case the drainage pipes/trenches are often also wrapped in the fabric.
- Woven geotextiles and polymeric geogrids are used as reinforcement to improve the stiffness and shear strength of granular soils layers by providing confinement and bridging support near the bottom of the granular layer, particularly when placed over soft subgrades.
- A number of geosynthetic products, often different types paired in layers, have been used to retard the propagation of reflection cracking; applications include asphalt layers placed over existing cracked asphalt layers, asphalt layers placed over existing jointed concrete pavement, or asphalt layers placed over cement- or lime-stabilized soils or base layers that may have the possibility of shrinkage cracking.

Geosynthetics are primarily made of polymers derived from petroleum or fiberglass. Each has their own inherent environmental impacts that have not been assessed in the current literature, but can be roughly quantified by considering the mass of the materials. The additional environmental impacts of using geosynthetics should be considered relative to their contributions to extended pavement life.

The potential constraints on the future recycling of pavements that incorporate geosynthetic systems should also be considered. These constraints occur if the materials make it difficult for recycling machinery to operate (such as milling and pulverization equipment) or if the materials will interfere with mixing and other construction processes.

Soil Modifiers/Stabilizers

There are various materials that can be used to modify or stabilize soils to improve their behavior during and after pavement construction. These include some previously discussed materials such as:

- Portland cement – Portland cement can be used to stabilize both fine-grained plastic, non-plastic, and granular materials (see http://www.cement.org/pavements/pv_sc.asp). Depending on the application, the dose of portland cement can be relatively small (to improve the mechanical properties of a problem soil) to relatively high (for binding aggregates together to form a solid base). The environmental impact of portland cement stabilization largely rests with the amount of cement that is used in the application.

- Fly ash – Fly ash is a commonly used soil stabilizer. It can be used alone if the fly ash is "self-cementing," which is characteristic of many Class C fly ashes. Class F fly ashes are also used for soil stabilization if combined with a source of reactive calcium such as lime, cement kiln dust (CKD), lime kiln dust (LKD), or cement. When using fly ash for soil stabilization, care must be exercised to avoid swelling resulting from the expansion of sulfate minerals. Additional information on the use of fly ash for soil stabilization can be found at: http://www.fhwa.dot.gov/pavement/recycling/fach07.cfm

- Asphalt stabilizers – Asphalt can be used as a stabilizer of non-plastic granular materials. The most common asphalt stabilizers are emulsions or foamed asphalt, which are often used as part of a full-depth reclamation. Additional information on asphalt stabilizers is found at: http://ict.illinois.edu/publications/report%20files/FHWA-ICT-09-036.pdf

In addition to the materials listed above, lime is one of the most common soil modifiers/ stabilizers used in pavement construction (NLA 2013). Lime reduces the plasticity of highly plastic soils, making them more compactable and significantly reducing differential soil expansion under wetting and drying cycles, which can be critical to the functionality of the pavement. Where siliceous components are part of the soil chemistry, lime provides calcium and thus can also lead to pozzolanic reactions creating soil cementing in addition to soil modification. In soils that do not have a reactive form of silica present, lime can be combined with fly ash to achieve soil stabilization. More information on lime for stabilization can be found at: (http://www.lime.org/index/). Similar to lime, CKD and LKD can be used to treat plastic soils if they possess sufficient free lime to chemically react with siliceous components in the soil; they also have the added advantage of being waste products that have the potential for beneficial use.

Care must be taken in applying soil stabilizers that chemically react with the soil (e.g., portland cement, lime, fly ash, CKD, or LKD) to be certain that they will gain expected strength with a particular soil, and not produce undesirable unintended effects such as high levels of expansion due to unwanted chemical reactions. This is particularly true if lime stabilizers are being used and if sulfates are present in the soil (or if fly ash, CKD, or LKD are used that contain sulfates). It is therefore necessary to conduct a thorough laboratory investigation with the proposed stabilizing agent and actual soils from the project prior to using them in a full-scale field application.

The environmental impacts of portland cement, fly ash, and asphalt have already been discussed previously. Lime is produced by calcining limestone, and thus considerable CO_2 is liberated in the conversion of calcium carbonate to calcium oxide (quick lime) as well as from the burning of fuel. This must be considered when evaluating the benefits of stabilization through the use of lime. CKD and LKD are waste products, and therefore allocation is based on transporting the materials from the source (cement or lime kiln) to the project site. If the local market for CKD or LKD becomes such that they obtain economic value beyond the cost of transportation and disposal, they then need to be treated as a co-product.

Soil stabilization has the potential to substantially reduce the thickness of the pavement structure and to increase the life, both of which can reduce environmental impact. Moreover, they can be used to provide an effective working platform, greatly expediting the construction process and making it more efficient. Consideration of alternative pavement structures including those with soil stabilization should consider the life cycle to obtain an understanding of the trade-offs between materials production impacts and life increases or pavement structure reductions.

Major Issues

- Fibers may improve the mechanical properties of concrete such that the thickness of the pavement structure may be reduced or its life extended, but those benefits must be balanced with the increased difficulty in handling fresh concrete and increased environmental impacts and increased costs of using the fibers.

- Geosynthetics represents a broad range of products, most based on polymers derived from petroleum and fiberglass that can be used to reinforce soil, aggregates, and even asphalt surfaces. Again, the benefits of extended life should be considered in terms of their environmental impacts and costs.
- A number of different soil modifiers are available to improve a range of soil conditions. As with the other items, the benefits of reduced structural thicknesses or extended life must be balanced with the increased environmental impacts and costs.

Strategies for Improving Sustainability

- Fibers are being used as reinforcement to improve the mechanical properties of concrete used in thin bonded overlays. They can potentially reduce the thicknesses of the concrete slab by making the concrete more ductile and less susceptible to cracking.
  - Some fibers may be used to extend joint spacing without increasing the risk of cracking.
  - Some fibers can be used to reduce the risk of plastic shrinkage cracking.
  - Macrofibers of sufficient volume can reduce the amount of cracking and severity of cracking that does occur.
- Geosynthetics are often used to stabilize areas where conventional techniques fail, contributing to the pavement structure while expediting construction. They can potentially reduce the thicknesses needed for other pavement materials.
  - Geosynthetics can reinforce soil and unstabilized subbase and base materials.
  - Geosynthetics can be used to reinforce asphalt pavements.
  - Geosynthetics can be used to minimize or control the development of reflection cracking.
- Soil modifiers are typically based either on cementitious systems or asphalt and thus suffer many of the issues previously described.
  - Some soil stabilizers, such as lime, have a high carbon footprint due to calcination of the limestone.
  - Others stabilizers, such as fly ash, CKD, and LKD, are RCWMs and thus may have a low carbon footprint if locally available and if acceptable performance can be achieved.
- Potential issues and trade-offs.
  - There are various fibers on the market and it requires knowledge to select the proper fiber for a given application. At the high-volume fractions needed to modify the hardened properties of concrete, fibers will negatively impact mixture workability and potentially affect the environmental impact of the concrete.
  - Geosynthetics must be carefully designed and placed to be certain that they provide sufficient desired benefits (e.g., reflection crack control, longer life) for their cost (Koerner 2005).
  - Some soil modifiers/stabilizers derived from RCWMs can have chemistries that result in soil heaving, resulting in poor pavement performance.

  – Other modifiers, such as lime, are made by calcining limestone and thus have a high carbon footprint. Lime can also negatively interact with some soil types resulting in heaving.

Concluding Remarks

This chapter reviews the range of materials that can be used for paving applications, primarily including aggregates, asphalt materials, and cementitious materials. The way that each of these materials affects the overall sustainability of the pavement system is described, along with strategies that can be used to improve that sustainability. The scope of the chapter is from the extraction of materials to the point where materials begin final transportation to the construction site.

Some of the major issues regarding aggregate production and use are:

- Environmental and social implications of aggregate acquisition and transportation.
- Special concerns regarding aggregate processing.
- Implications of aggregate durability.
- The utilization and performance of RCWMs as aggregates.

Some of the major issues regarding asphalt materials used for pavement are:

- Continued increases in the price of petroleum, and thus asphalt, which is a finite resource.
- Appropriate use of polymer, rubber, and other types of binder modifiers.
- Depletion of high-quality aggregates needed for some type of mixtures.
- Specialization of mixtures for safety, noise, and structural considerations and their environmental and cost implications.
- Use of RAP and other RCWMs including asphalt shingles, recycled tire rubber, and sulfur.
- Environmental, social, and cost implications of mixture design and durability.
- Future binder availability and alternatives.
- Ensuring asphalt material durability.

A summary of some of the major issues confronting the acquisition and production of concrete materials used for paving are as follows:

- The relatively high non-renewable energy consumption and GHG emissions inherent in the portland cement manufacturing.
- The relatively high GHG emissions associated with the production of traditional portland cement, and its impact on portland cement concrete mixtures with high cement contents.
- Water use associated with concrete production.
- Reducing the amount of cement used in concrete mixtures through improved gradations and increased use of SCMs.
- Increasing the use of RCWMs as aggregates without compromising performance.
- Ensuring concrete durability.

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CHAPTER 4. PAVEMENT AND REHABILITATION DESIGN TO IMPROVE SUSTAINABILITY

Introduction

This chapter describes sustainability considerations in the design of both new and rehabilitated pavement structures, with the latter including structural overlays and reconstruction. The first step in pavement design is to define the objectives based on the goals and policies of the owner/agency, which should include sustainability objectives. The design process results in the development of alternative pavement structures (including structural layers and thicknesses), specifications for materials that meet the performance objectives of the individual layers as well as the system as a whole, considerations for subsurface drainage (as appropriate), and governing construction specifications needed for the pavement to perform as intended.

As described in chapter 2, all pavement types can be designed to be more sustainable by considering costs, environmental impacts, and social needs together. This is true even for pavements built with relatively conventional materials and construction techniques, but as noted in chapter 2 it is up to the owner/agency to set the goals and establish the considerations that will receive greater emphasis in the development of "more sustainable" pavement designs.

In particular, this chapter reviews the decisions made in the design process (e.g., layer type options, materials, thicknesses, appropriate layer combinations, and geometric features) that can affect the overall sustainability of the resulting pavement, with a focus on pavement types, specific materials, and structural design considerations. The objective of the chapter is not to present innovative pavement designs but rather to communicate the need to critically evaluate the entire design process in order to make the pavement that is ultimately designed the most sustainable option for the stated design objectives and constraints.

The scope of this chapter, relative to several other related chapters, is shown in table 4-1. It is observed that, in addition to new and reconstruction design, this chapter includes structural overlays (both asphalt and concrete) as they require a design component (considering the existing pavement condition and future traffic levels) that leads to the provision of additional load-carrying capacity. Nonstructural overlays and pavement maintenance and preservation treatments are covered in chapter 7, and specific end-of-life strategies (e.g., full-depth reclamation, recycling) are covered in chapter 8.

The selection of alternate routes or alternative modes of transportation are outside the scope of this document. The design and construction of new geometry for roads, including consideration of the impacts of horizontal and geometric alignment on construction activities (e.g., excavation, material movement, tunneling, balancing of cut and fill) and vehicle operations (e.g., effects of vertical and horizontal curves on fuel economy, other vehicle operating costs and safety) are also outside the scope of this document. Research by various organizations over a number of years has identified the effects of road geometry on vehicle fuel consumption, other vehicle operating costs, and safety (see, for example, Claffey 1971; Watanatada et al. 1987, and Ko, Lord, and Zietsman 2013, among others). The net effects of environmental impacts considering earthworks and materials to construct different geometric designs, as well as the benefits from improved vehicle operating cost in the use phase, can be evaluated through LCA.

Table 4-1. Division of scope between design, maintenance and preservation, and end-of-life chapters.

Pavement Type	**Chapter 4. Pavement and Rehabilitation Design to Improve Sustainability**	**Chapter 7. Maintenance and Preservation Treatments to Improve Sustainability**	**Chapter 8. End-of-Life Considerations**
Asphalt Pavements	• New Asphalt Pavement Design or Reconstruction • Structural Asphalt Overlay • Bonded Concrete Overlay • Unbonded Concrete Overlay	• Crack Filling/Sealing • Asphalt Patching • Fog Seals/Rejuvenators • Chip Seals • Slurry Seals • Microsurfacing • Ultra-thin and Thin Asphalt Overlays • Hot In-Place Recycling • Cold In-Place Recycling • Ultra-thin Bonded Wearing Course • Bonded Concrete Overlays	• Central Plant Recycling • Full-Depth Reclamation
Concrete Pavements	• New Concrete Pavement Design or Reconstruction • Bonded Concrete Overlay • Unbonded Concrete Overlay • Structural Asphalt Overlay − Conventional − Crack/Break Seat − Rubblization	• Joint/Crack Sealing • Slab Stabilization/Slab Jacking • Diamond Grinding/Grooving • Partial-Depth Repairs • Full-Depth Repairs • Dowel Bar Retrofit • Slot/Cross Stitching • Ultra-thin Bonded Wearing Course • Bonded Concrete Overlays	• Concrete Recycling − In Place − Off site
Other Pavement Types	• New Composite or Semi-rigid Concrete • Pavement Design or Reconstruction • New Drainable Pavement Design or Reconstruction • New Modular Pavement Design or Reconstruction		

Pavement Design Considerations

Pavement design for a new or rehabilitation construction project is the process of:

1. Identifying the functional and structural requirements of the pavement including the design life and constraints.
2. Gathering key design inputs such as material properties, traffic loadings, and climatic factors.
3. Selecting the pavement type and associated materials, layer placement and thicknesses, and construction specifications to achieve the desired performance.
4. Considering design alternatives for all of the above to determine the preferred solution in terms of life-cycle cost, environmental impacts, and societal needs.

The identification of sustainability goals should be considered the first step in the process shown above. However, as described in chapter 2, although sustainability and life-cycle assessment are growing in importance, most highway agencies still primarily consider costs (either the lowest initial cost or the lowest life-cycle cost) in the pavement design process (GAO 2013). As will be seen in many cases in this chapter, pavement designs that improve environmental sustainability can often reduce life-cycle costs, largely as the result of reductions in natural resource requirements and energy consumption.

The following are items that may be included in project-specific requirements for the design of a particular pavement:

- Expected design life.
- Smoothness.
- Surface texture as it impacts friction and noise.
- Splash/spray.
- Stormwater runoff.
- Traffic delay associated with future maintenance.
- Reliability considering cost and level of interruption of service for maintenance and future rehabilitation.
- Ability to accommodate utility installation and maintenance.
- Potential for future obsolescence (the pavement will need to be replaced or removed before its design life is reached).
- Local thermal environment as influenced by pavement.
- Aesthetics.

Each of these considerations can have an impact on the sustainability of the pavement, but their relative importance will depend on the context of the design as well as the overall sustainability goals of the owner/agency and the specific project objectives. Each requirement should be assessed by the designer based on how the pavement will interact over its entire life cycle with users (both for passenger mobility and freight movement, where applicable, and primarily in terms of safety and efficiency), the surrounding community, and the environment (both local and global effects). The requirements of the users and community will also depend on the functional class of the roadway, and may also vary with time. Similarly, the overall benefits of different design approaches to improving sustainability will depend on the context of the design (such as location, traffic volumes and characteristics, support conditions, climatic conditions, and so on) and will also likely vary with time (Santero and Harvey 2010).

Some considerations and general guidance regarding the inclusion of sustainability as part of pavement design include the following:

- Surface performance.
  - Smoothness is often considered the most important surface characteristic; texture and deflection may also be considerations (see chapter 6 for details).

  - The pavement surface affects vehicle fuel consumption (see chapter 6 for details), vehicle life, and freight damage costs.
  - The consideration of future maintenance and rehabilitation and their effects on smoothness are important components to be considered in evaluating sustainability impacts.
  - Surface performance is context sensitive in that it is very critical to pavements exposed to higher traffic volumes and less important to pavements carrying lower traffic volumes. For pavements carrying heavy traffic volumes, the environmental benefits of keeping the pavement smoother can far outweigh the negative environmental impacts of materials production and construction.
- Design life selection.
  - The functional and structural life of the pavement is influenced by both traffic and environmental factors.
  - The selection of the design life should include the consideration of higher initial economic costs and environmental impacts associated with longer life designs versus higher future costs and environmental impacts associated with shorter life designs (due to the need for additional maintenance and rehabilitation activities).
  - The selection of the design life should include consideration of end-of-life alternatives (see chapter 8).
- Pavement type selection.
  - The pavement type selection impacts every phase of the pavement life cycle, including the selection of initial materials and construction as well as the future maintenance and rehabilitation, use phase, and end of life.
  - The relative sustainability impacts of different pavement types depend on location, design traffic, and available materials.
- Construction and materials selection.
  - The impacts of materials selection on sustainability depend on the local sources of materials and the transportation alternatives available (see chapter 3 for details).
  - The ability to achieve quality construction with available materials and construction equipment and expertise impacts the sustainability of the pavement (see chapter 5 for details).
  - Traffic delays in construction work zones may result in negative sustainability impacts where traffic volumes are high and traffic management plans (TMP) cannot mitigate delay; slowing traffic down may lead to small improvements in the sustainability impact.
- Construction quality requirements (see chapter 5 for details).
- Recycling strategies (see chapters 3 and 8 for details).

The impact on pavement sustainability that results from these types of decisions can be assessed through LCA and through sustainability ratings systems as part of an overall assessment process (see chapter 10 for details on these processes).

Consideration of Payback Time

One approach to evaluating whether sustainability goals are being met is the concept of "payback time." Payback time is defined as the period between the initial environmental impact and the time to achieve a zero difference compared to the standard approach, after which there is a net reduction in environmental impact; more simply, it is the time required to recoup the benefits (be they cost, environmental, or social) associated with a pavement design investment. This concept is useful when evaluating design approaches that require a larger initial cost or environmental impact as compared with standard practice, but which provide significant impact reductions over the rest of the pavement life cycle. Some typical examples involve long-life pavement designs, which increase the time (years) before the first rehabilitation or reconstruction, reduce the level and frequency of maintenance during the life, and keep a pavement smoother over its life, but will likely have a higher initial impact on cost and the environment because of the use of premium or unique materials or increased layer thicknesses. A payback analysis provides an indication of the uncertainty of achieving a reduction in environmental impact over the life cycle due to a design decision, with longer payback times have greater uncertainty regarding the ability of the assessment to accurately quantify them and whether they will actually occur.

An example of the payback time for a specific case study is provided in figure 4-1, which shows a comparison of the GWP of the materials production and construction phases for pavements with 20-, 40- and 100-year design lives (all using the same materials). It can be seen that the 40-year pavement initially has more GWP than the 20-year pavement, primarily due to a thicker structure, but that the difference is made up after 29 years; furthermore, over a 100-year analysis period the 40-year pavement has approximately half the GWP of the 20-year pavement.

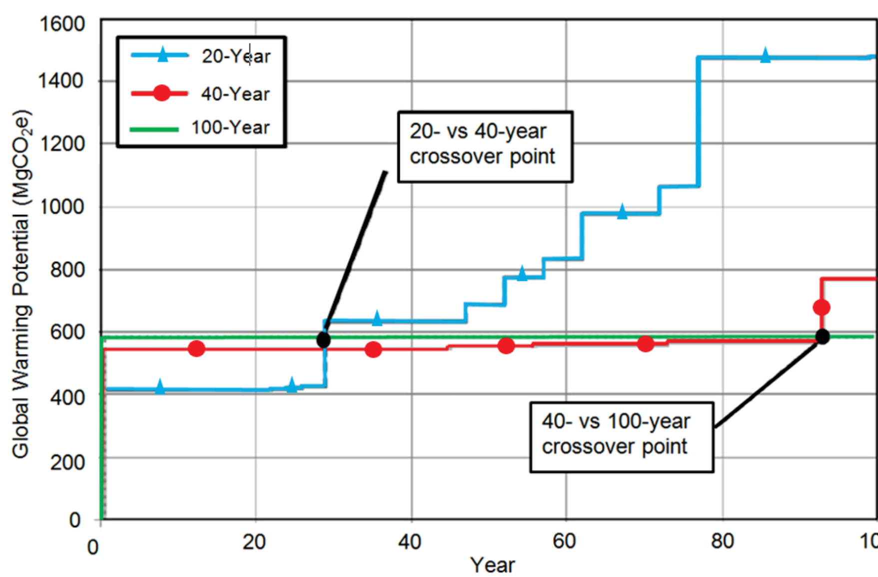

Figure 4-1. Example of payback time analysis considering only the material production and construction phases of three different pavement design lives (modified from Santero, 2009).

As noted previously, longer payback times indicate greater uncertainty in the final difference between alternatives. For example, it can be seen in figure 4-1 that the payback time (cross-over point) is 93 years between the 40- and 100-year design lives, and that the actual difference in initial GWP between those two alternatives is small. Longer payback periods also mean that the

AASHTOWare Pavement ME Design Software

The AASHTO mechanistic pavement design procedure (AASHTO 2008) and the accompanying AASHTOWare Pavement ME Design software (AASHTO 2012) are based on mechanistic-empirical design principles and provide a powerful tool for pavement engineers to predict pavement performance. Pavement ME considers different pavement types, layer types and thicknesses, material properties, traffic projections, and climatic data. It allows users the ability to evaluate multiple pavement designs over a specified analysis period and match future maintenance and rehabilitation needs with the predicted distresses. From the user defined layer types, properties, and general inputs, the software determines the minimum pavement surface thickness based on project and agency objectives and selected failure criteria. The Pavement ME software can also be used for forensic investigations to study the deficiencies associated with existing pavements.

The AASHTO Pavement ME is calibrated at the national level, and thus local calibration of the distress models may need to be completed; furthermore, particular scrutiny may need to be given to designs utilizing innovative designs, materials, and construction not part of the distress model calibration.

planet and humans are exposed to the environmental impact for an extended period before any environmental benefit is realized, although societal and economic impacts may occur. The example shown in figure 4-1 only considers the impacts of material production and construction, and consideration of use phase impacts will likely change the cross-over point. Approaches for considering the time dependency of impacts in LCA and carbon footprints are being developed (Kendall, Harvey, and Lee 2009: Harvey et al. 2010; Kendall 2012).

Mechanistic-Empirical Design Methods

Empirical pavement design methods, which are based on observations of the performance of in-service pavements without consideration of theoretical concepts of pavement behavior, can only consider how pavements perform within the narrow realm of the prevailing conditions (e.g., fixed material types, fixed pavement types and design features, fixed environmental conditions and traffic loadings). This design framework makes it more difficult to introduce innovative materials, designs, and specifications without constructing full-scale test sections and observing performance.

Mechanistic-empirical (ME) design methods offer much greater opportunity to consider alternative materials, pavement structures, and construction procedures. For both conventional and new paving materials, ME design directly considers key material properties (such as stiffness, fatigue resistance, low-temperature cracking properties, permanent deformation resistance, and thermal expansion) and is able to relate those properties directly to pavement performance through available response and performance models. ME design allows the development of designs even for new materials that have not been used before, based on their predicted mechanistic (the "M" in ME) response to traffic loads, temperatures, and moisture condition. The performance predictions can be improved as more empirical (the "E" in ME) performance data become available. Similarly, ME design permits the evaluation of changing construction specifications through consideration of their effect on input materials properties.

ME design can estimate key asphalt or concrete pavement distresses (such as cracking, rutting, faulting) and roughness (e.g., International Roughness Index [IRI]) versus time, which allows the designer to consider alternative trigger levels for maintenance and rehabilitation. ME design tools also allow the designer to analyze alternative decisions that will affect many of the factors in the pavement life cycle that are shown in figure 2-1 in chapter 2.

The AASHTOWare Pavement ME Design Software (see sidebar) uses an iterative process, with the designer calculating the expected performance of a proposed structure, and then changing aspects of the design to move towards design objectives, such as structural and functional performance levels, cost stipulations, and geometric constraints, but these objectives can also include environmental and societal impacts. The AASHTO Pavement ME is a tool for determining the pavement type and corresponding layer types and thicknesses for a wide range of new and rehabilitated pavement structures. Some state DOTs have developed and are using other ME design procedures and software tools (e.g., California, Minnesota, Texas) for different types of pavements and some states are using Pavement ME or other ME tools in combination with empirical procedures. There are also ME design tools available from industries, organizations, universities, and other countries that are too numerous to provide a comprehensive list of citations. All ME procedures including the AASHTO Pavement ME Design have various advantages and limitations in terms of models, extent of calibration, local applicability with regards to materials and environment, availability of input data, and ability to consider new pavement and rehabilitation alternatives such as many of those discussed in this document. Any ME procedure should be evaluated before it is used, and the results used with care by an experienced pavement designer.

Process for Consideration of Sustainability in Pavement Design

An example of an overall process for considering sustainability in pavement design is shown in figure 4-2. The process shown in the figure is particularly oriented towards the design-bid-build (i.e., low-bid) project delivery process.

There are numerous alternative pavement solutions that can be proposed for any set of design requirements. The pavement design process, whether asphalt, concrete, modular, or composite, must begin by defining the owner/agency design and policy objectives as well as any sustainability objectives. Once various pavement design alternatives have been developed, LCCA, LCA, and pavement rating tools can be applied to assess economic, environmental, and societal impacts to varying degrees as a way of improving the sustainability aspects of the proposed pavement designs. Chapter 10 provides additional information on those assessment tools.

Design Objectives

An owner/agency has a number of different objectives to consider when developing a pavement design. These may be explicit objectives included in policy, may be implicit to the local agency, or may be just emerging.

Performance Objectives

The overall performance objectives used in the design process will depend on agency policies. These polices are typically developed based on a number of items, such as acceptable distress and ride quality levels and economic analyses of agency initial and life cycle costs, and may also include some types of road user costs and funding agency guidelines.

In a design-bid-build (DBB) or design-build (DB) project delivery environment, it is assumed that the design methodology will adequately predict the ability of the constructed pavement to meet the performance objectives. Some examples of performance objectives in the DBB or DB delivery environment include:

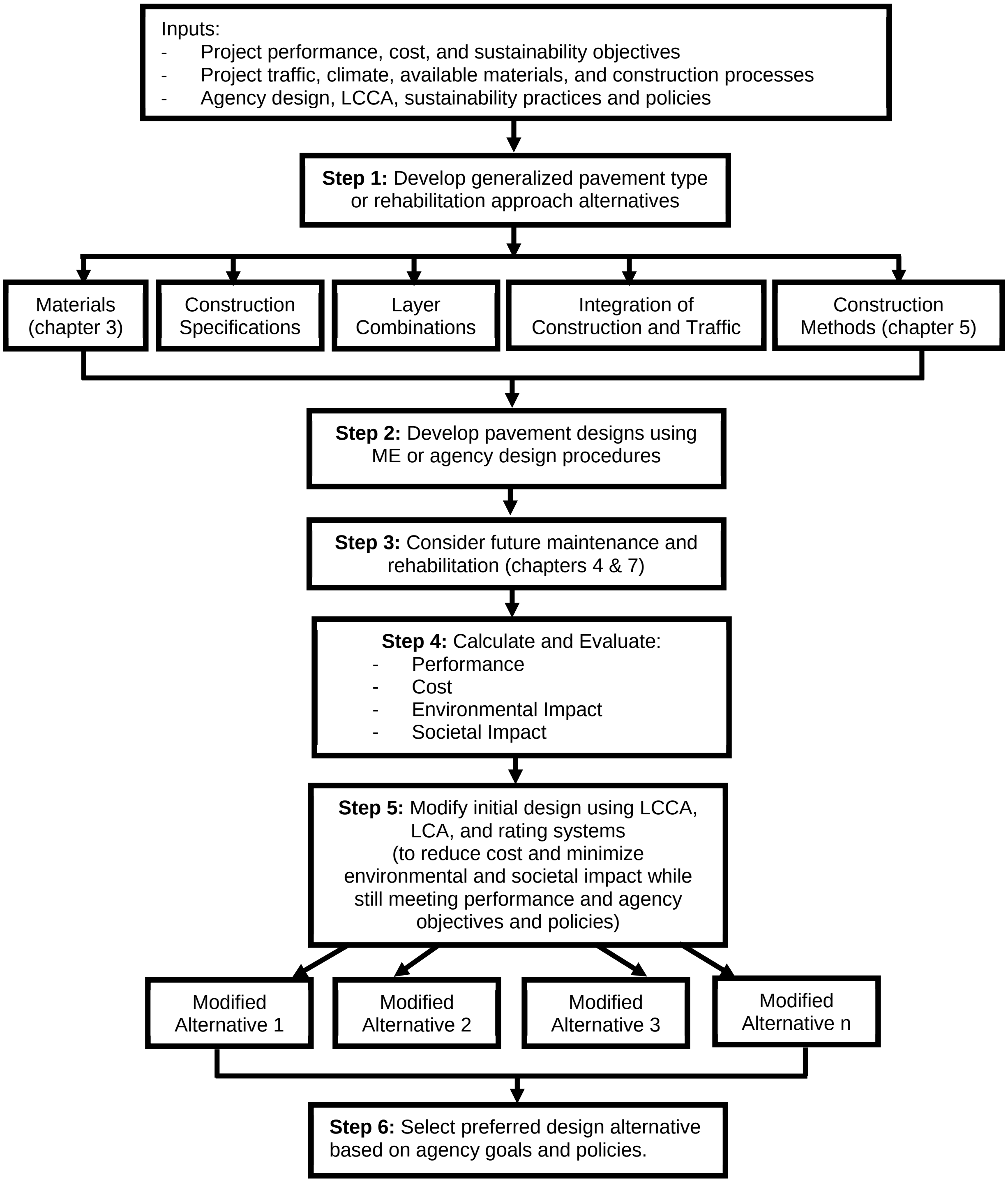

Figure 4-2. Overall process for considering sustainability in pavement design.

- Design life, or the number of years it takes to reach the defined end of life based on the effects of the predicted traffic loading and climatic impacts on the assumed pavement structure.
- Reliability, or the probability of reaching the design life before exceeding established distress or ride quality thresholds.

In a design-build-maintain (DBM) project delivery environment, performance objectives are explicitly written as contractual performance requirements that the contractor must deliver during the contract performance period. Some examples of performance requirements for DBM include:

- Maximum allowable IRI.
- Maximum amount of cracking or other indicators of structural deterioration.

Cost Objectives

It is common for an agency's cost objective to be to minimize the overall life-cycle cost of the pavement over a defined analysis period, or it may be to minimize the life-cycle cost while also operating within an initial cost constraint. Additional guidance on LCCA is found in chapter 10, with detailed information available from the FHWA (Walls and Smith 1998). The General Accounting Office has recently reviewed a sample of state LCCA practices and provided recommendations for improvements (GAO 2013).

Sustainability Objectives

Chapter 2 lists in detail the potential sustainability goals and objectives that are inherent as part of the pavement design process. This includes not only meeting the performance goals and cost requirements, but also minimizing environment impacts and meeting key societal needs.

Alternative Pavement or Rehabilitation Types

After the goals and policy objectives of the owner/agency have been defined, the project traffic and climate data have been compiled, and available materials and construction processes have been determined, the next step is the development of various pavement design alternatives. There are a variety of new and rehabilitated pavement structures that can be considered, broadly grouped into the following categories: asphalt pavements (including asphalt overlays), concrete pavements (including concrete overlays), composite pavements (asphalt over concrete and two-lift concrete on concrete), modular pavements, and fully permeable pavements. These are described in the following sections.

Asphalt Pavement Types

New or Reconstructed Asphalt Pavement Structures

As described in chapter 1, asphalt pavements are those with an asphalt surface layer of any thickness (even including only a chip seal), and may include various asphalt stabilized structural layers. They may also include granular support layers (bases and subbases) below the asphalt bound layers and above the subgrade. Full-depth asphalt pavements include only an asphalt surface and binder course layers paved on treated or compacted subgrade, as illustrated in figure 4-3.

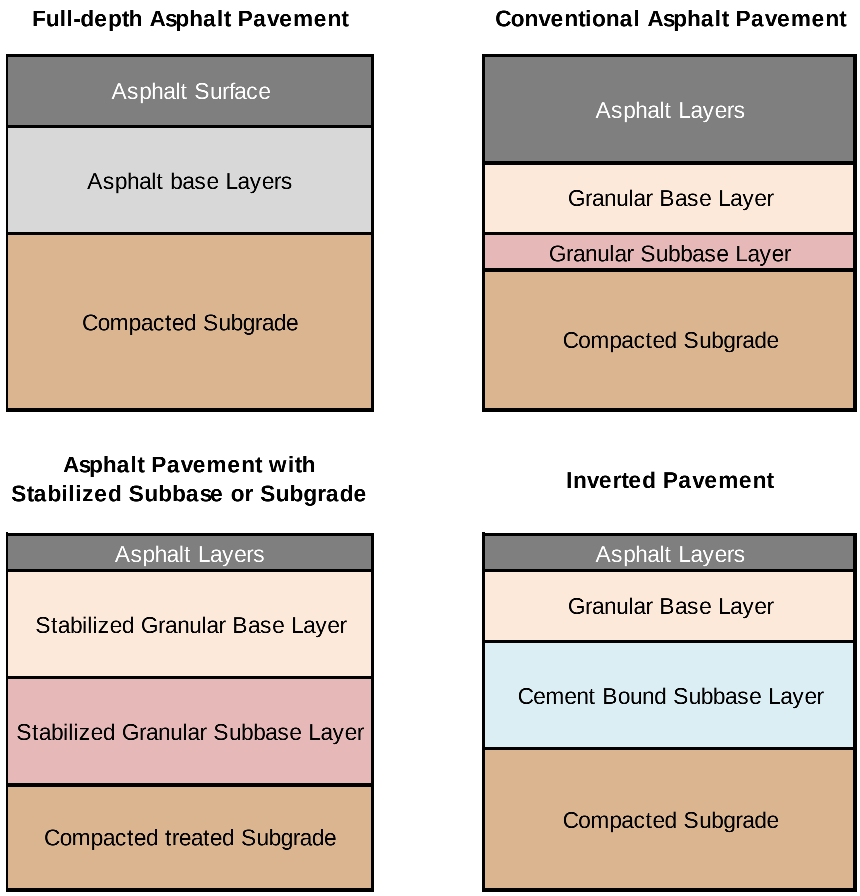

Figure 4-3. Cross sections of various asphalt pavement types (not to scale).

In some cases, granular layers may be used between the asphalt stabilized surface layers and a cement-stabilized subbase, a design referred to as an "inverted" pavement. The "inverted" nature of the design provides strong structural support for the pavement while eliminating the reflection of shrinkage cracks in the cement-stabilized subbase into the asphalt layers. A typical rehabilitation for asphalt pavements is the placement of a structural asphalt overlay, generally defined as having a thickness greater than 2 inches (51 mm). When the slabs in concrete pavements are "rubblized" and then paved with an asphalt overlay, the rubblized concrete effectively serves as an aggregate base.

A detailed description of the various materials used in asphalt pavements are discussed in chapter 3. In general, opportunities for using recycled materials exist in all layers of an asphalt pavement, including the use of RCA and RAP in the granular layers and rubber, RAP, and RAS in the asphalt-stabilized layers. Furthermore, asphalt concrete technology can be used to batch and construct the various asphalt layers. Effective compaction of all pavement layers is critical for improving the performance of all asphalt and granular layers as well as the subgrade, and achievable compaction specifications that maximize overall compaction and minimize the variability of compacted density will improve pavement performance without imposing any significant environmental impact from construction.

Open-graded drainage layers below the asphalt layers may be considered to help handle stormwater. Care must be taken to ensure that drainage layers below the surface have adequate cross-slope and will be maintained to provide free drainage for the life of the pavement and future rehabilitations. This includes providing filters to keep these layers from becoming clogged, and maintaining free flow from these layers away from the pavement either through "daylighting" to the shoulder or by maintaining shoulder drains.

Various types of interlayers may be considered to improve the performance of granular layers by providing confinement and tensile stress handling capability. Interlayers are designed to allow water to pass through but filter out soil particles, thereby preventing fine subgrade materials from moving into and contaminating granular base, subbase, and drainage layers under hydraulic pressures caused by traffic loadings.

Reconstruction of asphalt pavements consists of removing some or all of the existing structural layers and replacing them, substantially constructing a new pavement structure. There are often many alternatives for recycling materials removed from the existing structure in the new structure. The decision to reconstruct is based on comparison of rehabilitation alternatives considering the condition of the existing pavement and the overall objectives of the owner/agency for the project.

Open Graded Asphalt Surfaces

Open-graded asphalt surfaces are thin asphalt concrete layers (typically 0.5 to 2 inches [13 to 51 mm]) that are constructed with an air void content in the range of 15 to 25 percent of the total mixture volume. The porosity of the surface layer provides a number of potential benefits, including:

- High surface friction.
- Reduced hydroplaning potential.
- Reduction in and splash and spray.
- Improved visibility.
- Reduced noise levels.
- Reduction in urban heat island effects.

These benefits are highly dependent on mix characteristics of the asphalt layer, traffic levels (including the use of studded tires), climatic factors, and maintenance.

Various options exist for open-graded asphalt mix design to obtain these benefits for the longest period possible, while balancing performance with cost and environmental impact. Open-graded asphalt surfaces may be incorporated into a fully permeable pavement system, as discussed in chapter 6.

Asphalt Pavement Surface Types

Asphalt pavement surface layers may be selected to achieve certain functional and structural objectives. Examples of asphalt surface types are:

- Dense-graded asphalt concrete.
- High-friction materials (such as chip seals and microsurfacings).
- SMA for noise, durability, and friction.
- Open-graded asphalt courses for noise, splash/spray, and friction.

In addition to noise benefits, thin open-graded asphalt surfaces transmit stormwater below the surface of the permeable pavement laterally to the shoulder of the road where it is discharged. This causes a slowing of the rate of runoff, which reduces the peak flow of stormwater discharge and also results in pollutants being captured in the open-graded layer (Grant et al. 2003). All these surface layer types can include options for recycling. Additional details regarding tire-pavement noise and various asphalt surface types are provided in chapter 6.

For asphalt overlays, rubberized (using recycled tires) or polymer-modified overlays will often provide improved resistance to bottom-up reflection of existing cracking and top-down cracking. Stress absorbing membrane interlayers of various types are also sometimes used to slow reflection cracking.

Asphalt Pavement Rehabilitation Options

Structural rehabilitation strategies for asphalt-surfaced pavements include asphalt and concrete (bonded and unbonded) overlays, both of which provide additional load-carrying capacity to the existing pavement. Schematic cross sections of these various overlay types are provided in figure 4-4. Non-structural overlays, either asphalt or concrete overlays of thickness less than about 2 inches (51 mm), do not add significant structural load-carrying capacity and would be used to address functional pavement issues. Those non-structural overlays are discussed in more detail in chapter 7 (preservation and maintenance).

Overlays for Asphalt-Surfaced Pavements

- ✓ ***Structural asphalt overlays**: Thicker, new dense-graded asphalt layers placed on existing surface to improve structural capacity.*
- ✓ ***Structural concrete overlays**: Bonded overlays rely significantly on the thickness and stiffness of the existing asphalt pavement in the structural design whereas in an unbonded overlay the existing asphalt pavement functions as a base layer.*

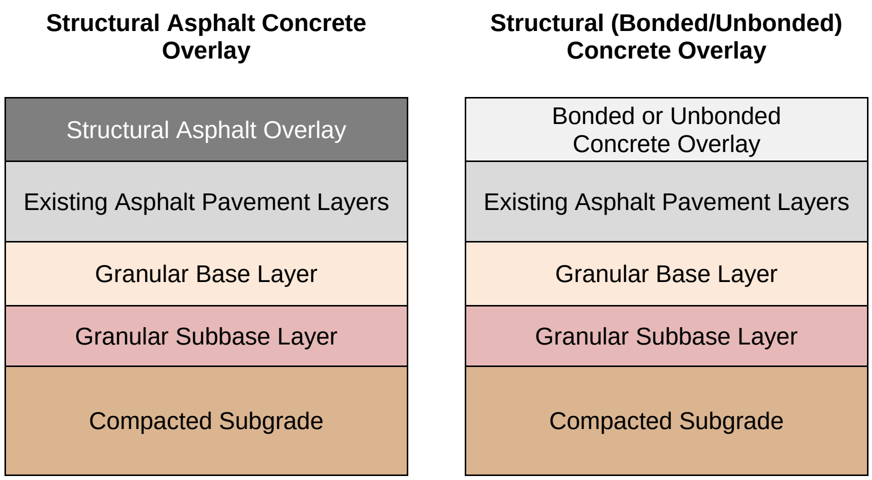

Figure 4-4. Cross sections of rehabilitated asphalt pavement structures (not to scale).

Structural asphalt overlays consist of placement of thicker new asphalt layers (typically more than 2 inches [51 mm]) on the existing surface to increase or restore the pavement's structural capacity as well as improve functional characteristics. Structural asphalt overlays commonly use conventional dense-graded asphalt concrete. For a structural asphalt overlay of an existing asphalt pavement, some or all of the existing asphalt surface layers may be milled in order to improve bonding to the existing surface, eliminate surface rutting, establish the desired surface elevation, and for removal of top-down cracking, old sealants, patching material, and oxidized asphalt materials. These millings are a source of RAP, and could be recycled into the same project or stockpiled for future use.

An alternative to milling is to recycle in place the upper 2 to 4 inches (51 to 102 mm) of the existing asphalt layers with either cold in-place recycling followed by an overlay or with hot in-place recycling (see chapter 7). However, full-depth reclamation (see chapter 8), with no stabilization or stabilized with cement, cement/foamed asphalt, asphalt emulsions or other stabilizers, may be a better selection if all of the existing asphalt layers are heavily cracked, if there is significant delamination between asphalt layers, if the asphalt layers have moisture damage at various depths, or if there are unbound base layers that will provide inadequate structural support to the asphalt layers.

Structural concrete overlays over existing asphalt surfaced pavements are classified as either unbonded or bonded based on the interface condition between the existing asphalt pavement and the new concrete overlay (Harrington 2008; Harrington and Fick 2014; Torres et al. 2012). Unbonded concrete overlays are placed over existing asphalt, composite, or semi-rigid pavement, with the existing pavement essentially functioning as the base and subbase layers. The unbonded concrete overlay (of thickness 7 to 10 inches [178 to 254 mm]) is typically designed as a new concrete pavement, either a JPCP or as a CRCP, with the existing asphalt pavement acting as a base. If the existing asphalt surface is highly distressed, a thin asphalt interlayer (typically less than 2 inches [51 mm]) may be placed on top to provide a smooth and durable layer beneath the concrete overlay. Part of an existing asphalt surface may also be milled and removed prior to placing the concrete overlay for the same reasons as for structural asphalt overlays on asphalt pavement.

Bonded concrete overlays of asphalt pavement consist of placement of a 3 to 6 inches (76 to 152 mm) thick layer of concrete bonded to an existing asphalt or semi-rigid pavement. The existing asphalt or semi-rigid pavement structure has a larger impact on the design of bonded concrete overlays and thus must be in relatively good structural condition. Slab sizes are much shorter, typically 4 to 6 ft (1.2 to 1.8 m), compared with unbonded concrete overlays that commonly (but not always) have more conventional joint spacing (typically about 15 ft [4.6 m]).

Concrete Pavement Types

New or Reconstructed Concrete Pavement Structures

Concrete pavements are constructed or reconstructed with a concrete surface layer resting on a base and possibly a subbase layer, depending on the traffic, climate, and foundation support conditions. As described previously, JPCP and CRCP designs are the most common types of concrete pavements, with typical cross sections of each depicted in figure 4-5.

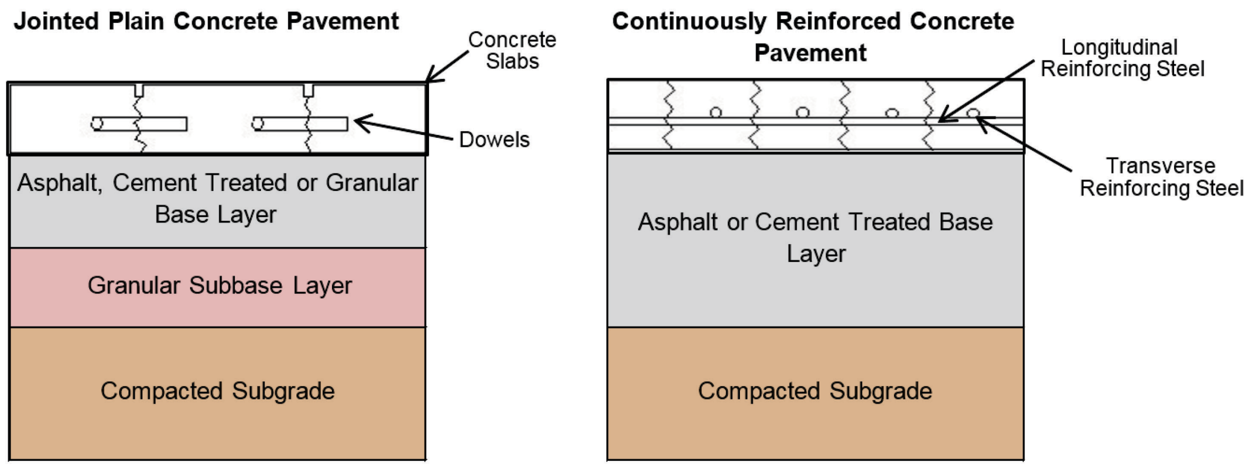

Figure 4-5. Cross sections of concrete pavement structure types (not to scale).

Noted characteristics of JPCP and CRCP designs are as follows:

- JPCP has transverse joints spaced typically about 15 ft (4.6 m) apart and contains no reinforcing steel distributed throughout the slab. Steel dowel bars across transverse joints provide effective load transfer at the transverse joints and significantly reduce joint faulting, pumping, and corner breaks, while JPCP without dowels will tend to have reduced load transfer when slabs contract under colder temperatures. Steel tie bars across longitudinal contraction and construction joints keep these joints tight and in alignment.
- CRCP has no regularly spaced transverse joints but typically contains 0.6 to 0.8 percent longitudinal steel reinforcement (expressed as a percentage of the cross-sectional area of the slab). The higher steel content both influences the development of transverse cracks within a desired spacing (about 3 to 6 ft [0.9 to 1.8 m]) and serves to hold them tightly together. Transverse reinforcing steel may also be used, primarily to support the longitudinal steel.

These traditional concrete pavement sections include opportunities for use of recycled materials in the base and subbase layers as well as various recycled materials in the concrete surface as described in chapter 3.

As with asphalt pavements, reconstruction of concrete pavements consists of removing some or all of the existing structural layers and replacing them with a substantially new pavement structure. There are often many alternatives for recycling materials removed from the existing structure in the new structure. Once again, the decision to reconstruct is based on comparison of rehabilitation alternatives considering the condition of the existing pavement and the overall objective of the owner/agency for the project.

Concrete Pavement Thermal Characteristics

Most materials expand when they are heated and contract when cooled. The degree to which this occurs is measured by the coefficient of thermal expansion (CTE), which is presented in terms of the change in unit length of a material as a function of an associated change in temperature. This behavior is important for concrete pavement design, as higher CTE values result in higher stress development due to temperature differences that exist between the top and bottom of the concrete slab. These temperature differences are affected by the albedo (solar reflectivity) of the surface and the conductivity and heat capacity of the concrete and other pavement layers.

CTE is a direct user input in the AASHTOWare Pavement ME Design procedure for concrete pavements. Higher CTE values result in higher predicted levels of slab cracking and joint faulting for JPCP (Hall and Tayabji 2011), and a greater incidence of punchouts and associated roughness on CRCP (Roesler and Hiller 2013).

The CTE of concrete depends primarily on the coarse aggregate used in the mixture. CTE values can range from around 4 x 10^{-6} in/in/°F (7 x 10^{-6} mm/mm/°C) for concrete containing limestone aggregate to a value of about 6.6 x 10^{-6} in/in/°F (11 x 10^{-6} mm/mm/°C) for concrete containing quartz aggregate.

Given the importance of the CTE in new ME design procedures, many highway agencies are working to characterize the CTE properties of their concrete mixtures. A test protocol for CTE testing has been standardized by AASHTO under T 336 (Hall and Tayabji 2011).

Concrete Pavement Surface Options

Concrete pavements have a number of surface textures that can be constructed to provide different functionality for friction and noise. Transverse tining has commonly been used to provide surface friction, but has been found to be a noisier surface (Rasmussen et al. 2008).

Other surface textures include longitudinal tining, diamond ground, diamond grooved, and various turf drags. Joint design and construction can affect also affect noise levels. More information on these surface textures is provided in chapter 5, and information on noise studies related to concrete pavement surface textures is provided in chapter 6.

Concrete Pavement Rehabilitation Options

Rehabilitation strategies for concrete surfaced pavements include structural asphalt overlays and structural bonded and unbonded concrete overlays (non-structural asphalt overlays are considered in chapter 7). Concrete overlays of existing concrete pavements are either unbonded or bonded (Harrington 2008; Harrington and Fick 2014; Torres et al. 2012). An unbonded concrete overlay utilizes a separation layer between the concrete pavement and the new concrete overlay (Smith, Yu, and Peshkin 2002). This has typically been a 1 to 2 inches [25 to 51 mm] thick asphalt material, although some agencies are now using non-woven geotextile materials as a separator layer (Harrington and Fick 2014). This separation layer is placed to ensure independent behavior between the two slabs, thereby minimizing the potential for reflection cracking. Unbonded concrete overlays are typically constructed between about 6 to 12 inches (152 to 305 mm) thick, with the structural requirements based on support conditions and projected traffic loadings. Unbonded concrete overlays are used when the existing pavement deterioration is so advanced that it cannot be effectively corrected prior to overlaying. Figure 4-6 shows the cross sections of rehabilitated concrete pavement structures.

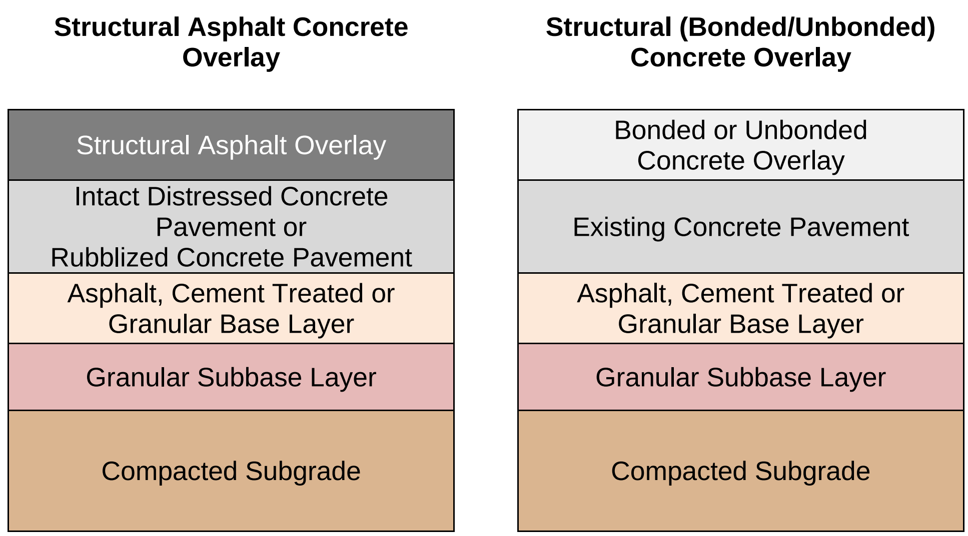

Figure 4-6. Cross sections of rehabilitated concrete pavement structures (not to scale).

Bonded concrete overlays consist of a thin layer of concrete (typically 3 to 4 inches [76 to 102 mm] thick) that is bonded to the existing concrete pavement (Smith, Yu, and Peshkin 2002). These are used to increase the structural capacity of an existing concrete pavement or to improve its overall ride quality. A critical construction and performance aspect of bonded concrete overlays is the achievement of an effective bond between the overlay and the existing concrete pavement in order to create a monolithic pavement system. Bonded concrete overlays of existing concrete pavement are not used frequently and require the existing pavement to be in good to excellent structural condition prior to placement (Harrington 2008; Harrington and Fick 2014).

For structural asphalt overlays of concrete pavements, the overlay is typically placed directly on the existing concrete pavement using a tack coat. The existing concrete pavement may be broken into smaller-sized pieces using crack and seat or rubblization procedures as a means of slowing or minimizing the development of reflection cracking (Thompson 1989; NAPA 1994; Hoerner et al. 2001; TRB 2006). When the concrete pavement is in poor condition with extensive patches or materials problems, rubblization will reduce the concrete to a state similar to aggregate base. However, rubblization may not be appropriate if the subgrade is too soft to support the rubblizing process, or if the pavement does not exhibit distresses for which rubblizing is the best alternative (Heckel 2002).

Overlays for Concrete-Surfaced Pavements:

- ✓ ***Structural asphalt overlays****: Overlay is placed on intact, distressed concrete using tack coat; if existing concrete is in poor condition, then crack and seat or rubblization procedures may be used.*
- ✓ ***Structural concrete overlays****: Bonded or unbonded. Unbonded overlays contain an interlayer between the existing and new concrete to provide separation; bonded overlays consist of a thin, concrete layer bonded to existing concrete pavement to produce a monolithic structure.*

Composite Pavement Types

Asphalt-Surfaced Composite Pavement

Asphalt-surfaced composite pavements refer to asphalt layers placed on a concrete pavement, either as part of new pavement construction or as part of a rehabilitation project. This type of design takes advantage of both paving material types, and may be used for a number of reasons, including reduced noise, increased friction, improved smoothness and rideability, and utilization of higher volumes of recycled materials in the concrete layer (if part of a new pavement construction). A thin asphalt layer with low noise emissions and high frictional properties can be placed over a durable and fatigue resistant concrete layer to achieve a quiet, safe, and potentially long-lasting structure. The asphalt layer may also help reduce negative temperature gradients (cold on top), reducing excessive tensile stresses that can lead to cracking (Rao et al. 2013a; Rao et al. 2013b). A typical cross section of an asphalt-surfaced composite pavement is shown in figure 4-7.

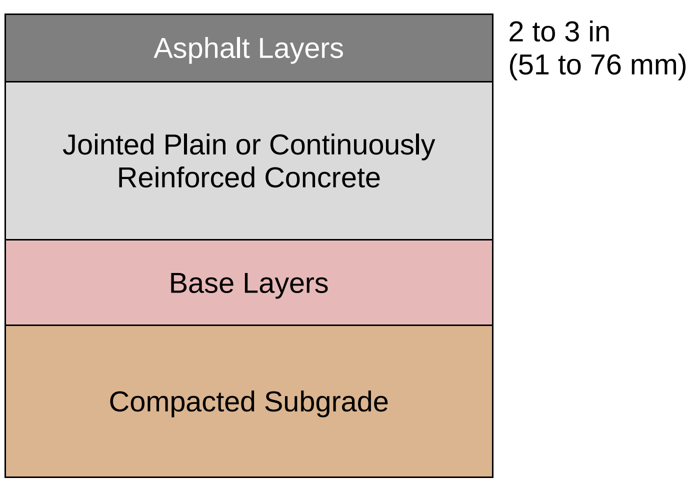

Figure 4-7. Cross section of asphalt-surfaced composite pavement.

Two-Lift Composite Concrete

Another type of composite pavement is constructed using two independent lifts of concrete that are placed "wet on wet" so that an effective bond develops between them. The properties of the two layers are designed for the specific application. The upper lift may consist of abrasion resistant and more durable materials optimized for surface characteristics such as noise and texture while the lower lift utilizes recycled materials or aggregates of lesser quality (Darter 1992; Hall et al. 2007; Van Dam et al. 2012; Rao et al. 2013b). This optimized approach serves to not only lower costs, but also reduces environmental impacts as well. A typical cross section of a two-lift concrete pavement is shown in figure 4-8.

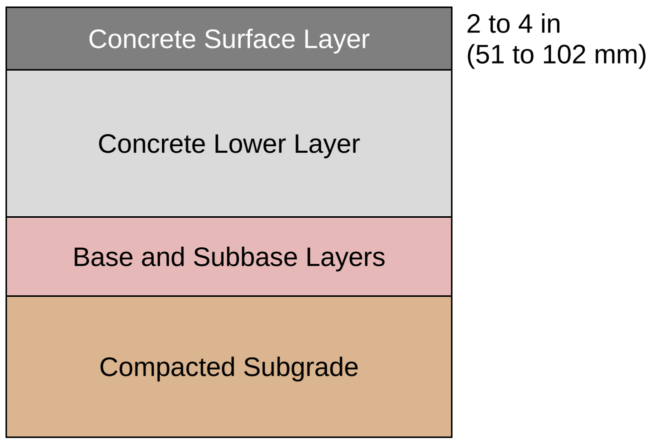

Figure 4-8. Cross section of two-lift concrete pavement.

Over the years, a number of projects featuring two-lift concrete have been constructed (Sommer 1994; Smiley 1995; Wojakowski 1998; NCPTC 2008; Tompkins, Khazanovich, and Darter 2010; Brand et al. 2012). Two recent examples of two-lift concrete pavements include:

- A composite pavement constructed by the Missouri DOT in 2011 consisted of an 8-in (203-mm) bottom lift of conventional concrete and a top lift of 2 inches (51 mm) of concrete containing photocatalytic cement on Route 141 in St. Louis County (Cackler et al. 2012; Sikkema 2013).
- A composite pavement on the I-88 Illinois Tollway consisted of an 8-in (203-mm) ternary concrete bottom lift containing 20 percent fractionated coarse RAP and a 3.5-in (89-mm) top lift of conventional concrete pavement materials (Brand and Roesler 2013).

Semi-Rigid Pavement

Semi-rigid composite pavements are composed of an asphalt surface course placed on a cementitious layer (e.g., CTB, LCB, or RCC). Semi-rigid pavements are often used where high-quality aggregate is not readily available. However, the reflection of shrinkage cracks from the cementitious layer into the asphalt surface may need to be addressed. One approach to minimize reflection cracking is to "microcrack" the cementitious layer with impact rollers as it is curing, which produces well-distributed, fine cracks that exhibit little movement (Sebesta 2004). Another approach is to saw narrow joints in the cementitious layer to more uniformly distribute crack movements and thereby slow the rate of reflection cracking. A final way to establish a tight cracking pattern is to introduce discrete cracks with an impact device (Cockerell 2007).

There are a number of potential opportunities for using large quantities of recycled materials in semi-rigid pavements. For example, the cementitious base layers can be produced either using plant-mixed materials, or through full-depth reclamation with cement stabilization (as described in chapter 8). A typical cross section of a semi-rigid pavement is shown in figure 4-9.

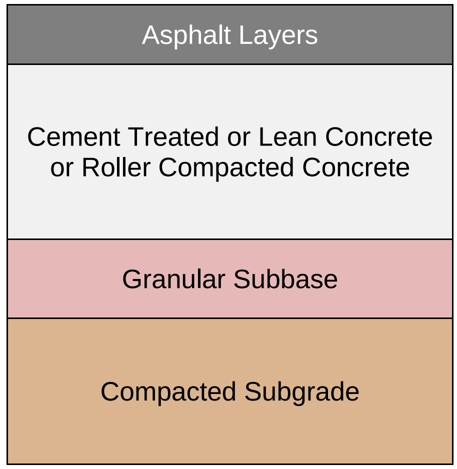

Figure 4-9. Cross section of semi-rigid pavement.

Rehabilitation of Composite Pavement

Rehabilitation alternatives for composite pavement types are the same as for other types of asphalt- and concrete-surfaced pavement.

Modular Pavement Systems

Modular pavement systems are composed of a wide variety of precast components in order to either rapidly construct or repair a section of roadway or to provide an aesthetically pleasing design. One type of modular pavement is precast concrete slabs, of which a number of different technologies have become available over the past 15 years (Tayabji, Ye, and Buch 2012). They are typically used for very short construction windows to minimize user delays and to provide better performance than might be obtained using rapid-setting concrete materials with cast-in-place construction. Better performance is expected because the precast concrete is cast and cured under controlled conditions, and is therefore not exposed to potentially poor field curing conditions and trafficking while curing. In addition, effective joint load transfer can be built into the slab either through unique doweling configurations or, for some systems, through post-tensioning (Merritt, McCullough and Burns 2003; Smith 2008; Smith 2012). Grinding is performed after some installations to improve smoothness.

Modular Pavement System Types

Intermittent Systems*: These are isolated pavement repairs conducted using precast concrete slabs and typically include full-depth repairs of deteriorated joints and cracks and full-panel replacement of severely deteriorated slabs. Several different systems are available, with successful installations in New York, New Jersey, and Michigan, among others locations.*

Continuous Systems*: These involve full-scale rehabilitation of asphalt and concrete pavements. Common systems that have been used in the U.S. include jointed precast concrete pavement systems with dowel bars and precast, prestressed concrete pavement systems formed by post-tensioning together a series of panels. These continuous systems have been constructed in a number of states, including California, Delaware, Texas, Missouri, New Jersey, New York, and Virginia.*

Another example of a modular pavement system is interlocking concrete pavements. These are often used on low speed facilities or in urban areas to provide aesthetically pleasing roadways (ASCE 2010; Smith 2011).

Modular pavements potentially permit thinner and longer lasting structures that could reduce environmental impacts over the life cycle. Modular pavement systems also allow easy access for utility cut repairs to reduce repair costs and minimize user delays.

Pavements and Stormwater Management

Pavements can be constructed using permeable materials to innovatively control, manage, and treat stormwater runoff. Permeable pavements can capture and store stormwater runoff, allowing it to percolate into the ground and thereby recharge groundwater supplies while also controlling outflow. Fully permeable pavements, shown in figure 4-10, are defined as those in which all layers are intended to be permeable and the pavement structure serves as a reservoir to store water during storm periods in order to minimize the adverse effects of stormwater runoff.

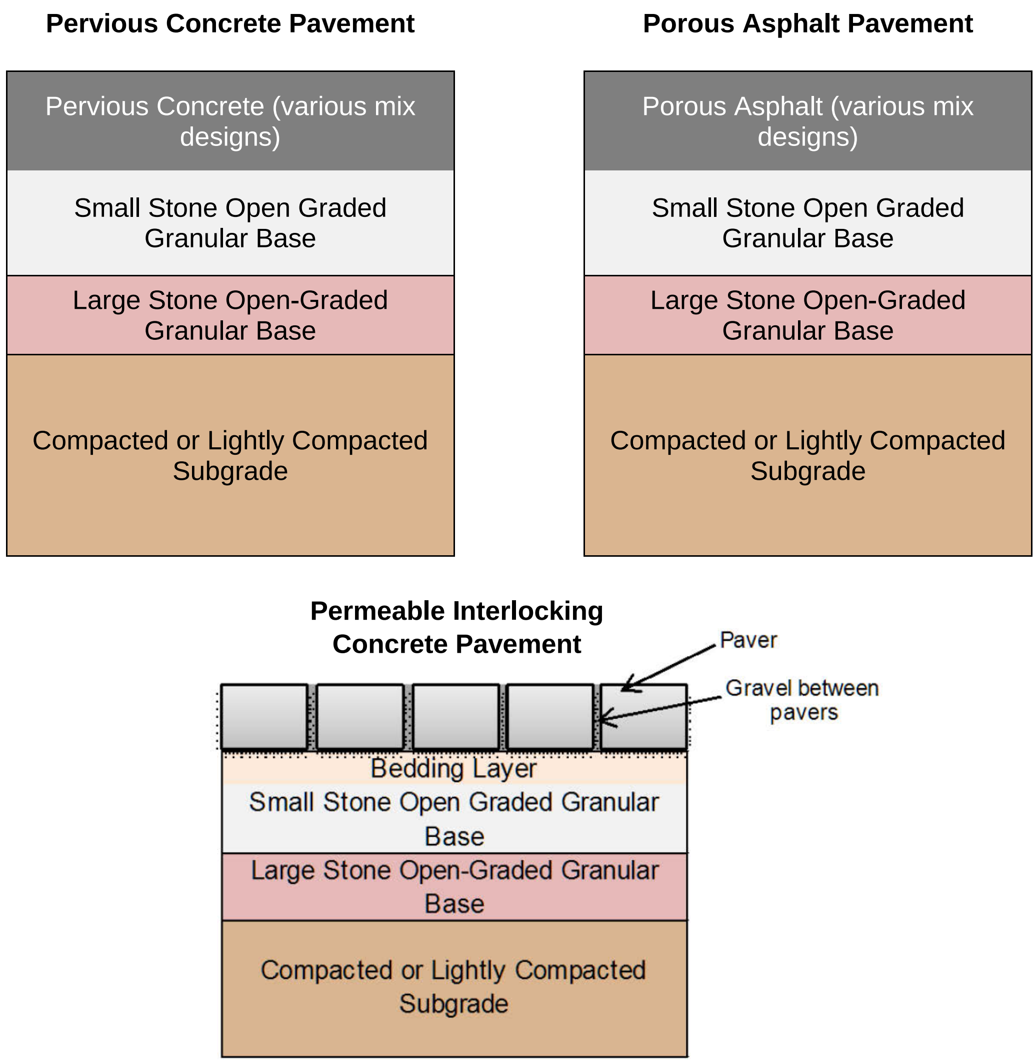

Figure 4-10. Cross sections of pervious concrete pavement, porous asphalt pavement, and permeable interlocking concrete pavement.

Most applications of fully permeable pavements in North America have not been subjected to high-speed traffic or heavy trucks, which reflects concerns about durability. Structural design methods are empirical in nature, and are available from the National Asphalt Pavement Association (Hansen 2008), the American Concrete Pavement Association (ACPA 2009), and the Interlocking Concrete Pavement Institute (Smith 2011) for design of porous asphalt, pervious concrete pavements, and permeable interlocking concrete pavements, respectively.

For state highway agencies, fully permeable pavements are being considered as a shoulder retrofit adjacent to conventional impermeable pavement with geofabric barriers to limit water affecting the layers in the impermeable pavement, and for some low-speed applications carrying trucks. An ME design approach and a preliminary LCCA have been produced for fully permeable pavements to carry trucks (considering both structural and hydraulic capacity) for California conditions (Jones et al. 2010; Li, Jones, and Harvey 2012a; Li, Jones, and Harvey 2012b). More information regarding fully permeable pavements is included in chapter 6.

Layer and Material Type Selection

The pavement type alternative determines what layer combinations and materials (virgin, recycled, or co-product) can be used. For the type of facilities considered here, all pavement types will have a permanent surface layer (asphalt or concrete), a higher quality base layer that may or may not be stabilized, and perhaps even a subbase layer to provide for added subgrade protection from moisture, frost, and repeated traffic loading. Base and subbase material properties and combinations are chosen for multiple reasons including transmitting and spreading the load-induced stresses to the subgrade, providing uniformity of support to the surface layer, providing subsurface drainage, protecting lower layers from frost penetration, and providing a working platform for surface course construction. Base and subbase material layers can often make use of more recycled and lower quality aggregates to reduce construction costs and emissions while still achieving the structural goals of the layer. To improve pavement performance and potentially reduce the thickness of the surface layer, these layers can be stabilized if desired. Trade-offs between the impacts of reduced surface layer thicknesses versus the impacts of foundation layers stabilization can be considered with LCA (see chapter 10), as can trade-offs between the impacts of increased thickness versus materials of lower quality but with reduced environmental impact.

Subgrades should always be compacted to improve stiffness and shear strength and to reduce permeability. Subgrades may also be treated or stabilized to further improve stiffness and shear strength. The improvement of these properties may permit thinner pavement structures above the subgrade to carry the same traffic. Treatment and stabilization materials can include cement, lime, asphalt emulsions, fly ash, kiln dust, or other cementitious materials. Guidance on stabilization selection, mixture design, and construction are available from the FHWA (Carpenter et al. 1992a; Carpenter et al. 1992b). These two volumes represent the revisions to original manuals prepared in 1980 (Terrel et al. 1980).

Clay subgrades may also be treated with lime to reduce plasticity and improve compaction, although care must be taken to check that a given subgrade soil will not be susceptible to swelling due to unwanted chemical reactions, such as certain expansive lime-clay reactions (Mitchell 1986). Trade-offs between the impacts of reduced surface layer thicknesses versus the impacts of subgrade stabilization can be considered with LCA (see chapter 10).

Chapter 3 provides an overview of the various virgin, recycled, co-product, and waste materials that are currently being used in pavements. The availability of recycled (e.g., RCA, RAP, RAS, rubber) and co-product (e.g., slag, fly ash, limestone dust) materials must be thoroughly explored as part of the design process since they may have a significant impact on the LCA in terms of cost, energy, and emissions. To effectively, efficiently, and safely use all available resources (virgin, recycled, and co-product materials), existing agency guidelines and specifications should be reviewed or new ones created to ensure the selected pavement sustainability strategies will provide the desired pavement performance.

One potential strategy for reducing the energy, emissions, and overall environmental impact of transporting pavement materials (see chapter 3 for details of minimizing material transportation) is to reduce the cross section of the new pavement or rehabilitation structure by using higher quality materials or by balancing the use of locally available materials with higher quality materials in critical pavement layer locations. ME design procedures, with appropriate material characterization, can be used to identify the required change in the cross section to ensure that performance requirements are still met even when sub-optimal recycled or local materials are employed.

As described in chapters 3, and 5, the main contributors to energy consumption, GHG emissions, and other environmental impacts in the paving materials production phase are cement, asphalt binder, and aggregate production, and the asphalt and concrete mixing plant operations. The production of polymers, crumb rubber, and other additives in asphalt mixtures and chemical admixtures for concrete pavements can potentially improve pavement performance or permit thinner structures, but may also result in increased energy and emissions. A full LCA analysis will assist in the selection of materials for use in the design (see chapter 3).

Consideration of energy dissipation due to structural responsiveness is an area of current research and validation, and contributions to energy use and GHG emissions may be a consideration in the structural design (see chapter 6).

Drainage

Poor drainage conditions can contribute to early failures and reduced pavement life, and therefore can significantly increase the environmental and cost impacts of the original pavement because of early and more frequent maintenance and rehabilitation activities. It is essential that the need for drainage be reviewed for all new and rehabilitation projects. Failing to remediate poor drainage, even where it affects a relatively small percentage of the project length, will lead to increased life cycle costs and higher environmental impacts.

Construction Quality Specifications

The sustainability of a pavement structure can be improved through any increases in pavement performance (e.g., longer service life, higher and maintained levels of smoothness and frictional properties). In many cases, this can be achieved with small increases in construction quality and concomitant reductions in overall variability. Because the development of effective construction quality specifications is part of the design process, a careful review of construction specifications is appropriate to see where increased levels of quality could be achieved and impact performance. Moreover, the implementation of an effective quality assurance plan promotes higher levels of quality should be part of the effort to improve pavement sustainability through design. More details regarding construction quality are presented in chapter 5.

Material Trade-Offs

As has been discussed previously, there are a number of trade-offs that can be evaluated regarding the use of materials in a pavement design; for example, trade-offs between the desirable characteristics of a material and the distance from which it must transported, or trade-offs in the thickness requirements of the material for it perform adequately versus the benefits of treating or stabilizing the material to reduce thickness. Materials specifications should be reviewed to determine whether they impose any restrictions on using materials that have lower life-cycle environmental impact but produce the same performance when used in a given structure. In some cases, the use of thicker layers of less desirable recycled or local material may still provide acceptable performance but with lower economic and environmental impacts.

It may be that some outdated specifications require virgin materials because the technology for effectively using recycled materials was not fully developed at the time the specifications were written. The use of empirical design methods requires that performance be observed for sufficient time to assess the risk of failure, which for many materials requires years of monitoring before considered acceptable for inclusion in routine designs. In other cases, there may be an assumption that virgin materials inherently possess superior properties compared with recycled materials. The more widespread use of ME design methods should speed the implementation of new and innovative materials through effective laboratory characterization.

Compaction

As described in chapter 5, more stringent compaction specifications for subgrade, unbound granular, cement-treated, and asphalt materials can result in increased pavement life. Increased levels of compaction improve the density, stiffness, and strength of unbound and cement-treated materials, and increase the stiffness, durability, rutting, and fatigue performance of asphalt-bound materials. Many agencies use a standard specification of 90 to 95 percent of standard AASHTO T 99 compaction for subgrades and granular materials. Increasing compaction to 95 to 100 percent for granular materials will result in increased pavement life with the increase in environmental impact primarily coming from the increased use of construction equipment. Airfield pavements use 100 percent of modified AASHTO compaction (AASHTO T 180) for aggregate bases with similar gradations to those used for highways. The use of 95 percent of standard AASHTO T 99 compaction for subgrades instead of 90 percent, or even 95 percent, of modified AASHTO T 180 compaction should improve pavement performance with minimal environmental impact. The primary trade-offs are increases in construction cost, potentially an extension to the construction schedule, increased quality assurance testing by the owner/agency for verification, and potentially some increase in construction equipment emissions. However, increases in pavement life and extension of the time that the pavement is smooth will often have a much larger positive impact than the additional equipment emissions required to achieve those higher levels of compaction. Verification testing should be performed to ensure that more stringent compaction specifications can be achieved for the given material. An example is given in chapter 5 regarding the benefits of increased life from improved asphalt compaction.

Smoothness

Obtaining good initial smoothness levels during construction of new or rehabilitated high traffic volume roadways, and designing the pavement to maintain those levels of smoothness throughout its life, can result in a large reduction of use-phase energy/emissions compared to impacts associated with materials production and construction. However, the impacts associated with the materials production and construction phases will likely be more important for lower volume routes (see chapter 6). Smoothness acceptance levels should be part of the construction specifications developed for the design (preferably in terms of IRI), with high-volume traffic facilities deriving greater benefits from higher levels of initial smoothness.

Construction Process and Traffic Management

One sustainability aspect that can be considered during the pavement design and construction process is the integration of traffic management plans in order to adequately consider and possibly minimize user delays. For example, more rapid means of pavement construction or rehabilitation can help reduce user delays. Construction analysis programs for pavements, such as CA4PRS (Lee, Harvey, and Samadian 2005; Lee and Sivaneswaran 2007; Lee at al. 2009; FHWA 2008; Caltrans 2013), can be used to analyze the effects of pavement design on traffic delays and construction window policies. The impact of traffic delays on vehicle GHG emissions and energy consumption relative to the impacts of materials production, construction, and the use phase will depend on the types of delay and the number and types of vehicles affected. It is possible that traffic slowing in a construction zone could conceivably have a beneficial effect on sustainability; for example, if traffic speed in a work zone is reduced from 65 mi/hr (104 km/hr) to 45 mi/hr (72 km/hr), the overall vehicle fuel economy is expected to improve.

Consideration of Future Maintenance and Rehabilitation

The design of new pavements and rehabilitation projects should include consideration of future maintenance and rehabilitation that will be required based on the design decisions. These future decisions should include consideration of maintaining the overall structural capacity of the pavements, its overall functional capabilities (e.g., smoothness, friction), and future roadway recycling and reuse (see chapter 8 on end-of-life strategies).

Sample Sustainable Design Strategies

Longer Life Pavement

Longer life pavements can be achieved as a policy objective in new, rehabilitated, and reconstructed pavements and are generally justified for higher volume facilities. Design lives may range from 30 to more than 60 years and can be accomplished using both asphalt and concrete designs. Longer life design options should be considered for new corridors and rehabilitation of existing pavements that are severely distressed and may also possess geometric deficiencies, and may afford the opportunity to reduce life-cycle costs, user delays, and environmental impacts as compared to a standard, 20-year pavement design.

A general rule for load-related cracking is that as critical tensile strains or stresses decrease (for either concrete or asphalt pavements), the overall structural capacity of the pavement (i.e., the number of truck loads it can carry) increases logarithmically. Therefore, when there are heavy volumes of traffic, higher structural capacity can be achieved by increasing the bending resistance of the pavement; this can be accomplished by increasing the thickness or by increasing the material stiffness (or both). Longer life designs can select innovative combinations of layer thicknesses and materials to achieve this, including the use of recycled materials in the lower layers. However, effective material and construction specifications are essential in order to reduce variability and maximize the performance of the selected materials. Because of the increased thicknesses or increased material stiffnesses, longer life designs may increase initial costs and possibly initial environmental impacts, but the overall life-cycle costs and environmental impacts over the life cycle are expected to be less.

Longer Life Asphalt Pavement

Longer life asphalt pavement designs can be developed to provide a number of sustainability benefits, including:

- Reduction in the amount of asphalt mixture through the selection of materials and construction requirements for better compaction that produce greater bending resistance than conventional materials; this reduces the cross-sectional area compared with what would be required with conventionally designed and compacted asphalt mixtures.
- Incorporation of higher quantities of RAP combined with stiffer and less viscoelastic asphalt binders in the middle layer; this reduces the amount of new asphalt binder used (and its commensurate environmental burden) and provides increased stiffness and reduced viscoelastic energy dissipation.
- Use of modified open-graded surfaces to reduce noise, slow stormwater runoff, and trap pollutants, and provide a sacrificial layer for top-down cracking.
- Use of recycled concrete pavement or building waste as the granular base layer.

If the longer life pavement is designed so that the tensile strain at the bottom of the asphalt layers is below the limit at which the potential for cracking begins, it is often referred to as a perpetual pavement (see figure 4-11). The composition of each of the layers in a perpetual pavement is described below (starting from the bottom of the pavement system and working to the surface):

- A fatigue-resistant bottom layer is provided that resists damage under tensile strains caused by traffic, and thus stops cracks from forming in the bottom of the pavement. This bottom-up fatigue cracking resistance can come from increasing the total pavement thickness such that the tensile strain at the bottom of the base layer is insignificant (which requires more asphalt), or by specifying air voids to between 0 and 3 percent and slightly increasing the asphalt content to achieve this high level of compaction (referred to as a "rich-bottom" layer).
- The next layer is designed specifically to increase the bending stiffness through the use of stiffer conventional asphalt and potentially higher RAP contents. This layer can also have an increased compaction requirement to increase the stiffness and fatigue resistance of the section.
- The third layer from the bottom is designed specifically to resist surface-initiated distresses such as top-down cracking, rutting, and low-temperature cracking (where applicable). Some typical mixtures used for the surface layer are polymer-modified asphalt concrete and SMA. ME pavement design procedures can be used to design the structure considering the different pavement materials (Timm and Newcomb 2006; Buncher and Newcomb 2000; Newcomb, Willis, and Timm 2010; Harm 2001).
- A fourth layer—typically either a high-quality polymer- or rubber-modified, open-graded or gap-graded mixture or a 1 to 2 inches (25 to 51 mm) SMA—can be placed on top of the rut resistant layer and is designed for abrasion resistance and vehicle safety. This layer is considered to be a sacrificial layer in a 30- to 50-year long-life asphalt pavement. Once its effectiveness is diminished (approximately every 10 to 15 years), it can be removed, recycled, and replaced. Many open-graded and SMA mixtures used for this layer can provide tire-pavement noise reductions when compared to dense graded materials (Rezaie, Harvey, and Lu 2012).

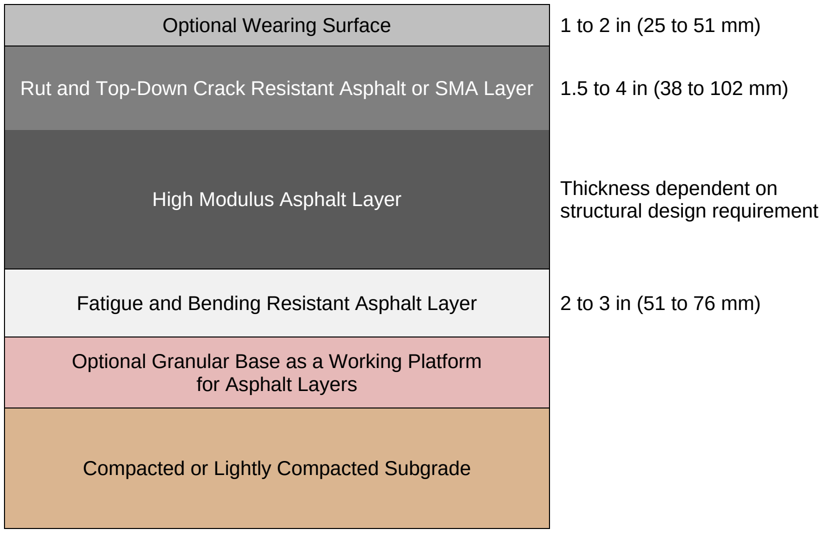

Figure 4-11. Perpetual pavement cross section.

For longer life structural overlays, the prudent use of polymer-modified asphalt materials may also be a way to achieve longer life (as compared to conventional materials). Polymer-modified asphalt can extend the life of the surface by increasing rutting resistance and decreasing susceptibility to top-down cracking. It can also be used to decrease reflection cracking in an overlay application. The increased life can help decrease the frequency of maintenance and rehabilitation, thus reducing some environmental impact. However, polymer modification should be used where its benefits are of most value, because polymer modification may increase overall GHG emissions of the asphalt pavement design due to the manufacture and production of the polymer itself (Bernard, Blomberg, and Southern 2012).

Longer Life Concrete Pavement

Longer life concrete pavements (either JPCP or CRCP), with anywhere from 35- to 60-year design lives, are designed to maintain structural integrity and require only periodic retexturing of the surface to restore smoothness, friction, and noise performance. Longer life concrete pavements are designed to resist the heavy truck traffic that will cause repeated load distresses such as fatigue cracking, faulting, and punchouts. These design objectives are achieved by using durable concrete mixtures, adopting slightly thicker concrete slabs placed on non-erodible bases, including properly designed and corrosion-resistant dowel bars or reinforcing steel, and incorporating stress-relieving design features such as tied concrete shoulders or widened slabs.

Figure 4-12 shows an example of a longer life CRCP designed for fatigue resistance and low maintenance requirements. The life-cycle environmental benefits of the longer life CRCP have to be evaluated using LCA and compared to the environmental impacts associated with the inclusion of the steel reinforcement.

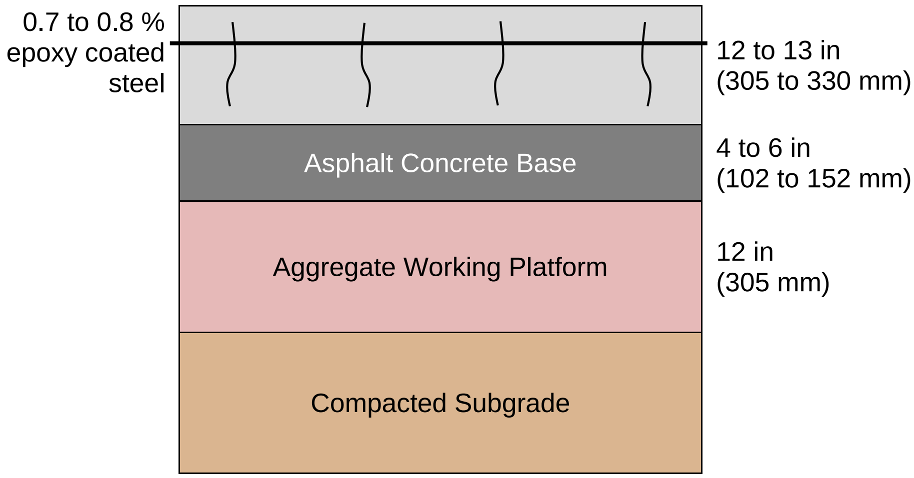

Figure 4-12. Example of CRCP longer life design.

Recycled concrete aggregate can be used in all layers of concrete pavements with the majority of the recycled concrete placed in the granular base or subbase layer to reduce subgrade stresses, protect against frost action, and to enhance subsurface drainage. Recycled concrete or coarse RAP can be used in the concrete mixture as long as the mixture design is adjusted for the expected changes to the fresh and hardened concrete properties (Snyder et al. 1994; Sturtevant 2007; Roesler, Huntley, and Amirkhanian 2011; Brand et al. 2012; Brand and Roesler 2013). Co-product materials such as fly ash and slag cement are commonly used in all types of concrete pavements including longer life designs, as these significantly improve the durability of the concrete (see chapter 3 for more information).

Design for Local Materials or Low Impact Transportation

Designing for the incorporation of local materials to reduce transportation costs should be considered for all aggregate materials, whether they are used in asphalt, concrete, or unbound layers. Minimization of earthwork hauling for the roadway foundation is also another consideration. Alternatives can be analyzed to minimize both costs and environmental impacts.

Accelerated Construction

Accelerated construction can be employed that minimizes the duration of construction and associated lane closure times. Construction processes and materials such as rapid-setting or high-early-strength concrete, modular concrete, or rubblization/asphalt overlays are examples of accelerated construction. Each of these options will expedite the construction process, thus reducing user delays, reducing emissions, and improving safety (by reducing the risk of crashes).

Single-Lane Rehabilitation

In many situations involving multi-lane highways, the outer (truck) lanes may be in need of a structural rehabilitation or reconstruction, while the inner lanes are still in relatively good condition. If a thick overlay (concrete or asphalt) is needed on the truck lanes, the inner lanes must receive the same treatment in order to maintain elevations. In these cases, consideration could be given to the reconstruction of the outer lane, with the new pavement structure either matching the surface elevation of the inner lanes, or perhaps slightly higher to accommodate the placement of a thin overlay on the inner lanes to restore functional performance. Computations can be made for the environmental impact of each scenario (complete overlay vs. outer lane reconstruction), including consideration of the recycling of the existing pavement and associated traffic delays.

Local reconstruction of the outer traffic lane can also be considered on corridors with mixed pavement types (i.e., different pavement types in adjacent lanes), provided that this does not impose any major maintenance issues. Existing asphalt pavements can receive either an inlaid reconstructed asphalt or concrete outer lane, and existing concrete pavements can receive new inlaid concrete truck lanes and an asphalt overlay on the passenger lanes that matches the elevation of the outer lanes. There are also opportunities for inlaid reconstruction with semi-rigid pavements in the truck lanes. The pavement materials that are removed can be recycled next to the construction site into the new truck lanes.

Consideration of Use Phase in Design

The main design factors that have the most significant effects on the use phase are:

1. Smoothness over the design life of the pavement. High levels of smoothness maintained throughout the life of the pavement will incur reduced environmental impacts.
2. Overall pavement longevity. This serves to not only decrease the life-cycle costs, but also reduces the environmental and social impacts associated with materials production, construction, and periodic maintenance and rehabilitation.

Which of these factors is most important depends on the context of a particular project. The importance of both depends, in large part, on the traffic volumes using the facility. Where there are heavy traffic volumes, the benefits of smoothness over the design life can be much larger than material production and construction impacts. Conversely, for low-volume roads and highways, material production and construction will often tend to dominate the net calculation of environmental impacts. Additional details on use-phase considerations are discussed in chapter 6.

Major Issues and Trade-offs in Designing More Sustainable Pavements

Based on the discussions presented in this chapter, the major design and policy objectives, associated approaches to providing sustainability improvements, and potential trade-offs with regard to economic, environmental, and societal impacts are summarized in table 4-2.

Future Directions and Emerging Technologies

There are a number of potential future directions and emerging technologies in the pavement design arena that may have a significant effect on improving overall pavement sustainability. These include:

- Improvements in ME design: testing, models, validation. Further improvements in the ability of laboratory testing to characterize materials properties that control performance, and in models that use those properties to predict pavement performance, will permit improved and more rapid consideration of new materials in pavement design. There are a number of accelerated pavement testing (APT) facilities around the world that can be used to provide more rapid feedback on the performance of full-scale constructed pavements to help validate new models, materials, and structures. This should result in a shorter time for their implementation. Balancing the risk versus reward in the use of new materials and structures, incorporating them into new testing and design procedures, and providing training of engineers to use them, are all significant challenges. ME design procedures will need to see more widespread use in order to provide more precise performance estimates with consideration for construction variability.

Table 4-2. Summary of major issues and trade-offs for improving pavement sustainability through design.

Design/Policy Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Achieve Longer Life	Use ME design to be able to consider alternative materials, construction specifications and structures to increase life for same pavement thickness[1, 2]. Use selected recycled materials to improve structural characteristics. Require higher construction quality.	Virgin materials may increase cost; increased construction quality may increase cost; reduced frequency of maintenance and postponement of rehabilitation may decrease cost.	Virgin materials may have higher environmental impact during production; decreased maintenance frequency may decrease emissions; increased pavement quality may decrease user emissions.	Stays smoother longer; less delay associated with maintenance.
Achieve Longer Life	Use of higher quality materials.	Increased cost of materials; decreased cost of maintenance.	Potential for increased emissions due to production and transportation of higher quality materials if not locally available; higher quality pavement may result in lower user and maintenance emissions.	Higher quality pavement; less delay associated with maintenance.
Achieve Longer Life	Improved construction specifications (less variability, greater density, stiffness, strength, durability depending on material)[2].	Somewhat increased initial cost; could decrease maintenance cost or upfront cost if reduced thickness is used.	Less frequent maintenance or reduced thickness will reduce environmental effects of construction and materials use; additional initial construction work may have minor impact.	Less delay associated with decreased maintenance.
Consider Inlaying New Truck Lane Pavements (vs. Multi-lane Overlay)	Minimize total material used for rehabilitation by not overlaying lanes to match grade that do not have structural needs.	Can reduce cost; may cause some additional traffic delay.	May reduce total amount of new materials needed; can consider recycling materials removed from old truck lanes.	May cause more initial traffic delay due to closure for reconstruction.
Obtain Same Life for Reduced Thickness	Use ME design to consider new materials, construction specifications, pavement structure types[1,2].	Virgin materials may have higher cost; increased construction quality may increase cost.	Potential increase due to production of virgin material; less material use lowers environmental impact due to reduction in production, transportation and construction.	May reduce traffic delay due to more rapid construction.
Reduce Noise Emissions	Use of noise reducing asphalt (open-graded) or concrete (new generation concrete surfaces) surfaces.[3]	Increased cost; more frequent replacement for the asphalt surface.	Minor impact of additional grinding/grooving for concrete; more materials use and construction.	Reduction of noise in surrounding areas.

Table 4-2. Summary of major issues and trade-offs for improving pavement sustainability through design (continued).

Design/Policy Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Achieve/ Maintain Pavement Smoothness	Consider smoothness over the pavement life as a key design parameter, especially for high traffic volume routes. Include construction specifications for smoothness, design features to maintain smoothness, and costing of maintenance to keep surface smooth.	Potential for small to moderate increases in initial costs but reduced life-cycle costs due to longer pavement lives. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use, particularly on high traffic volume routes.	Improved economic efficiency.
Maximize Use of Recycled and Local Materials	Use recycled pavement materials to replace virgin materials and minimize transportation distances for materials.[1]	Higher variability in recycled material quality may increase maintenance frequency and life-cycle cost; generally reduces initial cost.	Reduced impact of materials production and transportation; less use of scarce materials; use of stabilizers have an impact and can be compared with benefits of reduced need for resurfacing layers, transportation of materials, etc.	May increase maintenance delay if materials do not perform as expected in design; reduced landfill disposals.
Maximize Use of Recycled Material	Use recycled materials from other industries to replace virgin materials.[1]	Use where transportation cost feasible if not locally available; Evaluate variability in material quality to avoid increase maintenance and rehabilitation; generally reduces initial cost; additional processing or construction issues may increase initial cost.	Use where transportation and processing are environmentally beneficial; may reduce future recycling if inclusion of recycled materials makes future recycling too costly, unpredictable or difficult; reduced impact of virgin materials production; less use of scarce materials.	May increase maintenance delay if materials do not perform as expected in design; reduced landfill disposals.
Minimize Impact of Utility Construction	Eliminate or minimize utility cuts in pavement, or use pavement systems that allow easy restoration of pavement structure after utility work (utility corridors in pavement).	Higher initial cost; reduced life-cycle costs due to less frequent maintenance and rehabilitation; reduced cost of maintenance and rehabilitation with no manhole covers; reduced life-cycle cost if longer life designs are used.	Potential increased initial materials and construction impacts of utility corridor; reduced impacts due to longer pavement life, less frequent maintenance and rehabilitation. Keeping utilities out of pavement improves ability to do in-place recycling strategies.	Smoother pavement over life cycle; increased pavement life resulting from less frequent repairs and patching. Keeping utilities out of pavement improves ability to do in-place recycling strategies.

Table 4-2. Summary of major issues and trade-offs for improving pavement sustainability through design (continued).

Design/Policy Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Minimize Impact of Construction	Accelerated construction.	Often reduces initial user costs but increases agency costs; must maintain quality standards.	Difficulty with shorter construction may influence quality and functional life; accelerated materials may have a shorter performance life.	Reduced traffic delay.
Use Pavement to Capture Runoff Pollutants and Reduce Hydraulic Requirements from Storms[3]	Use partially permeable pavement (e.g., open-graded asphalt).	Increased cost; need for more frequent resurfacing.	Increased environmental impact of materials and construction for open-graded layers; reduced pollutants in water.	Cleaner water for surrounding area.
Use Pavement to Capture Runoff Pollutants and Reduce Hydraulic Requirements from Storms[3]	Use fully permeable concrete or asphalt pavement (very little application to date, only for highway shoulders).	Largely unknown; increased cost, need for more resurfacing; potential to reduce stormwater conveyance.	Requires more materials, thicker layers than conventional shoulders; reduced pollutants in water; groundwater recharge.	Cleaner water for surrounding area.
Use and Maintain Pavements that Reduce Urban Heat Island Effects and Reduce Lighting Costs where Warranted by Net Benefits	Where it is determined to be beneficial based on assessment of the life cycle for specific project type and climate region, engineer pavement to reduce heat island effects.[3]	Range of potential costs from net reduction to neutral to net increase if energy savings from air conditioning and lighting are less than pavement alternative life-cycle cost differences.	Increased impact of thickness and materials if not warranted by climate, urban environment, lighting requirements; potential for increased environmental impact of materials designed for thermal characteristics; reduced energy use due to less required lighting.	Less energy use from air conditioning in locations where pavements make substantial contribution to increased urban temperatures in late afternoon and evening.
Consider Fuel Use Due to Structural Responsiveness to Vehicle Loading (Once Research is Completed)	Once calibrated models are available, consider using them to determine where structural responsiveness is significant and develop appropriate strategies based on those results.[3]	Calibrated models will permit evaluation of alternative structures considering traffic, climate and other variables which will allow consideration of both road user and agency costs versus environmental benefits for designs.	Optimization may reduce environmental impact due to less fuel use, particularly on high truck traffic volume routes.	Optimization may improve economic efficiency particularly on high truck traffic volume routes.

Note: For more details on: [1]Materials, including recycled materials, see chapter 3
[2]Construction quality, see chapter 5
[3]Use-phase considerations, see chapter 6
[4]Maintenance and preservation, see chapter 7
[5]Interaction of cost and sustainability, see chapter 10

- Improvements in ME design: reliability. Data and methods for incorporating within-project and between-project as-built variability into design methods will need to be developed. Better consideration of reliability will be needed to consider the effects of increased use of recycled materials, to provide fair comparisons between alternative designs, and to better estimate future maintenance and rehabilitation activities.
- Integration of design and environmental impact analyses. As the pressure for consideration of environmental impacts in the pavement design decision-making process, there will likely be more integration of design, LCCA, and LCA in routine project development. There will be difficulties in balancing multiple design alternatives and selecting the optimal design based on costs (both agency costs and sometimes user costs), sustainability, and constructability. The process laid out in this chapter provides a starting point for agencies to identify major sustainability goals and then develop their own procedures for optimizing alternative design types based on sustainability considerations important to them. Methods for multi-criteria decision making will need to be developed, and this includes the selection of the best design approach for different project delivery environments (DBB with alternative designs, DB, and DBM).
- Development of new materials. Economic, environmental, and political pressures are resulting in much more competition between materials production industries, and potential creation of new industries that reduce the environmental impact of pavements. Increased recycling of pavement materials (such as RAP, RAS and RCA), and the inclusion of co-product materials (such as fly ash and slag cement) will drive much of the competition. Designers will need to consider new laboratory tests, models, and validation studies for newly developed materials as they are introduced by the industry at a faster pace. Specifications will need to be evaluated to ensure that they provide the contractor and materials supplier the flexibility to achieve the desired pavement performance while also maintaining owner/agency costs and risks at an acceptable level.
- Consideration of future maintenance and rehabilitation in design. There will be increased demand to accurately consider future maintenance and rehabilitation as part of the design process in order to provide better inputs to LCC and LCA analyses for both new pavement and major rehabilitation projects. Validated models will be needed for rehabilitation alternatives so that they can be compared on an equal basis. This is essential for DBM projects in order to estimate bid price and risk, but will also be increasingly used for other types of project delivery as well.
- Performance-related construction specifications. It is likely that there will be increased use of performance-related tests for pavement materials and requirements for contractors and materials producers to provide products meeting the properties assumed by the designer using ME design methods. Approaches for developing materials and construction quality specifications that lead to improvements in performance, while still being achievable with available materials and equipment, will be a challenge.
- Better models for smoothness performance. Designers will need to have and use better models for smoothness prediction, particularly as technology for real-time measurement of smoothness at construction is now practical and there is a growing recognition of the importance of smoothness on use-phase environmental impacts (see chapter 6).
- Approaches for designing better performing fully permeable pavements. The technology will likely improve for designing fully permeable pavements that can carry heavier loads and handle stormwater with less space, cost, and difficulty than many current stormwater

management practices. Designers will likely be faced with more opportunities and challenges in using these pavements.

Concluding Remarks

This chapter describes sustainability considerations through the design process for both new and rehabilitated pavement structures, including structural overlays and reconstruction. It specifically reviews the entire design process and identifies key areas that affect the overall sustainability of the resulting pavement. As noted in previous chapters, there are a number of trade-offs that must be considered, as improvements in one area might be detrimental to another, with the ultimate goals of the owner/agency ultimately determining which approach may be most suitable for a particular project.

The major issues for improving the sustainability of pavements through design decisions are summarized as follows:

- Achieve longer pavement life with the same quantity of materials, or achieve the same pavement life using thinner structures and less materials through design and construction specification decisions.
- Use design and construction specifications to maximize smoothness over the life cycle of the pavement to reduce environmental, economic, and social impacts related to vehicle operations, taking into consideration materials production and construction impacts.
- Consider maximizing the use of recycled materials and minimization of materials transportation where they can produce positive environmental and cost benefits, while not compromising pavement performance.
- Seek to integrate construction and traffic management into design decisions to minimize cost, materials use, and construction-related traffic delay.
- Consider use-phase impacts throughout the life cycle in design, including not only smoothness but other factors as well such as deflection, noise, and stormwater management.

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CHAPTER 5. CONSTRUCTION CONSIDERATIONS TO IMPROVE PAVEMENT SUSTAINABILITY

Introduction

Pavement construction practices have changed significantly over the last several decades, utilizing new technologies that have significantly improved pavement quality and construction efficiency while decreasing environmental impacts. These construction practices, in concert with an appropriate pavement structural design (chapter 4) that uses appropriate materials (chapter 3), can provide significant improvements to the overall sustainability of a pavement system. Critical areas of pavement construction that can have a significant effect on the overall sustainability of a paving project include:

- Fuel consumption (during material transport from the site and between the plant and the site and the construction operations themselves).
- Exhaust and particulate emissions.
- Traffic delays, congestion, and noise emissions generated during construction.
- Constructed characteristics of the pavement surface, which impacts surface friction (safety), noise, and possibly fuel efficiency during the use phase.
- Pavement performance and overall life (as a result of construction quality).

This chapter summarizes various approaches for improving the sustainability of pavement construction. It first begins with a discussion of general sustainability issues that are common to all types of pavement construction (such as energy consumption and effects on localized or surrounding areas), and includes a summary of specific strategies that can be used to address those issues. This is followed by separate sections that are devoted to strategies and approaches that can be used to improve the sustainability of both asphalt and concrete pavement construction. Note that material production (discussed under chapter 3) includes plant mixing, and thus construction starts "at the gate" with respect to asphalt and concrete mixtures.

Sustainability of Pavement Construction Operations: General Issues

The following are the general pavement construction factors that impact pavement system sustainability over the life cycle:

- Construction-related energy consumption.
- Effect on the surrounding area (including particulate and gas emissions, noise, effects on residents and businesses, and effects on wetlands and streams).
- Economics of construction practices, including user costs (due to construction-related traffic delays or normal operations).

An introduction to these factors is presented next, followed by a section on potential strategies for addressing them.

Construction-Related Energy Consumption and Emissions

In general, pavement construction is an energy-intensive process that involves excavation, earthwork movement, material processing and placement, and compaction/consolidation of the paving layers. Pavement construction equipment includes excavators and haul equipment, crushers, asphalt and concrete mixing plants (discussed as part of materials in chapter 3), graders, pavers, rollers, and more. The associated energy consumption of equipment is a function of the equipment/vehicle operation energy efficiency, which in turn is a function of the operation of that equipment within ideal power bands and minimization of idle time and engine speed during idle time. External factors (independent of equipment efficiency) that influence construction fuel consumption include site operations (e.g., haul distances, construction staging, and the need for multi-pass operations) and specific site-related conditions (e.g., quality and maintenance of haul road surfaces). Other factors that can affect energy consumption include fuel types (including the use of alternative fuels such as biodiesel and compressed natural gas) and the type of power source for stationary construction equipment (i.e., generator driven vs. grid powered).

The use of RAP and RCA in the base or subbase offers a strong potential for sustainable construction, particularly when the source materials are available and processed on site. In addition to offering the potential for reductions in construction-related fuel consumption and emissions, recycling (particularly on-site recycling) reduces the costs, fuel consumption, emissions, and land use associated with excavating, processing, and hauling virgin materials, as well as the economic and environmental costs of disposing of the old materials. Actual savings of fuel, emissions, and costs vary widely for a particular recycling project, depending on such things as the abundance of suitable local virgin aggregate sources, haul distances, crushing costs, and the potential for use of the recycled material in a higher type application (e.g., in new asphalt or concrete surface layers), which depends upon the quality of the source material. There may even be savings in surface material costs if the increased stiffness of a recycled base (due, for example, to the rough-textured, angular nature and secondary cementing action of RCA) provides additional structural capacity to allow a reduction in surface layer thickness. Additional guidance on the cost and energy savings and structural benefits associated with recycling asphalt and concrete pavements is available from ARRA (2001) and ACPA (2009), respectively.

Construction emissions are those generated from the operation of the various construction-related equipment due to direct construction activities, and also include the emissions that result from indirect construction activities (including vehicles using a roadway that experience construction-related delays). The emissions emanate from equipment powered by fossil fuels (using diesel, gasoline, or coal to heat or run equipment) and from electricity obtained from the grid used as part of the construction. Waste disposal should also be considered in order to account for a comprehensive measure of sustainability.

Emission categories for mobile sources used during construction activities usually include the following exhaust pollutants:

- Hydrocarbons (HC) or non-methane hydrocarbons (NMHC).
- Nitrogen oxides (NOx).
- Carbon monoxide (CO).
- Carbon dioxide (CO_2).
- Sulfur oxides (SOx).
- Volatile organic compound (VOC) (replaced all HCs by EPA [2005]).
- Particulate matter (PM).

There have been numerous studies estimating the contribution of roadway construction projects to the overall life-cycle energy consumption and emissions of a pavement system. As described in chapter 2, pavement construction activities are estimated to be responsible for 70 percent of the highway and street construction expenditures (USDOT 2010). Total GHG emissions due to all highway and street construction is estimated to be around 117 million tons (106 million mt), which is approximately 7 percent of the U.S. transportation total. Currently, a national effort is underway to develop a guidebook for selecting and implementing sustainable highway construction practices (under NCHRP Project 10-91, *Guidebook for Selecting and Implementing Sustainable Highway Construction Practices*).

With respect to the total life cycle of a pavement system, the construction stage constitutes approximately 5 percent of the total pavement production cycle, including plant production, transportation, and construction activities. In an overall roadway life cycle, which commonly may be 40 to 50 years, the total energy consumed can be 18 to 20 times that for pavement production, which includes plant production, transportation, and construction (Muench 2010). The total energy and associated emissions during the life cycle of a pavement include pavement production, use phase related to the operation of roadway (e.g., fuel consumption by vehicles, lighting, traffic signals, urban heat island), maintenance, and end-of-life strategies. A detailed discussion of the pavement life cycle is presented in chapter 2.

The EPA (2009) has introduced the concept of *emission intensity* to provide a means for comparing the relative emissions of GHGs between various industries or economic sectors while taking into account their economic output. Emission intensity is typically calculated as the ratio of the GHG emissions produced per dollar of gross domestic product (GDP). Within the construction sector, the highway construction subsector had the highest emission intensity at 0.54 tons (0.49 mt) of CO_2e emissions per thousand dollars of GDP (in 2002 dollars), with total annual emissions of 19.5 million tons (17.6 million mt) CO_2e.

Impact of Construction on Surrounding Areas

Emissions from Equipment Exhaust

The use of heavy equipment for earth moving and construction operations generates engine combustion emissions that may have significant impact on local air quality in surrounding areas, as well as on climate change. Heavy duty construction equipment is usually diesel powered, which yields NO_x, GHG, and diesel PM as significant emissions. The particulate fraction of diesel exhaust emissions is reported as a toxic air contaminant posing chronic and carcinogenic public health risks (AEP 2012).

The EPA regulates the emissions from all mobile sources including on-road and non-road vehicles and engines. Non-road vehicles and engines include a category called compression-ignition (CI) engines covering equipment used in various construction activities. The EPA has established stringent standards for carbon monoxide, volatile organic carbon, nitrogen oxides, and particulate matter that a vehicle and engine may emit, and manufacturers, refineries, and mixing plants are responsible for meeting those standards. A tiered approach was put forward by EPA depending on the vehicle's engine rated power and age. Figure 5-1 illustrates the limits proposed by EPA (EPA 2013a), and it is noted that the band of restrictions will become much tighter after 2015.

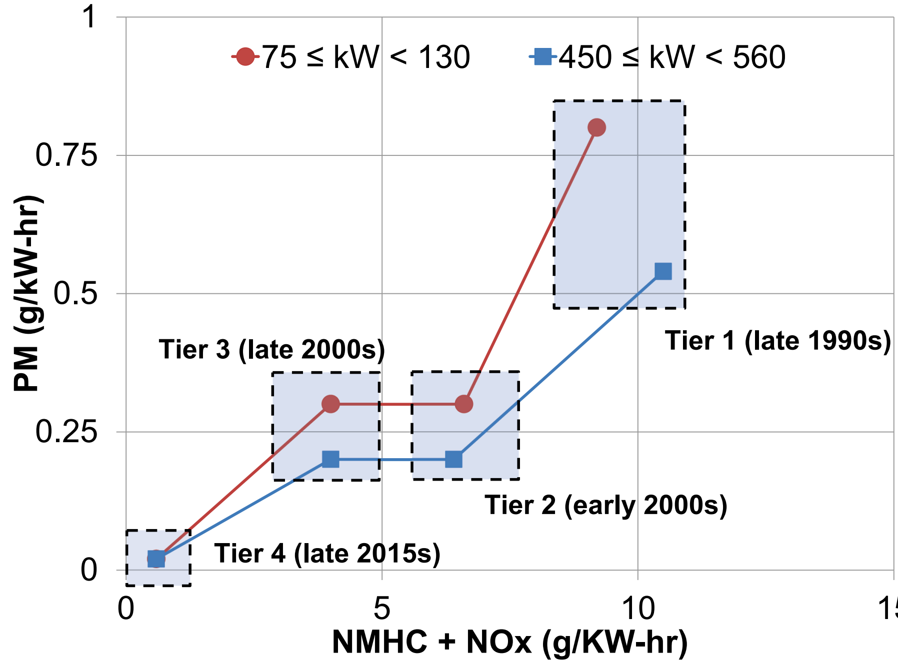


Figure 5-1. EPA non-road diesel engine limits for construction vehicles with two different ranges of rated power illustrating tightening of the emission limits (adapted from EPA 2013a).

Construction emissions can be calculated for all projects that are expected to exceed a certain threshold defined by the construction significance criteria (AEP 2012). Emissions can be calculated using the available databases, EPA sources, or commercial software using the construction activities and productivity of the equipment and use. For those projects exceeding the significance criteria, short- and long-term mitigation strategies can be applied, as described later in this chapter. An example of the construction emissions thresholds proposed by the California Environmental Quality Act (CEQA) is given in table 5-1.

Table 5-1. Thresholds of significance for construction operations (SLO county APCD 2012).

Pollutant	Daily Threshold	Quarterly Tier 1 Threshold	Quarterly Tier 2 Threshold
VOC + NO_x (combined)	137 lbs	2.5 tons	6.3 tons
Diesel PM	7 lbs	0.13 tons	0.32 tons
Fugitive PM (PM_{10}), Dust		2.5 tons	
GHG	*	*	*

1 lb = 0.45 kg; 1 ton = 0.91 metric ton
* *GHG emissions need to be combined with other life-cycle emissions and amortized over the life of the project.*

In order to estimate GHG emissions, the information related to equipment productivity is needed. Hourly equipment emission rates can be calculated using the following formula (Tang, Cass, and Mukherjee 2013):

$$Hourly\ Equipment\ GHG\ Emission\ Rate = O_t * L_f * HP * C_f * \varepsilon \quad \text{(Equation 5-1)}$$

where:

- O_t = Operating time factor (usually taken as 45 min per hr)
- L_f = Average load factor corresponding to actual operating horsepower
- HP = Average horsepower
- C_f = Fuel consumption rate (Gal/(HP*hr))
- ε = Emission rate (i.e., 22 lbs CO_2/Gal (2.6 kg/l) for burning conventional diesel)

Airborne Particulates from Construction Operations

In addition to the generation of particulates and pollutants from vehicle exhaust, pavement construction activities commonly generate dust, fine soil, and other airborne particulates from normal operations, particularly when construction takes place in dry or windy conditions. This is sometimes referred to as fugitive dust, and is primarily particulate matter that is less than ten microns in size (PM_{10}) (AEP 2012). There are a number of sources of fugitive dust, including the following:

- Haul vehicle traffic on dry, unstabilized surfaces (including haul roads, pavement foundation layers).
- Wind erosion of exposed unstabilized materials.
- Stockpiling, hauling, and placement of unstabilized materials.
- Tracking and subsequent breakdown of soils and construction materials on local roads near site and plant entrances.

The distribution of particulates can vary constantly with wind speed and patterns, precipitation events, and other factors. However, it can be controlled and mitigated through good construction practices.

Noise Generated from Construction Operations

Pavement construction generates noise from the excavation, movement, processing, and placement of large volumes of material using large, powerful machinery. The resulting noise from exhaust stacks, plant site operations, earthwork construction, material hauling, and so on can be irritating at best, and potentially hazardous to the health of workers or area residents in the worst cases. High noise levels contribute to many health problems, including hearing loss, sleep disturbance, interference with communication, and physical health issues typically associated with stress (e.g., cardio-vascular problems) (Hygge 1998; Berglund and Lindvall 1995). Similar to airborne particulates, construction noise problems can be affected by wind patterns and other weather conditions.

Construction Impacts on Local Traffic, Residences, and Business Operations

In addition to pollution, particulate, and noise concerns, construction activities can also impact local residents, businesses, and visitors by temporarily preventing or restricting access to residential and commercial buildings, creating congestion and contributing to significant travel delays, and generally making an area undesirable to visit. Congestion-related impacts can spread well beyond the immediate limits of the construction area, depending upon local traffic patterns and route capacities and the availability of alternate modes of transportation. Significant and prolonged access problems to commercial areas may cause financial hardship to business owners and, in some cases, may result in business failures, having financial impacts on both the business owners and the community in general.

Public safety, both on the road and in areas adjacent to the construction site, is also a concern, particularly in high business zones and residential areas. The use of private property for construction activities (whether through rental, purchase, or condemnation) is another social impact of construction activities.

Construction Near Streams, Wetlands, and Environmentally Sensitive Areas

The potential for soil erosion in construction zones is increased by the removal of vegetation during earthwork and grading operations, allowing for more rapid concentration of precipitation and subsequent higher flow rates and increased potential for erosion. In addition, surface water runoff from construction zones can carry potentially hazardous materials into local waterways.

The failure to control erosion and surface runoff during construction can cause both on-site and off-site impacts (NRCS 2000). On-site impacts include the loss of topsoil resulting in elimination of the soil's natural ability to provide nutrients to plants. Off-site impacts are related to the erosion from construction sites resulting in water quality problems through excess nutrients transported via eroded soil and excess sediment. Excess nutrients impact water quality through eutrophication, a process in which excess nitrogen and phosphorus transported into surface waters causes unwanted biological growth, raising the level of lake or river beds which can eventually convert the area to dry land (Lawrence, Jackson, and Jackson 1998). Transported sediments can also be detrimental to aquatic life by interfering with photosynthesis, respiration, growth, reproduction, and oxygen exchange in waterways (Waters 1995; Newcombe and MacDonald 1991; Illinois Tollway 2013).

Economics of Construction Practices, Including User Costs

The adopted or specified construction practices for any given pavement construction project have direct bearing on both the initial construction costs and the long-term life-cycle costs of the project. Changes in construction practices to enhance the sustainability of the project (such as noise and pollution reduction procedures, controlling erosion and stormwater runoff, and providing better local access) are expected to incur increased costs, which must be considered and weighed against expected benefits over the life cycle of the pavement to determine its effective impact. Changes that incur unacceptable economic expense may not be easily adopted in spite of potential environmental or societal benefits.

In addition, construction work often results in reductions in roadway capacity and throughput due to geometric restrictions, reduced speed limits, temporary closures, detours, and other congestion-inducing activities. Significant costs are associated with construction-related traffic delays and congestion, including lost time and decreased productivity for users, wasted fuel, and economic loss due to the inefficient movement of goods and services. Highway construction work zones account for nearly 24 percent of nonrecurring congestion in the U.S. (other sources include vehicle crashes and breakdowns, and weather conditions), which translates to 482 million vehicle hours of delay per year (USDOT 2006). Highway construction work zones are estimated to be responsible for 10 percent of all highway congestion in the U.S., which translates to an annual fuel loss of $700 million (Antonucci et al. 2005).

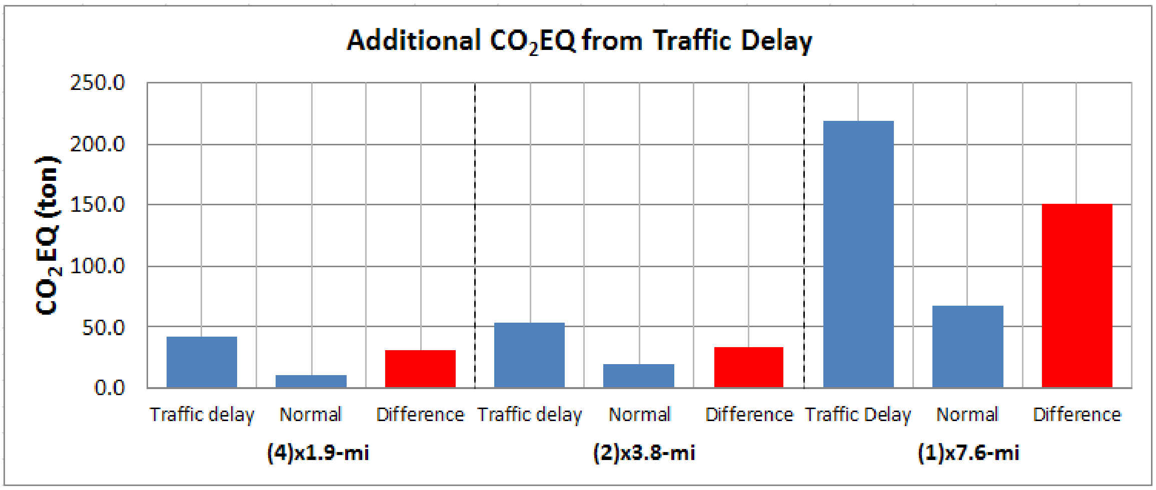
According to recent congestion reports, while the magnitude of these emissions varies widely, Chan (2007) has reported an increase in emissions related to traffic delay as traffic volume increases, but generally less than the emissions associated with material production. In another study, Häkkinen and Mäkelä (1996) reported that fuel consumption and corresponding emissions due to the disruption of normal traffic flow by construction and maintenance activities are in the range of 1 percent of the total life-cycle emissions of asphalt and concrete pavements. These numbers may vary depending on the type of the pavement and sequence of construction activities and the assumptions of use-phase traffic related emissions.

In order to calculate emissions from traffic delays during construction and maintenance activities, the modeling effort must consider the stop and go nature of traffic flow as it approaches, passes through, and leaves the construction zone. For example, consider a typical vehicle traveling at 55 mi/hr (89 km/hr) that stops as it approaches a construction zone and remains stopped for 10 minutes; it then proceeds through the construction zone at a constant speed of 45 mi/hr (73 km/hr) and at the end of the construction zone accelerates to once again reach the posted speed limit (Mukherjee, Stawowy, and Cass 2013). This travel schedule can be modeled in various available programs to calculate emission factors for the given traffic and project construction data. The final outcomes of this analysis are the emissions and fuel usage from traffic delays triggered by highway construction activities. The EPA's Motor Vehicle Emission Simulator (MOVES) software is one program that can be used to calculate emissions due to construction and maintenance activities (see http://www.epa.gov/otaq/models/moves/).

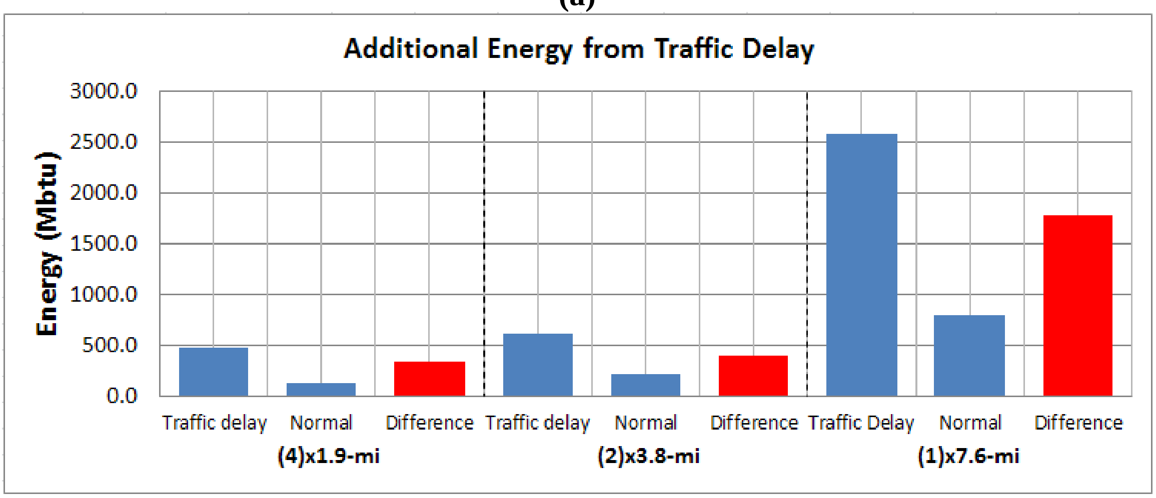
Different road closure strategies and their impacts on the pavement construction energy consumption and GHG emissions were calculated by Kang et al. (2014). Three hypothetical scenarios were generated for a reconstruction project on the I-90 highway corridor around the Chicago area. The Kentucky Highway User Costs Program (KYUCP) model, developed by the University of Kentucky, was used to estimate driving schedules due to road closure scenarios. The emissions associated with changing driving schedules were predicted using EPA's MOVES software. The following scenarios for work zone closures and construction schedules were considered in the traffic and emissions simulations for a 7.6 mi (12.2 km) work zone:

- The first case assumed that the 7.6 mi (12.2 km) work zone was divided equally into four 1.9 mi (3 km) work zones. For the construction of each 1.9 mi (3 km) work zone, a nighttime closure strategy was assumed between 9 p.m. and 5 a.m. in order to minimize additional emissions from traffic delay by avoiding the time period when peak traffic volumes would be experienced.
- The second case assumed that the 7.6 mi (12.2 km) work zone was divided in half. For the construction of each of the two 3.8 mi (6.1 km) work zones, a 16-hour closure between 10 p.m. and 2 p.m. (following day) was assumed to avoid the time period when peak traffic volumes would be experienced.
- The third case was based on the construction of the entire 7.6 mi (12.2 km) in a single stage. A 32-hour closure was assumed for this scenario from 9 p.m. to 5 a.m. (2 days later).

The simulation results for energy consumption and CO_2e emissions are provided in figure 5-2. Total emission and energy during construction activities were compared in the figure to the baseline case assuming traffic flow at the posted speed limits. The additional emissions and energy from work zone traffic delay increased slightly as the length of the work zone doubled from 1.9 mi (3 km) to 3.8 mi (6.1 km) because no traffic queue was developed during the nighttime closure. The emissions and energy consumption drastically increased in the third case when the entire 7.6-mi (12.2-km) work zone was assumed to be closed for 32 hours. Total energy and emissions were converted to the functional unit of LCA to evaluate the impact of traffic delay on pavement construction and material acquisition phase. Global warming potential due to traffic delay was reported to be 1.3 percent (best case scenario) to 2.7 percent (worst case scenario) of the total GWP including material and construction phases.



(a)



(b)

Figure 5-2. Impact of construction-related traffic delay: (a) addition emissions, (b) additional energy consumption for normal traffic and traffic delay scenarios for work zone lengths of 1.9 mi (four 8-hr nighttime closures avoiding morning and evening peak hours), 3.8 mi (two 16-hr night and daytime closures avoiding evening peak hours), and 7.6 mi (32-hr closure). (Traffic delay case indicates the case in which traffic delay due to work zone construction is developed; normal case indicates the traffic when all lanes are open with no work zone construction activity) (Kang et al. 2014).

Quality and Performance of Constructed Pavement System

Even with the most durable materials and the most effective pavement designs, the overall pavement performance expectations will go unrealized if poor construction practices or inadequate quality assurance are performed. The quality of constructed roads becomes even more critical as transportation agencies need to maintain the facilities with limited resources. Performance specifications have been recently accepted as a way to improve the quality of construction and also to encourage contractors to develop innovative solutions that save time, minimize traffic delays, and enhance durability. SHRP 2 project R07 was charged to develop such performance specifications (Scott et al. 2014). The implementation of performance specifications are discussed in the context of various contract delivery methods including design-build, design-bid-build, and other innovative contracting variations. The findings of the study support the use of performance specifications.

Providing an effective working platform to facilitate construction activities is critical in ensuring adequate pavement performance. The load bearing capacity of native subgrade soil is generally improved through soil stabilization. Several techniques can be used to stabilize subgrade soils depending on site-specific characteristics and the predominant soil type; these include pulverization and homogenization using existing materials (without additives); stabilization using a single additive such as lime, cement, or asphalt binder (or less commonly, fly ash or other mineral fillers); and stabilization using multiple additives such as lime-fly ash (LF) or lime-cement-fly ash (LCF) combinations. These materials and technologies were introduced in chapters 3 and 4.

One of the primary factors that control the sustainability of a pavement system through the use phase of its life cycle is the durability and longevity of the pavement. Pavements that deteriorate quickly and require frequent repairs and rehabilitation result in greater agency and user costs, greater environmental impacts (i.e., fuel consumption and emissions), and undesired levels of service to the users.

The overall quality of the pavement must be reflected in both its structural and functional characteristics. For example, even a strong and durable pavement that has poor ride quality will result in relatively higher levels of user fuel consumption (and resulting vehicle emissions), lower levels of service, and may even increase average vehicle maintenance costs and damage to transported goods (or increases in required packaging costs). Specific issues and strategies for improving the quality of construction for asphalt and concrete pavements will be discussed later in this chapter.

Strategies to Improve Sustainability of General Pavement Construction Operations

Table 5-2 summarizes several different strategies for improving the sustainability of construction operations that are applicable to all highway construction projects, regardless of pavement type. These strategies revolve around four major objectives (reduce fuel consumption and emissions, reduce noise, accelerate construction, and control runoff, erosion, and sedimentation), and the economic and environmental impact and trade-offs associated with each strategy are described. Additional discussion on these strategies is provided in the following sections.

Table 5-2. Approaches for improving general sustainability of pavement construction operations.

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Fuel Consumption and Emission	Minimize haul distances	Reduced fuel costs	Reduced GHG emissions and air pollutants	
	Select appropriate equipment type and size for the job	Reduced fuel costs but may require capital investment	Reduced GHG emissions and air pollutants	
	Idling reduction	Reduced fuel costs; may require some capital investment to minimize idling	Reduced GHG emissions and air pollutants	Improved air quality
	Use alternative fuels	Varies	Reduced emission	Improved air quality
	Retrofit construction equipment, use hybrid equipment, or both.	Will increase costs due to initial capital investment	Reduced GHG emissions and air pollutants	Improved air quality and may decrease construction related noise
Reduce Noise	Construction time restrictions	It may lead to reduction in construction productivity	May increase emissions if construction is prolonged	Less noise and may affect air quality
	Equipment maintenance or modification	Increased capital investment	No environmental impact	Less noise
Accelerate Construction	Effective traffic control and lane closure strategies	Reduced fuel costs for users and agency	May reduce traffic delays and associated emissions	Less traffic disturbance
	Establish performance goals and measures for work zones	Reduced fuel costs for users and agency costs	May reduce traffic delays and associated emissions	Less traffic disturbance
	Use project management software for construction sequencing and managing traffic delays	Reduced fuel costs for users and agency; extra effort for agency/contractor	May reduce traffic delays and associated emissions	Less traffic disturbance
	Implement intelligent transportation warning systems	Increased agency costs	May reduce traffic delays and associated emissions	Less traffic disturbance and improve work zone safety
Control Erosion, Water Runoff, and Sedimentation	Use perimeter control barriers (fences, straw bales, etc.)	May result in increased project costs	Reduced sedimentation, prevent degradation of water quality	No direct impact on society
	Minimize the extent of disturbed areas	May result in increased project costs	Reduce disturbed areas	May reduce impact on surrounding residential areas
	Apply erosion control matting or blankets	May result in increased project costs	Reduced sedimentation	May reduce impact on surrounding residential areas
	Store/stockpile away from watercourse	No significant economic impact	May reduce potential water pollution	May reduce potential impact on area water

Strategies to Reduce Construction-Related Energy Consumption and Emissions

Opportunities to Reduce Energy Consumption and Emissions

There are a number of opportunities in the pavement construction process where energy and GHG emissions can be reduced. These opportunities can be grouped into three major categories:

1. Fuel use (moderate to major effect).
2. Electricity conservation (moderate to major effect).
3. Selection of construction materials (no to minor effect).

This section focuses on activities that contractors can control or influence to reduce energy and GHG emissions. Often, steps taken to reduce these parameters can provide a number of auxiliary benefits, such as increased equipment life and improved working conditions.

Fuel Use

According to the estimates reported by EPA (2009), nearly three-quarters of the GHG emissions in various industrial processes are due to fossil fuel combustion. This is true for pavement construction, where fuel type and its efficient use can play a major role in the reduction of GHG emissions. Table 5-3 presents the emission factors for commonly used fossil fuels, that is, the emissions generated (in terms of lbs of CO_2) per gallon of fuel used. It also shows the potential reduction in GHG emissions for two assumed levels of increased fuel efficiency resulting in either a 3 percent or a 10 percent reduction in fuel consumption for highway construction activities. Clearly, even a modest reduction in fuel usage can have a significant effect on GHG emissions.

Table 5-3. GHG emissions reduction scenarios from fossil fuel use (EPA 2009).

Fuel Type	Emissions, lbs CO_2 per unit material[1]	Estimated GHG[2] Reduction Using 3% less fuel	Estimated GHG[2] Reduction Using 10% less fuel
Diesel	22.37 lbs CO_2/gallon	600 million lbs CO_2	2000 million lbs CO_2
Gasoline	19.54 lbs CO_2/gallon	186 million lbs CO_2	621 million lbs CO_2
Natural Gas	11.7 lbs CO_2/1,000 ft^3	106 million lbs CO_2	353 million lbs CO_2

[1] Emission factors are taken from EPA (2009).

[2] GHG reduction is calculated using the data provided in EPA (2009) and percentage of highway construction sector (13.4 percent) in total GHG of entire construction sector. The reduction in GHG is derived from the total construction sector emissions reported in EPA (2009). For example, using 3 percent less fuel may reduce CO_2 emissions by 4,455 million lbs (2,022 million kg) as an estimate of sector-wide emissions, with highway construction responsible for approximately 13.4 percent of total emissions. Therefore, such reduction in fuel use may contribute to an emission reduction of 600 million lbs (272 million kg).

The EPA (2007) recommends several low-cost strategies to reduce construction equipment emissions, including improved operating strategies, fuel strategies, and equipment strategies. Additional details on these strategies are provided below.

Operation Strategies for Fuel Reduction

Equipment idle control, engine preventive maintenance, and operator training are some of the primary strategies for reducing fuel consumption and resultant emissions. For example, a typical

Class 8 diesel engine at high idle may consume 1.2 gal (4.5 L) of fuel per hour, a value that translates to the release of 26.1 lbs (11.8 kg) of CO_2 emissions per hour (EPA 2009). At low idle, the fuel consumption can be cut by one-half to 0.6 gal (2.3 L) of fuel per hour. For many contractors, fuel reduction simply involves changing work practices or investing in low-cost equipment. A summary of some of the recommended strategies for reducing fuel consumption, along with anticipated costs and benefits, is presented in table 5-4 (EPA 2007). In addition, carefully selecting material sites and plant locations for a specific job, as well as maintaining a stable haul road, can contribute to reduced fuel consumption.

Table 5-4. Operational strategies to reduce emissions incurred due to construction activities (EPA 2007).

Operation Strategy	Costs	Benefits
Equipment idle reduction and control	Low administrative costs for training and tracking of idling Upfront investment if on-board idle reduction equipment[1] is used (cost varying \$500-\$9000)[2]	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Longer engine life and reduced maintenance costs
Engine preventive maintenance	Low administrative costs for tracking equipment maintenance needs	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Longer engine life and reduced maintenance costs
Equipment operator training	Upfront investment for training programs	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Improved operator efficiency
Construct choose and maintain stable haul roads	Upfront investment may be required to construct and maintain haul roads	Smooth haul roads improve fuel consumption Longer engine life and reduced maintenance costs
Select proper size and type of equipment depending on the production rate and road conditions	No investment is required	Reduction fuel consumption Longer engine life and reduced maintenance costs
Minimize haul distances by optimizing the plant and materials storage site location	No investment is required	Reduction fuel consumption

[1] Idle reduction technologies recommended by EPA's SmartWay Technology Program can be found at the following web address: http://www.epa.gov/smartway/

[2] The benefits of idling can be calculated using the worksheets developed by Argonne National Laboratory for heavy-duty and light-duty vehicles (Argonne 2011).

Fuel Use Strategies

Ultra low sulfur diesel (ULSD), biodiesel fuels, and compressed natural gas (CNG) are examples of alternative fuels that are being used in construction equipment to help reduce emissions. ULSD is a diesel fuel that has gone through additional processing to remove sulfur, and hence is a cleaner-burning fuel that can be used in any diesel engine. For example, regular non-road diesel has a sulfur content of 3,000 to 5,000 parts per million (ppm), whereas ULSD has a sulfur content of 15 ppm or less. Biodiesel is a renewable fuel made from domestically grown crops such as soybeans, cottonseed, peanuts, and canola. Biodiesel is usually available at the pumps blended with conventional petroleum diesel (e.g., B5, 5 percent biodiesel; B20, 20 percent biodiesel). CNG is made by compressing natural gas (which is mainly composed of methane, CH_4) to less than 1 percent of its volume and storing it in special containers under high pressure (up to 3,600 lb/in^2 [25 MPa]). Table 5-5 summarizes some of the alternative fuel strategies with associated benefits and trade-offs.

Table 5-5. Alternative fuel use strategies to reduce emissions (EPA 2007).

Operation Strategy	Costs	Benefits
Ultra-low sulfur diesel (ULSD)	Higher price at the pump Lower energy content	Reduce PM and SOx emissions Reduce engine wear Increase oil change interval
Biodiesel (B5 and B20)	Higher price at the pump Increase NOx emissions Power loss and decreased fuel economy Degradation and wear in engine hoses or gaskets	Reduce PM, CO, and HC emissions Improve lubricity and reduce engine wear
Compressed natural gas (CNG)	Retrofit from gasoline and diesel vehicles is required Limited vehicle availability	Lower price at the pump Reduction in PM and greenhouse gas emissions

Equipment Optimization Strategies

Modifying and retrofitting existing construction equipment is another way to reduce emissions during construction activities. The initial investment required for this strategy is relatively high compared to the aforementioned strategies. Major equipment modification approaches include repowering or upgrading older diesel engines and using grid electricity or hybrid equipment (EPA 2007).

Diesel retrofitted devices can be installed on new or existing equipment as a post-treatment pollution control to reduce PM, NOx, HC, and CO. Diesel oxidation catalysts, diesel particulate filters, selective catalytic reductions, and exhaust gas recirculation are some of the retrofit technologies available in the market (EPA 2013b).

Switching to dual-fuel generators or grid electricity, when it is available, can provide modest emissions benefits. On average, an approximate reduction of 15 percent can be achieved using grid electricity over the use of diesel generators, although this can be much higher depending on the source of the grid electricity.

Other equipment optimization strategies may include selecting haul equipment (type, size, and quantity) based on production rates, haul route conditions, and maneuverability requirements; matching plant production, hauling needs, and paving operations; and avoiding extended time of heavy equipment idling.

Strategies to Reduce Impact of Construction on Surrounding Area

Air Quality Assurance Practices during Construction (Other than Vehicle Emissions)

There are a number of practices that can be adopted to improve air quality issues associated with pavement construction, other than those that result from vehicle emissions. Some of these strategies include water sprinkling and other dust control techniques, regular maintenance of dust collectors at concrete and asphalt plants, and consideration of the proximity of residential and light commercial areas in the selection of plant and materials storage locations.

Construction Noise Control

Among the potential activities that could be considered to help control pavement construction noise are selecting plant and material storage locations away from residential and light commercial areas, limiting and mitigating excessive noise from haul vehicles (e.g., loud exhaust, banging tailgates), employing noise-reducing equipment modifications, and applying time-of-day construction restrictions.

Effective Traffic Control, Lane Closures, and Work Zone Safety

Establishing work zones imparts restrictions on the highway driving space, and can result in traffic congestion with a number of detrimental impacts, including lost time, increased fuel consumption and air pollution, inefficient movement of goods, decreased productivity, and potentially compromised roadway safety. The contribution of emissions from construction-related traffic delays to total life-cycle emissions varies with construction schedule and duration, roadway capacity, and traffic volume and control. A wide range of emissions and additional fuel consumption has been associated with traffic delays (Chan 2007). Based on several construction and reconstruction projects studied in Michigan, the contribution of traffic delays to overall pavement service life emissions was comparable to

Transportation GHG Analysis Tools

A number of tools are available for use in analyzing GHG emissions on construction projects.

State Inventory Tool (SIT): *This tool from the EPA consists of eleven modules for applying top-down approach to calculate GHG emissions and provides an aggregated total for each sector (industrial, commercial, residential, and transportation) at the state level. Emissions for specific construction activities are not included.*

NONROAD: *This tool from the EPA helps to estimate emission factors from all non-road vehicles (except locomotives, aircrafts, and commercial marines). This tool can differentiate equipment type and other characteristics and can be used to calculate emissions from specific construction activities.*

MOVES: *This is a comprehensive tool from the EPA for all on-road vehicles providing detailed reports on vehicle emissions. Vehicle operation characteristics, fuel type, geographic location, vehicle miles traveled, and other factors that may contribute to emissions are considered. However, since non-road vehicles are not considered, this model cannot be used alone to estimate construction related emissions.*

PE-2: *This is a web-based pavement LCA tool applying a project based approach. The focus of the tool is estimating emissions associated with highway transportation projects over their life cycle, including production, construction, maintenance, and use phase.*

GreenDOT: *This is an Excel-based greenhouse calculator from the operations, construction, and maintenance activities of state DOTs. It was developed under NCHRP Project 25-25 Task 58.*

production stage emissions for high-volume roads; however, projects with Average Annual Daily Traffic (AADT) less than 20,000 vehicles per day (vpd) did not show a significant contribution to pavement total emissions and fuel use (Chan 2007).

An FHWA study reported on the analysis of 3,110 work zones on the National Highway System, covering thirteen states (Wunderlich and Hardesty 2003). Analysis of the collected data shows that the work zone closures resulted in a loss of 60 million vehicles of capacity per day. Among the work zones examined, 58 percent of them had lane closures primarily during the daylight hours, 33 percent had closures primarily during the nighttime hours, and 9 percent had continuous, 24-hour closures. The average work zone had lane closures for 11 hours a day and occupied 6.8 mi (10.9 km) of roadway for an average of 125 days (Wunderlich and Hardesty 2003).

Several strategies can be considered to reduce the impact of work zone delays, including the following (FHWA 2007):

- Implementing effective road and lane closure strategies – Effective traffic control strategies should reduce the period of time that work zones are active. This minimizes traffic delays and resultant emissions while keeping the motorists and construction workers safe. Some of the specific work zone strategies include using narrower lanes or shoulders, applying weekend lane or road closures, and charging lane rental, where contractors are charged for closing down lanes with an incentive to accelerate the time of construction.
- Establishing performance goals and measures for work zones – Highway agencies can set goals to help manage their work zones, and could target such items as reducing work zone delays, reducing queue length, and minimizing GHG emissions. This strategy has been implemented by some DOTs and by some European countries, including Germany and the Netherlands. For example, in the Netherlands the target work zone delay is 6 percent of all traffic delays. This number in the U.S. has been reported as 10 percent, based on national averages (Cambridge Systematics 2005).
- Incorporating lane/road closure analysis strategies during project planning – Different project management software programs can be incorporated into the planning and design phase to predict the impact of various lane or road closure strategies on traffic delays and emissions, and can also be used during construction to obtain feedback and monitor progress. This type of analysis in the planning stage can help sequence the schedule of activities while optimizing the process to reduce the impact on the users and the environment. Examples of the tools that can be used for this purpose include QuickZone, CA4PRS, and Dynasmart-P. CA4PRS is available free of charge to all highway agencies and is available at: http://www.fhwa.dot.gov/research/deployment/ca4prs.cfm.
- Implementation of intelligent transportation systems (ITS) – ITS technologies measure, analyze, and regulate traffic speed and volume and can help reduce traffic congestion in work zones by advising drivers of downstream traffic conditions. Components of an ITS may include dynamic message signs, a highway advisory radio, a citizen band radio channel, portable signs, a portable trailer, variable work zone speed limits, speed warning systems, and web cameras (Antonucci et al. 2005). Providing alternate routes or modes to drivers can also significantly reduce traffic demand in the work zone (Lee, Choi, and Lim 2008). A case study in Michigan that adopted ITS technology and a dynamic lane merge (DLM) system (which encourages motorists to merge lanes well before reaching

the work zone) found that the DLM can increase safety while reducing the delay in lane closure area in work zone (Paniati 2004). Monitoring and optimizing the entrance and exit of operation equipment to the construction site is also an important activity to reduce delays in the work zone.

Erosion/Stormwater Runoff and Sedimentation Control

Generally, highway construction projects that involve earthwork removal require a plan for erosion and sedimentation control. Temporary erosion and sedimentation control plans or stormwater pollution prevention plans may be needed for the highway project that includes earthwork removal. In addition to conventional approaches, a number of innovative methods are being used in this regard, such as harvesting the existing vegetation mat and then reinstating it after the earthwork has been completed, and performing only a partial cleaning of the bottom of the ditch so that the upper part of the vegetation remains in place. However, even on project sites where recommended practices or innovative procedures are employed, sediment can continue to be discharged at concentrations dangerous to aquatic life. For example, in one construction project, it was reported that suspended solid concentrations increased by 500 percent on the downstream side of the construction site (City of Toronto 2006). Hence, effective best management practices to prevent erosion and to reduce the risk of costly sedimentation control measures and environmental damage are part of sustainable pavement construction.

The unique characteristics of each pavement construction project challenges contractors to meet the governing regulatory agency requirements (conservation authorities, municipal, provincial, and federal). Therefore, it is critical to have an environmental assessment to determine the extent of environmental constraints to ensure implementing sustainable construction practices. The control plan should include a multi-barrier approach to control erosion during construction and sediment transport from the construction site. In addition, timely consideration of environmental constraints is critical to reduce delays and undesired environmental implications. The suggested plan for erosion control may include the following (City of Toronto 2006):

- Minimize the extent of disturbed areas by construction sequencing, preserving and protecting natural cover, and immediately stabilizing disturbed areas.
- Establish erosion control protocols for the site considering topography, site conditions, and infiltration rates; these protocols may include vegetation (e.g., mechanical seeding, terraseeding, hydroseeding, sodding, tree and shrub planting), erosion control matting or blankets, and scarification of disturbed surfaces.
- Apply sediment transport control measures when vegetation practices could not be implemented. This includes perimeter controls, settling controls, and filtration controls.
- Limit duration of soil exposure and phase construction when possible.
- Minimize slope length and gradient.
- Store/stockpile away from watercourse (e.g., greater than 40 ft [12.2 m]).
- Ensure inspection and maintenance of the implemented sediment and erosion control practices.
- Perform revegetation of plant and construction sites as soon as is practical.

Construction Sequencing and Planning

Knowledge-based construction and scheduling analysis tools can be used to estimate optimum rehabilitation schedules, balance pavement design requirements, and develop effective traffic management plans. With a strong need to maintain traffic while rehabilitating or reconstructing a deteriorated pavement, accelerating the overall construction process becomes the key to reducing problems with congestion, safety, and user delays, particularly in heavily traveled urban areas. The CA4PRS software, mentioned earlier, is one tool that can help planners and engineers select economical rehabilitation strategies while minimizing disruption to drivers and the surrounding community (Lee, Harvey, and Samadian 2005). Several demonstration projects illustrated that the tool was beneficial in increasing productivity and reducing work zone related traffic delays. For example, the concept of a 55-hour, extended weekend closure was first validated on the I-10 Pomona project in California, achieving a 40 percent increase in production when compared to traditional nighttime closures (Lee, Harvey, and Thomas 2005). Other construction planning tools available include QuickZone and Dynasmart-P.

Software Tools to Support Construction Practices

CA4PRS *is a software tool supporting the analysis of project alternatives for different pavement design, construction logistics, and traffic operation options and is designed to help highway agencies and contractors develop construction schedules to minimize traffic delay and reduce agency costs.*

QuickZone *is a software tool for traffic analysis that compares traffic impacts for work zone mitigation strategies and estimates traffic delays and cost.*

Dynasmart-P *is a dynamic traffic assignment analysis tool used in decision making for regional work zone management. It models the evolution of traffic flows resulting from travel decisions of the individual travelers. It can be used to evaluate traffic management strategies for highway construction projects, and can also help assess the impacts of ITS technologies.*

Construction Materials Storage and Waste Management

Management of construction materials and waste can be critical in controlling stormwater pollution. Best practice management plans should be prepared for dealing with contaminated soils; vegetative waste and excess paving materials; materials removed from ditches, drains, and culverts; waste piles; and other material that can affect stormwater quality (ICF 2006). In addition, plans for hazardous waste management should be developed during construction when applicable, and may include critical recommendations such as:

- Groundwater resources should be protected from leaching by placing an impervious material on areas where toxic liquids are to be stored.
- During rain events, stockpiles of cold-mix asphalt should be covered.
- During rain events, stockpiles of soil should be covered or protected with a temporary sediment barrier.
- During rain events, stockpiles of hydraulic cement concrete and asphalt concrete rubbles should be covered or protected with a temporary sediment barrier.
- Aggregate segregation during storage and handling should be avoided.

Evaluation of Sustainable Contracting Alternatives for Environmental Considerations

The level of emissions associated with construction operations is considerable and thus effective mitigation strategies are needed. For example, contract specifications may require contractors to use construction equipment certified by EPA, or may require that diesel retrofit devices be installed to reduce emissions. Some examples of such contract specifications used in public projects include the Central Artery project by Massachusetts Highway Department, the Dan Ryan Expressway construction by Illinois Department of Transportation, and in every recent contract by the New York Metropolitan Transportation Agency (Ahn 2012). The primary intent of these specifications is mainly to reduce critical air pollutants rather than GHG emissions. There are currently only a few agencies (e.g., Metropolitan Transportation Commission in San Francisco area and the Capital District Transportation Committee in Albany) attempting to quantify GHG emissions associated with construction and maintenance activities (ICF 2008).

Innovative and alternative contracting and bidding methods may also be considered as a means of reducing the environmental burden of construction activities; otherwise, contractors may not voluntarily take the necessary steps to reduce GHG emissions or critical air pollutants. As one example, in 1994, the New York State DOT introduced "A+B" bidding (also referred to as cost plus time bidding) to encourage contractors to more actively manage their work schedules and adopt innovative and aggressive scheduling and construction management processes to accelerate construction completion. The "A" in the term refers to the cost associated with the amount of work to be completed, while the "B" refers to the calendar days proposed by the bidder to complete work multiplied by a daily user costs. The success of the A+B bidding method laid the groundwork to introduce environmental costs in the bidding process; for example, Ahn (2012) proposed "A+C" and "A+B+C" bidding methods, in which "C" refers to an environmental component. Environmental costs are defined based on the concept of the eco-costs (Vogtländer, Brezet, and Hendriks 2001; Ahn 2012). However, emission estimates, eco-cost of emissions, fossil fuel use, and eco-cost of natural material depletion need to be known to calculate the "C" component, and thus bidders are required to use LCA to estimate emission and energy consumption values.

Strategies for Improving Sustainability of Asphalt Pavement Construction Practices

Asphalt pavement construction generally entails the preparation and compaction of the subgrade, granular or treated subbase and base layers, and asphalt mixture layers, as described below:

- The construction activities for unbound and treated layers (subgrade and subbase/base layers) may include excavation, leveling, hauling of excavated or borrow materials, and layer compaction to design density levels. Locally available crushed aggregates are usually used for layer construction.
- Construction of asphalt mixture layers usually involves asphalt mixture preparation, transportation, material placement, and compaction. Asphalt mixture preparation involves the mixing of multiple aggregate stockpiles at predetermined ratios, heating the combined aggregate, and mixing it with hot asphalt binder at a specific temperature, as described in chapter 3. The resulting asphalt mixture is transported directly to the project site or stored for later transport. The asphalt mixture is placed utilizing a paver and then compacted at predetermined temperature using appropriate rollers of defined types and with specified loading magnitude and frequency. A schematic of the overall asphalt pavement construction process is presented in figure 5-3.

Surface HMA Course

Binder HMA Course

Base Course

Compacted Subgrade

Natural Subgrade

Construction Activity	*Fuel Factor*
Subgrade Preparation (grading and finishing)	0.300-0.700 gals/cubic yard
Base Layer Preparation (hauling, placement, and compaction)	0.400-0.600 gals/ton
Asphalt Mix Production (diesel)	1.500-2.000 gals/ton
Asphalt Mix Hauling (>15 miles)	0.514 gals/ton
Asphalt Mix Placement	0.273 gals/ton

Figure 5-3. Generalized asphalt pavement construction processes and associated fuel factors (fuel factor source: Skolnik, Brooks, and Oman 2013).

Major equipment used in asphalt pavement construction and their contribution to energy use and emissions should also be noted. Approximate levels of energy use and GHG emissions associated with the construction and equipment used in various asphalt pavement construction activities are presented in table 5-6.

Table 5-6. Energy efficiency and CO_2 emissions for common equipment used in asphalt pavement construction (compiled from Santero and Horvath [2009a]; Skolnik, Brooks, and Oman [2013]).

Construction Activity	Equipment	Horsepower Range	Fuel Consumption Range (gal/hr)	CO_2 Emissions Range (lb/hr)
Asphalt Paving	Paver	125-225	35-50	90-136
	Pneumatic Roller	100-135	6-12	45-136
	Vibratory Roller	100-135	4-6	226-1130
Milling	Milling Machine	400-875	2-6	113-339
Excavation and Placing	Excavator	100-320	10-50	136-226
	Vibratory soil compactor	100-180	5-15	271-361
	Bulldozer	250-500	6-10	90-136

1 gal = 3.8 l; 1 lb = 0.45 kg

General approaches to improving pavement sustainability with regard to the construction of asphalt pavements are summarized in table 5-7. It is recommended that a comprehensive LCA be used to verify the precise environmental benefits or trade-offs that may result from employing any of these specific strategies. The following sections describe these strategies in more detail.

Placement and Laydown

Every year 500 million tons (453 million mt) of new asphalt pavement material is produced in the U.S. at approximately 4000 asphalt mixing plants (NAPA 2013). Because of the widespread use of asphalt mixtures, even small changes in asphalt pavement technology can lead to significant savings in fuel and energy consumption and reductions in GHG emissions. In addition, opportunities exist to reduce exposure to asphalt fumes and other potential hazards associated with asphalt mixture production and placement. Table 5-8 presents some of the best practices that can be implemented at the plant and paving site to reduce fumes, emissions, and odors.

Asphalt pavement system layers must be placed in accordance with prevailing standards and specifications. The effective placement and compaction of bound and unbound subbase and base layers ensures the needed foundation for the surface layers, while the placement and compaction of asphalt concrete layers are elements critical to long-term performance. The proper placement and compaction of asphalt concrete layers prevents the development of segregation and longitudinal joint deterioration, ensures that the proper grade and cross slope of the pavement are met, and achieves the specified density and smoothness requirements. Recommended practices for asphalt concrete placement and compaction are summarized below.

Segregation Control

Asphalt concrete may undergo aggregate or temperature segregation, which can occur during any stage of production, transportation, or placement due to improper mixing or handling. Hence, addressing segregation usually involves troubleshooting different stages of production and placement. At the asphalt plant, production must be monitored carefully to avoid segregation (checking aggregate stockpiles, storage silos, and loading of the hauling trucks). In the production stage, modifying the mixture design, correcting improper material transfer from the stockpiles to the bins and from the bins to mixers, and improving handling and movement of mixtures in the storage are some of the key items to be considered. During the paving operation, paver hopper and auger are the two key areas that need to be monitored to prevent segregation. The use of a material transfer vehicle (MTV), a transfer vehicle positioned between the truck and the paver, helps minimize segregation since it serves to remix the asphalt and makes the temperature of the asphalt more uniform.

Proper Construction of Longitudinal Joints

Improperly constructed longitudinal joints in asphalt concrete surface layers result in an overall reduction of pavement service life and ride quality due to potential density variations. Joint failures can be due to a combination of low density, segregation, and lack of adhesion between two adjacent lanes. Minimum density requirements at the longitudinal joints are usually specified, being no more than 2 percent less than the mat density and with no density measurement being less than 90 percent of the theoretical maximum density, although some agencies accept densities as low as 88 percent (Buncher 2012). A notched wedge joint is recommended when the lift thickness is between 1.5 and 3 inches (38 and 76 mm). Joint adhesives (overbanding with sealants) or tacking the existing face of joint with emulsion or asphalt binder can also be considered. Recommended practices must be followed to avoid mixture segregation.

Table 5-7. Approaches for improving sustainability of asphalt pavement construction operations.

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Achieve Target Density Requirements	Increase thickness to nominal maximum aggregate size ratio	Potentially reduce costs since it can reduce number of lifts constructed	Reduce environmental impact through less hauling trips Increased pavement life due to better compaction Better resistance to top-down cracking	Longer life and less frequent interventions
	Use warm-mix technologies	Potentially increase costs due to additives and capital investment	Reduce environmental impact by lowering compaction temperature	Reduce construction related air pollution and potential for irritation for sensitive workers
	Follow laydown temperature requirements	No change in cost	Accelerate construction due to achieving required mat thickness and density at a faster rate	Less exposure to traffic delays
	Select proper equipment for placement and compaction equipped with smart technology	Need capital investment and increased agency costs but has long-term benefits to contractors and agencies	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
Prevent Segregation	Use thermal cameras to avoid erratic mat temperatures and temperature related segregation	May increase contract costs due to capital investment	Reduce environmental impact through good quality materials and longer life pavements	No direct impact
	Use of material transfer vehicles	May increase contract costs	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
	Proper handling of materials during transportation, placement, compaction	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
Construct Effective Longitudinal Joints	Avoid segregation during transportation and placement	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Improve ride quality Longer pavement life Less intervention
	Use of adhesives or sealants overbanding the joint	May increase contract costs	Reduce environmental impact through good quality materials and longer life pavements	Improve ride quality Longer pavement life Less intervention
	Proper compaction to achieve joint density	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Improved ride quality Longer pavement life Less intervention
Achieve Target Smoothness Requirements	Proper placement and compaction techniques	No cost associated with this approach	Reduce environmental impact through reduced fuel consumption	Improve ride quality Longer pavement life Less intervention

Table 5-7. Approaches for improving sustainability of asphalt pavement construction operations (continued).

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Use Innovative Contracting Alternatives	Implement multi-parameter bidding systems (i.e., A+B+C)	May increase contract budgets due to consideration of time to complete projects and environmental damage	Reduce environmental impact since lowest bidder will win and accelerate construction	Less exposure to traffic delays
	Incentivize equipment retrofits	No additional agency costs if federal grants or tax reduction incentives are in place	Reduce air pollutants and greenhouse gas	Reduce impact on local air quality

Table 5-8. Best practices to control fumes, emissions, and odors from asphalt mixture plant and paving operations.

Location	Best Practices[1]
Plant	Select plant mixing temperature by consulting asphalt supplier
Plant	Read the material data safety sheet for all materials
Plant	Regularly calibrate thermocouples
Plant	Collect continuous data on aggregate moisture and fuel/energy usage
Plant	Have stack gases tested to check limits
Plant	Keep a record of fuel usage over time
Plant	Do not use diesel fuel and kerosene as release agents
Paving Site	Keep paving temperatures as low as possible (blue smoke indicates overheating) consistent with achieving adequate compaction of the mat
Paving Site	Check paver ventilations systems regularly
Paving Site	Ensure that tail pipe and ventilation stacks exhaust above the height of the paver operator
Paving Site	Consider increasing mat thickness prior to an increase in plant temperature

[1] Compiled from APEC (2000) and NYSDOT (2003).

Meeting In-Place Density Requirement

The two main objectives of compaction are achieving prescribed layer densities and meeting smoothness requirements. Most minimum density requirements are in the range of 92 to 93 percent of the theoretical maximum density. A strong correlation between service life and in-place density of asphalt concrete layers is reported in the literature (Puangchit et al. 1983; Christensen 2006; Buncher 2012). For example, figure 5-4 shows the estimated impact on pavement life by improving the density of the asphalt concrete (expressed in terms of a reduction of the air voids from 8 to 5 percent) and thus reducing bottom-up fatigue cracking. An optimized mixture density reduces rutting and cracking potential (Harvey et al. 2004).

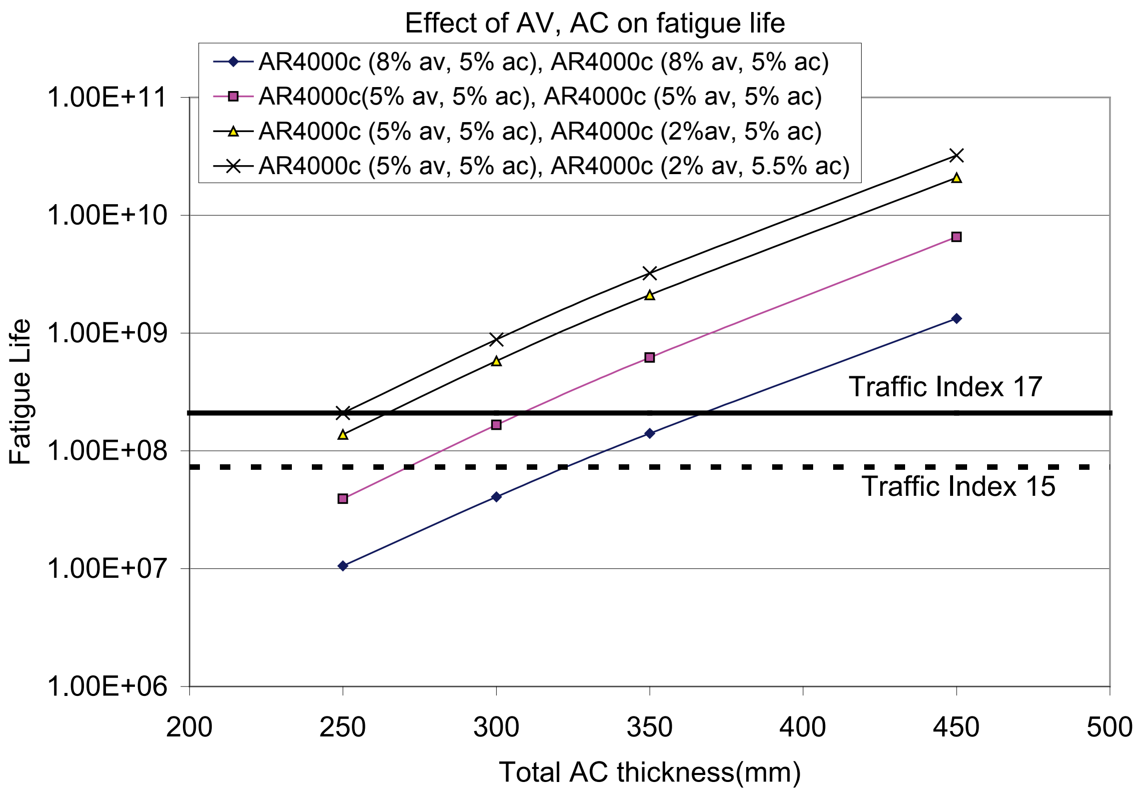


Figure 5-4. Effect of compaction on predicted bottom-up fatigue life for two-layer beam specimens in mixture using a AR4000c binder (binder type used in several western highway agencies prior to Superpave) and at different air void and binder content levels (after Harvey et al. 2004).

Improved compaction requires no additional materials, and usually requires no new equipment, but does demand strong attention to details, effective temperature monitoring and control, and management of the factors controlling the compaction process. Unlike changing mixture design parameters (e.g., changing the binder content in an asphalt concrete material, using a softer binder to improve reflection cracking resistance in an asphalt concrete material, or increasing the cement content of an FDR material), increasing the density of a material by compaction will improve both the rutting and cracking resistance. Overall, the factors affecting asphalt concrete compaction can be categorized into five classes:

1. Mixture properties (aggregate, binder, and mixture design) – The pavement construction stage has little to no influence on the selection of mixture properties. Selecting the materials and design of pavements with proper materials is discussed in chapters 3 and 4.
2. Environmental conditions – Most highway agencies follow standard specifications that address air and surface temperature requirements, seasonal limitations, and weather requirements. In general, asphalt concrete shall not be produced and placed in rainy weather and when ambient temperatures are less than 35 to 60 °F (2 to 16 °C) (based on the mixture type).
3. Laydown temperatures – The temperature of the mixture is one of the main factors affecting compaction. The lower and upper temperature limits at which compaction is effective is approximately in a range of 185 to 350 °F (85 to 176 °C) (NCDOT 2012). At

the time of placement, the temperature can be considered uniform in the mat; however, the mixture quickly starts cooling down and at a higher rate on the surface resulting in a temperature gradient through the mat. The rate of cooling is a function of the mixture type, design, base temperature, air temperature, and layer thickness. The allowable time recommended for compaction as a function of these variables is summarized in table 5-9.

Table 5-9. Typical minimum requirements for laydown temperatures as a function of base temperature and lift thicknesses (NCDOT 2012).

Lift thickness	**½ in**	**¾ in**	**1 in**	**1-½ in**	**2 in**	**+3 in**
Base Temperature	Mixture Temp (°F)	Mixture Temp (°F)	Mixture Temp (°F)	Mixture Temp (°F)	Mixture Temp (°F)	Mixture Temp (°F)
20-32	NA	NA	NA	NA	NA	285
32-40	NA	NA	NA	305	295	280
40-50	NA	NA	310	300	285	275
50-60	NA	310	300	295	280	270
60-70	310	300	290	285	275	265
70-80	300	290	285	280	270	265
80-90	290	280	275	270	265	260
+90	280	275	270	265	260	255
Rolling Time (min)	4	6	8	12	15	15

ºC = 5/9 (ºF – 32); 1 in = 25.4 mm

4. Lift thickness – Lift thicknesses are commonly selected based on the nominal maximum aggregate size (NMAS) in the mixture and the mixture type (leveling or surface course). The thickness may vary from 0.38 to 3 inches (9.5 to 76 mm) from smaller to larger aggregate size, respectively. The rule of thumb for the ratio of lift thickness to NMAS is at least 3:1 for fine-graded mixtures and 4:1 for coarse-graded mixtures (Brown et al. 2004). Fine graded and coarse graded refer to the ratio between the coarse aggregate in a mixture (create voids) and the fine aggregate (fill voids) relative to the control sieve for a particular mixture. The lift thickness is one of the factors governing in-place density as it influences the cooling rate and provides space for aggregate movements. As the lift thickness increases, the lift can retain the heat for longer time periods thereby increasing the compaction time and allowing desirable density levels to be more easily achieved (Brown et al. 2004). The lift thickness has an impact on the environment as well, since it influences compaction productivity due to cooling time.
5. Compaction equipment and procedures – Compaction is done using several types of compactors including vibratory, static steel, static pneumatic rubber, and oscillatory rollers. The compactor type and applied loading amplitude and frequency are selected based on the layer characteristics. In recent years, rollers are equipped with intelligent compaction systems to ensure the pavement material is appropriately compacted. Additional details on intelligent compactors are provided later in this chapter.

Achieving Smoothness

There are numerous benefits of achieving specified initial pavement smoothness. Some of these benefits are reduction in dynamic loads on pavements, enhanced rideability over a longer period of time, reduced fuel consumption, and reduced vehicle wear and tear in the use phase. In addition, studies have shown that pavements constructed smoother initially stay smoother longer, all other things considered equal (Smith et al. 1997).

Most highway agencies have adopted smoothness specifications, along with incentive and disincentive provisions, to encourage the construction of smooth pavements. At the same time, recent years have seen a number of agencies move to the use of lightweight inertial profilers to assess initial smoothness, although a few agencies still use profilographs. During placement and compaction of asphalt concrete layers, pavement smoothness can be adversely affected by lack of uniformity in paving operations, variations in mixture temperature, variations in paver speed, segregation, and improper rolling. Critical items to help ensure that high levels of initial smoothness are achieved include (NCDOT 2012):

1. Maintain continuous operation of the paving train and minimize paver stops.
2. Correct irregularities in lower courses by adding or removing materials.
3. Leave adequate amount of material in the paver hopper between loads to prevent rough texture due to end of the load segregation.

Construction Quality Assurance

Quality assurance (QA) activities performed during pavement construction are necessary to ensure that the material and workmanship meet the project specifications. This includes proper placement and compaction of all pavement layers and ensuring that specified smoothness criteria are met. Pavements constructed in accordance with specifications and meeting all quality standards are likely to achieve their design life and exhibit lower maintenance costs and corresponding lower use phase and maintenance-related environmental burdens.

Effective specifications and adherence to rigorous construction inspection procedures play a significant role in achieving the expected quality of pavements. QA plans have been implemented by contractors and agencies to improve the quality of materials and processes used in the construction of highway projects and to reduce life-cycle costs. The QA plan often covers all phases of asphalt concrete construction, including production, placement, and compaction. In many highway agencies, asphalt concrete acceptance and payments are based on contractor's fulfillment of inspection, sampling and testing, resident engineer's inspection, and statistical evaluation of specified quality characteristics (Caltrans 2009). Important pavement quality characteristics during asphalt concrete placement may include subgrade density, ambient and mixture temperature, layer thicknesses, joint construction, segregation, in-place density, and smoothness.

Many highway agencies are using percent within limits (PWL) statistical methods as part of their acceptance criteria. The PWL method is used to assess the "quality" of the constructed pavement by estimating the percentage of the quality characteristic population that falls within the specification limit; the results can be used to determine pay factors (incentives or disincentives) based on the anticipated effects of the quality characteristic on pavement performance (Hand and Epps 2006).

Some of the common quality characteristics used to determine PWL (and pay factors) for asphalt pavements are in-place density or air voids and initial smoothness. This framework is designed with an assumption that there is a relationship between these quality characteristics and the long-term performance of the pavement. There is clearly a need for developing advanced methods and procedures for performing real-time monitoring and measurement of some of these key quality characteristics, and some advancements are being made in the use of ground penetrating radar (GPR), intelligent compaction (IC) technology, and infrared thermography (IRT) for this purpose.

The quality assurance of as-constructed pavement smoothness is performed by profile testing. Smoothness is one of the most critical pay items in most asphalt pavement contracts, and pavements that do not meet specification requirements can be subjected to expensive corrective actions and significant price adjustments. There is a strong correlation between in-service pavement smoothness and fuel consumption by vehicles using the pavement, as discussed in chapter 6.

Improving Sustainability through the Use of Innovative and Emerging Technologies

Traditionally, various field and laboratory tests using field-extracted cores have been used for asphalt pavement density measurements. However, these conventional methods have several shortcomings. For example, in situ field tests (such as nuclear density gauge measurements) provide data from only a limited number of test locations. Similarly, extracted cores provide data from only a few locations on the pavement, in addition to being a destructive test (Al-Qadi et al. 2010; Leng 2011; Leng, Al-Qadi, and Lahouar 2011; Leng et al. 2012; Shangguan, Al-Qadi, and Leng 2012; Shangguan et al. 2013).

The application of nondestructive testing (NDT) methods, such as GPR and IRT, can overcome some of the shortcomings of the conventional QA methods. For example, figure 5-5 shows continuous density measurements of an asphalt pavement using the GPR technique. This method is rapid, provides greater coverage area, allows real-time monitoring of compaction efforts, provides near real-time density data, and, when calibrated for the specific aggregate used, provides greater accuracy than nuclear gauges (Leng 2011).

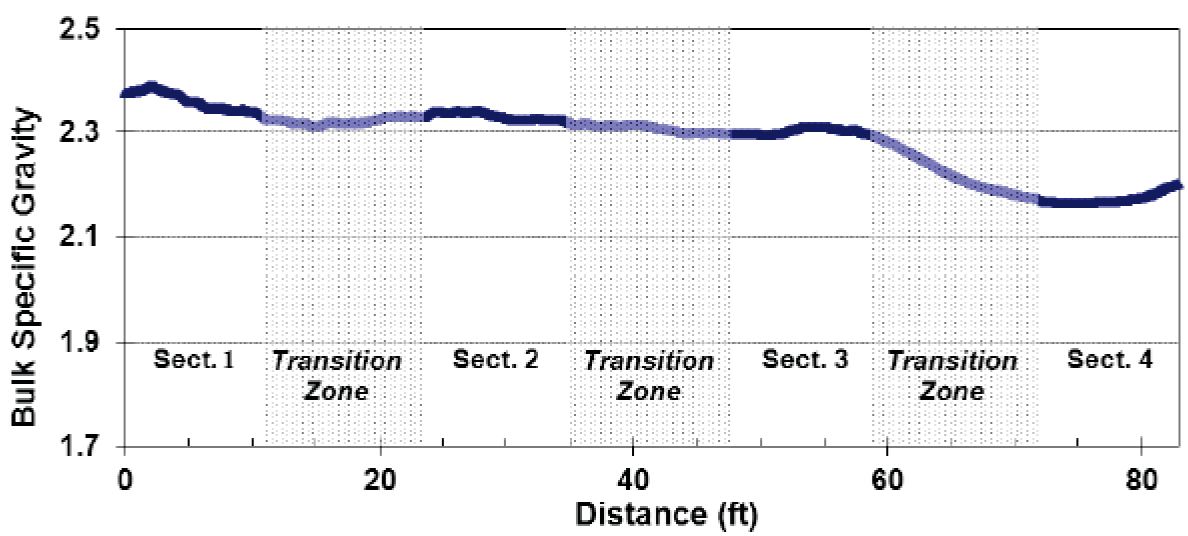


Figure 5-5. Bulk specific gravity profile of one test lane (Leng 2011).

Infrared thermographic scanning carried out immediately behind the paver screed can be used to monitor asphalt concrete materials and pavement surface temperatures. When temperature differentials exist in an asphalt pavement, the degree of compaction varies due to the viscoelastic material response to loading. The ability to detect and address thermal segregation during construction reduces potential pavement irregularities and, hence, improves the rideability and durability of asphalt pavements (Mahoney et al. 2003).

Another innovative construction QA method that can be used to optimize the compaction and desired density of unbound materials is intelligent compaction. The IC system uses a double-drum vibratory roller equipped with a measurement/control system. Unlike conventional asphalt pavement compaction equipment, IC rollers are equipped with technology such as a GPS-based system, color-coded display, and a temperature measurement system that can help monitor pavement construction data in real time, including the number of roller passes, roller speeds, and asphalt pavement surface temperatures, and can store these data for later evaluation (Horan et al. 2012).

It is noted that the application of IC for asphalt materials is limited to compaction process monitoring at this time. Measurements are affected by the material temperature and the stiffness of the supporting layers.

During the asphalt paving process, the use of spray pavers and MTVs can also be beneficial. A spray paver includes the functions of both a conventional paver and tack coat distributor (see figure 5-6). Thus, a tack coat can be placed immediately before the asphalt concrete layer is placed. This approach saves time, reduces the use of a distributer vehicle, and prevents contamination from the passage of paver treads over the tack coat thereby enhancing bond potential. And, as previously described, the use of an MTV is also expected to improve pavement sustainability by reducing potential segregation and temperature variation and maintain material consistency and uniformity.

Intelligent Compaction

Since 2008, the FHWA has been leading a national effort to advance the implementation of intelligent compaction (IC) technology to improve compaction of materials that include granular and cohesive soils, stabilized bases, and asphalt pavements. One of the emphasis areas in its Every Day Counts (EDC) initiative, the FHWA defines IC as a process that includes vibratory rollers equipped with a measurement and control system that can automatically control compaction parameters in response to materials stiffness measured during the compaction process. The roller must be equipped with GPS measurements and a documentation system that allows for continuous measurements of the roller location and the corresponding stiffness-related output. Through this process, improvements in the quality and uniformity of constructed pavements are achieved, resulting in better performing, longer lasting pavements. Moreover, IC efficiencies also produce significant time, cost, and fuel savings.

Additional information on IC is found at http://www.intelligentcompaction.com/.

Figure 5-6. Spray paver on the left and material transfer device on the right used in the overlay construction in Illinois (Al-Qadi et al. 2012).

Strategies for Improving the Sustainability of Concrete Pavement Construction Practices

Concrete pavement construction generally consists of the following activities:

- Preparation of the subgrade (including any required excavation, hauling, borrow, leveling, and compaction of multiple lifts of material).
- Hauling, placement, trimming, and compaction of subbase and base layers, which may also include curing.
- Proportioning and mixing of the concrete materials (see chapter 3).
- Hauling and placing of the concrete materials.
- Finishing, texturing, and curing of the concrete pavement.

This general process is depicted in figure 5-7. Throughout every stage of this construction process, there are numerous opportunities for improving the environmental, economic, and societal impacts (i.e., the sustainability of the process).

Long service life is one of the primary drivers of pavement sustainability. The ability to achieve that long service life is strongly impacted by the quality of construction. In fact, the potential gains in sustainability afforded by the optimization of structural design, the use of highly durable or recycled materials, and the improved efficiencies in the production of cement and other materials can be completely negated by poor construction quality and improper construction techniques. The following subsections describe the various impacts of construction quality on pavement service life and sustainability and provide strategies and techniques for improving the same.

Previous portions of this chapter describe many of the strategies that can be considered for pavement construction processes in general, and those are not repeated here. Furthermore, chapter 3 describes techniques for improving the sustainability of the production of concrete materials, including the production of cement and the operation of concrete batch plants, and those topics are generally not repeated here other than to discuss how they impact the sustainability of concrete pavement construction operations.

Concrete Pavement

Base Course (optional)

Subbase course (optional)

Subgrade Layer(s)

Construction Activity	***Fuel Factor***
Subgrade Preparation (grading and finishing)	0.300-0.700 gals/cubic yard
Base Layer Preparation (hauling, placement, and compaction)	0.400-0.600 gals/ton
Concrete Mix Production	0.09 gals/c.y.
Concrete Hauling (short)	0.60 gals/c.y.
Concrete Placement	0.267 gals/c.y.

Figure 5-7. Generalized concrete pavement construction processes and associated fuel factors (fuel factor source: Skolnik, Brooks, and Oman 2013).

General approaches to improving the sustainability of concrete pavement construction operations, along with a qualitative assessment of the interactions and trade-offs between their economic, environmental and societal impacts, are summarized in table 5-10. A comprehensive LCA must be considered to provide quantitative estimates of the benefits and impacts that result from any proposed sustainability-improving action.

Site Prep Work

Preparation of Support Layers

The accurate grading and uniform compaction of foundation layers are essential for ensuring the economy and long-term performance of all pavement types. These are accomplished by 1) providing a solid and accurate paving platform that allows the construction of the pavement surface (usually the highest quality and most expensive material in the structure) to the proper grade and cross slope without using unnecessary material; and 2) providing uniform as-designed support to ensure long-term ride quality and resistance to distress. The latter item is particularly true and important for concrete pavements because the rigidity of the pavement surface resists deformation due to movement in the underlying layers. Studies have also shown that, all things being equal, improvements in initial ride quality translate directly into longer pavement service life (when structural or material durability problems are not present) (Smith et al. 1997). Care must also be taken that any required interlayer materials are properly installed to ensure isolation of the surface (i.e., over cement-treated or lean-concrete base layers, where required).

Table 5-10. General approaches for improving the sustainability of concrete pavement construction.

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Protect Water Resources	Concrete wash water collection and reuse	Increased cost for collection and removal, but reduced costs of remediation and clearing drains.	Positive impact by eliminating localized vegetation kills and pH impact on local surface waters.	Negligible to slightly positive impact.
Reduce Use of Virgin Materials	On-Site Recycling	Reduced haul costs, reduced material costs.	Reduced fuel consumption, reduced GHGs, reduced consumption of resources.	Negligible to slightly positive impact.
	Two-Lift Paving	Negligible to slightly higher construction costs.	More energy consumed in construction, improved use of local and recycled materials, potential reductions in use-phase fuel consumption and GHGs.	Negligible to slightly positive impact.
Improve Initial Ride Quality (Minimize Use- Phase Fuel Consumption and Emissions)	Two-Lift Paving	Negligible to slightly higher construction costs.	More energy consumed in construction, improved use of local and recycled materials, potential reductions in use-phase fuel consumption and GHGs.	Positive impact of improved ride quality, reduced use-phase costs for vehicles.
	Real-Time Profile Measurement	Capital cost of equipment.	Potential reductions in use-phase fuel consumption and GHGs.	Positive impact of improved ride quality, reduced use-phase costs for vehicles.
Increase Pavement Service Life	Improved Construction QA (including Dowel Alignment Measures)	Additional testing costs.	Potential for longer life cycle.	Potential for extended time between maintenance activities, longer life cycle, and lower user costs.
	Good Curing Materials and Practices	Negligible to modest increase in construction costs.		
Balance Surface Friction and Tire-Pavement Noise	Selection and Design of Surface Texture	Negligible to modest increase in construction costs (depending upon surface texture selected).	Potential to reduce tire-pavement noise inside and outside of vehicles.	Potential for improvements in friction, safety.
Minimize Construction Fuel Use and Emissions	On-Site Recycling (Foundation Layers)	Reduced haul costs, reduced material costs.	Reduced fuel consumption, reduced GHGs, reduced consumption of resources.	Negligible to slightly positive impact.
	Match Construction Equipment and Production Capacities	Cost savings	Reduced fuel consumption and GHGs, less wasted material.	Minor impact.
	Single-Lift Construction	Cost savings over multi-lift construction processes	Lower fuel consumption and GHG emissions.	Negligible to favorable impact, depending upon time savings.
	Use Roller-Compacted Concrete	Significant construction cost savings (mainly due to materials)	Lower fuel consumption and GHG emissions in construction	Minimal impact for low-speed pavements; generally inadequate ride quality (without overlay or diamond grinding) for high-speed roadways
	Use Early Entry Saws	Reduced cost	Reduced construction fuel consumption and GHG emissions.	Negligible.

Installation of Dowels, Tie Bars and Slab Reinforcement

Dowels, tie bars, and slab reinforcement are essential structural elements of concrete pavement systems. As with any structure, these elements can only perform their intended functions properly if they are installed at the correct locations, at the proper elevations, and in the correct alignment or orientation. For example, reinforcing steel that is placed too close to the pavement surface may cause surface distresses that require costly and disruptive repair activities. Dowels, an essential element for the performance of heavy-duty concrete pavements, may be misaligned or mislocated in one or more of five different ways (three translational modes, two rotational modes), each of which has a different potential impact on pavement performance. Mislocated tie bars may cause surface spalls, may fail to hold joints tightly together and in alignment, or may improperly interfere with the function of other joints.

Ensuring the proper location and alignment of dowels, tiebars, and slab reinforcing can require maintenance and calibration of insertion equipment, proper location of baskets and support systems, proper anchoring of basket and support systems (to prevent shifting and overturning during paving), and adequate joint marking and sawing practices (to ensure that joints are sawed over properly located dowels and tie bars). The specification and use of corrosion resistant (or corrosion proof) dowels, tiebars, and reinforcing is a design issue, but is worth mentioning again as an important component in the context of the construction of long-life, durable concrete pavement systems.

After the concrete has been placed, the measurement of in situ dowel alignment can be performed nondestructively using one of several relatively new devices. The MIT-SCAN2-BT, which uses magnetic tomography to determine dowel alignment, was first introduced to the market in 2001, and is probably the most widely adopted dowel alignment measurement device in the U.S. Additional information on this device can be found at the websites of the manufacturer[1] and the FHWA.[2] GPR-based devices for measuring dowel alignment include the GSSI StructureScan™ Mini HR[3] and the Hilti PS 1000.[4] An additional device, the MIRA Tomographer, uses ultrasonic tomography to measure dowel alignment. More information on this device can be found at the manufacturer's website.[5] Overall guidance concerning dowel alignment tolerances is available in several recent publications (Snyder 2011; ACPA 2013).

Proportioning Concrete Mixtures – Impacts on Sustainable Construction Practices

Strategies for developing and producing durable, economical, and sustainable concrete mixtures are covered in chapter 3. However, one key point worth repeating is concrete mixture proportioning, largely because of its impact on concrete pavement constructability and paving operations, as well as its effect on pavement longevity.

Mixture proportions must be developed to achieve the proper balance of economy, strength, durability, and workability (defined as the property of fresh concrete that determines the ease with which it can be mixed, transported, placed, consolidated, and finished to a homogenous condition). Improvements in any two or three of these criteria are generally achieved at the expense of the others. For example, reductions in the water-cementitious materials ratio

[1] http://www.mit-dresden.de/en/produkte/duebelmessgeraet/kurzbeschreibung1.html

[2] http://www.fhwa.dot.gov/pavement/concrete/mitreport/mits03.cfm

[3] http://www.geophysical.com/

[4] http://www.hilti.com/holcom/page/module/product/prca_rangedetail.jsf?&nodeId=-450121&selProdOid=1107542

[5] http://www.germann.org/Brochures/Catalog-NDT-2010.pdf

generally increase both strength and durability, but may adversely affect concrete workability and finishing characteristics if other mixture adjustments are not made as well (e.g., changes in aggregate gradation or the use of chemical or mineral admixtures). A mixture with poor workability and finishing characteristics may require additional energy for mixing, placing, strike off, vibration, screeding, and finishing. Furthermore, paving production rates may be lower and construction-related energy and labor costs may also increase.

Concrete Hauling and Placement

The best concrete hauling, placement, and finishing operations cannot add to the quality and longevity of a concrete pavement; they can only serve to achieve the potential intended by the design and materials engineers. Substandard operations can, however, negatively affect concrete pavement and material properties, thereby adversely affecting long-term pavement performance and sustainability.

One way in which the sustainability of the pavement *construction process* can be improved is by maximizing the efficiency of the overall operation. This requires that the most efficient equipment be selected for the critical operation (typically, the paving operation) and that the production capacities of other operations be matched to that efficiency. For example, the type and size of equipment to be used for hauling operations must be selected with consideration of the project haul routes and maneuverability requirements, and the number of units must be chosen to allow continuous operation of the paver at its most efficient speed. Table 5-11 presents typical ranges of fuel consumption and emissions for concrete mixing, paving, and texturing activities and illustrates the potential impact of “right-sizing” equipment to minimize fuel consumption and emissions. It should be noted that the ranges presented also reflect potential variations in operational efficiencies, which are affected by the stiffness, workability, and finishing characteristics of the paving mixtures.

Table 5-11. Energy efficiency and CO_2 emissions for typical equipment used for concrete pavement construction (compiled from Santero and Horvath 2009a and Skolnik, Brooks, and Oman 2013).

Construction Activity	Equipment	Horsepower Range	Fuel Consumption Range (gal/hr)	CO_2 Emissions Range (lb/hr)
Concrete mixing in truck	Mixing truck	--	6-10	136-226
Concrete Paving	Slipform paver	100-250	5-13	113-294
	Texture/curing machine	70	5	113
	Concrete saw	10-40	0.5-1	11-23

Competing sustainability measures involving economics (initial and life-cycle costs) and environmental impacts (fuel consumption and emissions) must be weighed and balanced in considering the construction of single-lift pavement surfaces versus multi-lift pavement structures (including two-lift concrete paving [discussed at the end of this chapter], typical asphalt pavement construction, composite pavement construction, and even “staged construction”). Single-lift construction offers clear benefits in terms of reducing the number of paving passes (and rolling and compacting passes for asphalt and RCC pavements), and may even result in the operation of fewer pieces of construction equipment for a given project (e.g., two paving machines and two batch plants are often employed for two-lift concrete paving versus one of each for single-lift paving). In addition, the placement of a single lift of paving may expedite project completion. However, the construction of multi-layer pavement structures, whether concrete or asphalt, generally results in better initial pavement smoothness, which can extend pavement maintenance cycle times and service life. Multi-layer paving also facilitates the use of different types of materials in the various paving layers (e.g., in two-lift concrete pavement, recycled concrete aggregate in the lower lift and hard, angular rock in the top lift).

Skolnik, Brooks, and Oman (2013) recently compiled updated typical fuel usage factors for many aspects of pavement construction; these values can be used to compare the relative fuel consumptions associated with single-lift versus multi-lift construction activities. This information can then be weighed against the other benefits and costs of each construction technique while keeping in mind the overall sustainability goals and objectives of the agency.

There are many aspects of concrete pavement construction for which QA is essential in order to achieve the full potential longevity (and, therefore, sustainability) of concrete pavements. These include (but are not limited to): stringline setup and maintenance, plant certification, proper equipment setup and hauling (including haul time restrictions in normal and hot weather), proper placement of the concrete (to minimize segregation and maintain a constant load ahead of the paver), control of water use at the job site, proper materials quality assurance (e.g., monitoring mixture consistency through air, slump and unit weight testing, as well as thickness control and strength or maturity testing), proper concrete consolidation of concrete without overvibration (through the use of vibratory frequency monitors and their adjustment with variations in the concrete mixture), and proper selection and use of curing materials, among others. Best practices for all of these aspects of concrete paving are described in detail in several key references (ACPA 2008; ACPA 2010).

All hauling, paving, and finishing equipment must be maintained in a way that prevents the buildup of hardened concrete. This is particularly true for haul trucks, where old concrete material can become a “contaminant” and cause finishing or performance problems in future loads.

Haul trucks and other equipment must be washed out frequently, but concrete wash water is toxic to fish and aquatic life and can contaminate drinking water supplies. In addition, washout sediment can clog pavement drain systems. Therefore, concrete wash water must be prevented from entering waterways, drainage systems, and groundwater. Best management practices include the return of all concrete waste and wash water with each concrete truck for disposal at the concrete batch plant. If this is not possible, an on-site, concrete washout area should be established to collect washout water.

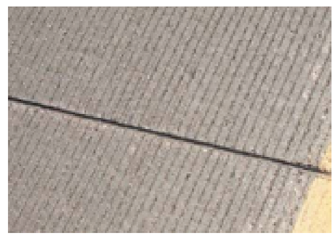
There are several options for on-site, concrete washout water collection, including prefabricated containers (for which some supply companies offer maintenance and disposal services) and self-installed, above-ground or below-ground containers (which may be less reliable and more prone to leaks than the prefabricated containers) (Ecology 2012). Any on-site containers should be placed 50 ft (15.3 m) or more from drains, ditches, and surface waters, and must be properly sized. Ecology (2012) provides good guidance on the design of on-site, washout water-collection facilities.

Technologies for using increasing amounts of "grey water" (from washing concrete production equipment and trucks) are rapidly becoming more common and accepted. Chapter 3 presents a schematic illustration for recycling concrete wash water into batch plant mixture water and also summarizes typical limits on chlorides, solids, and other potentially harmful contaminants in recycled water.

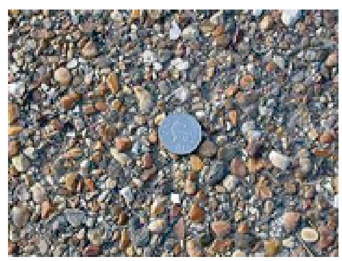
Concrete Pavement Surface Texture

A number of different concrete pavement surface textures are used by highway agencies, as shown below. The FHWA provides guidance on the selection and creation of each of these textures and allows for the use of other textures "if research indicates long-term safety performance is achieved." (FHWA 2005).

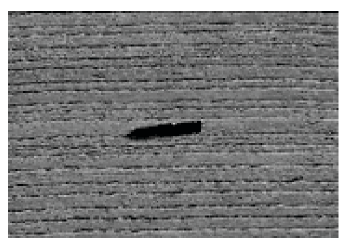
Turf Drag



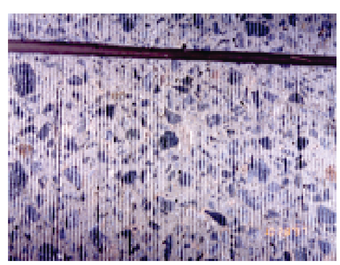
Long. Tining



Exposed Agg



Trans. Tining



Diamond Grind

Photos courtesy of ACPA.

Finishing, Texturing, Jointing, and Curing

Finishing, texturing, jointing, and curing have the potential to impact pavement service life (which affects maintenance activities and life-cycle costs) and initial smoothness (which impacts fuel efficiency and vehicle wear and tear in the use phase). The following subsections briefly describe sustainable practices these aspects of concrete pavement construction.

Finishing

If good mixture proportioning, hauling, and placement practices are followed and if the paving equipment is properly set up and well maintained, very little hand finishing is needed. Hand finishing should be used sparingly and only as necessary to correct significant pavement surface flaws and profile defects. Overfinishing and the use of water added to the surface as a finishing aid must be avoided because loss of surface durability may result. ACPA (2010) provides additional details concerning best practices for concrete pavement finishing.

Texturing

Concrete pavement surface texture must be constructed to provide both adequate surface friction (sustainability through safety and reduced crash rates, particularly in wet weather) while also minimizing the generation of noise through tire-pavement interaction. There are many concrete pavement surface texture options, including transversely oriented textures (e.g., transverse tining, brooming and grooving), longitudinal textures (e.g., longitudinal tining, brooming, grooving, turf drag and diamond grinding), and textures with no particular orientation (e.g., porous concrete, and exposed aggregate finishes). Details concerning the tire-pavement noise and friction characteristics of each of these surface types throughout the use phase of the pavement life cycle are presented in chapter 6.

The success of some of these types of texture require specific mixture design characteristics (e.g., the inclusion of siliceous fine aggregate for microtexture, specifically graded and shaped coarse aggregate particles for exposed aggregate finishes, and low water-cementitious ratios for durable turf drag finishes) and construction techniques to achieve proper texture depth and pattern spacing.

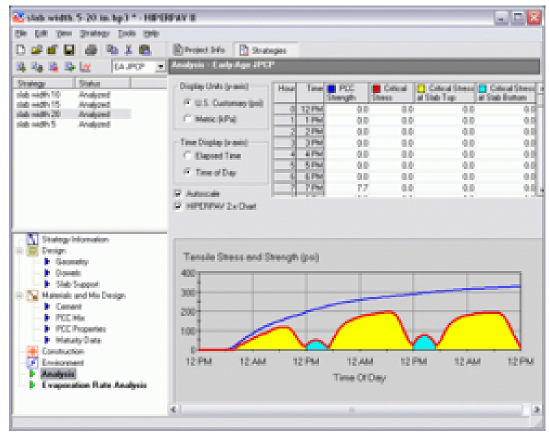
Jointing Considerations

All concrete pavement contraction joints must be sawed in a timely manner to prevent the development of uncontrolled cracking. Successful joint cutting requires that the contractor accurately determines the window of sawing opportunity: too early and the concrete will ravel and be damaged by the sawing operation, too late and the pavement may crack randomly and not at the planned joint locations. Contractor experience can play a major role in the timing of joint saw cuts, but tools such as the HIPERPAV program (which considers factors such as mixture components, proportions, and temperature in the context of ambient environmental conditions) can also be used to determine appropriate sawing times. HIPERPAV can be downloaded free of charge at http://www.hiperpav.com/.

Early entry saws, which can be used to make a shallower joint sawcut at an earlier age, typically require less operational energy and can be used to improve the sustainability of the joint sawing operation (although extra care must be taken to avoid damaging the young concrete with the early sawing operation).

HIgh PERformance concrete PAVing Software (HIPERPAV)

HIPERPAV® is software that can be used to analyze the early-age behavior of jointed concrete pavements, continuously reinforced concrete pavements, and bonded concrete overlays. Developed under FHWA funding, the program considers concrete mixture design materials and proportions, pavement geometry, environmental conditions, and additional inputs to determine the development of stresses caused by temperature and moisture gradients (i.e., curling and warping).



The program then compares these stresses with the predicted strength development for the specified mixture and provides users with a graphical indication of when cracks can be expected to develop (i.e., when stresses exceed strength) if they aren't controlled by joint sawing.

HIPERPAV can also perform an analysis of potential evaporation rates for the specified mixture and environmental conditions (ambient temperature, relative humidity and wind speed), which is useful in ensuring timely application of curing techniques to prevent shrinkage cracking.

It is very important that the joint locations be accurately established prior to sawing and that the saw operators take care to cut the joints precisely. Failure to do so may result in an effective longitudinal translation of any dowel load transfer devices, even if the basket placements or insertion processes were accurate. Significant longitudinal translations can result in poor joint behavior and premature failures. ACPA (2010) provides guidance on joint sawing operations and ACPA (2013) provides guidance on limitations for dowel longitudinal translation (and, therefore, accuracy of joint saw cutting).

Curing

Good curing practices are essential to the control of early-age pavement temperatures and the prevention of moisture loss, which can result in decreased concrete strength, shrinkage cracking, slab warp and curl (and their associated stresses), loss of concrete durability, and other problems that can reduce concrete pavement performance life and, therefore, sustainability. The use of effective curing materials (applied at the proper time and (for liquid curing compounds) at the proper rates of application is essential. Research suggests that there is a wide range of effectiveness in moisture retention among commonly accepted curing techniques (Whiting and Snyder 2003; Vandenbossche 1999).

Improving Sustainability through the Use of Innovative and Emerging Technologies

Two-Lift Concrete Paving

Two-lift concrete paving involves the placement of the concrete in two layers (wet-on-wet) rather than the single-lift paving that is typically used. Two-lift paving can provide improved ride characteristics, facilitate the effective use of local, recycled, or marginal quality aggregates (in the lower layer), increase the use of SCMs (in the lower lift), and reduce overall material costs without sacrificing pavement quality and service life (Fick 2010). Environmental impacts are expected to be less because of the use of SCMs and RCWMs, and construction costs may also be reduced, although this will be project specific.

Two-lift concrete pavements have been constructed in the United States since 1891, when the first U.S. concrete pavement was constructed in Bellefontaine, Ohio as a "two-course" pavement. Two-lift construction was widely used to facilitate the placement of mesh reinforcing in jointed reinforced concrete pavement (JRCP) designs that were widely used in the 1960s and 1970s, but fell from common practice when short-panel, unreinforced slab construction became the norm. Only a handful of two-lift concrete pavements were constructed in the U.S. in the 1980s and 1990s, but two-lift paving technology was identified as a high-priority implementation technology as a result of the May 2006 FHWA SCAN tour of European concrete pavements. The strong potential for improved sustainability in this type of construction has been demonstrated in several countries, including

Two-Lift Paving

Kansas Demonstration:

In October 2008, the Kansas DOT (KDOT) constructed a two-lift paving demonstration project on I-70 in Saline County, Kansas. Dense, wear-resistant rhyolite aggregate was imported for the top lift, while a more porous local limestone was used for the lower course. A Class F fly ash-gypsum combination was substituted for 20 percent of the cement in the top lift to reduce permeability and assist in mitigating any possible ASR. In addition, cement-treated recycled concrete aggregate from the original pavement was used as a base layer. Several different surface textures were used in various sections to evaluate their effects on tire-pavement noise.

Missouri Demonstration:

In September 2010, a portion of Route 141 in St. Louis County was reconstructed with an innovative section of two-lift concrete paving that was highlighted by the use of photocatalytic cement in the top lift, along with pervious concrete pavement in the shoulders.

Open Houses were held for both of these demonstration projects, and the presentations and other reports and handout materials from the open houses are available through the National Concrete Pavement Technology Center at:
http://www.cptechcenter.org/research/research-initiatives/two-lift/

http://www.cptechcenter.org/events/archive/2lift-StL-page.cfm

Austria, where 100 percent of the old concrete pavement is recycled into a bound subbase and the lower lift of a two-lift concrete pavement (Hall et al. 2007).

Between 2008 and 2010, two major two-lift PCCP demonstration projects were constructed in the U.S. (in Kansas and Missouri – see sidebar for additional information) in order to demonstrate the technology and assess the potential economic and environmental benefits of two-lift concrete paving. Moving from demonstration to routine practice, the Illinois Tollway made two-lift concrete paving (using reclaimed asphalt pavement and crushed concrete in the lower lift) a major component of the 2012-2016 reconstruction and widening program of more than 180 lane miles of Interstate 90 between Elgin and Rockford.

Roller Compacted Concrete (RCC) Paving

RCC is a no-slump concrete mixture that is initially compacted using the paver screeds and tamping bars of a traditional asphalt paving machine or high-density paver, followed by the use of heavy vibratory and rubber-tired rollers—much like conventional hot-mixed asphalt concrete.

RCC consists of the same basic ingredients as conventional concrete, but has different mixture proportions, and has similar strength properties. The most significant difference between RCC mixtures and conventional concrete pavement mixtures is that RCC has a higher percentage of fine aggregates, a lower cement content, and a very low water-cementitious material ratio (hence the very low slump). Load transfer dowels are not used with stiff, dense RCC mixtures, and transverse joints are either not sawed or are sawed at greater-than-usual spacing (due to the reduced shrinkage potential of the mixtures) mainly for aesthetics. Load transfer across transverse cracks and joints is provided mainly by aggregate interlock.

The initial compaction of the RCC allows for almost immediate use of the pavement by light vehicles (support is provided through particle-to-particle contact), with cement hydration providing excellent, long-term strength and durability (without the use of air-entraining admixtures). The resulting ride quality is generally adequate for lower-speed traffic, but diamond grinding and overlays are often used to provide an improved surface profile for higher speed traffic.

RCC offers the superior load-carrying capacity and longevity of concrete pavements while having reduced material costs (due to lower cement contents and fewer admixture requirements), reduced construction costs (due to the use of lower-cost paving equipment and often no sawing of contraction joints), and lower local impact to traffic because of the ability to allow limited traffic access within just a few hours of placement.

A comprehensive review of the design and construction of roller-compacted concrete pavements is available from the Portland Cement Association (Harrington et al. 2010).

Real-Time Smoothness Measurements

The measurement of concrete pavement profiles (useful in computing indicators of pavement ride quality and smoothness, like IRI and various forms of the Profile Index [PI]) has historically (and necessarily) been performed after the pavement has hardened and can be subjected to foot or light vehicle traffic. Two major disadvantages of this approach to profile measurement are: 1) pavement texturing and joint forming operations can affect profile measurements (usually adversely), and 2) corrective measures (to address existing profile problems and to prevent problems with further paving) are limited.

Non-contact surface profilers are now available to provide real-time measures of pavement profile directly behind the paving machine, thereby eliminating the effects of measuring texture and pavement joints while allowing for construction process corrections that will prevent continuing and recurring profile problems (Rasmussen et al. 2013). The data collected can still be used to produce IRI or PI values, and are also useful in establishing baseline profiles for pavement curing or curling/warping studies. Some real-time profile measurement devices can also be used for prepaving checks of stringline setup and subgrade/subbase profile (to maximize paving yields).

Real-time profile measurement of concrete pavements offers potential sustainability advantages in improving initial pavement smoothness, which should produce corresponding increases in vehicle mileage in the use phase and may also result in deferment of ride-related maintenance and rehabilitation actions, as well as extended overall pavement service life.

Available real-time profiling equipment comes in different options for mounting directly on the paver, on a work bridge, or on a separate piece of specially designed and dedicated profile measurement equipment. More information on two of the available systems can be found at http://www.gomaco.com/Resources/gsi.html (for the Gomaco Smoothness Indicator [GSI] system) and at http://www.amesengineering.com/RealTimeProfiler.html (for the Ames Engineering SmoothPave RTP [Real-Time Profiler]).

Concluding Remarks

Pavement construction activities offer many opportunities to adopt practices that improve the sustainability of the pavement system. Obvious and highly visible example practices include the use of on-site recycling to produce pavement foundation layers and the protection of groundwater and local fauna by collecting and removing (for recycling) concrete waste water. Less obvious are the impacts that good construction practices can have on fuel consumption and user vehicle expenses and agency repair costs during the use phase.

The potential impacts of the construction phase (i.e., construction equipment and activities) on overall life cycle assessment for a given roadway may be relatively small, particularly when compared to the impact of the materials phase and the use phase (Santero and Horvath 2009b). For example, Zapata and Gambatese (2005) indicate that the "placement phase" consumes only about 3 percent of the total energy in the pavement life cycle. However, the construction phase is a phase over which engineers and contractors have a great deal of influence. Therefore, it is important to be cognizant of the many ways that construction phase activities can influence overall pavement sustainability. This chapter provides a good perspective of the many opportunities for improving (or maintaining) pavement sustainability during the construction phase of the overall pavement life cycle.

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CHAPTER 6. USE-PHASE CONSIDERATIONS

Introduction

This chapter reviews environmental and social impacts of pavements in the use phase, which includes the influence of the pavement on vehicle operations and the interaction between the pavement, the environment, and humans. This chapter identifies use-phase impacts and considerations, provides current information regarding their effects, and describes current efforts to better quantify them in order to improve pavement sustainability. Figure 6-1 indicates various pavement characteristics and their potential impacts on the use phase.

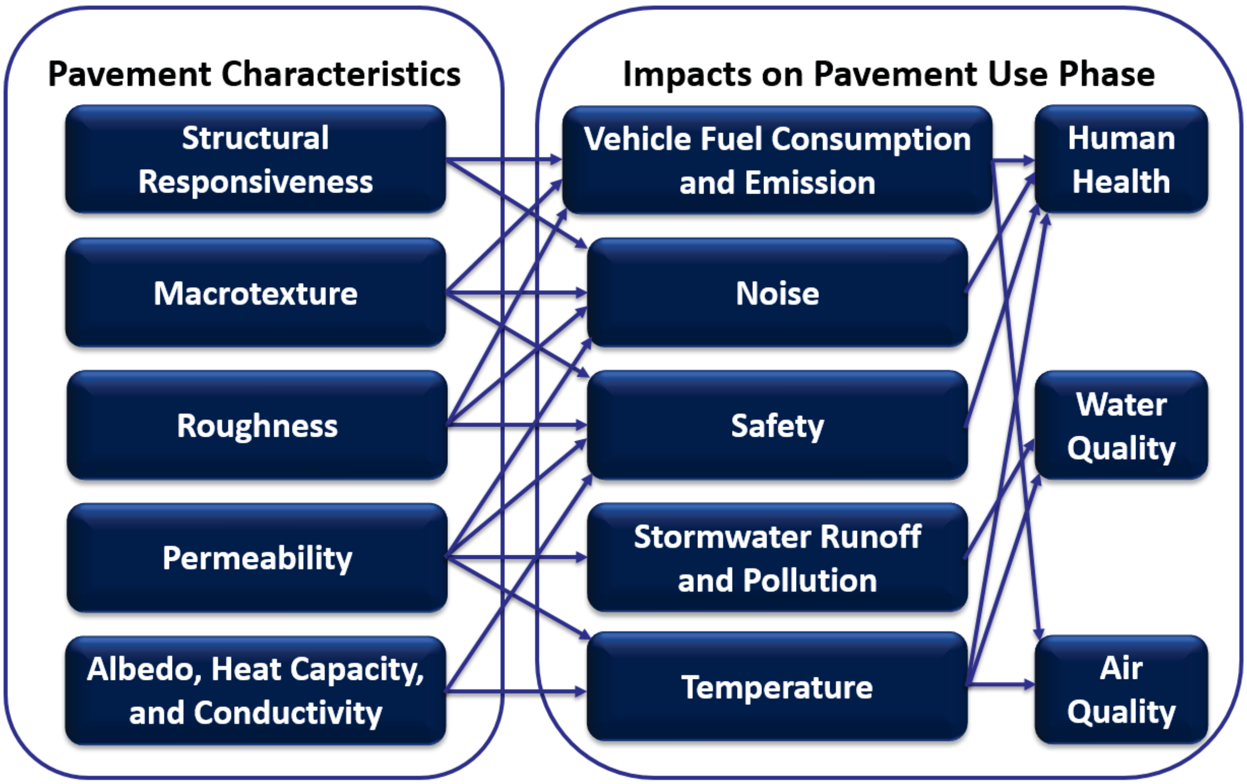

Figure 6-1. Pavement characteristics and influences on use-phase objectives.

As shown in figure 6-1, pavement roughness (or smoothness), structural responsiveness (related to stiffness, damping, and deflection under traffic), and macrotexture have all been identified as affecting vehicle fuel consumption, and as a result can have significant economic and ecological implications on vehicle operating costs and emissions. In addition, those same factors may contribute to freight damage while impacting the safety and comfort of road users. Moreover, pavement surface texture, permeability, and other pavement surface characteristics can impact the noise generated by the tire-pavement interaction, which can affect humans both in vehicles and within the acoustical range of the vehicles operating on the pavement; they also have important safety considerations with regards to surface friction, hydroplaning, and wet-weather crashes.

The permeability of the pavement system can influence stormwater runoff and surface friction, and potentially the costs associated with stormwater treatment. Pavements that are partially or fully permeable can flatten flow-duration curves to reduce the peak flow rate and can also affect pollution flow into receiving water bodies and their water temperatures.[1]

Major Issues:

- ✓ *Trade-offs between negative effects of material production and construction activities during maintenance and rehabilitation versus use-phase benefits.*
- ✓ *Consideration of smoothness over the entire life cycle and achieving highest level of smoothness possible during initial construction and subsequent maintenance and rehabilitation activities.*
- ✓ *Consideration of pavement structural responsiveness to loading*
- ✓ *Preserving smoothness in locations with utilities (avoiding utility cuts when possible)*

The albedo (reflectivity), heat capacity, and thermal conductivity of the pavement all affect the absorption of energy from the sun and the emission of reflected and thermal energy from the pavement, which can potentially affect energy consumption of building cooling and lighting systems, vehicle cooling systems, air quality, and human health (depending on a number of factors). The global balance of energy (radiative forcing) is also influenced by surface albedo. For some applications, the luminance of the pavement may also have an effect on the energy needed for roadway lighting for nighttime safety, visibility of objects, and the ability for drivers to see pavement markings and obstacles. Some of the decisions regarding use-phase effects that can affect sustainability are made at the network level and can be implemented through effective pavement management systems (PMS), while others can only be implemented at the project level through design and construction decisions. There are trade-offs that may be considered within many of these decisions, including important safety issues. As is discussed in this chapter, many of these trade-offs are sensitive to project context, particularly traffic levels and climate. Project context also often has a large influence on the relative importance of environmental impacts of different phases of the pavement life cycle; for example, use-phase impacts on routes with heavy traffic are often much greater than material production and construction phase impacts, while the opposite may be true for low-traffic routes.

Only those use-phase effects that can be changed by pavement decisions are considered in this chapter, and it must be recognized that many of these effects are not currently well quantified. Other impacts that occur from the use of the pavement but are outside the control of pavement engineers, managers, and decision makers—such as the addition of new lanes to existing roads, the selection of new road locations and alignments, and the impacts of vehicle operation that are not influenced by pavement decisions—are also not considered in this chapter. In addition, safety is a critical concern and is addressed in this chapter where decisions regarding pavement-related environmental impacts also have safety implications. However, this chapter is not intended to be comprehensive in its treatment of safety issues, and the reader is referred to a series of highway safety reports available from NCHRP for additional information.[2]

[1] Permeable pavements can refer to pavements constructed with permeable pavers, porous asphalt, or pervious concrete, but the terms "permeable," "pervious," and "porous" are used interchangeably in this chapter.

[2] NCHRP Report 500, *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*. (http://www.trb.org/main/blurbs/152868.aspx)

Vehicle Fuel Consumption and Pavement Characteristics

Background

Vehicle fuel consumption and associated emissions from combustion are influenced by a large number of factors including vehicle and cargo mass, engine size and type, fuel type, tire type and inflation, driving behavior, vehicle maintenance, grades and curves, traffic congestion, traffic control, wind, and several other factors, as well as the number of miles traveled. In fact, many of these have a greater influence on fuel economy than pavement characteristics. However, pavements can influence the fuel efficiency of vehicles—and therefore the associated GHG and air pollution emissions as well—through three mechanisms that together are called *pavement-related rolling resistance*. A discussion of the basic concepts of rolling resistance considering the total system of the vehicle components, pavement and road geometry, and measurement techniques is included in a report edited by Sandberg (2011). Another report (Jackson et al. 2011) also includes a summary of the principles of rolling resistance and its measurement. The pavement influences on these rolling resistance mechanisms are summarized as follows:

1. Roughness—consumption of vehicle energy through the working of shock absorbers and drive train components, and deformation of tire sidewalls as the wheels pass over deviations from a flat surface in the wheelpath with wavelengths greater than 1.6 ft (0.5 m) and less than 164 ft (50 m). The working of these vehicle components converts mechanical energy into heat that is then dissipated into the air, requiring greater work by the engine than would be necessary to propel it along a flat surface. Roughness is both built into the pavement during construction and materializes over time as the pavement ages and distresses develop, and is further influenced by subsequent maintenance and rehabilitation treatment applications and timing. Roughness on some pavement types can undergo relatively small changes with daily temperature fluctuations. For a given roughness condition, this rolling resistance mechanism affects all vehicles all the time.
2. Macrotexture—consumption of vehicle energy through the viscoelastic working of the deformable tire tread rubber in the tire-pavement contact patch as it passes over positive surface macrotexture and converts it into heat dissipated into the rest of the tire and into the air. Positive macrotexture is produced by stones or other texture protruding above the average plane of the pavement surface with wavelengths of 0.2 to 2 inches (5 to 51 mm). It is the primary pavement characteristic controlling surface friction at high speeds under wet conditions and the associated potential for hydroplaning (Anderson et al. 1998; Panagouli and Kokkalis 1998; Flintsch et al. 2002). Pavements serving high-speed vehicles must have a minimum amount of surface macrotexture and/or sufficient permeability to remove water films from the pavement surface so that frictional resistance is maintained for steering and braking. Macrotexture is provided by the characteristics of the surfacing materials (primarily relevant to asphalt surfaces) and texturing (primarily relevant to concrete surfaces), as well as subsequent maintenance and rehabilitation timing and treatment type. Macrotexture does not change due to daily or seasonal temperature and moisture conditions, although it can increase or decrease with age depending on the pavement surface materials, texture type, traffic, climate and use of chains or studded tires. For a given macrotexture, this rolling resistance mechanism affects all vehicles all the time.
3. Structural Responsiveness—consumption of vehicle energy in the pavement itself through deformation of pavement materials under passing vehicles, including delayed deformation of viscoelastic materials and other damping effects that consume energy in

the pavement and subgrade. This mechanism has also been characterized in terms of the delayed deformation of the pavement under the wheel such that the moving wheel is continually on a slope (Flugge 1975; Chupin, Piau, and Chabot 2013). Pavement structural responsiveness to loading is determined by layer thicknesses, stiffnesses and material types that determine viscoelastic and elastic pavement response under different conditions of wheel loading and vehicle speed, and temperature and moisture conditions. For a given pavement structure, the effect of this mechanism on viscoelastic materials such as asphalt can be highly dependent on daily and seasonal changes in pavement temperatures (particularly near the surface), and is more sensitive to vehicle speeds and loading than are roughness and macrotexture. Structural responsiveness can change with time.

As noted above, roughness, macrotexture, and structural responsiveness can change over the life of the pavement surface. In addition, roughness and structural responsiveness can change under daily and seasonal temperature and moisture conditions depending on pavement type and other conditions. The effects of these mechanisms over the life cycle are controlled by decisions regarding design, construction, and maintenance and rehabilitation applications.

High levels of roughness can be built into the pavement during construction because of poor practices and lack of specifications controlling constructed roughness. Roughness typically increases after construction due to the development of pavement distresses, such as rutting and cracking on asphalt surfaces and faulting and cracking on concrete surfaces. Smoothness can be improved with some maintenance and rehabilitation treatments and through greater attention to achieving smoothness during construction.

Initial macrotexture depends on the surface texture created during construction of the new pavement or later maintenance or rehabilitation treatments. Some surface types, such as some open-graded asphalt mixtures, chip seals with large aggregates, and improperly textured concrete, can exhibit high positive macrotexture from the time of construction. Positive macrotexture can increase over time due to raveling of asphalt surfaces or where concrete surfaces lose the paste around the large aggregates. Studded tires and chain wear can rapidly increase the macrotexture of both asphalt and concrete surfaces. Positive macrotexture can be reduced with time if the aggregate is susceptible to polishing under traffic, sometimes even to unsafe levels such that surface friction under wet weather conditions is compromised. Macrotexture can be changed through replacement of the surface materials for asphalt or concrete pavements, and through grinding or grooving for concrete surfaces.

The pavement structural responsiveness at the time of construction under different conditions of temperatures, traffic speeds, and wheel loadings is determined by the pavement type, the materials used, and the design of the structural section. The overall deformation of the pavement structure is controlled by the stiffness and thickness of the layers, and the extent of viscoelastic (delayed elastic) stiffness behavior that the layer materials exhibit under different temperatures and at specific times of loading. Together, these factors determine the energy dissipated in the pavement and the effect on vehicle fuel economy. Thicker and stiffer layers reduce the deformation response of the pavement, with a given percent change of thickness generally having a greater effect than the same percent change in stiffness.

Most concrete and cement-stabilized materials demonstrate elastic response and do not change stiffness under the range of temperature and traffic loading conditions typically experienced by in-service pavements. Concrete generally exhibits stiffness values in the range of about 4.3 to 7.3 million lb/in^2 (30,000 to 50,000 MPa). Fatigue damage in concrete is generally localized and does not decrease the stiffness much, if at all. Somewhat higher deflections occur at concrete pavement joints with poor load transfer under cold temperatures when the joints are open (Snyder 2011; Harvey et al. 2003).

For asphalt layers and asphalt-stabilized layers, the stiffness and extent of delayed elastic response is dependent on the type of asphalt binder, the temperature, and the traffic speed, with stiffness decreasing under hotter temperatures and slower moving wheel loads, and increasing under colder temperatures and faster moving wheel loads. The stiffness of new asphalt concrete under these conditions can vary between about 43,000 and 4.3 million lb/in^2 (300 and 30,000 MPa), corresponding to hottest temperatures/slowest moving loads and coldest temperatures/fastest moving loads, respectively. The interaction of variations in temperature profiles through the asphalt layers and variations in traffic loading and speeds with the materials properties determines the structural responsiveness of the asphalt layers throughout the year. Because temperatures change more at the surface, these effects are most important near the surface. Asphalt materials tend to "age" over time, increasing in stiffness and having less viscoelastic and more elastic response, which reduces deflections but is also associated with increased risk of top-down cracking. Aging occurs most rapidly over the first 5 years after placement, and is also greater near the surface due to increased exposure to heat, UV light from the sun, and atmospheric oxygen. The stiffness of asphalt layers in the wheelpaths can be reduced towards the end of their structural life as a result of fatigue damage caused by repeated loading.

The stiffness of unbound granular layers depends on the applied stress (both magnitude and duration) and the saturation of the material. Subgrade materials can also be a source of damping. High moisture contents in the subgrade and granular pavement layers, due to unsealed surface cracking or poor drainage, can cause significant reductions in their stiffness.

The additional fuel use for on-road vehicles caused by different levels of roughness, macrotexture, and structural responsiveness can have an environmental impact. From a life cycle perspective, these impacts must be balanced with consideration of the environmental impacts of building, maintaining, and rehabilitating pavements in order to maintain a smooth condition, minimize excessive positive macrotexture, and elicit lower levels of structural responsiveness. For example, as can be seen in figure 1-1 for sources of GHG emissions in the U.S., the transportation sector is a leading source of emissions, but it must be remembered that the production and transportation of pavement materials such as asphalt, cement, steel, lime and aggregate, as well as the consumption of fuel by construction equipment, also produce emissions. The construction of longer life pavements and the application of more frequent pavement maintenance and rehabilitation treatments can reduce pavement roughness, provide positive surface texture, and therefore reduce vehicle fuel consumption and GHG emissions over the life cycle. At the same time, constructing longer life pavements and applying more frequent maintenance and rehabilitation treatments also requires additional energy and produces additional emissions. Maintenance and rehabilitation treatments can also influence structural response depending on changes in thickness, stiffness, and properties of the treatment. Optimization of the longevity of the pavement design and of the maintenance/rehabilitation treatment type and frequency must take into consideration all of the life-cycle phases (materials production, construction, use and end-of-life), but is also highly dependent on the level of traffic using the pavement.

The relative impact of pavement-related rolling resistance on fuel economy and vehicle emissions depends primarily on the level of roughness, surface texture, and structural responsiveness. Vehicle types, traffic volumes and speeds, and climatic conditions also play an important role. For two pavements sharing similar characteristics, the total impact of the pavement on energy use and vehicle emissions then depends on the number and type of vehicles using it. If there are relatively few vehicles using the pavement, then all of these mechanisms (i.e. roughness, macrotexture, and structural responsiveness) will produce fewer emissions and other environmental impacts (resulting from materials production, construction, and maintenance and rehabilitation of the pavement) will play a larger role. For very heavily trafficked pavements, the cumulative effects of roughness, macrotexture, and structural responsiveness can become much greater than those produced by materials production and construction.

The relative impact of changing an agency's practices regarding different elements of pavement-related rolling resistance depends on the starting points for roughness, macrotexture, and structural responsiveness for the network and the individual pavement sections in the network. For example, if the network is already particularly smooth, then those practices should be continued, and additional changes in practice to further improve smoothness will likely have a small effect. On the other hand, if the network has high roughness, particularly on high-volume routes, then improvements in smoothness may result in high returns in reduced environmental impacts. Similar analyses can be applied to the other factors influencing pavement-related rolling resistance.

Roughness and Macrotexture Effects

There are four components of pavement texture defined based on the maximum dimension of their deviation (wavelength) from a true planar surface: roughness (also called unevenness, with wavelengths of 1.6 to 164 ft [0.5 to 50 m]), megatexture, macrotexture (wavelengths of 0.02 to 2 inches [0.5 to 51 mm]), and microtexture. The relative scale between each component is shown in figure 6-2 (Sandberg 1997). As part of network-level pavement management, agencies routinely collect profile data in the wheelpaths on a regular cycle (typically annually or bi-annually) using high-speed vehicles equipped with laser profilers (different laser technologies need to be used for asphalt and concrete pavements to avoid an upward bias in IRI caused by directionally textured concrete surfaces). A roughness index, the most common being the IRI, is calculated from the collected profile data. The IRI is one parameter for characterizing roughness and was primarily developed to consider the riding comfort of vehicle occupants. Although IRI was not primarily developed to capture the effects of pavement roughness on fuel consumption—and there are likely better parameters for that purpose—IRI does correlate with vehicle fuel use for all vehicle types, and is used by most highway agencies.

Macrotexture can be measured on asphalt-surfaced pavements and concrete pavements that do not have directional textures (tining, grooving, grinding) using the same profiler vehicles when equipped with high-speed profilers, and can be measured for directionally textured concrete pavements using other measurement techniques. The relationships between different types of concrete directional textures and vehicle fuel economy are not as clear as it is for asphalt-surfaced pavements.

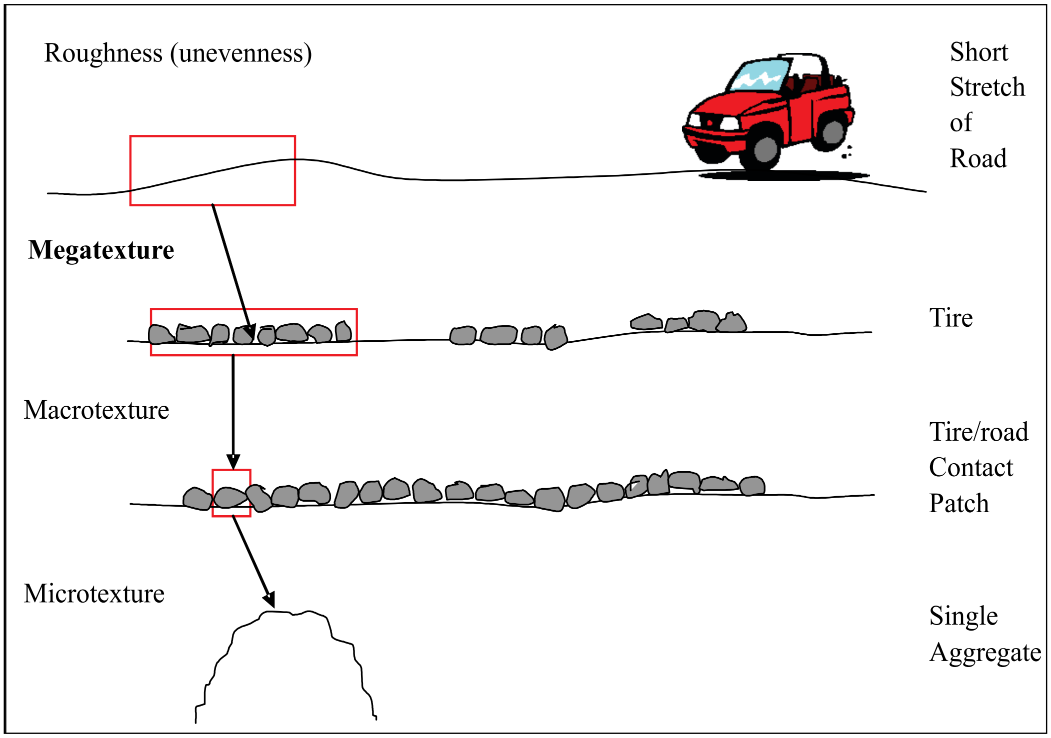

Figure 6-2. Pavement texture and wavelength (Sandberg 1997).

A recent evaluation/calibration of the World Bank's HDM-4 model (PIARC 2002) for vehicle operating costs, using measurements made with a fleet of representative North American vehicles, found the following when comparing roughness and macrotexture without consideration of the structural response (Chatti and Zaabar 2012):

> *For fuel consumption, the most important factor is surface roughness (measured using IRI). An increase in IRI of 1 m/km (63.4 in/mi) will increase the fuel consumption of passenger cars by about 2% irrespective of speed. For heavy trucks, this increase is about 1% at normal highway speed (96 km/hr or 60 mph) and about 2% at low speed (56 km/hr or 35 mph).*

In another study of fuel consumption, measurements were made at WesTrack using two automated heavily loaded articulated trucks traveling around a closed circuit track for many hours a day over a 7-week period both before and after rehabilitation on a set of test sections (Sime and Ashmore 2000). The results showed that the fuel efficiency was about 4.5 percent higher when trucks traveled on a smoother pavement (the IRI was reduced from 150 in/mi [2.3 m/km] to 75 in/mi [1.2 m/km] through the placement of an overlay). The winds and temperatures were similar during the two periods, and the grade was controlled. This is the most extensive testing regarding the effect of IRI that has been documented. Most other recent experimental results are based on less than 10 replicate runs, possibly repeated several times over a year.

Regarding surface texture, the effect is generally less than that of roughness for typical ranges of roughness and macrotexture in the U.S., with Chatti and Zaabar (2012) reporting that:

…the effect of surface texture is statistically significant at [the] 95 percent confidence interval only for heavier trucks and at low speed. An explanation of this observation is that at higher speeds, air drag becomes the largely predominant factor in fuel consumption. The increase in rolling resistance (i.e., fuel consumption) due to texture is masked by the increase in air drag due to speed.

Chatti and Zaabar (2012) include coefficients for surface texture, measured by mean profile depth (MPD), in the recommended model and found that for heavy trucks *"an increase in MPD of 1 mm (0.039 in) will increase fuel consumption by about 2% at 56 km/hr (35 mi/hr),"* with no statistically significant effect for other vehicles or for heavy trucks at highway speeds. Positive macrotexture (stones and texture protruding up from the average surface elevation of the pavement) is expected to have a much greater effect on fuel economy than negative texture (downward gaps below the average surface elevation of the pavement).

On pavements carrying high volumes of traffic, the effects of pavement smoothness on fuel economy and the resulting impacts on energy use and GHG emissions in the use phase can be much greater than any differences caused by different materials or construction techniques during the material production and construction phases. This can be seen in figure 6-3 (Wang et al. 2012), which shows for an example segment of highway the relative effects on energy use (in terms of MJ and equivalent million gallons of gasoline) of applying a pavement preservation treatment (materials and construction), and the resulting savings from vehicle use on the smoothened pavement compared to letting the pavement remain rough.

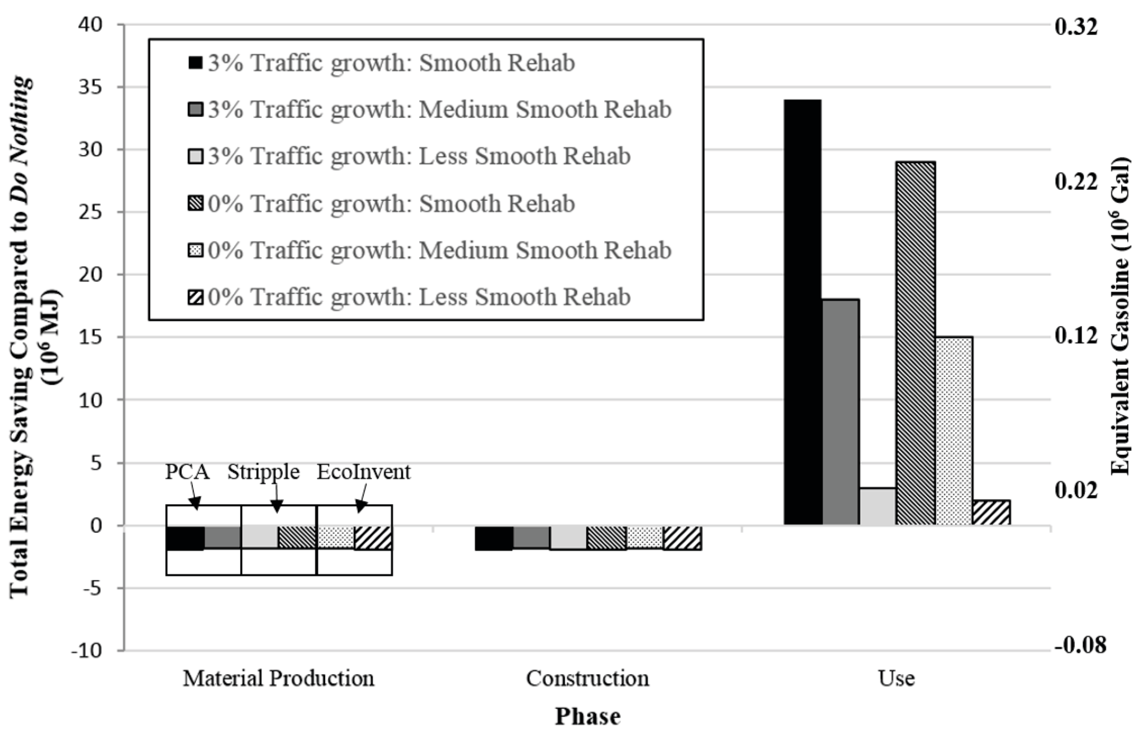

Figure 6-3. Energy savings in MJ and equivalent gallons of gasoline for a medium-to-high-volume route over 10-year analysis period for preservation treatment versus leaving the pavement rough (Wang et al. 2012). (Note: material production values calculated using three alternative sources of information shown [PCA, Stripple, EcoInvent] in order to test sensitivity of results to data source).

The example shown in figure 6-3 is for one direction of a 5-mi (8-km) segment of a medium-to-high-volume two-lane highway carrying 5,600 vpd with about 29 percent trucks. The current IRI is about 190 inches/mi (3 m/km), and the average (Medium Smooth Rehab) reduction in the IRI to about 105 inches/mi (1.7 m/km) was simulated by typical results achieved at initial construction consisting of grinding and some slab replacements followed by increases in IRI under traffic over the 10-year period. The results were calculated using the HDM-4 models calibrated by Chatti and Zaabar (2012) and coupled with emissions models in the EPA's MOVES software (EPA 2010a). Similar simulations were analyzed for asphalt overlays on asphalt pavement in the same study. Models for changes in macrotexture (measured as mean texture depth [MTD] for concrete) caused by the treatment and later traffic and their effect on fuel consumption are included in the simulation shown in figure 6-3 and in other simulations in the study, but had a much smaller effect than the change in IRI for both the concrete and asphalt cases. The structural responsiveness to vehicle loading was assumed to not change with the treatments because the pavement structures did not change much. Additional benefits of the preservation-type treatments simulated in the study due to extension of the life of the underlying pavement were not considered in the analyses.

The sensitivity analysis shown in figure 6-3 indicates that the smoothness achieved by the contractor has a major impact on the benefits. The figure shows analysis results for high-quality (Smooth Rehab = mean IRI minus two standard deviations, 57 to 72 inches/mi [0.9 to 1.2 m/km]), and low-quality (Less Smooth Rehab = mean IRI plus two standard deviations, 140 to 144 in/mi [2.2 to 2.3 m/km]) smoothness from construction of the treatment based on historical data from similar projects, in addition to the average (Medium Smooth Rehab) result. These results indicate that a strong construction smoothness quality assurance program can have a significant effect on vehicle fuel use for high-volume routes with high roughness. The changes in IRI over the life of the pavement after construction also significantly affect the net impact of the preservation treatment. Also shown in the figure are scenarios for 0 and 3 percent growth in total traffic over the 10-year analysis period. It can be seen that the construction smoothness had a much larger effect than the differences in the traffic growth rate and, paradoxically, there are greater relative savings when more traffic uses the smoother pavement, although the overall impact is greater for the higher traffic growth. Again, in terms of optimizing fuel economy on a network, construction smoothness is most important on higher volume routes and is not as important on lower volume routes (of course, smoothness is still important to the users of those lower volume routes).

The effects of vehicle speed have some interaction with roughness, but it does not change the overall trends or have much effect on the sensitivities of fuel economy to roughness (Chatti and Zaabar 2012). Modeling results also indicate that the effects of pavement roughness on fuel economy under stop-and-start congested traffic are similar to those under steady-state traffic, even including stop-and-start traffic in congested areas (Wang, Harvey, and Kendall 2013).

Since fuel economy goes down as driving speeds increase above 45 mi/hr (72 km/hr), one question that arises in discussions regarding the effectiveness of keeping pavements smooth is whether improving smoothness results in faster driving speeds under free-flow conditions that can reduce the fuel economy benefits of smoothness. Modeling by Hammarström et al. (2012), using driver speed behavior measurements from Sweden (Ihs and Velin 2002), indicated that increased driver speeds essentially cancel out the benefits of improved smoothness. On the other hand, a recently completed study in California (Wang, Harvey, and Lea 2013), using a large number of traffic speed measurements before and after pavement maintenance (on the same concrete sections with grinding plus slab replacements or asphalt overlays, and on the same asphalt sections with asphalt overlays), indicated that a reduction of IRI of 63 inches/mi (1 m/km) leads to only about a 0.3 to 0.4 mi/hr (0.48 to 0.64 km/hr) change in free-flow speed on freeways, which has a negligible effect on vehicle emissions or energy consumption.

In urban areas, pavement roughness is often affected by the quantity of utility cuts and the quality of the repairs. Poorly constructed utility cuts can immediately cause large increases in roughness in an otherwise smooth pavement. Even if utility cuts are initially constructed with a smooth surface, they can adversely affect the pavement smoothness if they are not well compacted or well bonded to the existing pavement, leading to an increase in vehicle fuel use. An alternative for new pavement construction is to place utilities in locations on the right of way outside of heavily trafficked portions of the paved areas. The timing of utility upgrades should be scheduled before maintenance or rehabilitation, as it will otherwise affect the pavement life. Utility cuts causing roughness are of greatest concern on higher volume routes.

With respect to the costs of timely application of maintenance and rehabilitation treatments, research has shown for asphalt pavements that applying a pavement maintenance treatment before a pavement reaches an advanced level of cracking can potentially reduce the life-cycle cost compared with waiting until the pavement damage reaches a critical level that a major rehabilitation is required (Lee, Rezaie, and Harvey 2012).

Pavement Structural Responsiveness to Loading Effects

Pavement structural response to loading, the third mechanism of rolling resistance that can affect fuel consumption, has been modeled as two phenomena:

1. Dissipation of energy in the pavement due to the pavements structural response under traffic loading.
2. Pavement surface structural responsiveness modeled as a change in geometry between the tire and the surface.

For both phenomena, larger deflections and greater delayed elasticity (more viscous damping as opposed to elastic behavior) will increase the pavement rolling resistance. The first pavement structural responsiveness phenomenon, dissipation of energy in the pavement structure due to the viscoelastic nature of asphalt materials, has been the subject of recent model development by the LUNAM University/IFSTTAR (Chupin, Piau, and Chabot 2013), the University of Lyon, France (Pouget et al. 2012), and by the University of Nottingham (Thom, Lu, and Parry 2010). There have also been a number of previous studies employing various approaches to model structural responsiveness (e.g., Kelly 1962; Perloff and Moavenzadeh 1967; Huang 1967; Hopman 1993; Hajj, Sebaaly, and Siddharthan 2006) that consider viscoelastic properties for some or all layers.

The second phenomenon is the subject of recent and ongoing model development at the Massachusetts Institute of Technology (Akbarian et al. 2012). Flugge (1975), Chupin, Piau, and Chabot (2013), and Loughalam, Akbarian, and Ulm (2013) have derived or reviewed relationships between the energy needed to move vehicles forward based on the position of the wheel in the deflection basin as it is affected by the delayed elasticity of viscoelastic deflections (the second structural responsiveness phenomenon described above) and the energy dissipated in the pavement (the first phenomenon).

It is interesting to note that the work by Akbarian et al. (2012), Chupin, Piau, and Chabot (2013), Pouget et al. (2012), and Thom, Lu, and Parry (2010) produce somewhat similar results for energy consumption for the distinct pavement structure, traffic speed, and temperature conditions that come from their modeling, yet draw opposite conclusions as to the overall importance of energy dissipation due to structural response under loading. This is because the researchers have not applied their results for the combined effects of traffic speed, temperature, structure and hourly traffic volumes as they occur together over a year for a given pavement, or for a range of different pavement structures. For example, Pouget et al. (2012) modeled an 8.7-inch (220-mm) thick asphalt structure with a 2.4-inch (60-mm) polymer-modified asphalt surface (and the rest conventional asphalt) as it was subjected to uniform temperatures throughout the asphalt; the results of the model (which was not calibrated with field data) indicated that, for a 7,300 lb (32 kN) truck wheel loading condition, reductions in fuel economy occur when the speed is reduced from 60 mi/hr (100 mi/hr) to 30 mi/hr (50 km/hr). The estimated reductions in fuel efficiency were approximately 0.1 percent at an asphalt temperature of 50 ^{o}F (10 ^{o}C), 1 percent at 95 ^{o}F (35 ^{o}C), 3 percent at 122 ^{o}F (50 ^{o}C) and 5.5 percent at 140 ^{o}F (60 ^{o}C) (Pouget et al. 2012). It is emphasized that this result is for one structure, one type of heavy truck, one truck wheel load, and for the two vehicle speeds over the described range of temperatures. The net result for a road section would depend on the joint occurrences of vehicle travel and pavement temperatures across each day and night and across all the seasons of the year.

A number of field studies have also been performed to measure the effects of pavement type on vehicle fuel economy, including those by Zaniewski et al. (1982), Taylor and Patten (2006), Ardekani and Sumitsawan (2010), Bienvenu and Jiao (2013), and Hultqvist (2013). For automobile traffic, the study by Zaniewski et al. (1982) showed no measureable difference in fuel economy between asphalt and concrete pavement. The study by Taylor and Patten (2006) had limited results for an automobile driven over 11 test sections that included concrete, asphalt, and composite (asphalt surface over concrete) paved roads in Ontario and Quebec; two seasons (winter and summer) and two travel speeds (37 and 62 mi/hr [60 and 100 km/h]) were included. All of the pavement sections had IRI values less than 126 inches/mi (2 m/km) and the IRI was considered directly in the results, but the study did not control for or measure pavement surface texture. Of the statistically significant results, the study showed a small increase in fuel use for asphalt pavement compared to concrete pavement for one season, and a small increase in fuel use for concrete pavement compared to composite for one season (the opposite was observed for the other season). The pavements considered by Ardekani and Sumitsawan (2010) consisted of four rough to extremely rough urban streets (IRI values of 170 to 325 inches/mi [2.7 to 5.2 m/km]) tested using a Chevy Astro van with a relatively small number of replicate runs and no consideration of texture or roughness. The study by Hultqvist (2013) showed about a 1 percent difference in fuel economy for cars when tested on one asphalt and one concrete pavement on the same route in the Swedish summer. However, the authors concluded that these results were primarily due to the higher macrotexture from studded tire use on the asphalt pavement based on modeling results. The pavement structures were not characterized for their stiffnesses.

Noting possible problems with measurements in two earlier phases of their work, Taylor and Patten (2006) performed a Phase III study on the Canadian pavements listed above using a heavy articulated truck outfitted with different weights and running at two travel speeds (37 and 62 mi/hr [60 and 100 km/h]) to establish if loading was a contributing factor to truck fuel consumption differences among the three different pavement types (concrete, asphalt, and composite). Testing was performed under different seasonal conditions in eastern Canada. The study found statistically significant fuel use savings for trucks traveling on concrete pavements for most of the five seasons and day/night conditions across the range of vehicle loadings, with greater differences noted at 37 mi/hr (60 km/hr) (1.3 to 3.9 percent) than at 62 mi/hr (100 km/hr) (0.8 to 1.8 percent). The study also found statistically significant fuel saving results for most of the seasonal and day/night conditions for concrete pavements compared to composite pavements, again with larger differences at 37 mi/hr (60 km/hr) (1.9 to 6.0 percent) than at 62 mi/hr (100 km/hr) (0.8 to 3.1 percent). Interestingly, statistically significant results under the hottest conditions on summer days found the opposite result, with the trucks consuming less fuel on composite pavements than on concrete pavements, with larger differences at 37 mi/hr (60 km/hr) (2.4 to 3.0 percent) than at 62 mi/hr (100 km/hr) (about 1.4 percent). The models developed in the Phase III study also noted that "The insensitivity of the fuel consumption differences to temperature, load and speed is somewhat counterintuitive to the engineering physical models"; however, no explanation for this lack of sensitivity was identified in the study. Thicknesses of the pavement structures were noted, but no structural evaluation or characterization of the pavements (other than being classified as asphalt, concrete or composite) was included in the analyses of the fuel consumption results. Texture was not measured or considered.

Coast-down measurements were also performed as part of the Taylor and Patten (2006) study on the asphalt and concrete sections to measure rolling resistance. Coast-down tests consist of measuring how far a vehicle (the loaded truck in this case) will roll without braking and after shutting off the engine and putting the transmission in neutral. The results showed no significant differences between the asphalt and concrete structures included in the fuel economy studies.

The truck results from the study by Hultqvist (2013) showed up to a 5 to 7 percent difference in fuel efficiency for heavy vehicles operating on hot days on one concrete and one asphalt pavement. The differences were attributed to a combination of structural responsiveness and macrotexture, with macrotexture levels higher on the asphalt pavement while the IRI was slightly higher on the concrete pavement. The effects of texture and structural responsiveness were not separated for the truck measurements, and the authors expressed concern about the presence of relatively strong winds during testing. As noted previously, the pavement structures were not characterized for their stiffnesses. The Swedish study is unique in that the sections were used to check a mechanistic model of pavement energy consumption from vehicles called VETO (Hammarström et al. 2012), which showed results similar to the measurements for the test sections. Many of the models in VETO are similar to those in HDM-4.

A field study by Bienvenu and Jiao (2013) along 28 mi (45 km) of Interstate 95 in Florida indicated that passenger vehicles on a concrete pavement use 3.2 percent less fuel compared to asphalt pavement. The study also showed that, along the same corridor, loaded tractor trailers traveling on the concrete pavement experienced 4.5 percent better fuel economy than on the asphalt pavement. The asphalt pavement consisted of 9.25 inches (235 mm) of asphalt (including an open-graded friction course) on 5 inches (125 mm) aggregate base and 12 inches (300 mm) of treated subgrade. The concrete pavement consisted of a 13-inch (330 mm) JPCP resting on a 1-inch (25 mm) asphalt-treated permeable base and 4-inch (100 mm) asphalt base. The pavement structures were not characterized for their structural responsiveness nor were the surface textures measured or considered.

The previously cited study by Chatti and Zaabar (2012) had as a secondary objective the evaluation of fuel economy for vehicles traveling on asphalt and concrete pavements. It included 11 pavement sections in Michigan divided between asphalt and concrete, five types of vehicles operating at different speeds, daytime winter and summer measurements (for most vehicles), and ranges of roughness and texture levels. As with the other studies cited, there was very little characterization of the pavement structure besides being noted as being either asphalt or concrete. The results of the study indicated that "pavement type [does] not affect the fuel consumption of any vehicle class except for heavy trucks." More detailed analysis of the same data indicated that articulated (heavy) trucks and light trucks had statistically significant higher fuel consumption, with about a 4 percent difference for the heavy trucks when operated on asphalt pavements included in the study at 35 mi/hr (56 km/hr) in the daytime in the summer, but there no statistically significant difference at speeds of 45 or 55 mi/hr (72 or 88 km/hr) or when the trucks operated during the winter. As noted there was no characterization of the pavement structures in terms of the structural responsiveness to vehicle operating conditions and temperature that would permit generalized application to other structures and other temperature and loading conditions.

From the review of the various studies noted here, it can be said with reasonable certainty that the influence of structural responsiveness on fuel economy and associated environmental impacts has not been comprehensively validated with an experiment that has accounted for the broad range of environmental conditions or the various types of pavement structures used in the nation's highway network (e.g., composite pavements, semi-rigid pavements, rubberized and polymer modified mixtures, doweled and nondoweled JPCP, and CRCP). The field studies conducted to date to measure the effects of dissipated energy on vehicle fuel efficiency suffer from a serious lack of characterization of the pavement structures in terms of their structural responsiveness to loading as a function of the stiffness and thickness of the pavement layers or the viscoelastic nature of the materials under different conditions of temperature and traffic speed. Without consideration of those variables, it is difficult to use the results for model validation, and, without validated models, it is difficult to calculate the net results of all of the variables affecting this mechanism. The structural responsiveness to vehicle loading of pavements depends on subgrade, subbase, and base support conditions, and, particularly for asphalt pavements, the temperature and time of loading. To complicate matters, these responses change as the pavement materials age and deteriorate. Therefore, consideration of pavement structural responsiveness effects must be analyzed separately for each project considering the intersection of structural responsiveness, traffic levels, traffic speeds and pavement temperatures, and the moisture conditions in the underlying unbound layers, which may vary widely with daily and seasonal climatic fluctuations.

Although deflection testing using a falling weight deflectometer (FWD) does not replicate the effects of a vehicle moving across the pavement, deflection testing has been used to help understand the effects of structural response and energy consumption. Studies that considered FWD testing include those performed by Ullidtz et al. (2010) and by Faldner and Lenngren (2012).

While it is known that water, snow, and ice on the pavement will also impact rolling resistance, the fuel economy studies cited above were all carried out under dry pavement conditions (Karlsson, Carlson, and Dolk 2012). Modeling results from Sweden (Hammarström and Karlsson 1987) indicate that water depths of 0.039, 0.078, and 0.156 inches (1, 2 and 4 mm) can increase vehicle fuel use by 30 percent, 90 percent, and nearly 80 percent, respectively, compared to dry pavement (Karlsson, Carlson, and Dolk 2012). These results indicate that pavement designs and materials that can remove water from the pavement surface quickly may contribute to substantial reductions in fuel use and environmental impact, particularly in areas with high rainfall; they will also contribute positively to overall safety. In general, open-graded friction courses and directional texturing are used on asphalt and concrete surfaces, respectively, to reduce water depths under tires. Some of these textures also tend to increase macrotexture and might slightly reduce fuel consumption. It should be noted that these modelling results are also not yet validated.

It must be again emphasized that none of the effects on vehicle fuel consumption and pavement characteristics matter much if only a few vehicles are using the pavement, and that these effects should only be considered for higher traffic volume locations from the standpoint of environmental impact on the network. This is borne out for the case of IRI as described in the next section of this chapter.

Network-Level Considerations

As has been noted previously, the effects of a pavement on vehicle fuel economy and the associated energy and environmental impacts are controlled by the number of vehicles using the pavement. The previously cited study by Wang et al. (2012) analyzed the net effects of several pavement preservation treatments on the GHG emissions and energy use as a function of traffic level, with the materials production and construction effects being the same and the reductions in GHG emissions and energy use depending on traffic flow during the use phase. The study included consideration of pavement deterioration after the treatment, and showed that the net effect can be positive or negative, depending on the traffic level and the constructed smoothness. Furthering this concept, another study by Wang, Harvey, and Kendall (2013) determined trigger levels for the same typical California preservation treatments (5- to 10-year design lives) on asphalt and concrete roads optimized to reduce GHG emissions as a function of traffic level. The modeling in the study did not consider changes in structural responsiveness of treatments in the use phase because the treatments did not change the pavement type (asphalt surfaces remained asphalt and concrete surfaces remained concrete) and the treatments did not significantly change the structural responsiveness of the typical existing pavement. The results indicated that optimized IRI trigger values for different traffic flows, in terms of daily passenger-car equivalent (trucks count as 1.5 cars) per direction, were on the order of (Wang, Harvey, and Kendall 2013):

- 101 inches/mi (1.6 m/km) for the highest traffic levels (directional daily traffic above 34,000 passenger-car equivalents).
- 127 inches/mi (2 m/km) for directional daily traffic levels between about 12,000 and 34,000 passenger-car equivalents.
- 177 inches/mi (2.8 m/km) for directional daily traffic flows between 2,500 and 12,000 passenger-car equivalents.
- Use-phase savings from treatments to reduce roughness were generally less than the GHG emissions from materials production and construction regardless of IRI for directional daily traffic flows below about 2,500 passenger-car equivalents.

As can be seen from these values, the optimum IRI trigger level decreases as the traffic level increases, and emissions from construction and materials used in the treatment could not be recovered in the use phase for low traffic flows. Although specific trigger values would be expected for different agencies and treatments (preservation, rehabilitation, reconstruction), the overall trends are expected to be the same.

Summary

A general summary of the effects of pavement characteristics on vehicle fuel economy, and the resulting environmental impacts of fuel economy changes, is presented below:

- Roughness as measured by IRI generally has the greatest effect on fuel economy for typical ranges of IRI on U.S. highway networks, compared with structural responsiveness and macrotexture. The effect is essentially linear, with sensitivity depending on the vehicle type. According to recently calibrated models (Chatti and Zaabar 2012), an increase in IRI from 63 inches/mi (1 m/km) to 190 inches/mi (3 m/km) increases passenger car fuel consumption by 4.8 percent at 86 ºF (30 ºC), 55 mph (88 km/hr) with zero grade, and an MPD (macrotexture) value of 0.04 inches (1 mm). For heavy articulated trucks the same change in IRI increases fuel consumption by 2.9 percent under the same conditions. SUVs show a change of 4.1 percent, and light trucks and vans show changes of 1.6 and 1.8 percent, respectively Although the effects of roughness vary somewhat with temperature and vehicle speed (Chatti and Zaabar 2012), it has an effect on fuel economy for every vehicle throughout the year. Given its impact, pavement roughness can be controlled by three methods:
  - Consideration of smoothness performance (smoothness over time) and having smoothness over the life cycle as a key parameter in the pavement design process.
  - The implementation of effective smoothness specifications, since pavements "born rough" will start rough and only get rougher with time.
  - The timely application of maintenance and rehabilitation strategies that restore and promote smoothness before the pavement gets too rough, including consideration of traffic volume when determining IRI trigger values for treatment.
- Macrotexture as measured by MPD on asphalt and MTD on concrete (MPD and MTD are generally considered interchangeable in terms of values for fuel economy models) has a linear effect on vehicle fuel economy. The effect of macrotexture is generally much smaller than that of IRI, to the point that it is statistically insignificant for all but heavy trucks at slow speeds for typical ranges of well-maintained pavement occurring on state highway networks in the U.S. According to the recently calibrated models (Chatti and Zaabar 2012) an increase in MPD or MTD of 0.04 inches (1 mm) will increase heavy truck fuel consumption by about 2 percent at 35 mi/hr (56 km/hr), when IRI is held constant at 63 inches/mi (1 m/km), while for other vehicles and heavy trucks at highway speeds the effect was statistically insignificant. Macrotexture is controlled by pavement surface type selection (minimizing positive texture for both concrete and asphalt) and timely maintenance (e.g., repairing raveled asphalt surfaces, degraded concrete surfaces, chain wear). However, sufficient macrotexture must be maintained to provide a pavement with adequate surface friction. Macrotexture improves wet-pavement surface friction by providing drainage between the tire and the pavement; this reduces the risk of hydroplaning, which is the phenomenon in which a film of water develops between the moving tire and the pavement surface leading to the tire losing contact with the pavement. The risk of hydroplaning increases as vehicle speed increases. Increased macrotexture may help with wet-weather fuel economy by reducing water film thicknesses, which for some pavement textures could otherwise consume vehicle energy by increasing rolling resistance (particularly in wet climates). Macrotexture is primarily controlled by surface materials selection and maintenance practices.

- Structural responsiveness and its effect on vehicle fuel economy is the subject of several models that have been developed, and a number of field studies have been performed measuring vehicle fuel economy on different pavement structures under different conditions. These studies provide indications that under certain conditions the structural responsiveness of different pavements to vehicle loading can have a measureable effect, which like that of roughness and macrotexture, is variable depending on vehicle type and operating conditions. Unlike roughness and macrotexture, the effect of structural responsiveness is highly variable, depending on temperature and the underlying support conditions which undergo daily and seasonal fluctuations. In general, the effects of different pavement structures range from approximately no difference under some conditions of vehicle type/operation and climate conditions to effects of the same order of magnitude as high levels of highway roughness under the most extreme temperature and loading conditions at certain times of the year. This effect also depends on the viscoelastic properties of the pavement materials, primarily the type and age of asphalt materials located near the surface.

  In general, modeling and measurements to date indicate that lighter and faster vehicles, as well as colder conditions, result in the least differences in rolling resistance between different pavements whereas heavier and slower vehicles under hotter conditions result in larger differences. The frequencies at which these conditions occur in combination with traffic patterns control the net effect on fuel economy of structural responsiveness for a given structure.

  However, the influence of structural responsiveness on vehicle fuel economy has not yet been comprehensively validated with any experiment that has characterized the pavement structures in terms of their responsiveness under different conditions. As a result, the available models have not been calibrated with the type of data that allows the general application of the models to evaluate in-service pavements under the range of traffic and climatic conditions that occur daily, seasonally, and from location to location. Research is needed that uses field measurements of fuel economy for a range of vehicles, climates, and pavement structural responses, controlling for roughness and macrotexture, to complete calibration and validation of models that can be used to make design and management decisions.

- Environmental impacts and energy use from all three rolling resistance mechanisms are a function of the number of vehicles using the pavement in the use phase. Beneficial environmental impacts from managing roughness, macrotexture, or structural responsiveness decrease as the number of vehicles using the pavement decrease.

- The relative impact of decisions affecting the different vehicle use phase mechanisms discussed in this section are highly context sensitive, with the benefits from changing existing practices dependent on the baseline conditions in terms of existing roughness, macrotexture conditions, and pavement structures. For example, a network with generally low roughness on high traffic routes will not see much improvement in emissions from focusing on improving roughness, although keeping the pavement smooth to avoid increasing emissions will be important. The relative effects of the different mechanisms also depend on vehicle types, loads, and speeds, daily and seasonal pavement temperature fluctuations, and interaction with the distributions of vehicle variables listed above across the years.

Strategies for Improving Sustainability

Practices that are available to pavement managers, designers, and specification developers that might be optimized to help meet GHG emission, energy use, and other environmental objectives associated with the influence of pavement characteristics on vehicle fuel economy are summarized in table 6-1.

Table 6-1. Summary of strategies for improving vehicle use phase fuel consumption and potential trade-offs.

Vehicle Fuel Consumption and Pavement Objective	Vehicle Fuel Consumption Sustainability Improving Strategy	Economic Impact	Environmental Impact	Societal Impact
Reduce Fuel Use Due to Roughness	Implement pavement design process that considers smoothness over the pavement life as a key design parameter, especially for high traffic volume routes.	Potential for small to moderate increases in initial costs but reduced life-cycle costs due to longer pavement lives. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use, particularly on high traffic volume routes.	Improved economic efficiency.
	Implement construction specifications to incentivize maximum possible smoothness, especially for high traffic volume routes.	Potential for small increases in construction costs, reduced life-cycle costs due to longer treatment lives from reduction in dynamic loading. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use, particularly on high traffic volume routes.	Improved economic efficiency.
	Optimize timing of maintenance and rehabilitation based on IRI trigger value and traffic volume.	Potentially increased agency initial costs if results in earlier treatment than current practice. Potentially reduced agency life-cycle cost from pavement preservation. Reduced vehicle operating costs for road users as pavements are kept in smoother condition.	Increased environmental impact of materials production and construction when treatments are more frequent; reduced environmental impact due to less fuel use. Benefit can be offset if vehicle speeds increase because of improved smoothness.	Emphasis on maintaining high-volume routes in smoother condition may improve economic efficiency and average road user cost, but may result in neglect of lower volume routes depending on funding levels.
	Minimize pavement roughness due to utility cuts through regulation, construction practice enforcement and better planning.	Reduced pavement maintenance costs. Increased enforcement costs. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use when poorly repaired utility cuts cause roughness, particularly on high traffic volume routes.	Improved economic efficiency. Improved urban aesthetics.

Table 6-1. Summary of strategies for improving vehicle use phase fuel consumption and potential trade-offs (continued).

Vehicle Fuel Consumption and Pavement Objective	Vehicle Fuel Consumption Sustainability Improving Strategy	Economic Impact	Environmental Impact	Societal Impact
Reduce Fuel Use Due to Macrotexture (where impact is significant)	Avoid high positive macrotexture on routes with high heavy truck traffic volumes at slow speeds while maintaining safety.	May result in less use of some low-cost maintenance treatments with high positive macrotexture over the life cycle on high-volume heavy truck routes.	Reduced environmental impact due to less fuel use on high traffic volume heavy truck routes.	Improved economic efficiency, reduced tire wear. Potential for increased crashes due to reduced surface friction if also high speed traffic.
Calibrate and Validate Models for Fuel Use Due to Structural Responsiveness to Vehicle Loading (use them once research is completed)	Perform research to calibrate and validate models for vehicle fuel use as a function of pavement structural responsiveness to vehicle loading. Calibration requires experiments that characterize responsiveness of pavement sections and then measure fuel use on same sections. Calibrated models can be used to determine where structural responsiveness is significant and develop appropriate strategies based on those results.	Calibrated models will permit evaluation of alternative structures considering traffic, climate and other variables which will allow consideration of both road user and agency costs versus environmental benefits for designs.	Optimization may reduce environmental impact due to less fuel use, particularly on high truck traffic volume routes in certain climates.	Optimization may improve economic efficiency particularly on high truck traffic volume routes.

Future Directions and Emerging Trends

Highway agencies are moving towards construction smoothness specifications based on IRI for new pavement construction and rehabilitation and maintenance activities. The implementation of improved methods for quality assurance for as-built smoothness will have a great impact not only on pavement serviceability but also on fuel consumption. These improvements and the potential for maximizing the specified smoothness on high-traffic volume routes should result in decreases in fuel use and decreases in its associated environmental impacts.

As pavement management systems become more sophisticated, they can be used for explicit consideration of the timing of maintenance, rehabilitation, and reconstruction treatments to optimize net reductions in energy use and environmental impacts considering the pavement life cycle (materials production, construction, use, and end-of-life phases). Improvements in life-cycle inventories (LCI) for each of these phases are needed to improve the ability to optimize. Requirements in the federal transportation legislation (MAP-21) for pavement management systems to track the performance of pavement management decisions may help push implementation of this type of approach.

Improved mechanistic-empirical models for predicting pavement smoothness over the life cycle of the pavement will aid in making design decisions that result in reduced vehicle fuel use. At the same time, improved models that consider the effects of pavement structural responsiveness on vehicle fuel use, and the calibration/validation of those models with experimental data, will provide pavement designers with better information for selecting pavement structures that reduce vehicle fuel use.

Improvements in pavement deflection measurement technologies, such as rolling wheel deflectometers that measure deflections at highway speeds, will likely result in greater consideration of structural responsiveness as part of network-level monitoring. Measurement methods for texture using high-speed lasers (for pavements that do not have directional texture) and deflection using rolling wheel deflectometers (FHWA 2011a) have been developed and are being evaluated by a number of different state agencies. Methods for directly measuring pavement rolling resistance due to texture and structural responsiveness are also being developed (Bergiers et al. 2011; FHWA 2011a).

Tire-Pavement Noise

Background

Noise can be defined as unwanted or unpleasant sound. All sound is produced by vibrating objects and transmitted by pressure waves in a compressible medium such as air. Sound waves are often characterized in terms of amplitude (strength of the wave) and frequency (speed of their variation) (Snyder 2006). Sound pressure or sound intensity levels are used to quantify the loudness of an ambient sound. The frequencies of sound audible to humans range from 20 to 20,000 Hz, and sound pressures range from 20 micropascals (µPa), the threshold of hearing, to 120 pascals (Pa), the threshold of pain (Norton 1989).

Major Issues:

- ✓ *Noise effects on humans and wildlife.*
- ✓ *Noise is partly controlled by pavement surface characteristics, but tire characteristics are typically more important.*
- ✓ *Methods available to measure tire-pavement noise.*

The broad range of sound pressures important to human noise perception (seven orders of magnitude) has led to the common use of a logarithmic scale for sound pressure levels (SPL), which is normalized to a reference standard of 2×10^{-5} Pa and has units of decibels (dB). Sound intensity, which is a measure of energy flow through a unit area, is also typically discussed using a logarithmic scale with units of Watts/m^2, normalized to a reference standard of 10^{-12} W/m^2. The unit of the linear sound intensity scale is also the decibel. The reference standards for SPL and sound intensity have been chosen to obtain the same reading in decibels regardless of whether SPL or sound intensity is used to define the sound wave, and irrespective of whether pressure or intensity in an acoustic free field is measured. Because of the logarithmic scale for noise, the emissions from multiple noise sources cannot be added linearly. For example, two noise sources, each emitting at 70 dB, produce a noise level of 73 dB, not 140 dB (Ongel et al. 2008). Noise is usually adjusted to reflect human sensitivity, the units of which are expressed in terms of adjusted decibels (dBA).

Human perception of changes in sound energy is also non-linear. Most observers perceive an increase or decrease of 10 dB in the sound pressure level as doubling or halving of the sound, as shown in table 6-2 (FHWA 2011b). It can also be seen in the table that a change of 3 dBA is barely perceptible to most people. For this reason, changes in highway noise of less than 3 dBA are generally considered to be relatively insignificant. However, the information shown in table 6-2 is based on laboratory studies of humans listening to pure tones in a laboratory setting, such as in a common hearing test. Many people can hear differences in tire-pavement noise less than 3 dBA and can perceive differences in the frequency content of two tire-pavement noise sources that have the same sound intensity as measured in dBA, with different sound patterns and frequencies of sound being more irritating than others.

Table 6-2. Decibel changes, energy loss, and loudness (FHWA 2011b).

Sound Level Change (dBA)	Change in Sound Energy (%)	Human Perception
0	0	No change
-3	50	Barely perceptible
-5	67	Readily perceptible
-10	90	50% as loud
-20	99	25% as loud
-30	99.99	12% as loud

Noise levels are also affected by the distance from the source, with near-ground sources spreading out over a hemispherical volume. Noise wave energy is conserved with the result that sound intensity variation is proportional to the square of the distance from the source as it is spread over a wider surface. Therefore, the sound intensity level is decreased by a factor of four when the distance from the source is doubled.

Noise pollution has become an increasing concern in the U.S. and worldwide. Highway noise affects people in adjacent residences and businesses as well as people in vehicles; road noise effects on wildlife have also been identified (Clevenger et al. 2002). Various health and quality of life effects on humans from noise pollution have been identified by the World Health Organization (WHO 2013). Although somewhat controversial, attempts have been made to calculate the economic consequences of noise (Berglund, Lindvall, and Schvela 2000).

Public awareness of road noise has increased over the past 40 years and most industrialized countries have introduced noise emission regulations. In the U.S., regulations have been developed by the FHWA and other agencies for dealing with highway noise. For example, as required by the Federal-Aid Highway Act of 1970, the FHWA developed Regulation 23 CFR 772, *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, which applies to highway construction projects where a DOT has requested federal funding for participation in the project. The regulation requires the highway agency to investigate traffic noise impacts in areas adjacent to federal-aid highways for proposed construction of a highway on a new location or for the reconstruction of an existing highway to either significantly change the horizontal or vertical alignment or increase the number of through-traffic lanes (FHWA 2013).

The FHWA states that effective control of undesirable highway traffic noise requires a three-part approach: noise compatible planning, source control, and highway project noise mitigation

(FHWA 2013). If the highway agency identifies impacts, it must consider abatement and must incorporate all feasible and reasonable noise abatement measures into the project design. FHWA cannot approve the plans and specifications for a federal-aid highway project unless the project includes adequate noise abatement measures to comply with the standards (FHWA 2013).

Modeling of noise level contours around a highway project is performed using the FHWA Traffic Noise Model (TNM) (see www.fhwa.dot.gov/environment/noise/traffic_noise_model/). The TNM has the capability to consider different pavement types when modeling noise, although an assumed pavement type has typically been used in practice.

The regulations contain noise abatement criteria, which represent the upper limit of acceptable highway traffic noise for different types of land uses and human activities, as presented in table 6-3 (FHWA 2011b). The regulations do not require meeting the abatement criteria in every instance, but instead require the agency to make every reasonable and feasible effort to provide noise mitigation when the criteria are approached or exceeded. Abatement typically consists of noise barriers (sound walls), although other measures are also included. Quieter pavement surfaces are not considered adequate for abatement because the long-term performance of many of those surfaces has not yet been fully demonstrated, and there is the possibility that surfaces will not retain their low-noise characteristics if they are not sufficiently maintained.

Table 6-3. FHWA noise abatement criteria in dBA (hourly A-weighted sound level) (FHWA 2011b).

Activity Category	NAC, L_{eq}(h)*	Description of Activity Category
A	57 (exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 (exterior)	Residential
C	67 (exterior)	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings
D	52 (interior)	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios
E	72 (exterior)	Hotels, motels, offices, restaurants/bars, and other developed lands, properties or activities not included in A-D or F.
F	-	Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing
G	-	Undeveloped lands that are not permitted for development

* L_{eq}(h) is the sound pressure averaged over 1 hour.

Highway noise generated by passing vehicles comes from three sources: air passing over and around the vehicle (aerodynamic noise); the operation of the engine, exhaust, and drive train system (propulsion noise); and several mechanisms occurring as the tire passes over the pavement (tire-pavement noise) (Nelson and Phillips 1997; Sandberg 2001). As shown in figure 6-4, for passenger cars the tire-pavement noise dominates over propulsion noise at speeds above 20 to 30 mi/hr (30 to 50 km/hr), while at lower speeds the propulsion predominates. For heavy-duty trucks, it was found that propulsion noise dominates during acceleration from 0 to 50 mi/hr (0 to 80 km/hr), but tire-pavement noise dominates for all driving conditions above 50 mi/hr (80 km/hr) (Rasmussen et al. 2008). Tire-pavement noise depends on pavement surface characteristics, vehicle speed, environmental conditions, type of tire, and the dynamics of the rolling process (McDaniel and Thornton 2005). The tire-pavement noise level increases logarithmically with increasing speed (Sandberg 2001).

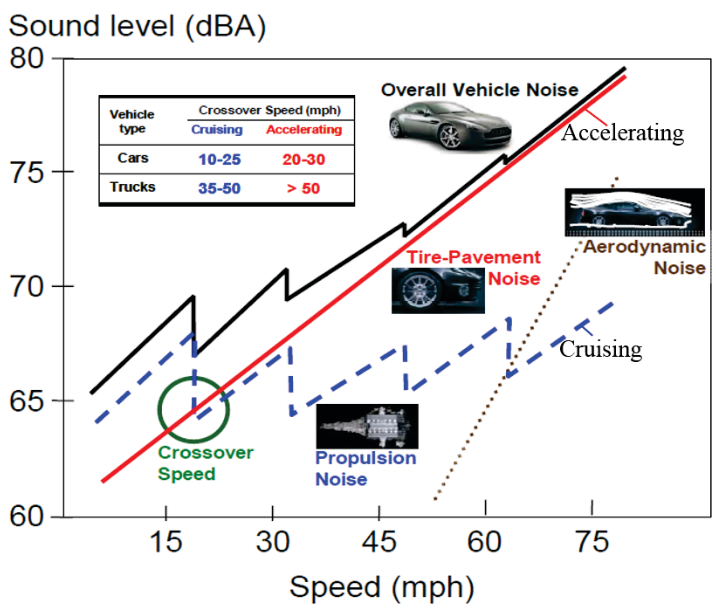

Figure 6-4. Estimate of light vehicle noise due to tire-pavement noise, powertrain noise, and aerodynamic noise at cruise speed (Rasmussen et al. 2008).

Noise at the side of the road from all of these sources is primarily measured via pass-by methods. Pass-by measurements can either be made with individual vehicles, which is referred to as the Controlled-Pass-By (CPB) method, or by measuring the total noise from all of the vehicles in mixed flow, which is referred to as the Statistical-Pass-By method (SPB) (ISO 1997). Noise measured using pass-by methods is the parameter of concern for modeling and decision making regarding the need for noise mitigation. However, such testing requires one or more days to conduct, is difficult and expensive to perform because it requires placement of microphones at different heights and at different distances from the edge of the road, and only provides measurements for small numbers of locations where this detailed arrangement can be installed.

Two test methods have been developed that permit continuous noise measurements along a roadway at highway speeds and also focus on the tire-pavement noise alone (which can be addressed through pavement design and management). The first method is called the Close Proximity method (CPX), which uses the equipment shown in figure 6-5. The CPX method involves the use of directional microphones inside of an acoustically insulated enclosed space built on a trailer that is towed behind the vehicle. This device is primarily used in Europe.

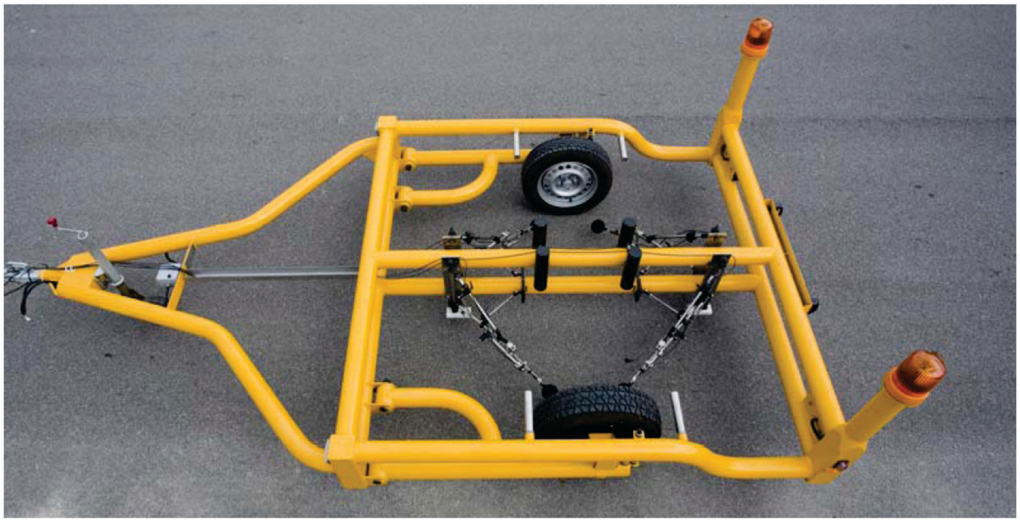

Figure 6-5. Close Proximity (CPX) test trailer (Bendtsen and Thomsen 2008).

The second method is called the On-Board Sound Intensity (OBSI) method, and is illustrated in figure 6-6. This method was developed in the U.S. based on technology originally developed by General Motors Corporation and recently introduced into the pavement community (Donavan and Lodico 2009). OBSI measurement involves the use of directional microphones placed at the leading and trailing edges of the tire-pavement contact patch, just above the pavement, and is performed in accordance with AASHTO TP-76-09. Comparisons between the OBSI and CPX methods have been performed, and show that they have similar sensitivity to pavement characteristics (Donavan 2006). The OBSI is primarily used in the U.S. because the equipment is mounted on the vehicle and it does not require the use of a trailer as does the CPX method.

Figure 6-6. On-Board Sound Intensity (OBSI) setup (photo courtesy of John Harvey).

Tire tread characteristics are major determiners of tire-pavement noise, and standard tire-pavement noise testing should include careful control of tire type and condition (Donavan and Lodico 2009; Lu, Wu, and Harvey 2011). A special type of test tire has been developed for pavement testing and other purposes called the Standard Reference Test Tire (SRTT). Comparisons have been made between OBSI and CPB noise levels (with the CPB testing performed using automobiles equipped with the SRTT), and the resulting correlations have been good, as shown in figure 6-7 (Donavan and Lodico 2009).

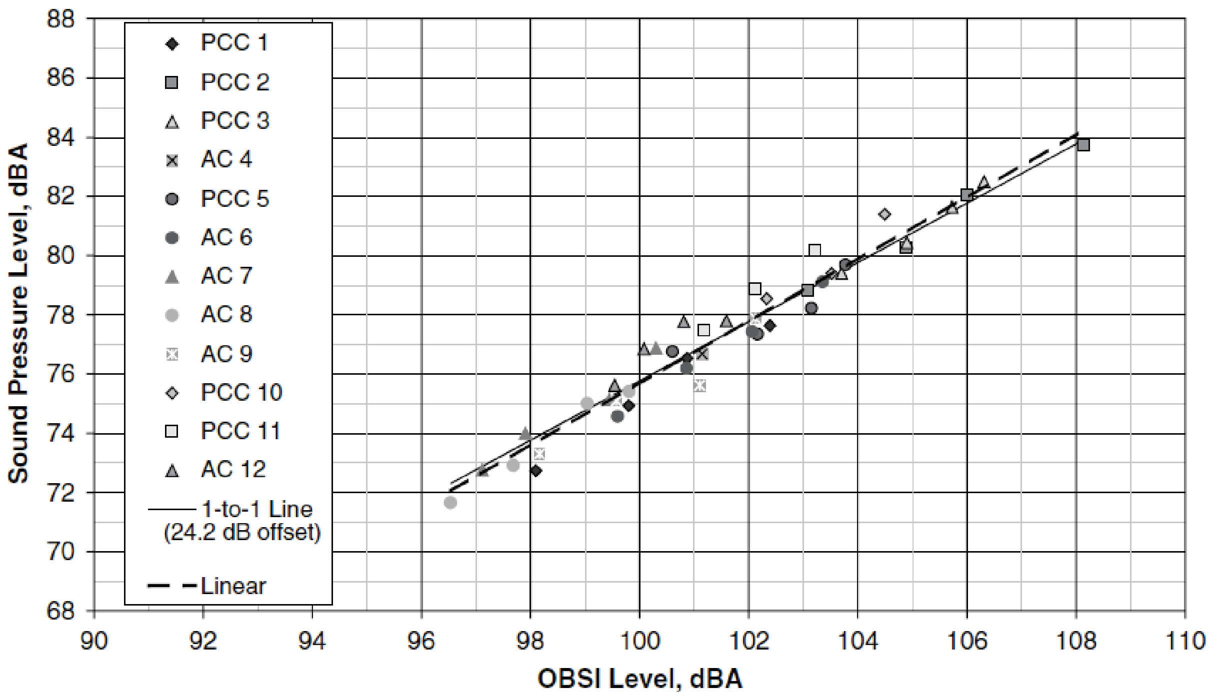

Figure 6-7. Controlled vehicle pass-by levels at 25 ft (7.6 m) versus OBSI level for the SRTT at all test sites and speeds—normalized data (Donavan and Lodico 2009).

Nelson and Phillips (1997) have further separated the phenomenon of tire-pavement noise into different mechanisms, as summarized below by Ongel et al. (2008):

- Tire tread/road surface impacts. This component of tire-pavement noise results from vibrations that occur as the tire tread initially contacts the pavement surface, and again as the tire tread breaks contact with the pavement surface and returns to its normal radius, which is referred to as "block snap out" (Bergmann 1980). These vibrations are transmitted through the tire, and from the tire to the air, creating noise. The flattening of the tire in the contact patch is resisted by friction between the tire and the pavement, which can also vibrate the tire when there is slip. The generation of vibrations on a rolling tire is dependent on the design of the tire tread, the macrotexture of the pavement (see figure 6-2, usually expressed in terms of MPD), and frictional adhesion between the tire and the pavement surface (Sandberg and Descornet 1980; Kropp 1992). In addition, Sandberg and Descornet (1980) suggested that stiffer pavements (concrete or asphalt) may generate more noise, which has also been advanced by Biligiri and Kaloush (2010). However, Beckenbauer and Kuijpers (2001) did not find that to be true, and Ongel et al. (2008) also disputed that hypothesis after accounting for other explanatory factors when comparing softer rubberized and stiffer conventional asphalt mixtures.

The noise generated due to the vibration of the tire tends to occur at frequencies up to 1,000 Hz (Nelson and Phillips 1997; Morgan, Nelson, and Steven 2003; Van Keulen and Duškov 2005), with the frequency of vibrations increasing as the tire rotation speed or the block tread length decreases. This phenomenon occurs because the tire acts as a low-frequency band-pass filter, attenuating the noise radiation at higher frequencies. Tire vibration is also increased as the tire tread pattern becomes more aggressive with deeper channels and larger lugs (or blocks) that are further apart.

- Aerodynamic processes between the tire and the road surface. Noise is generated by various mechanisms that occur as air moves in the contact patch. The most important of these mechanisms is called "air pumping," which is the sudden expelling of air that is trapped in the tread grooves or pavement texture due to the reduced groove volume when the tire makes contact with the road surface, and the sudden suction of air when the tire leaves the contact patch (Hayden 1971). The air-pumping mechanism may cause significant levels of noise in the frequency range above 1,000 Hz. Noise due to air pumping can be reduced by providing the air with more and larger pathways to move under the tire and through the pavement (Sandberg and Descornet 1980; Petterson 1988; Kropp 1992). These pathways can be provided by space between the stones due to macrotexture from stones on the surface, texturing of the surface (particularly concrete), and increasing the air permeability of the surface (particularly asphalt).
- Adhesion mechanisms. These mechanisms are caused by tire vibrations associated with the frictional forces that develop at the contact patch between the tire and the pavement surface (Nelson and Phillips 1997). The tire flattens at the contact path, causing tangential forces due to the changing radial deflections. These forces are resisted by the friction between the pavement surface and the stiffness of the tire, and the remaining forces are dissipated by the slip of the tread over the pavement surface. Friction between the tread and the pavement has two components: adhesion and hysteresis. The adhesion component is governed by microtexture of the surface, and the hysteresis component is largely controlled by macrotexture. Adhesion involves the formation and breaking of bonds at the contact patch followed by the hysteresis component of friction. This process, known as slip/stick, occurs at the contact patch and excites the tire vibration.

Noise-generation mechanisms are illustrated in figure 6-8. These general effects of the tire vibration and air pumping mechanisms are shown in figure 6-9 on a plot of OBSI measurements from a set of asphalt sections with the frequencies divided into 1/3 octave bands.

The mechanisms discussed above all assume that the pavement is dry. Phillips (2002) measured noise on wet surfaces and found an increase in the noise levels and also that the noise is dominated by the tire and pavement interacting with the water under wet conditions.

Macrotexture can be divided into two types: negative and positive texture. Positive macrotexture occurs when the texture is dominated by protrusions above the mean surface, while negative macrotexture occurs when the texture is dominated by indentations below the mean surface. From this discussion, it can be seen that positive macrotexture increases surface impact (tire vibration) mechanisms while at the same time increasing the air passages that reduces the noise at higher frequencies caused by aerodynamic processes (air pumping). Negative texture does not necessarily produce tire vibration.

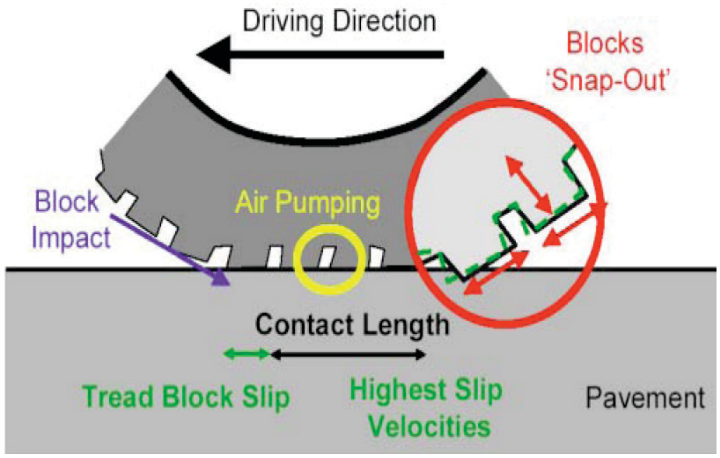

Figure 6-8. Noise-generation mechanisms on dry pavement (Olek, Weiss, and Garcia-Villarreal 2004).

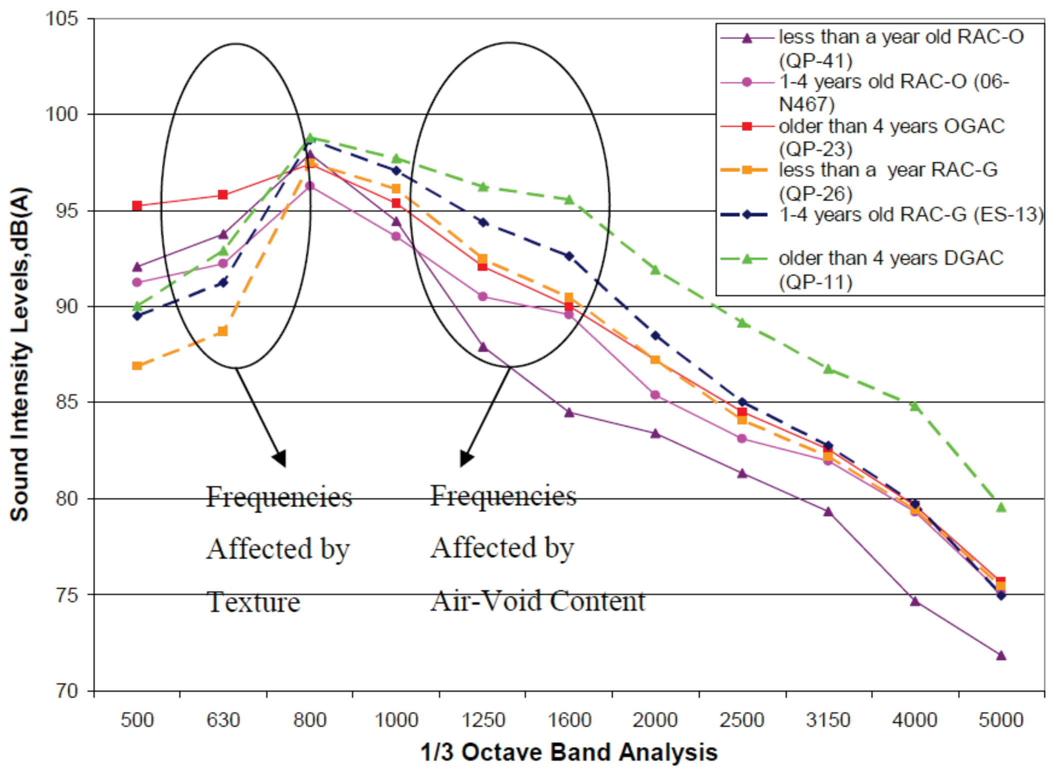

Figure 6-9. Example plot of one-third octave frequency content for several asphalt mixtures and influence of tire-pavement noise mechanisms (Ongel et al. 2008).

Asphalt pavements that have higher positive macrotexture include open-graded mixtures (especially those with larger maximum stone sizes), raveled dense-graded mixtures, and chip seals (again, particularly those with larger stones) (Rezaei, Harvey, and Lu 2012). The surface labeled "older than 4 years OGAC" in figure 6-9 is an open-graded asphalt concrete mixture that has raveling.

Pavement surfaces that can provide and maintain both negative macrotexture and air permeability are likely to reduce tire-pavement noise at the lower and higher frequencies, respectively (Bendtsen and Thomsen 2008; Lu and Harvey 2011; Ongel et al. 2008). Some asphalt surface examples include open-graded friction courses that have good raveling resistance (such as the rubberized open-graded asphalt concrete labeled "1-4 years old RAC-O" in figure 6-9) and some SMA mixtures (Donavan 2006). In addition to raveling resistance, open-graded asphalt surfaces also need to maintain surface air permeability to exhibit their high frequency noise reducing properties. Surface air permeability is more important than average air void content in noise-reducing asphalt mixtures (Reyes and Harvey 2011; Ongel et al. 2008). Surface permeability in the wheelpaths tends to diminish with time because of filling of the surface with mineral particles, oil, and tire rubber, as well as the additional compaction caused by trafficking.

The durability of noise benefits for asphalt surface mixtures will depend on their raveling and air permeability performance. As an example, the average life of noise benefits (defined as a 2 dBA or greater overall OBSI reduction compared to a standard, dense-graded asphalt) for rubberized open-graded asphalt concrete in California is about 10 years over a range of traffic levels and climate regions, which was found to be longer than for conventional open-graded mixes which raveled at a faster rate (Lu and Harvey 2011). The Arizona DOT has reported noise benefits for high-binder content rubberized open-graded mixtures lasting approximately 8 years on freeways in the Phoenix area (Scofield and Donovan 2003).

As previously described, new concrete pavements can be constructed with a number of different surface textures, including transverse tining, longitudinal tining, broom drag, burlap drag, and turf drag. Diamond grinding or diamond grooving can also be performed at the time of construction or as a later rehabilitation or preservation measure. Of these surfaces, diamond grinding and diamond grooving have been found to be the quietest, followed by longitudinal tining. Transverse tining is generally the noisiest type of texture, as shown in figure 6-10, although there can be a fairly wide tire-pavement noise distributions within each texture type (Rasmussen et al. 2012; Rezaei and Harvey 2012). Transverse tining can produce a "whine" (tonal spike) in the middle of the frequency spectrum, at about 1000 to 1500 Hz, with the frequency at which the spike occurs being a function of both the tine spacing and the speed at which the vehicle tires are passing over them (ACPA 2006).

Longitudinal tining of concrete pavement surfaces is being more commonly used by highway agencies. The noise levels of longitudinal tining and other texture types depends in part on the amount of positive texture that they produce, and the shape and depth of the negative texture that allows air to escape from under the tire. If there is loss of mortar around the coarse aggregates in the concrete pavement surface, it can create positive macrotexture similar to that caused by raveling of asphalt surfaces, with associated increases in noise.

In addition to surface texture, other factors can also make major contributions to tire-pavement noise. For asphalt pavements, weathering/raveling of the surface increases noise levels through the creation of positive macrotexture. For concrete pavements, wide, deep sawed joints (those with high cross-sectional area) increase noise levels due to a "flute" effect (Donavan 2009), while transverse joint faulting causes a thumping noise as the tire passes over the joint (Kohler and Harvey 2010). Transverse cracks due to low temperatures or shrinkage due to aging (sometimes showing as block cracking) cause similar thumping in asphalt pavements, especially when there is collapse of the edges of the crack, or when the edges of the crack are "tented" up. For both asphalt and concrete pavement, overbanding of sealant over joints or cracks produces positive texture that can increase noise.

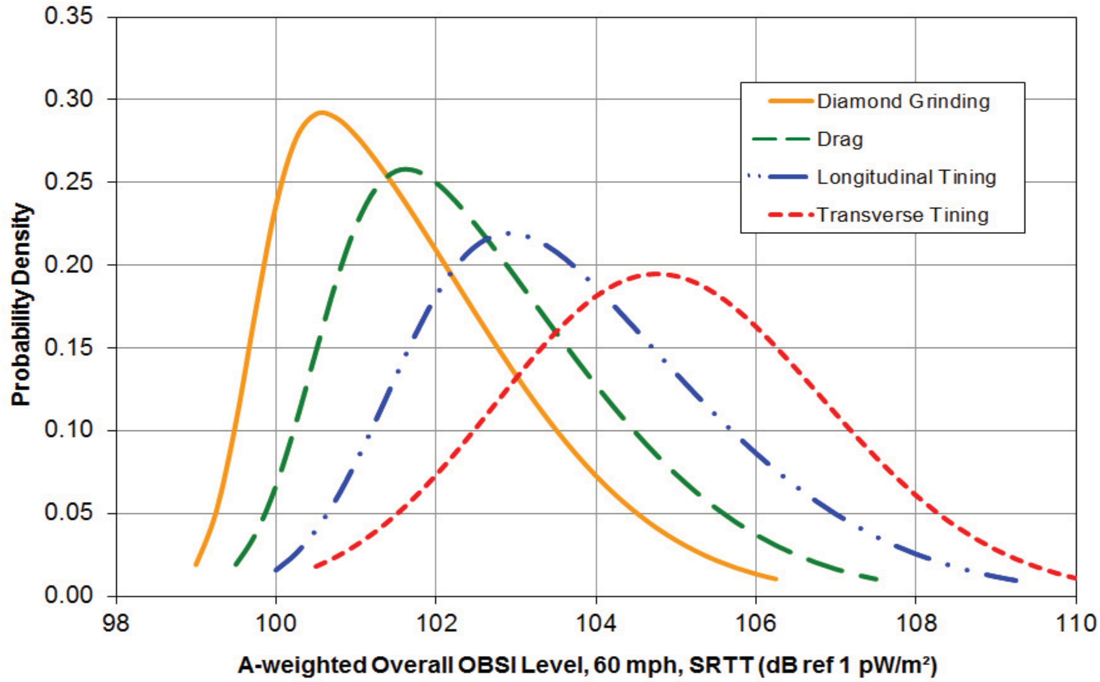

Figure 6-10. Normalized distributions of OBSI noise levels for conventional concrete pavement textures (Rasmussen et al. 2012).

The combined effects of faulting, sealing, and joint cross-sectional area can increase overall tire-pavement noise levels, and together are referred to as "joint slap" on concrete pavement (IGGA 2011). The magnitude of noise generated by joint slap can be estimated using a web tool (ACPA 2013) that considers joint geometry, existing pavement texture noise level, and vehicle speed using data from the Purdue University Tire Pavement Test Apparatus in the laboratory with some field validation at the MnROAD test track in Minnesota (ACPA 2007). Spalling of joints and cracks in all pavement types is also expected to increase noise levels.

Narrow joints and control of faulting in concrete pavement, good sealing practice (no overbanding), and good pavement preservation practices that minimize the extent and severity of cracking for both asphalt and concrete pavement will help maintain quieter pavements. Diamond grinding for concrete pavement and thin overlays (using durable polymer-modified or rubberized open-graded asphalt or SMA) for asphalt pavement are preservation treatments particularly suited to maintaining quiet pavements.

Innovative pavement surfaces are being developed based on studies indicating that negative macrotexture and paths that allow air to escape result in quieter pavements. For concrete pavement, laboratory investigations led to the development of the Next Generation Concrete Surface (NGCS), which features flush grinding (to minimize positive texture and remove faulting and old texture) and grooving (to provide passages for air and water) (Dare et al. 2009). These surfaces are under investigation in several states (Wilde and Izevbekhai 2010; Guada et al. 2013) and show some promise based on early performance, with noise levels below those of conventional diamond grinding. It has been observed that the NGCS is susceptible to accelerated wear under the action of studded tires/chains and therefore should not be used under such conditions (Anderson et al. 2014).

Figure 6-11a shows the frequency content of an example test section in three conditions: before treatment (designated as PreCDG [pre-conventional diamond grinding]), after treatment (designated as CDG [conventional diamond grinding]), and after flush grinding and grooving (designated as GnG (grinding and grooving, an NGCS texture). Figures 6-11b and 6-11c illustrate the surface textures corresponding to the CDG and NGCS treatments, respectively.

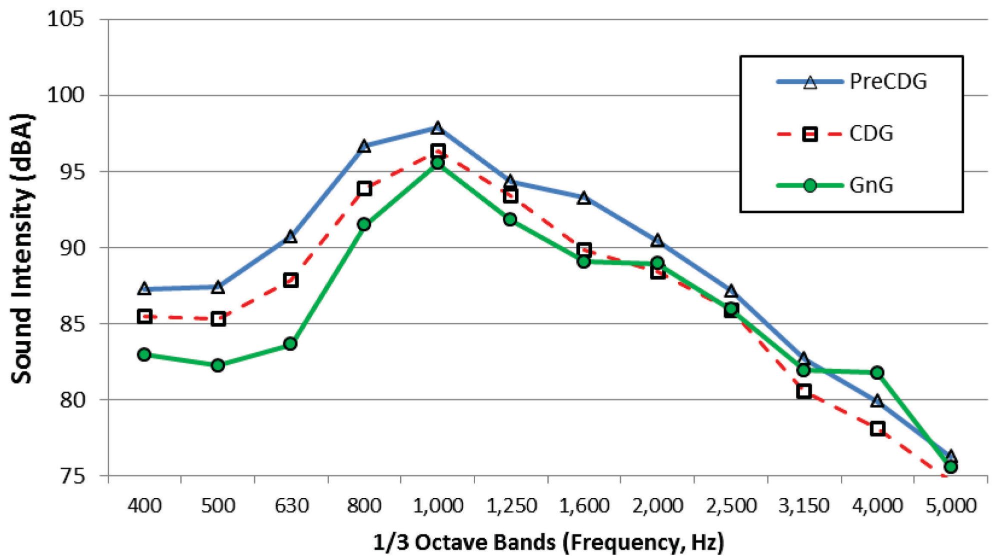

Figure 6-11 (a). Frequency content of OBSI measured at 60 mi/hr (97 km/hr) for pretreatment (PreCDG), conventional diamond grinding (CDG), and NGCS (GnG in the figure) for a California test section, Yolo 113– PM R0.5/R2.5 (Guada et al. 2013).

Figure 6.11 (b). Conventional diamond-ground surface showing "fins" that are eventually removed by traffic (Guada et al. 2013) (c). Conventional diamond-ground surface with the Next Generation Concrete Surface showing definition of "land area" between grooves (Guada et al. 2013).

Field measurements and laboratory work have led to the development of asphalt mixtures with smaller maximum aggregate sizes (passing # 4 [4.25 mm] sieve) and open gradations and air-void contents of 15 percent or more to provide air permeability. Although these have not been tested under high-speed traffic, preliminary laboratory testing (Lu and Harvey 2011; Wu et al. 2013) indicates improved raveling performance and high frequency tire-pavement noise performance compared with larger stone size mixtures (see figure 6-12a) and low-speed OBSI results on a test section indicate improved initial noise performance (see figure 6-12b).

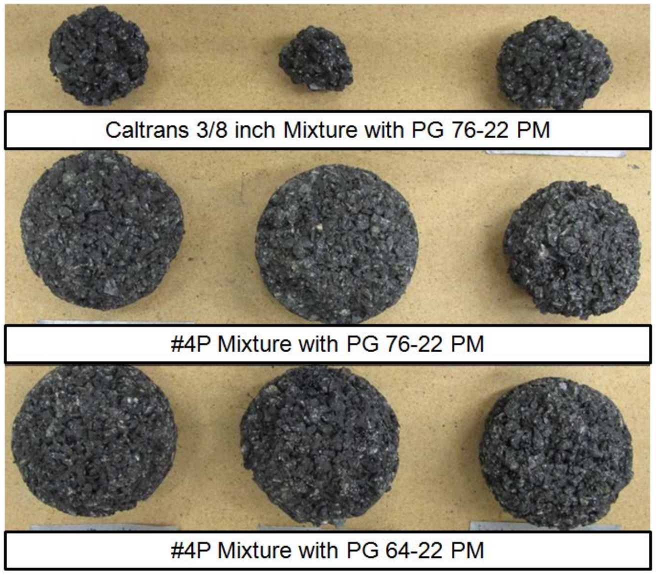

Figure 6-12 (a). Examples of residual specimens after Cantabro testing for raveling of the same OGFC mixtures (Wu et al. 2013). Each original specimen had a diameter of 4 inches (100 mm).

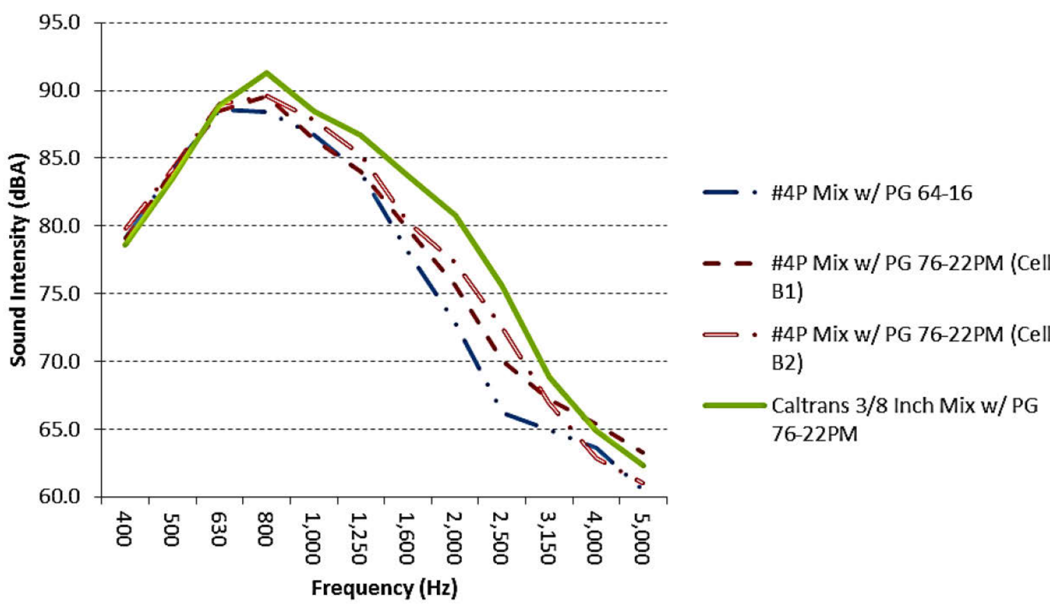

Figure 6-12 (b). Frequency content of OBSI measured at 35 mi/hr (56 km/hr) for Caltrans open-graded asphalt mixtures with typical 0.375 inch (9.5 mm) and #4 (4.75 mm) maximum aggregate sizes (Wu et al. 2013).

The Arizona DOT is currently involved in a Quiet Pavement Pilot Program (QPPP) in partnership with the FHWA. Several other states have Quieter Pavement Research (QPR) efforts underway that are producing research results such as those shown in this chapter, including California, Colorado, Florida, Texas, Virginia, and Washington (FHWA 2011c).

Strategies for Improving Sustainability

Practices that are available to pavement managers, designers, and specification developers that might be used to address tire-pavement noise are summarized in table 6-4.

Table 6-4. Summary of strategies for improving tire-pavement noise and potential trade-offs.

Tire-Pavement Noise Objective	Tire-Pavement Noise Improving Strategy	Economic Impact	Environmental Impact	Societal Impact
Reduce Noise on New and Existing Asphalt Pavements	Use durable open-graded or SMA mixtures	Open-graded mixtures generally have shorter lives than dense graded mixtures. SMA mixtures are more expensive than dense graded. Life-cycle cost analysis can be performed.	Quieter pavement benefit. Trade-offs depend on surface mixture impact and longevity. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife.
Reduce Noise on New Concrete Pavement	Eliminate transverse tining by using longitudinal textures; use quieter textures; use narrow (single-saw cut width) joints with recessed sealant if sealant is used.	Depends on alternative texture used. Generally very small cost compared to construction cost.	Quieter pavement benefit. Trade-offs depend on surface texture and longevity. Texturing generally low impact. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife. Must have adequate surface friction.
Reduce Noise on Existing Concrete Pavement	Retexture with conventional diamond grinding or NGCS	Relatively low cost treatment that also improves smoothness and removes faulting. Increased cost compared to Do Nothing.	Quieter pavement benefit. Trade-offs depend on surface texture and longevity. Texturing generally low impact. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife. Must have adequate surface friction.
Minimize Noise on Existing Pavement	Perform pavement preservation to minimize cracking, faulting and other surface imperfections that contribute to noise; use good practice for sealing to prevent overbanding	Can also reduce life-cycle cost	Quieter pavement benefit. Impact depends on traffic and interaction of smoothness and vehicle use. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife. Must have adequate surface friction.

Future Directions and Emerging Trends

The most important emerging trend in this area is the greater attention being paid to tire-pavement noise, and the increased consideration of pavement effects on highway noise in planning, traffic noise modeling, and pavement maintenance and rehabilitation design decisions.

Important future directions include the development of new materials and surface textures for concrete and asphalt that reduce noise while maintaining adequate surface friction, and the potential to set performance requirements for tire-pavement noise measured with OBSI for new construction and during long-term maintenance contracts.

Addressing Stormwater Runoff through Pavement Permeable Surfaces

Background

> ***Major Issues:***
> - ✓ *Permeable surfaces may help economically handle stormwater quality and runoff rates.*
> - ✓ *Currently best suited for low-speed, low-volume roadways and parking areas.*
> - ✓ *Requires more frequent cleaning and maintenance.*
> - ✓ *Due to runoff drained through permeable surfaces, groundwater sources may be contaminated.*

Conventional paved pavement surfaces are relatively impermeable, allowing precipitation to run off much faster than it does from vegetated or undeveloped surfaces. In addition, runoff from impermeable surfaces is often directed to stormwater collection systems and thus is not absorbed into the nearby soil. That runoff, because it does not benefit from being naturally filtered through the soil, can pollute and raise the temperature of the nearby surface waters and streams to which it is being diverted. Furthermore, the collection of runoff in this manner during high precipitation events can cause stormwater collection systems to overflow, potentially resulting in flooding and erosion because of the speed with which the runoff leaves the paved surface. In cases where the stormwater collection system is combined with the sanitary sewage system, the release of raw sewage may occur as the result of the system being overwhelmed during high precipitation events, causing significant environmental and economic impact for treatment and clean up. Finally, typical stormwater management solutions, including the reliance on retention ponds, are difficult to accommodate in areas with space constraints (such as built-up urban areas); consequently, innovative solutions to reducing road surface runoff are needed.

Research has shown that pavement materials themselves do not significantly contribute pollutants to stormwater runoff. Laboratory experiments on a range of concrete and asphalt pavements, including open- and dense-graded materials and different cement- and asphalt-binder sources (including asphalt rubber and aged specimens), showed that pollutant contributions to runoff were generally extremely low (Kayhanian et al. 2009; Kayhanian et al. 2010). From the laboratory study performed by Kayhanian et al. (2010) it was concluded that the major sources of pollutants measured from road surface runoff are mostly associated with vehicles and airborne deposition. One pollutant of concern in runoff is polyaromatic hydrocarbons (PAHs). These toxic compounds, which are primarily related to the combustion of transportation fuels and are deposited on the pavement surface through vehicle exhaust, are present at low concentrations in urban and highway runoff (Lau, Kayhanian, and Stenstrom 2005; Kang et al. 2009). It is important to note that large concentration of PAHs are reported in coal tar sealant and if these are used on a pavement then high PAH concentrations in the surface runoff would be expected (Van Metre and Mahler 2010; USGS 2011). However, the use of coal tar pitch or tar sealant are mostly isolated to residential driveways and parking lots in some regions of the U.S. and are rarely used on pavements for urban roads or highways.

Another pollutant of concern is metals. The laboratory study by Kayhanian et al. (2009; 2010) found amounts of toxic metal above the reporting limits in simulated runoff on a few of the concrete mixtures tested, which was attributed to the cement sources used. Additional information related to the type and concentration of different organic and inorganic pollutants observed from highway runoff can be obtained from a recent review article prepared by Kayhanian et al. (2012b).

Thin open-graded surfaces placed on otherwise impermeable pavements, such as thin open-graded asphalt surfacing, can help slow runoff and capture solids and pollutants, improving the quality of stormwater runoff (Pagotto, Legret, and Le Cloirec 2000; Barrett and Shaw 2007).

An innovative solution to actually reducing or eliminating runoff is through the use of fully permeable pavements, which were introduced in chapter 3. As described in chapter 3, permeable pavements can be constructed using pervious concrete, porous asphalt, or permeable interlocking pavers. Vegetated pavements have also been used effectively for low-volume traffic applications, most prominently as parking lots. All of these pavements types allow major portions of the stormwater runoff to pass through the surface and be absorbed into the underlying ground. This has the advantages of minimizing or eliminating the need for a stormwater collection system, recharging the groundwater table, filtering the runoff naturally through the soil, and reducing the direct discharge of runoff and any contaminants associated with them into nearby surface water. These applications can potentially be applied to the traveled way of the pavement, to the shoulders or strips of pavement outside the traveled way, or to parking areas.

Pervious concrete and porous asphalt pavements (see figure 6-13) are created by greatly reducing the fine aggregate fraction in a mixture, increasing the percentage of void space. In the case of interlocking permeable pavers (figure 6-14), void space is often created at the gaps between the pavers, and these voids are filled with permeable aggregate. For porous asphalt, the same mixtures used for thin surface open-graded layers can also be used for fully permeable pavements. With the increase in void space, rainwater can drain through the surface into a base/storage layer designed for hydraulic performance to retain the design rainfall, from where it seeps into the ground reducing the amount of runoff while recharging the groundwater. The natural filtering that occurs in the soil removes the majority of particle-bound inorganic and organic contaminates, but there may be an increased risk of groundwater contamination from regulated dissolved pollutants and thus it is not recommended to construct permeable pavements in locations near drinking groundwater supplies (EPA 1999).

Figure 6-13. Pervious concrete (left, courtesy John Kevern) and porous asphalt (right, courtesy National Asphalt Pavement Association).

Figure 6-14. Permeable interlocking concrete pavers (courtesy Interlocking Concrete Pavement Institute).

Another permeable pavement solution is the use of vegetated pavement. Vegetated pavements, an example of which is shown in figure 6-15, use a lattice of concrete, plastic, or metal to provide stability while vegetation is encouraged to grow between the lattices. The vegetation allows for a more natural infiltration of stormwater runoff and also can provide a more visually appealing surface compared to hard surfaces. Vegetated pavements can have comparable load-carrying capacity to conventional pavements, but are typically used in low-traffic conditions such as alleys, parking lots, residential streets, and trails in order to minimize damage to the vegetation. Also, they are best suited to climates with adequate summer moisture to keep the vegetation alive (EPA 2008).

Figure 6-15. Vegetated pavement (photo courtesy of Soil Retention Products, Inc.).

Water that passes through the pavement surface and is stored below the surface can also reduce pavement temperatures by means of evapotranspiration, where the heat that is stored in the pavement is released through the conversion of the stored water into water vapor. There is also significantly more surface area associated with the increased void space and thus the increased exposure to air increases the heat conductivity of the pavement. Consequently, permeable pavements (whether pervious concrete, porous asphalt, permeable interlocking pavers, or vegetated pavements) can be used in urban areas to help alleviate the need for other stormwater management devices such as retention ponds, sand filters, and swales (PCA 2011).

At the present time, the EPA (2010b) cites the use of pervious concrete and porous asphalt pavements as a Best Management Practice (BMP) for handling stormwater runoff on a local and regional basis. The majority of current pervious concrete and porous asphalt pavements are used as BMP in low-traffic, low-speed applications, such as shoulders or parking lots. When using these types of pavements, they need to be regularly maintained (typically using vacuum cleaning machines with no sweeping) in order to ensure continuous infiltration with no or minimum surface overflow. Surface infiltration can be measured through permeability measurements. In one recent study, the surface permeability of 20 pervious concrete and porous asphalt parking lots were measured in California and the results showed a large variability within each parking lot and among all parking lots, although localized impermeability did not affect the overall drainage of the facilities (Kayhanian et al. 2012a). The permeability value was directly related to the age of pavement as the older pavements had lower infiltration rates. The lower permeability in older permeable pavements was suspected to be impacted by particles from atmospheric deposition or from surrounding area soil erosion. Some densification under truck loads at hot temperatures may have contributed to reduced permeability in the porous asphalt materials in addition to clogging.

A similar study was performed on 40 permeable pavement sites in North Carolina, Maryland, Virginia, and Delaware (Bean et al. 2007). Again, localized low permeability was observed but often it did not hinder the overall performance of the facility as long as there was also localized areas with high permeability. In another study on open-graded asphalt under accelerated pavement testing, the addition of particles on the pavement surface was found to be partially responsible for surface void and permeability reductions; however, most of the void and permeability reduction was due to densification and rutting under loading (Coleri et al. 2013).

The use of permeable pavement for stormwater runoff management may not necessarily be limited to parking lots and other low-traffic or low-speed facilities. Preliminary research, although not yet validated by field sections or accelerated pavement testing, indicates that it may be possible to design and construct permeable pavements for the highway environment. For example, one innovative approach on a high-speed or high-volume roadway is to retrofit the shoulders of the impermeable pavement with a permeable pavement to capture the runoff from the impermeable mainline pavement. The technical feasibility of this design concept was recently simulated by researchers and the results of both structural and hydraulic performance simulations are reported by Li, Harvey, and Jones (2012) and by Chai et al. (2012), respectively. Extended periods of saturation of moisture-sensitive subgrade soils is a major concern for the design of permeable pavements to carry heavy loads. The simulation results indicated that thick layers of crushed permeable aggregate are needed to reduce shear stresses to acceptable levels at the surface of saturated clay subgrades.

One critical design consideration is that care must be taken to prevent water stored in the fully permeable shoulder from infiltrating back into the pavement layers and the subgrade of the adjacent impermeable pavement. Several example designs of permeable pavements for highway shoulder retrofits were proposed and simulated (and not yet validated by field or accelerated pavement testing sections) under heavy truck traffic at low to medium speeds and found to be technically feasible (Li, Harvey and Jones 2012). The study recommends that test sections be evaluated using APT or in actual field trials. The use of a full-depth permeable shoulder retrofit for highways was also recently investigated as part of an NCHRP project (Hein et al. 2013). As part of that study, several conceptual designs are proposed (not validated) and recommended for further investigation and verification under pilot and field conditions.

In addition to the benefit gained for stormwater management, other added benefits regarding the use of both porous asphalt surfaces and fully permeable asphalt, concrete, and paver pavements are improved surface friction and safety during rainstorms due to the open-graded surface. There may be noise benefits as well, although only open-graded asphalt materials have been evaluated for noise performance and the noise performance of pervious concrete and permeable interlocking pavers has not been evaluated. There are also reported water quality benefits from the use of various kinds of permeable pavements (Barrett, Kearfott, and Malina 2006; Bean, Hunt, and Bidelspach 2007; Brattebo and Booth 2003; Roseen et al. 2012; Sansalone, Kuang, and Ranieri 2008). In addition, Roseen et al. (2012) reported that lower salt application is required for the porous asphalt pavements investigated and no adverse freeze-thaw effects were observed in cold climates; for that reason, the life span of porous asphalt is expected to exceed that of typical pavement applications in cold climates. The concern about freeze-thaw resistance is also often raised for permeable concrete pavements, but testing and performance has shown mixtures with good freeze-thaw performance can be achieved through the proper fine aggregate grading, coarse aggregate absorptivity, and possible use of fibers (Kevern et al. 2008; Kevern et al. 2010). Freeze-thaw deterioration would generally not be expected to be a concern for permeable paver pavements unless the pavers themselves have high permeability.

There are a number of trade-offs to evaluate when considering the use of permeable pavements, including the potential for clogging, the additional cost of construction and cleaning, and potential moisture damage. The cost consideration is related to the underlying permeable aggregate layer used as the reservoir that causes the pavements to be more expensive than conventional pavement construction. This increased cost can often be overcome when considering the value of the land that would be needed for use as a retention basin (or other stormwater management requirements) (NAPA 2008). Another consideration is the maintenance of the permeable surface, which typically consists of vacuum sweeping and is essential to prevent dust and other particle matter from clogging the surface and rendering the pavement ineffective (Levine 2011). However, a preliminary analysis of life-cycle costs indicated that a full-depth permeable shoulder retrofit for highways is economically justifiable for stormwater management compared to conventional BMPs (Jones et al. 2010). In addition, a study performed by Houle et al. (2013) concluded that low impact development (LID) systems (including permeable pavements) generally have lower marginal maintenance burdens as measured by cost and personnel hours when compared to conventional treatment systems.

Care must be taken in the design of permeable pavements, particularly asphalt pavements, to minimize long-term saturation that would otherwise weaken the surface layers; however, water draining through these layers should not cause problems. Therefore, hydraulic design should aim to keep the water level in the pavement below the surface layers most of the time. The use of rubber-modified or polymer-modified binders and anti-stripping additives may help extend the life of open-graded asphalt mixtures. A study performed by Liu and Cao (2009) demonstrated that permeable pavement mixtures with typical neat asphalt were prone to be seriously damaged by water, whereas high-viscosity binders demonstrated better resistance to moisture damage, rutting, and raveling.

Strategies for Improving Sustainability

Practices available to pavement managers, designers, and specification developers that can be used to address stormwater runoff issues are provided in table 6-5.

Table 6-5. Summary of strategies to address stormwater runoff issues and potential trade-offs.

Stormwater Runoff Objective	Stormwater Runoff Improving Practices	Economic Impact	Environmental Impact	Societal Impact
Increase Structural Capacity for Application in High-Speed, High-Load Areas.	Pervious concrete. Porous asphalt.	Increased initial cost over comparable impermeable concrete and asphalt. Cost of handling and treating stormwater may be less than other BMP.	Improved stormwater quality. Impact on other impact categories has not been evaluated.	Uncertain.
	Permeable pavers.	Not applicable for high-speed applications.	Not applicable for high-speed applications.	Not applicable for high-speed applications.
	Vegetated pavement.	Not applicable for high-speed applications.	Not applicable for high-speed applications.	Not applicable for high-speed applications.
Create Lower Maintenance Permeable Pavement Surfaces.	Pervious concrete. Porous asphalt. Permeable pavers.	Research is still underway to develop improved durability without sacrificing hydraulic performance, and to develop better structural designs. Trade-offs between initial and life-cycle costs to be determined.	Longer life pavement designs should reduce environmental impact of materials production and construction.	Longer life pavement designs should improve societal impact of repeated construction.
	Vegetated pavement.	Improved designs for vegetation selection and management should reduce economic, environmental (water use) and societal impacts.	Improved designs for vegetation selection and management should reduce economic, environmental (water use) and societal impacts.	Improved designs for vegetation selection and management should reduce economic, environmental (water use) and societal impacts.
Understand the Potential for Ground-water Contamination.	All permeable pavement types.	Investment required in research to determine level of risk and mitigation approaches, although initial results positive.	Uncertain. Once the level of risk is fully assessed it can be weighed against alternatives, as needed.	Uncertain. Once the level of risk is fully assessed it can be weighed against alternatives, as needed.

Future Directions and Emerging Trends

One major initiative in the stormwater management area is integrating permeable pavements into urban designs, with benefits including reduced runoff, improved water quality, and the potential to reduce the localized urban heat island (UHI) effect through evaporative cooling. This is still under investigation. In addition, coupling permeable pavement surfaces with photocatalytic additives and/or coatings is also being studied, particularly with pervious concrete pavement and permeable interlocking concrete pavers. The presence of voids inherent in these surfaces increases the photocatalytic area exposed to the atmosphere, thus increasing the photocatalytic efficiency per unit of pavement surface area.

There is strong interest in using permeable pavement surfaces as part of mainline pavement construction. The initial effort thus far has been in parking areas and on mainline pavement shoulders, but work continues on evaluating designs that can perform well under heavier traffic loadings.

Scholz and Grabowiecki (2007), among others, have introduced the idea of developing a heating/cooling system that can be installed within the subbase of modern permeable pavement systems in urban areas. The energy gained from the below-ground pump can be used as a substitute for energy derived from fossil fuel and hence has the potential for reducing CO_2 emissions. The research suggests that the development of a combined geothermal heating and cooling, water treatment, and recycling pavement system is promising (Scholz and Grabowiecki 2007).

Pavement Thermal Performance and Contribution to Urban and Global Climate

Pavement Properties Affecting Thermal Performance

The thermal performance of a pavement is defined as the change in its temperature (most often surface temperature) over time as influenced by properties of the paving materials (e.g. albedo, thermal emittance, thermal conductivity, specific heat, and surface convection) and by the ambient environmental conditions (sunlight, wind, air temperature). It can also be influenced by evaporative cooling, which is related to ambient conditions, permeability, and the availability of near surface water (most often a factor if fully pervious pavement systems are used).

Albedo (or solar reflectance) is a measure of the ability of a surface to reflect solar radiation. Solar reflectance values range from 0 (no sunlight reflected) to 1 (all sunlight reflected). Light-colored materials generally have higher solar reflectance values than dark-colored materials, although color alone is not the only indicator of solar reflectance (NCPTC/NCAT 2013).

Emittance is the efficiency with which a surface emits radiant energy, and is defined as the ratio of energy radiated by the surface to the energy radiated by a black body (a perfect absorber and emitter) at the same temperature. Emittance ranges from 0 (no emission) to 1 (perfect emission). Thermal emittance is the emittance of a surface near 300 K (81 ºF or 27 ºC). Most nonmetallic surfaces have thermal emittances in the range of 0.80 to 0.95. The thermal emittances of dense-graded concrete and asphalt are similar, being in the range of 0.90 to 0.95.

Thermal conductivity is a measure of the ability of a material to conduct or transmit heat. It is the ratio of heat flux (power per unit area) to temperature gradient, and is expressed in units of W/m•K. A material with a high thermal conductivity will transfer heat at a higher rate than a material having a low thermal conductivity. The thermal conductivity of pavement materials varies widely in the reported literature from 0.8 W/m•K to 2.0 W/m•K or greater, with similar values reported for dense-graded asphalt and concrete.

Specific heat is the energy needed to raise a unit mass of a substance by one unit of temperature, typically expressed in units of J/kg•K. The specific heat of dense-graded asphalt and concrete are very similar, being about 900 J/kg•K.

Of these material properties, albedo is the most important with regards to how pavements interact thermally with the environment when exposed to sunlight. Thermal emittance, thermal conductivity, and specific heat capacity of the materials are second order factors (Li et al. 2013). However, as will be discussed, understanding the thermal characteristics of the pavement materials alone is insufficient to fully understand how pavements thermally interact with the urban and global environments.

The means by which solar radiation warms a pavement surface, the underlying layers, and the surrounding atmosphere during the day and then releases the absorbed energy as heat at night is illustrated in figure 6-16 (NCPTC/NCAT 2013). During the day, the pavement's surface will reflect some of the incident sunlight and absorb the rest. The absorbed solar energy is emitted as long-wave radiation from the pavement, convected to the air moving over the pavement, conducted into the pavement and ground below, and/or dissipated by evaporation of water. Some of the solar energy stored in the pavement during the day is released at night through emitted long-wave radiation and convection, and some is released laterally to cooler zones through conduction.

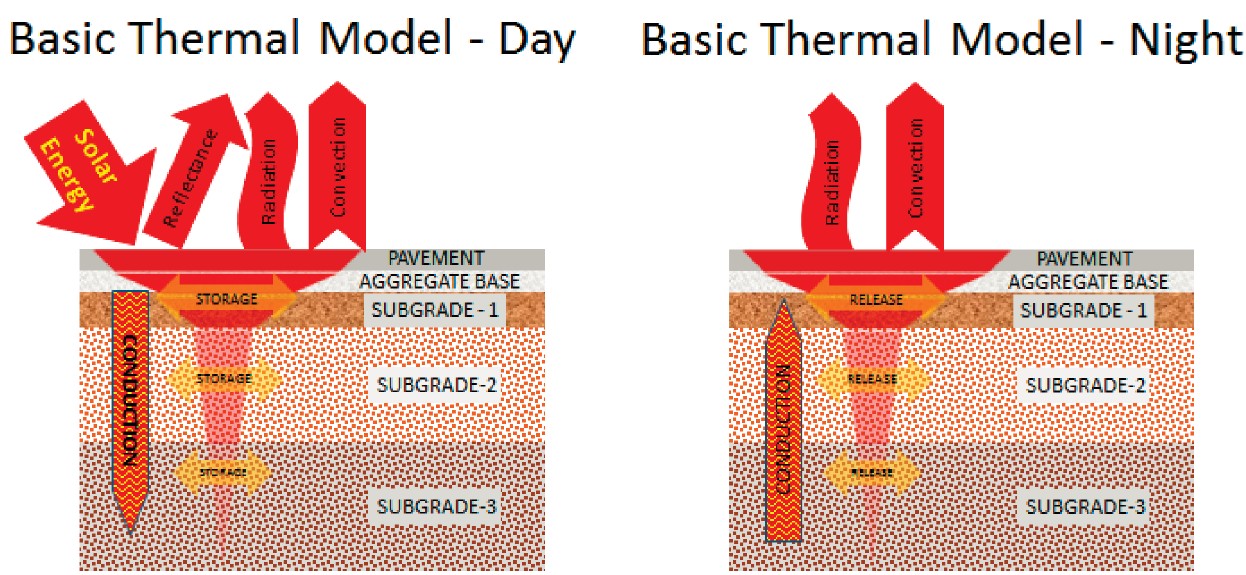

Figure 6-16. Heat flow and the basic thermal model for day and night (NCPTC/NCAT 2013).

The thermal emittance, thermal conductivity, and specific heat of common paving materials are influenced by their density (which is largely controlled by mixture porosity and aggregate type and gradation), the amount of binder (cement, asphalt or other materials) if they are present, and the moisture content (Li et al. 2013). As discussed, the thermal emittance, thermal conductivity, and specific heat of common dense-graded paving materials are similar and therefore differences in the thermal performance of pavements are largely the result of differences in albedo. It is noted that many additional factors contribute to how pavements interact thermally with their surroundings, which is the focus of the remaining discussion of this section.

Urban and Global Warming Effects

The Urban Heat Island Effect

On a summer afternoon, urban areas are generally warmer than surrounding rural locations (Jones et al. 1990), as illustrated in figure 6-17 (EPA 2003). This urban–rural air temperature difference, known as the urban heat island effect (UHIE), is driven by a variety of factors including the prevalence of dark, dry surfaces in cities and heavily urbanized locations.

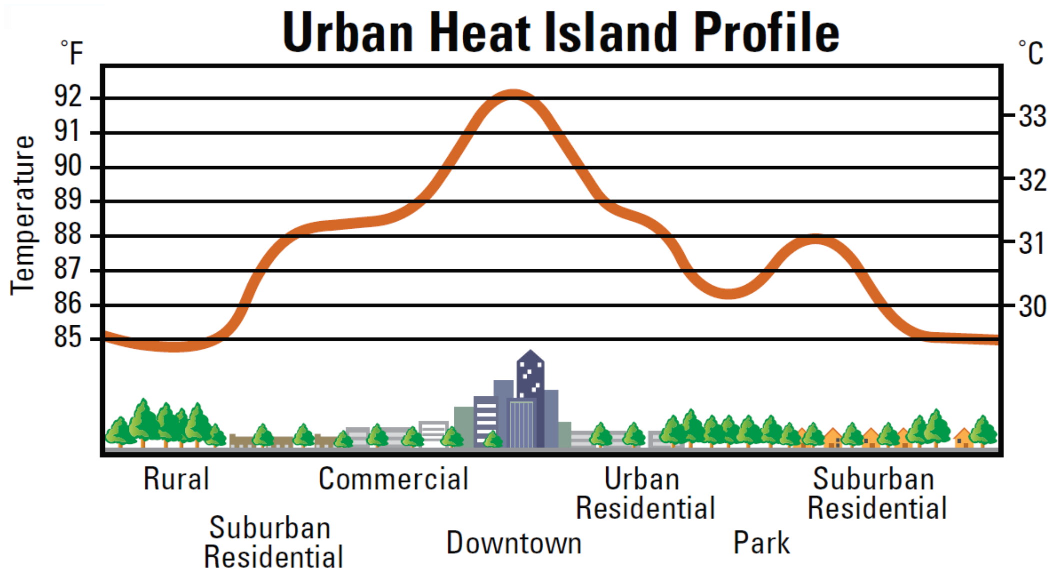

Figure 6-17. Heat islands for various areas of development (EPA 2003).

Although urban heat islands (UHIs) are most often thought of as existing in the atmosphere above the city, they actually exist at many different levels, including at the ground/pavement surface, in the air just above the surface (near-surface), and in the ambient air temperatures well above street level, as well as in the atmosphere above the city. In many cases, it is convenient to consider near-surface heat islands, which are characterized by increased ambient air temperature just above the ground/pavement surface, typically at 3 to 6 feet (1 to 2 m) where human outdoor activities occur (Li et al. 2013). Surface and near-surface heat islands can potentially affect human thermal comfort, air quality, and energy use of buildings and vehicles. Atmospheric heat islands can affect communities by increasing summertime peak energy demand, electrical grid reliability, air conditioning costs, air pollution and GHG emissions, heat-related illness and death, and water quality.

As illustrated in figure 6-17, the rise in the temperature of man-made urban areas is quite noticeable compared with the other land uses. Although heat islands may form on any rural or urban area, and at any spatial scale, cities are favored since their surfaces are dark and dry, which increases solar heat gain and reduces evaporative cooling.

The increased air temperatures associated with UHIs can contribute to greater energy demands (and the associated environmental impacts of increased electrical energy production) when and where increases in air temperatures result in greater use of air conditioning to cool buildings. In places that are already burdened with high temperatures, the UHIE can make cities warmer, more uncomfortable, and occasionally more life threatening (FEMA 2007). Furthermore, increases in temperature increase the probability of formation of ground-level ozone (commonly called smog), which exacerbates certain respiratory conditions such as asthma. Thus, it is believed that in most urban environments any potential benefits that might be derived from the UHIE (such as reduced winter heating requirements) are outweighed by their otherwise negative effects of extreme summer temperatures that can lead to increased air pollution, increased energy use for air conditioning, increased CO_2 emissions, and adverse health and economic impacts (Navigant Consulting 2010).

It is estimated that paved surfaces for travel, parking, and pedestrian use can account for around one-third of the land surface area in urban areas. Multiple studies have concluded, through simulation modeling, that low solar reflectance of paving materials can contribute to the formation of urban heat islands (Akbari, Rose, and Taha 1999; Taha, Konopacki, and Gabersek 1999; Rose, Akbari, and Taha 2003; Rosenzweig et al. 2006; Millstein 2013; Li et al. 2013; Santamouris 2013). Although research has demonstrated through the evaluation of satellite imagery the efficacy of using reflective roofs to lower urban temperatures in a city such as Chicago (Mackey, Lee, and Smith 2012), field data demonstrating the extent that pavement surface albedo contributes to the UHIE have not been found in the literature. This is partly because the relationships between the contribution of pavement surface albedo and the UHIE are complex and as of yet not fully defined due to urban areas having differing sizes, pavement densities, tree canopies, building patterns, latitudes, and climates (Navigant 2010). Furthermore, factors such as building ordering and heights create three-dimensional “urban canyons” that impact the flow of air through the urban environment and appear to have a significant effect on urban warming (Sobstyl 2013). And as pavements are for the most part at ground level, they are often shaded by buildings and trees in an urban environment.

To address these shortcomings, many simulation efforts have incorporated urban canopy models (UCMs) that accommodate the effects of urban canyons and complex urban morphology (Taha 2008a; Taha 2008b; Chen et al. 2011; Li and Bou-Zeid 2014; Li, Bou-Zeid, and Oppenheimer 2014). The most sophisticated models recognize the three-dimensional nature of urban surfaces, taking into account the impacts of vertical surfaces (walls) and horizontal surfaces (roofs and pavements) and considering shadowing, reflections, and radiation trapping in urban canyons (Chen et al. 2011). The exchange of energy between building interiors and the outside atmosphere can also be modeled to evaluate this important interaction. The model sophistication is such that calculations can be made on overall building energy consumption due to air conditioning and interior artificial lighting needs. These simulation efforts will continue to improve in complexity through better resolution and incorporation of even more sophisticated models, likely resulting in more definitive results focused exclusively on the impact of pavement albedo on the UHIE.

Published studies have evaluated the effect of changing both the albedo of roofs and pavements together, and as a result the impact of changing pavement albedo alone cannot be easily interpreted (Taha 2008a; Taha 2008b; Li et al. 2013). However, at least one study has been published that included the modeling of the urban canyon in which only the pavement albedo has been altered. In that study, Hamdi and Schayes (2008), when simulating the city of Basel, Switzerland, found that a mid-day summer temperature reduction of 1.1 °F (0.6 °C) could be obtained when the albedos of the road surfaces in the city were increased from 0.08 to 0.30. The effect of the urban canyon was investigated, showing that narrower streets with higher buildings resulted in a decrease in UHIE due to shadowing. Still, much more work is needed to determine to what degree pavement albedo alone has on the UHIE in typical North American cities. Efforts employing these sophisticated models to solely evaluate the effect of pavement albedo within a realistic range (0.05 to 0.50) are currently underway in California (CARB 2013).

With regards to the effects of pavements being shaded, pavement albedo is most relevant with regards to warming the pavement if the surface is exposed to direct solar radiation. Thus, not only is shading from buildings and trees relevant, but so is cloud cover and latitude. Figure 6-18 shows the average June flat plate solar radiation map of the U.S. illustrating that the southwestern U.S. has some of the highest annual levels of solar radiation nationally (as well as worldwide), whereas other areas of the country have far less (NREL 2012). June was chosen in this figure as it is the month where solar radiation is most direct, and is also a month where the UHIE becomes most relevant in many North American cities. Similar solar radiation trends exist monthly throughout the year.

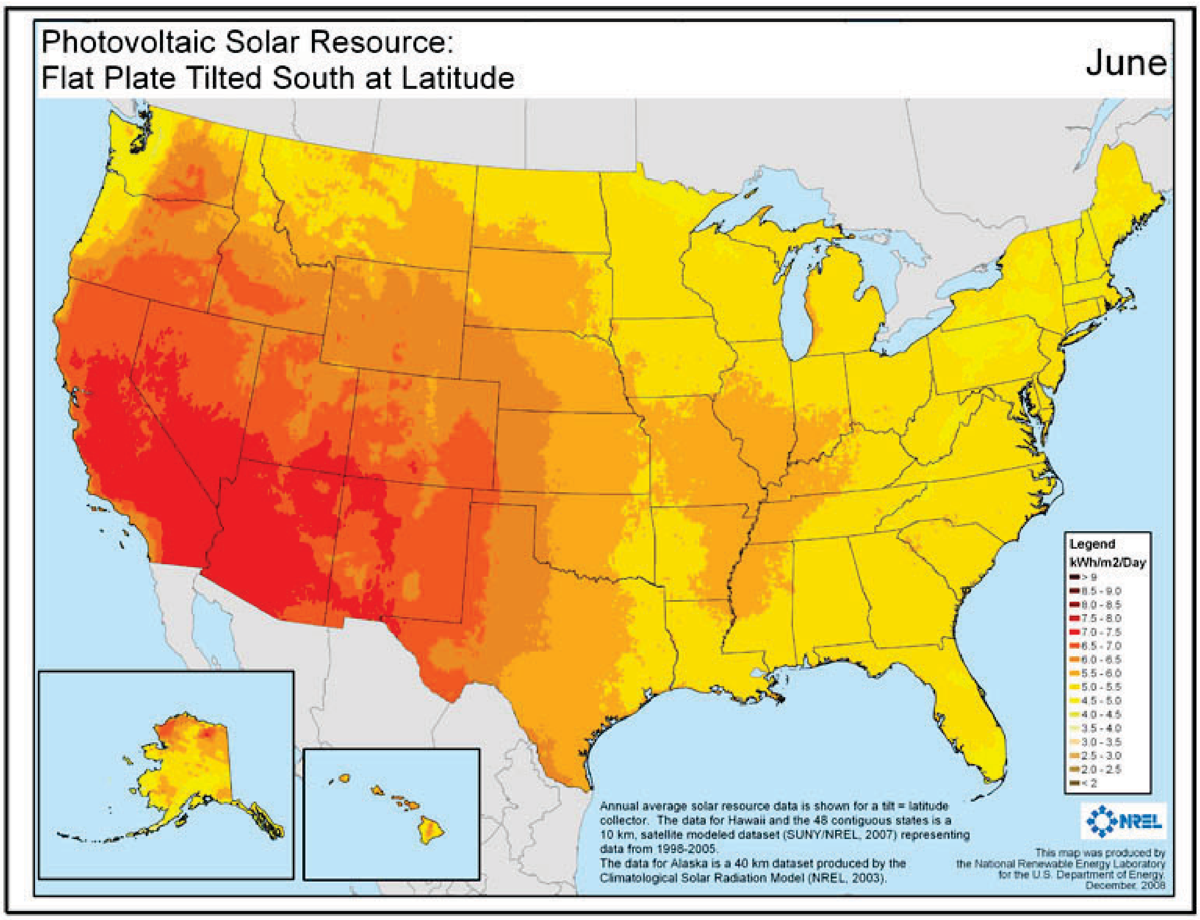

Figure 6-18. Average June horizontal flat plate solar radiation map of the U.S. (NREL 2012).

Figure 6-18 illustrates why the impacts of pavement albedo (with all other factors held constant) would be far greater in Phoenix compared to cities such as Chicago or New York. To some degree, this is reflected in the literature as a number of papers on the UHIE have been published focusing on Phoenix and on cities in California. On the other hand, there are also papers discussing the effectiveness of cool roof and pavements in Chicago (Mackey, Lee, and Smith

2012), New York City (Rosenzweig et al. 2006), and for many other regions in the U.S. (Taha, Konopacki, and Gabersek 1999), all of which demonstrated a reduction in their UHIE through the use of reflective surfaces. As another example, Li, Bou-Zeid, and Oppenheimer (2014) modeled a heat wave that occurred in the Washington-Baltimore metropolitan area in June 2008 showing that more reflective roofs and pavements could have helped mitigate some of the UHIE. This illustrates the importance of considering location and local climatic conditions, including singular events such as heat waves, when evaluating the impact of pavement albedo on the UHIE.

It is also apparent in the literature that simply reflecting more light off of paved surfaces in an urban environment may have unintended negative impacts. For example, a study modeling the impact of increasing the albedo of impermeable surfaces from 0.15 to 0.5 found that although this strategy was the most effective at reducing urban surface and near surface air temperatures, at periods of high sun (noon) it had a negative impact on modeled human comfort (Lynn et al. 2009). This is because although the pedestrian on a higher albedo surface experiences a reduction in thermal radiation due to the reduced pavement and near surface air temperatures of the high albedo surface, the increase in reflected solar flux is greater resulting in an increase in the effective temperature experienced.

In another example, a modeling study investigating reflective pavements (albedo of 0.5) found that although a small decrease in urban air temperature could be realized, high pavement reflectivity actually contributed to increased building energy use for summer cooling, especially for pre-1980 buildings constructed in Phoenix in areas having certain urban configurations (Yaghoobian and Kleissl 2012). In an associated press release, the authors state that the biggest increase in cooling energy use would be incurred in office park settings with older mid-rise office buildings that have large expanses of windows and do not have solar-control coatings (UCSD 2012). The press release also stated that this additional cooling energy could potentially be offset by utilizing the additional natural reflected lighting as one watt of daylight replaces up to two watts of fluorescent lighting, which could reducing electrical energy consumption and also cooling needs by reducing interior heating from the artificial lights. The authors concluded by stating further study is needed to quantify these potential savings (UCSD 2012).

Experimental results from Li (2012) conducted on a paved test site in Davis, California found that a more reflective surface reduced the paved surface temperature by 27 °F (15 °C) as compared to a less reflective surface on a hot summer day; however, it was also observed that the temperature of an adjacent painted wall (albedo around 0.3) was actually 5 °F (3 °C) warmer for the reflective versus the non-reflective pavement surface. The basis of these observations is found in the heat flow schematic presented in figure 6-16. Raising pavement albedo increases the short-wave flux incident on a nearby vertical surface, such as a wall or vehicle, but decreases the long-wave flux incident on the surface. The change in the surface's overall radiative heat gain will depend on the albedo and thermal emittance of the vertical surface.

In this context, some recent studies have questioned the overall regional and global climate impact of using highly reflective surfaces in urban areas, including roofs and pavements. Although these studies universally acknowledge that increasing the average urban albedo will reduce local air temperatures, the broader regional and global climate impacts are less clear. For example, Jacobson and Ten Hoeve (2011) used global climate simulations to conclude that white roofs would be expected to reduce local urban temperatures, but may result in a "net effect on globally-averaged temperatures that may be warming," although it is stated that a great amount of uncertainty still exists regarding this conclusion. The biggest effects were due to a decrease in cloud cover resulting from the stabilization of air masses over the city, which in turn reduced cloud cover and precipitation away from the urban areas. This had the net result of increasing the incidence of solar radiation in the affected regions and decreasing soil moisture.

In another paper, Millstein and Menon (2011) used a fully coupled regional climatic model and compared the results to previous work conducted at the Lawrence Berkeley National Laboratory (LBNL) that did not include coupling of the land-surface model to the atmospheric circulation scheme. The results found increased regional variability, characterized by a general cooling of the urban areas investigated but with some regional warming influences in rural areas that in some cases were significant. Even with the increased variability, the researchers concluded that the improved modeling showed greater normalized temperature reductions overall compared to past studies, although broader climatic effects were acknowledged. As climatic models continue to improve, the potential trade-offs between urban and surround rural areas, as well as broader regional and global effects, will be better understood and improved decisions can be made regarding the circumstances (e.g., climate, location, surface hydrology, emission profiles, chemistry transport) in which increasing the surface albedo of a city can have a net positive impact.

The majority of the analyses of the UHIE and the role of pavements has focused primarily on pavements with high albedo. To fully understand the impact of pavement strategies to address the UHIE, all pavement life-cycle phases must be considered, including material acquisition and pavement construction, while factoring in the longevity of the pavement treatments specifically directed at increasing albedo. A research project is currently underway, funded by the California Air Resources Board and the California Department of Transportation, to perform an LCA for implementation of high albedo pavement strategies in different cities and climate regions compared to normal practices (CARB 2013).

In summary, the degree to which pavement albedo contributes to the UHIE depends on a variety of local variables. All things equal, the surface of pavements with lower solar reflectivity (albedo) will become hotter when exposed to solar radiation. But the complexity of the urban fabric and local conditions make it difficult to ascertain what the overall impact of pavement albedo is on the development of the atmospheric UHIE. Further, the impact of reflective pavements on the overall energy balance of nearby buildings is yet to be resolved. Research strongly suggests that localized cooling can be achieved in certain urban areas by increasing average albedo of roofs and pavements, but the broader regional and global climatic impacts of uniformly increasing urban albedo are unclear. The variation in cooling potential will depend on local urban properties such as pavement area, shading, and building height, as well as on regional weather patterns.

As a result, cooling potential may be negated in locations where complex interactions exist between urban heating and cloud formation, which leads to decreased cloud formation as urban albedo increases. This effect could also result in some downwind rural areas experiencing low levels of surface warming due to increases in urban albedo. Climatic modeling efforts are being directed at developing a better understanding of the context in which the application of cool pavement strategies is justified for specific urban areas.

Radiative Forcing

In addition to UHIEs, there is a growing body of knowledge that relates planetary solar reflectance to global warming as a result of changes in radiative forcing. The concept of radiative forcing is fairly straightforward, but in practice it is a very complex phenomenon. A complex and complete definition of radiative forcing was presented by the Intergovernmental Panel on Climate Change (IPCC 1996), stating that radiative forcing is "the change in net (down minus up) irradiance (solar plus irradiance long-wave; in W•m^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values." A common and more accessible definition is that radiative forcing is the difference between the radiant energy received by the earth and the energy radiated back into space (Wikipedia 2014).

Basically, solar energy is constantly flowing into the atmosphere on half of the Earth's surface. Some of this sunlight (about 30 percent) is reflected back to space and the rest is absorbed by the planet. Like any warm object in cold surroundings, some of the absorbed energy is radiated from the Earth back into space as long-wave (thermal infrared) radiation. A positive forcing (more incoming energy than outgoing) warms the system, while negative forcing (more outgoing energy than incoming) cools it. The factors contributing to radiative forcing are many, complex, and often interact with each other. They including the natural incoming solar irradiance (which changes with solar activity), atmospheric aerosols, GHGs, cloud microphysics, and changes to the land surface (Cubasch et al. 2013). The latter two categories (changes to the atmosphere and land surface) are influenced by both natural processes and human activities. The contribution of pavements to radiative forcing lies primarily in changes to the land surface by changing surface albedo, as illustrated in figure 6-19 (Cubasch et al. 2013).

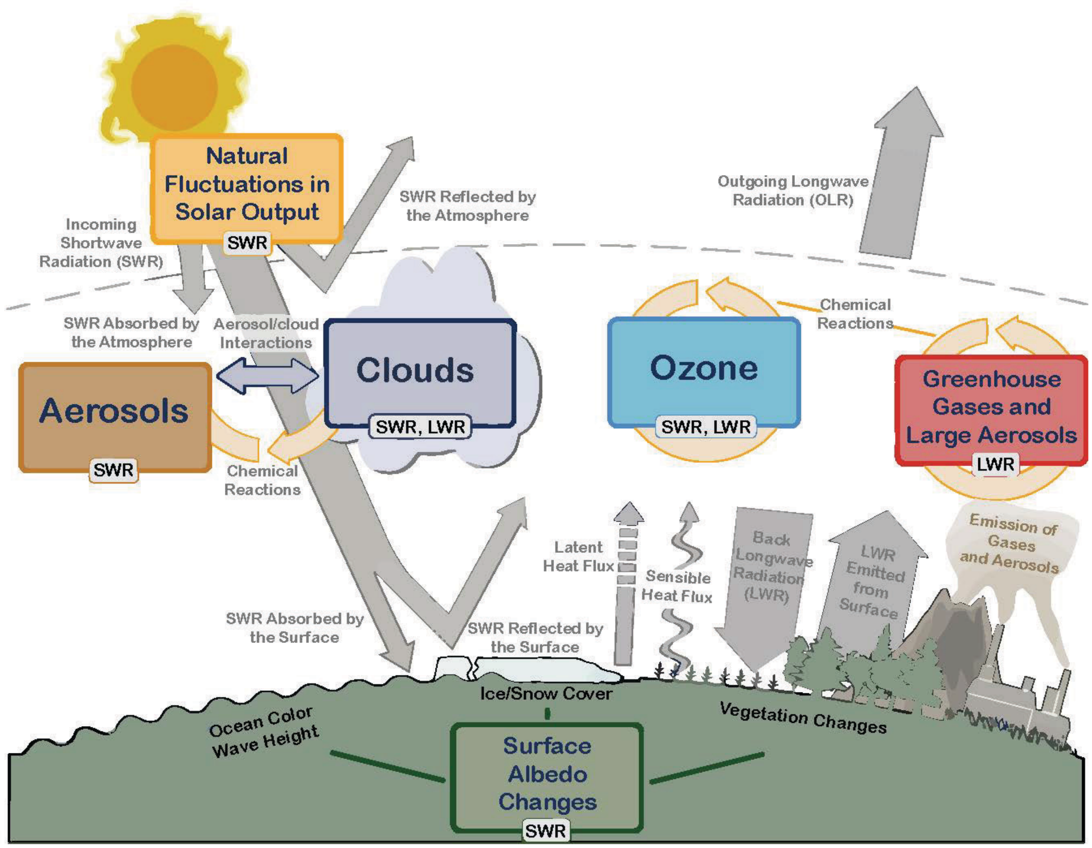

Figure 6-19. Illustration of the main drivers of climate change (Cubasch et al. 2013).

Although much of the work conducted on the contribution of pavements to radiative forcing has focused on urban areas (since those are most affected by human development), radiative forcing is considered in addition to the UHIE because it is a factor wherever the land surface albedo has been changed through human activity. Multiple studies have used modeling to demonstrate how increasing roof and pavement albedo (increasing reflection of sunlight to space) can reduce urban solar heat gain, lower urban surface temperatures, and thereby decrease both convection and thermal radiation of heat into the atmosphere (Akbari, Menon, and Rosenfeld 2009; Millstein and Menon 2011; Akbari and Matthews 2012). Related work concluded that the global warming mitigation effect of increasing the average albedo of urban environments worldwide by 0.1 could be on the order of 49 billion short tons (44 Gt) of CO_2 (Menon et al. 2010). Roughly 55 percent of this benefit (27 billion short tons [24 Gt]) would result from increasing the albedo of roofs by at least 0.25, whereas the remainder would derive from increasing the albedo of pavements by at least 0.15 for roadway and parking surfaces. These prospective savings equate to almost an entire year's estimated anthropogenic CO_2e emissions (roughly 50 billion short tons [45 Gt] CO_2e). Follow-up work, focusing on the continental U.S. and using a fully coupled regional climatic model joining the land-surface model to the atmospheric circulation scheme, found increased regional variability but concluded that overall even greater impacts could be achieved by increasing the average urban albedo of horizontal surfaces (Millstein and Menon 2011).

On the other hand, conclusions drawn in another paper found that an increase in average surface albedo will result in less local cloud cover, thus actually increasing local incident solar radiation and potentially contributing to global warming (Jacobson and Ten Hoeve 2011). Further, that study suggested that reflected short-wave solar radiation from higher albedos for white roofs (changes in pavement albedo were not considered) will result in additional heating of black and brown soot particles in the atmosphere resulting in increased localized atmospheric warming, although this effect was considered minimal and thus requires additional investigation to determine if it is of significance.

In closing, the use of high albedo pavements to provide global cooling through radiative forcing is uncertain. If there is no interaction with clouds, more reflective pavements could provide important global cooling benefits. However, once feedback to cloud formation is accounted for, the answer is not definitive and may depend on whether pavement albedo is universally increased in all locations, or whether high albedo pavements are constructed in select locations where effectiveness is demonstrated. The question of whether global changes in pavement albedo can provide global cooling benefits remains an active area of research.

Stormwater Warming

Hotter, impermeable pavements also hold the potential to warm stormwater, which may affect sensitive biological communities (e.g., trout) in the receiving waters if their thermal regimes are altered by the stormwater runoff (NRDC 1999; OEC 2007; Jones and Hunt 2007). This is a particular issue in locations that receive significant rainfall during hot seasons and where heated stormwater is not cooled before entering the sensitive area, but should not be an issue in climate regions that have little or no summer rainfall. Fully permeable pavements (discussed earlier) can be used to mitigate stormwater heating if designed to retain water before releasing it into the environment.

Pavement Type and Thermal Performance

From the preceding discussion. it is clear that the solar reflectance of paved surfaces can be a strong contributor to pavement warming and that this warming has the potential to impact the UHIE in those built environments that experience hot weather and are large enough to generate a heat island. Furthermore, pavement reflectance may also contribute to overall global warming through radiative forcing although, as noted, additional research is needed to more clearly demonstrate that effect. In this section, studies specifically focused on various pavement types are reviewed.

Typical albedo values range from 0.04 to 0.16 for asphalt pavements and from 0.18 to 0.35 for concrete pavements (Pomerantz et al. 2003), although the albedo of new concrete can be as high as 0.69 (Marceau and VanGeem 2007). These albedo values are correlated to the color of the pavement whether it is asphalt (black) or concrete (grey or white), but the exposure of aggregates at the surface also plays a role in determining albedo. New asphalt pavements are quite black and have little exposed aggregate and thus have low albedos (less than 0.10). This will result in high pavement surface temperatures during hot, sunny periods when not shaded by trees or buildings (Li et al. 2013). With pavement albedo values around 0.10, extreme high pavement surface temperatures of 158 to 176 °F (70 to 80 °C) have been measured on hot summer days in mid-afternoon in Phoenix, Arizona, and up to 158 °F (70 °C) for similar pavements in Davis, California (Li et al. 2013). Figures 6-20 and 6-21 illustrate how pavement surface temperatures were greatly affected by pavement albedo both in Phoenix (Cambridge Systematics 2005) and in Davis (Li et al. 2013), respectively.

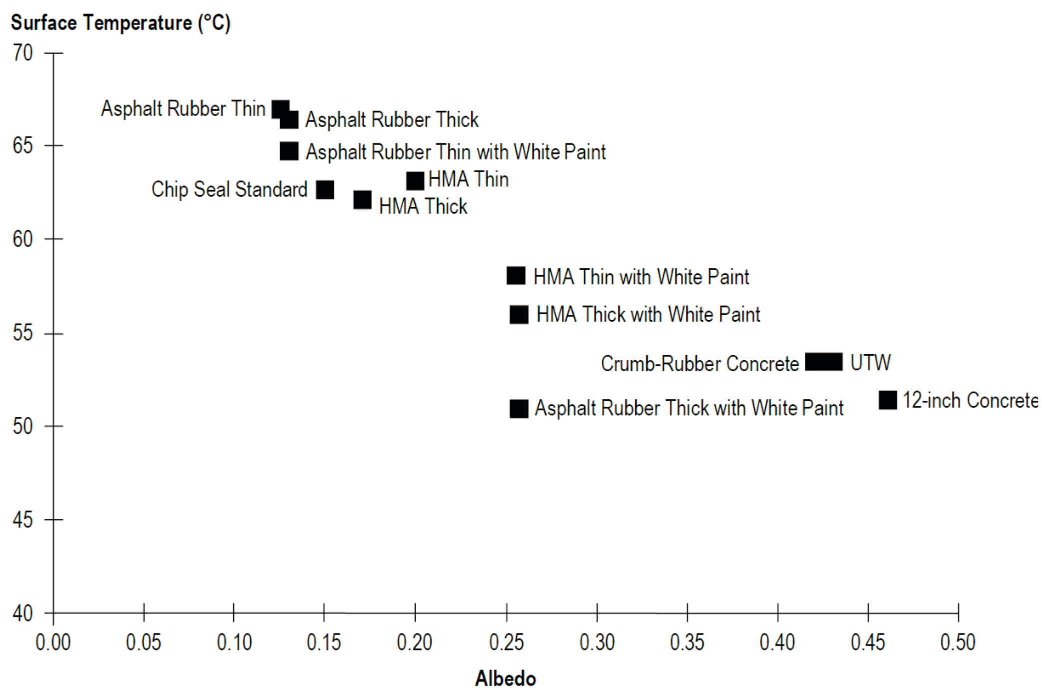

Figure 6-20. Surface temperature and albedo for selected types of pavements in Phoenix, Arizona (note: UTW = ultra-thin whitetopping) (Cambridge Systematics 2005).

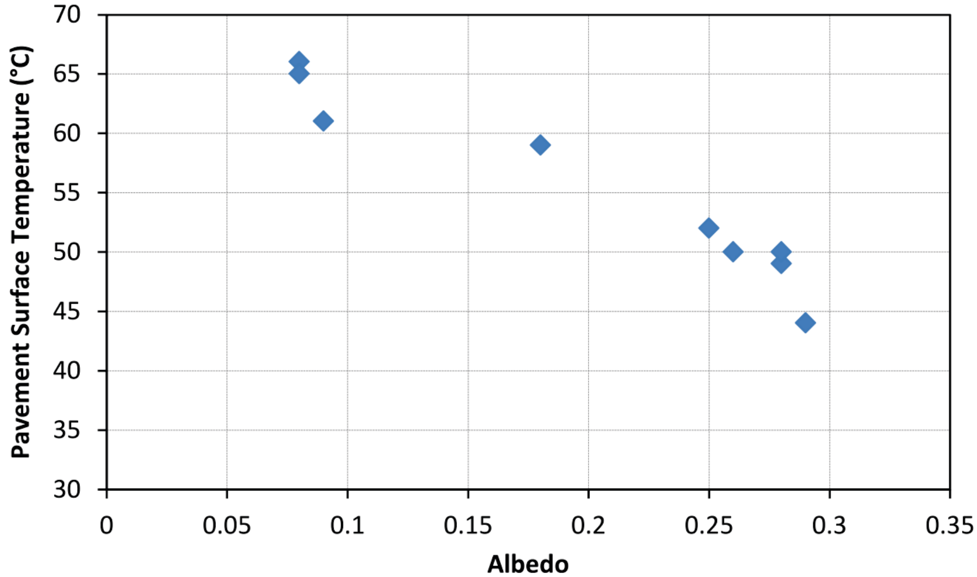

Figure 6-21. Effect of albedo on pavement surface temperature in Davis, California (16:00 9 July 2012) (Li et al. 2013).

New concrete pavements are typically light in color as long as no pigments are added. Even though over 90 percent of all paved surfaces in the U.S. are asphalt (NAPA 2013), in urban areas it is not uncommon to find a higher level of concrete in use as a paving material (14 to 20 percent of all paved surfaces including sidewalks [Levinson and Akbari 2001]). Work by Levinson and Akbari (2001) characterized the albedo of various concrete constituents (cement, sand, and coarse aggregate) and of the concrete produced from combinations of those constituents, and found that the albedo of unworn/unsoiled concrete was largely controlled by the albedo of the cement and sand, with cement albedo having a disproportionately strong influence on the albedo of concrete. Similar conclusions were made by Marceau and VanGeem (2007), who found that the solar reflectance of the cement has the largest single effect on concrete albedo compared to other constituent materials. Since the color of cement is largely affected by the iron content, cements being low in iron generally are lighter in color. For example, cement with a reported iron oxide content of 3.5 percent had a measured albedo of 0.32, whereas the albedo of a white cement with a reported iron oxide content of 0.2 percent had an albedo of 0.87 (Levinson and Akbari 2001).

The reflectance of concrete can be either enhanced or diminished depending on the type and color of SCMs or pigments added to the concrete. Marceau and VanGeem (2007) studied this in detail and found that fly ash can have an albedo either less than or greater than cement, and thus can darken or lighten the concrete. Slag cement on the other hand has a solar reflectance that is much higher than ordinary portland cement or fly ash and thus its use results in higher albedo concrete. The white cement included in the study had the highest albedo of any of the cementitious materials and thus could be used to create concrete with an albedo of 0.69. Further, it is not uncommon that pigments are added to concrete to change its color for aesthetic affect, almost always resulting in a decrease in albedo. For example, it is known that “lamp black” is routinely added to municipal concrete in areas of California to darken it (significantly reducing its albedo) so it will better match the color of existing concrete that may be several decades old.

Interlocking concrete pavers can also be manufactured to have high albedo. For example, the City of Chicago used highly reflective permeable concrete pavers featuring a photocatalytic surface to keep the pavers clean on the Cermak Road reconstruction project, a high-profile "green" pavement (CDOT 2013).

A recent study evaluated a number of different pavement types to investigate their thermal performance and how they interact with the surrounding environment (Li 2012; Li et al. 2013). A total of nine 13.1 ft (4 m) square instrumented asphalt, concrete, and interlocking concrete paver pavement sections were constructed and monitored for over a year. Climate and pavement temperature monitoring over the course of the year clearly showed that peak pavement temperature was strongly correlated to albedo, as shown previously in figure 6-21. Furthermore, the near-surface air temperature measured 2 inches (50 mm) above the surface was higher for the dark asphalt pavement compared to the conventional concrete pavement and conventional concrete pavers. As stated by Li et al. (2013), this increase in near-surface air temperature is thought to decrease the comfort level of human beings (especially the young) and contribute to the formation of ground-level ozone. Typical near-surface air temperatures for the four seasons in Davis, California are shown in figure 6-22.

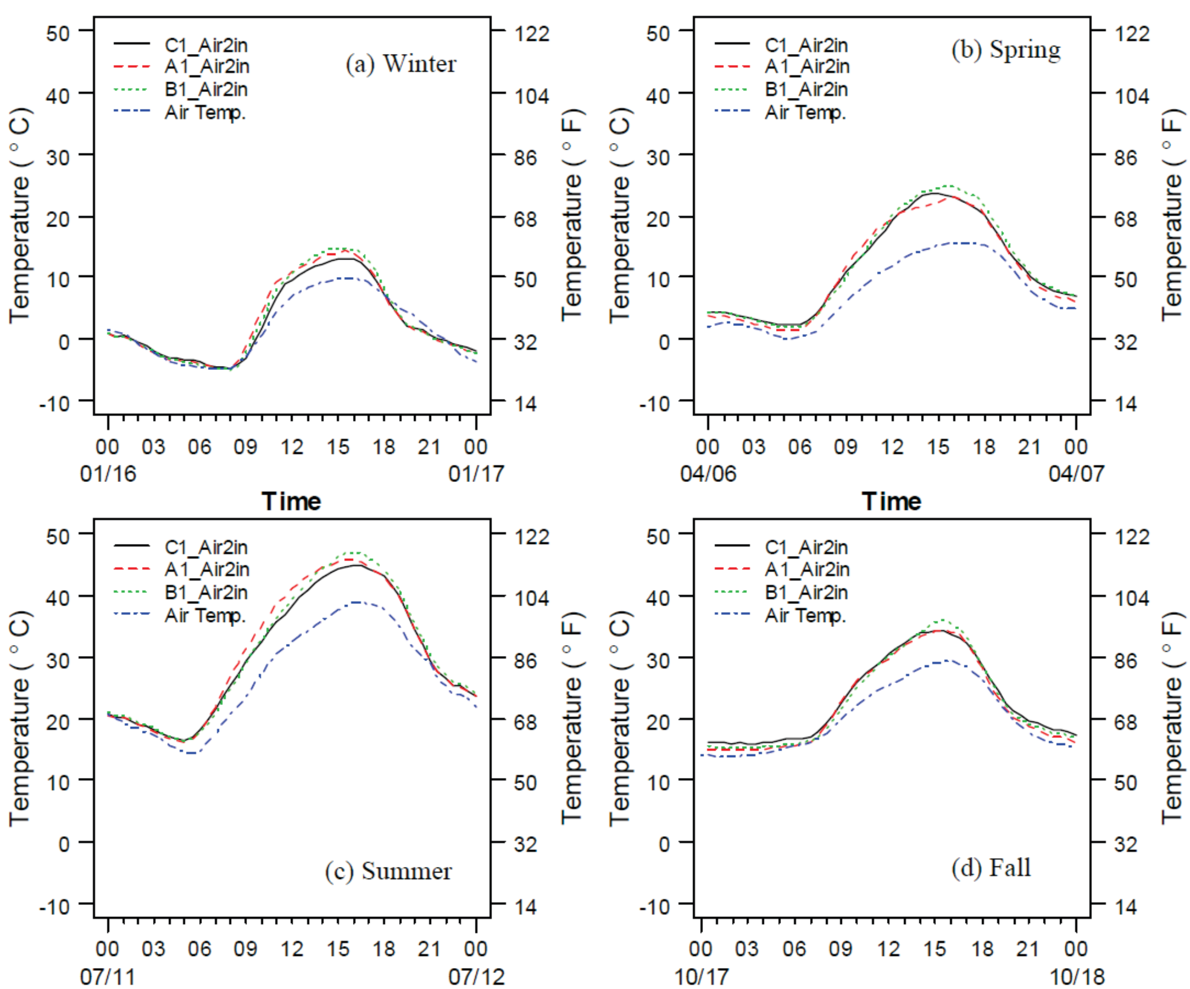

Figure 6-22. Near-surface air temperatures of different pavements measured 2 inches (50 mm) above the surface (Li 2012).

These results clearly demonstrate the effect of convection, in which heat from the pavement surface warms the air at the boundary. Based on this alone, it is understood why the use of highly reflective pavements exposed to sunlight will reduce pavement temperatures and lessen the temperature of the air immediately above them compared to lower albedo pavements.

Nevertheless, as discussed previously, the effect of albedo on the urban environment is more complex. This is partly explained by figure 6-23, where q_ref is reflected short-wave solar radiation; q_em is emitted long-wave radiation; q_radio is radiosity which is equal to q_ref + q_em; and q_conv is convective heat.

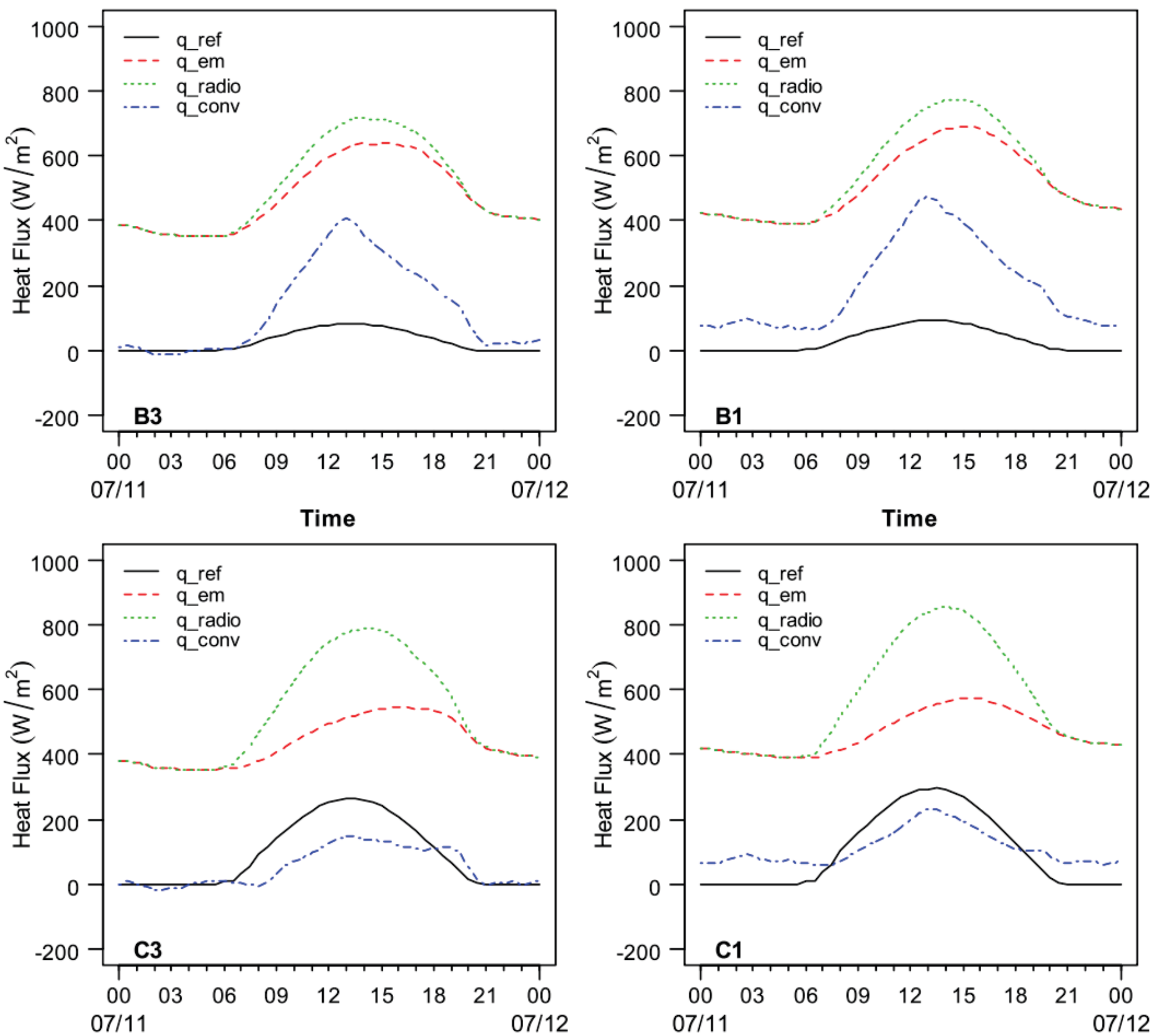

Figure 6-23. Heat flux from pavement surfaces for 1 full day during July 2012 (Li et al. 2013).

As shown in figure 6-23, the convective heat and emitted long-wave radiation is highest for pavements with the lowest albedo (B1, B3). Pavements with high albedo (C1, C3) will absorb the least solar radiation and thus have the highest reflected short-wave solar radiation. This results in higher pavement and near-surface air temperatures in the low albedo pavements, but in some cases the total radiosity is higher with the high albedo pavements. This is reflected in figure 6-23 where the conventional concrete (C1) has the highest radiosity of the four sections. Reflected short-wave solar radiation transmitted into space contributes to negative radiative forcing. However, if it is absorbed by nearby buildings or cars it can result in increased cooling energy needs or if by humans it can increase discomfort, modeling of which has not been validated. Research is currently underway modeling the effects of light and energy reflected from pavements on the energy use for interior lighting of nearby buildings, in addition to energy use for cooling and heating.

But the broader impacts of this are far less clear. For instance, 33 feet (10 m) of air will absorb only 1.6 percent of reflected short wavelength sunlight, but will absorb 22 percent of emitted long wavelength thermal radiation. Thus, at a path length of 0.6 miles (1 km), absorption is 9 percent and 61 percent, respectively. Hence, emitted long wavelength thermal radiation heats the air much more effectively than reflected short wavelength radiation. Further, the albedo of the surface of a wall, vehicle, or even the clothing worn by a person has a large impact on the radiative heat gain from reflected light. Radiosity is thus not equivalent to radiative heat gain, and thus all these factors have to be accounted for when considering increased cooling needs for buildings or human comfort. Consequently, the overall influence of reflected solar radiation is uncertain and needs further evaluation.

Permeable surfaces (porous asphalt, pervious concrete, and permeable pavers) show trends similar to impermeable surfaces regarding the impact of albedo on pavement surface temperature and near-surface air temperature when the pavement is dry. The addition of surface voids in permeable surfaces decreases albedo as well as thermal conductivity and specific heat capacity, and thus it is common for the peak surface temperature of pervious pavement alternatives to be higher than those of comparable impervious pavements if the pavement is dry (Li, Harvey, and Jones 2013). Independent of albedo, the effects of the lower thermal conductivity and lower specific heat are to trap heat nearer the surface and resulting in more rapid heating. For the same reasons, once solar radiation diminishes at the end of the day, permeable surfaces also cool more rapidly and have less heat energy to emit than impermeable surfaces (Li, Harvey, and Jones 2013).

If there is a source of near surface water, permeable pavements will undergo evaporative cooling that has been found to significantly reduce peak surface temperatures. Under these conditions, even though comparable permeable surfaces would have a lower albedo, the peak surface pavement temperature and near-surface air temperature is lower than the conventional impermeable pavement counterparts (Li, Harvey, and Jones 2013).

An additional complicating factor is that the solar reflectance of both asphalt and concrete pavements changes over time. For example, at the time of initial construction, a dense-graded asphalt pavement will have a very low albedo (typically below 0.05), but over time that asphalt surface oxidizes and becomes lighter, increasing the albedo. In addition, the asphalt film on the surface of the pavement wears away under traffic, exposing the underlying coarse aggregate and potentially increasing the solar reflectance, particularly if a light-colored aggregate was used in the mixture.

Similarly, as concrete is abraded under the action of traffic, the albedo of the coarse aggregate becomes more important; if the aggregate is light in color, the albedo may not be negatively impacted and may even increase, but if a dark coarse aggregate is used, the surface will become less reflective. Additionally, even the lightest colored concrete pavement will become soiled over time from road grime, oil, and tire rubber, reducing the albedo. Figure 6-24 illustrates this concept, qualitatively showing the change in solar reflectance (albedo expressed as a percentage) of typical concrete and asphalt pavements over time. This figure shows that the reflectance of the two surfaces gradually begin to approach one another. There is a study underway to better characterize changes in pavement albedo over time (NCPTC/NCAT 2013).

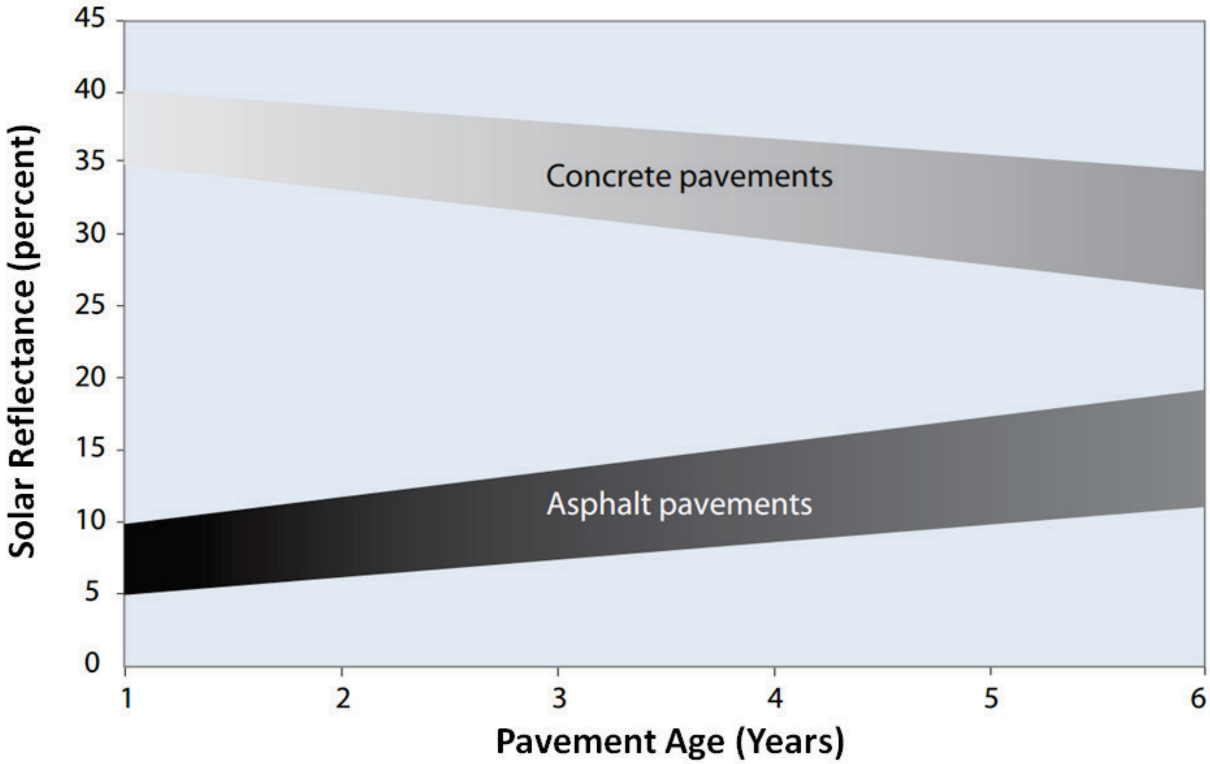

Figure 6-24. Typical pavement solar reflectance of conventional asphalt and concrete pavements over time (EPA 2008).

Another factor to consider regarding albedo is the application of pavement maintenance and rehabilitation treatments. In general, any treatment that changes the color of the pavement surface will impact the albedo. With regards to asphalt pavements, surface treatments can either decrease or increase the albedo, depending on the nature of the treatment. Those that leave a lot of asphalt binder exposed, such as conventional fog seals, slurry seals, sand seals, and microsurfacing, will have a tendency to darken the surface and reduce the solar reflectance. These treatments are a common application to "weathered" asphalt surfaces, the very surface that has increased solar reflectance due to oxidation. It is the tendency of many maintenance engineers to "restore" a weathered asphalt surface through these treatments that yields a "like new" surface that may adversely affect solar reflectance if the project is located in an area where UHIEs are a concern.

Decreasing the reflectivity of existing asphalt pavements with maintenance treatments such as fog seals can potentially increase the risk of rutting because of increased pavement temperatures, particularly in those locations with hot climates and heavy, slow-moving truck traffic. Reducing the near surface temperatures in asphalt pavements through the use of higher albedo surface materials—such as chip seals with more reflective aggregate or highly reflective surface coatings—can potentially reduce the risk of rutting by lowering peak pavement temperatures.

Such reflective coating may also help reduce aging in the asphalt binder, which in turn can reduce the probability of top-down cracking and thermal cracking in the winter months (Pomerantz, Akbari, and Harvey 2000). It is noted that the stiffening of an asphalt binder that occurs as it ages helps resist rutting, so a balance between reducing the risk of rutting and increased risk of cracking needs to be struck.

Where solar reflectance is important, treatments that can lighten the surface, such as chip seals using light-colored aggregate or pigmented/colored surface seals, should be favored (Nichols Consulting Engineers 2012). Regarding the latter, pigmented/colored surface seals continue to evolve with a number of proprietary materials becoming available for coating pavement surfaces that are designed specifically to reduce the pavement surface temperature not only through using a lighter color, but actually preferentially reflecting infrared radiation through the use of infrared reflective pigments (Wan et al. 2009; Synnefa et al. 2011; Santamouris et al. 2012). The long-term durability of pavement coatings and the environmental impacts of their manufacture have not yet been fully documented and are currently being evaluated.

The albedo of concrete pavement can be changed by diamond grinding, which removes a thin layer of the surface to restore ride quality, while also removing tire rubber, oil drippings, and other deposited materials that may have darkened the pavement surface. Figure 6-25 shows a typical diamond ground surface in which the coarse aggregates have been exposed. If the coarse aggregate is light colored, diamond grinding will likely increase the solar reflectance. On the other hand, grinding a concrete pavement made with dark coarse aggregates may reduce albedo.

For both asphalt and concrete pavements, rehabilitation featuring the use of overlays will have obvious impacts on the solar reflectance of the resulting surfaces. All the same considerations exist for asphalt and concrete overlays as exists for newly constructed asphalt and concrete pavements.

Figure 6-25. Diamond ground concrete pavement surface.

Other Strategies to Reduce Pavement Temperatures

In addition to solar reflectance, there are other pavement factors that contribute to reducing the temperature of pavement surfaces. A few of these are highlighted below:

- Permeable pavements (discussed previously), in addition to their capability of providing a mechanism for stormwater management, are known to contribute positively to a reduction of the peak pavement temperature if near surface water is available for evapotranspiration (Tran et al. 2009). This is well documented in a recent study showing that permeable pavements (including concrete, asphalt, and concrete pavers) under wet conditions have reduced surface temperatures compared to impermeable pavements of similar solar reflectance (Li et al. 2013). This was largely the result of evaporative cooling, which is dependent on the availability of near surface water and a high rate of evaporation. The benefit disappears once the pavement dries out. Combining high reflectance with a permeable surface was found to be especially effective.
- There are coatings that can be applied to a pavement surface that do not actually change the visible color of the pavement, but instead only increase the reflectance of the near infrared spectrum (Kinouchi et al. 2004; Wan et al. 2009). These can create a dark pavement with a relatively high albedo, thus reducing the pavement surface temperature. These are still experimental in nature and their effectiveness and durability have not been fully established.
- Strategies that use shade to minimize exposing pavements to direct sunlight, particularly through vegetation, is a well-practiced strategy employed in many urban environments to mitigate the UHIE (McPherson 1994; Akabari, Pomerantz, and Taha 2001; EPA 2003; Nichols Consulting Engineers 2012). Solar panels have also been used to provide shade to pavements (particularly in parking lots) while also providing a renewable source of electrical energy.
- As described earlier, the use of vegetated permeable pavers in parking and low-volume traffic areas is an innovative approach to addressing both stormwater management and the UHI effect (EPA 2008; Nichols Consulting Engineers 2012). These pavers are made of plastic, metal, or concrete lattices that provide support to traffic while allowing grass or other vegetation to grow in the substantial voids space.

Strategies for Improving Sustainability

Practices available to pavement managers, designers, and specification developers that can be used to reduce peak pavement temperatures and might be used to address UHI issues are provided in table 6-6.

Future Directions and Emerging Trends

A number of pavement technologies continue to emerge that have the potential to address or reduce the UHIE, as listed below:

- Photocatalytic cements and coatings. Certain forms of titanium dioxide are known to be photocatalysts, using solar energy to accelerate chemical reactions without being consumed in the process. In the presence of sunlight, organic materials such as dirt components (soot, grime, oil, and particulates), biological organisms (mold, algae, bacteria, and allergens), airborne pollutants (VOCs, NOx and SOx), and chemicals that cause odors are all decomposed by the photocatalytic effect (Burton 2011). Not only does titanium dioxide help to reduce air pollution, but it can help maintain a high albedo for pavements by removing surface contaminants that typically darken the concrete surface (PCA 2013). This technology is in the earliest phases of implementation, being employed both in white cements and in concrete pavers, as well as in coatings for asphalt pavements. Its long-term effectiveness and the environmental footprint of producing these materials are still being investigated.

- Alternative binders. Resin-based binders (such as clear tree resins) are being used in place of the typical black petroleum-derived asphalt binder, which allows the pavement to have the natural appearance of the aggregates used in the mixture. Resin-based binders have been used to construct pavements for hiking and biking trials, but have not been used for highway applications. Aside from resin-based binder, a variety of colorless and reflective synthetic polymer binders are available that have been used with light-colored aggregates, typically for surface courses for sports and leisure areas (Tran et al. 2009).
- Reflective chip seals. The development of exposed aggregate surfaces for asphalt pavements with light-colored aggregates that are more suitable to urban environments than current chip seal technologies hold promise and should be further investigated.
- Coatings and pigments. There are a number of coatings that increase the solar reflectance of an asphalt surface, either by changing the color of the surface through the addition of a thin layer and/or by preferentially increasing the reflectivity of the surface in the near infrared spectrum (Kinouchi et al. 2004; Wan et al. 2009). The long-term effectiveness of such coatings on high-traffic facilities has not been demonstrated. Similarly, there have been studies investigating the use of pigments to lighten the asphalt binder and thus increasing solar reflectance, but these have only been used on a limited basis and their long-term effectiveness has not been established.

Table 6-6. Summary of considerations to address UHIE issues and potential trade-offs.

UHIE Objective	Sustainable Approach and Trade-offs	Economic Impact	Environmental Impact	Societal Impact
Improve Understanding of Pavement Solar Reflectance and the UHIE	Systematically collect data on the solar reflectance of various pavement types at various ages	Initial cost for conducting data collection and research effort	Better information will support better decision making improving the environmental and societal impacts	Improve understanding of pavement solar reflectance and the UHIE
	Improved modeling of pavement solar reflectance and the impact on the surface, near surface, and atmospheric UHIE	Initial cost for conducting research and modeling effort	Better modeling capabilities will support better decision making improving the environmental and societal impacts	Wise use of available funding for global warming solutions requires informed decisions
Utilize a Robust, Repeatable Methodology to Assess Pavement Solar Reflectance	Requires a concerted effort by the pavement community to establish standards for specifying and assessing pavement solar reflectance	Initially high, but over time low once procedures are established	Improved as a standard approach for assessing solar reflectance will increase implementation	Improved as a standard approach for assessing solar reflectance will increase implementation
Increase the Albedo of New Pavement Surfaces (where it is determined to be beneficial)	For concrete pavement, use light colored cement	White cement is more costly than typical grey portland cement	Can be negative if using white cement as it has a higher production environmental footprint	Improved human comfort
	For concrete pavement, use light colored SCMs	Generally less expensive or cost neutral	Improved as reduced need to landfill industrial waste	Improved as a potential waste is beneficially used
	For asphalt pavement, apply high albedo coatings, such as exposed light colored aggregate treatments such as chip seals or specialized coatings	Initial and long-term costs dependent on cost of material and frequency of applications required	Specialized coatings may have high environmental footprint	Improved through reduced UHIE
	Employ permeable pavement technologies where applicable (water must be available during critical UHIE periods)	Permeable pavement technologies can be cost neutral to slightly increased cost	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management
	Use high albedo interlocking concrete pavers where applicable	Typically more costly than conventional pavement alternatives	Reduced environmental footprint and improved social benefit through reduced UHIE	Reduced environmental footprint and improved social benefit through reduced UHIE
	Use vegetated pavers in low-volume traffic and parking areas	Less expensive than conventional pavement alternatives	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management

Table 6-6. Summary of considerations to address UHIE issues and potential trade-offs (continued).

UHIE Objective	Sustainable Approach and Trade-offs	Economic Impact	Environmental and Societal Impact
Maintain High Albedo Over Time (where it is determined to be beneficial)	Use light colored aggregates in concrete and asphalt mixtures	Cost neutral to increased cost depending on local availability	Lower UHIE over time but may have increased environmental and societal impact if aggregate not locally available
	Use high albedo surfaces, including reflective coatings, thin overlays and light colored chip seals, to maintain asphalt pavements	Cost neutral to significantly increased cost depending on local availability of reflective aggregates and proprietary nature of coating	Lower UHIE over time but may have increased environmental and societal impact if aggregate not locally available or if proprietary coatings contain environmentally damaging constituents
	Use diamond grinding to expose light colored aggregates if present for concrete pavements	High initial cost if not done to also improve ride quality	Lower UHIE, while also improving ride quality and reducing tire-pavement noise provides environmental and societal benefits
	Use photocatalytic surface on concrete pavement to reduce soiling	High initial cost	Lower UHIE over time but may have increased environmental and societal impact if the photocatalyst has large environmental footprint
	Use cleaning program to maintain high solar reflectance of high albedo surfaces	Increased maintenance cost	Trade-off between improved UHIE and energy and water use for cleaning Lower societal impacts through reduced UHIE
	Concrete overlays on concrete and asphalt pavements	High initial cost, but potentially reduced long-term expenses depending on design and application, and also depends on cost of cleaning to maintain albedo	Lower UHIE and improved structural capacity over time but may have increased environmental and societal impact due to materials production and construction environmental impacts, traffic delays and materials cost.
Employ System-wide Strategies to Reduce Pavement Temperatures Where it is Determined to be Beneficial	Use vegetation, trees and solar panels to shade pavements as appropriate	Slightly higher initial cost	Lower UHIE plus the multiple environmental and social impacts of increasing plant density or low impact energy production in an urban environment

- Enhanced data and thermal modeling. A number of efforts are underway to better characterize the contribution of pavements to the UHIE, as well as the broader issue of radiative forcing (e.g., NCPTC/NCAT 2013 and initiatives undertaken by the Heat Island Group at Lawrence Berkeley National Laboratory and by the Global Institute of Sustainability at Arizona State University).

The UHIE has emerged as a statewide issue in California with the passage of Assembly Bill No. 296 in the 2011-2012 session (see http://leginfo.legislature.ca.gov/faces/billSearchClient.xhtml).

Among other things, that legislation requires the California DOT to develop a standard specification for sustainable pavements that can be used to reduce or minimize the UHIE. The research currently underway to support implementation of that legislation includes modeling of the effects of changing pavement albedo in cities in California using a statewide WRF climate model similar to that used by Chen et al. (2011), and initial life cycle assessment modeling of the net effects on GHG, energy use, and emissions affecting air pollution of changing pavement albedo on material production, construction, and the use phases (building energy use for cooling, heating, and lighting).

Artificial Lighting

Background

Major Issues:

- ✓ *High energy demand of current lighting has high economic and environmental impact.*
- ✓ *Providing appropriate amount of artificial lighting for driver safety*
- ✓ *Reducing amount of light pollution*
- ✓ *Understanding impact of pavement reflectivity/luminosity on nighttime and daytime safety.*

Roadway lighting is an often overlooked component in roadway and pavement design, even though it can have a large impact on safety, energy consumption, and generation of emissions. As a means of perspective, it was estimated that 131 million luminaires were used in the U.S. in 2007 for street and area lighting, consuming 178.3 terawatt hours (TWh) of electricity each year (Navigant Consulting 2008). This lighting was predominately provided by high pressure sodium lamps (39 percent), with metal halide (27 percent), mercury vapor (13 percent), fluorescent (6 percent), halogen quartz (8 percent), and incandescent (2 percent) lamps also being used.

Solid-state lighting, using light-emitting diode (LED) technology, is an energy efficient option in roadway lighting. LEDs produce light by moving electrons through a semiconductor compared to traditional light bulbs that use a filament that heats up and ultimately burns out. LED lighting can reduce energy consumption by up to 75 percent compared to the mercury lamps that are in common use today for street lighting (Wu et al. 2008). On top of comparative energy savings, LED lighting can be better positioned to direct most of the light directly on to the roadway where it is needed. This requires less light or energy to sufficiently and safely light the roadway and also reduces light pollution, which affects both people and wildlife, especially migrating birds (Rich and Longcore 2005). Furthermore, the characteristics of the light provided by an LED (color rendering, lighting distribution, and enhanced nighttime lighting conditions) may permit a reduction in total lumen output from an LED light source relative to the most common high-pressure sodium light source, resulting in further savings (Cook, Shackelford, and Pang 2008).

Solid-state LED lighting technology is fully embraced by the U.S. Department of Energy (DOE).[3] It is estimated that a 100 percent market penetration by more efficient solid-state LED technologies could save 44.7 TWh/yr, which is equivalent to the electrical consumption of 3.7 million residential households (Navigant Consulting 2008). The U.S. DOE has participated in the GATEWAY Demonstrations[4] in which the effectiveness of high-performance LED lighting products have been demonstrated on real world projects in multiple cities and also established

[3] http://www1.eere.energy.gov/buildings/ssl/index.html

[4] http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html

the Municipal Solid-State Street Lighting Consortium[5] to further promote that technology (U.S. DOE 2013). The City of Boston, for example, began installing LED street lighting in 2010 and has seen up to a 60 percent decrease in energy use and carbon emissions (City of Boston 2013). The City expects the LED lamps to last up to three times longer than conventional lamps and, although the initial cost is higher, it is expected that the payback period is 2 to 3 years.

In addition to energy conservation, light pollution from roadway lighting, which results in "skyglow," "light trespass," and "glare," has become a major social concern in many urban areas (AASHTO 2008). Sky glow is a brightening of the night sky caused by natural and human-made factors, while glare is an objectionable brightness or reflection of light and a driving hazard especially bothersome to older drivers. Light trespass is the actual light that falls off the right-of-way and can be measured and quantified. Although safety is of paramount concern, there are ways to reduce the amount of light pollution while still providing a completely safe amount of light. Positioning the light to be directed at the roadway surface and reducing the amount that is projected elsewhere is important regardless of the light sources. Also, reducing the amount of light that is being used (i.e., maintaining safe levels without overdesign) is another part of the solution. Finally, as previously mentioned, using more efficient solid-state LED lighting with high light quality can provide the same level of safety at lower lumens, thus contributing less light pollution.

From a pavement perspective, the color and texture of the pavement can also aid in reducing the amount of lighting needed (Gajda and VanGeem 2001; Adrian and Jobanputra 2005; MnDOT 2010; FHWA 2012). Lighter, more reflective pavement surfaces, or those with less texture, can provide the same level of luminance (the intensity of light emitted from the surface) at reduced illuminance (the amount of luminous flux per unit area) values. This can result in energy savings either by increasing the spacing between luminaries or by reducing the required lumens per luminary to achieve similar illumination. This is illustrated in figure 6-26, which shows that for the same illuminance values (e.g. lighting energy) across the two lanes, the lane on the right has twice the luminance value due to reflective differences in the pavement surfaces due to color and texture (FHWA 2012).

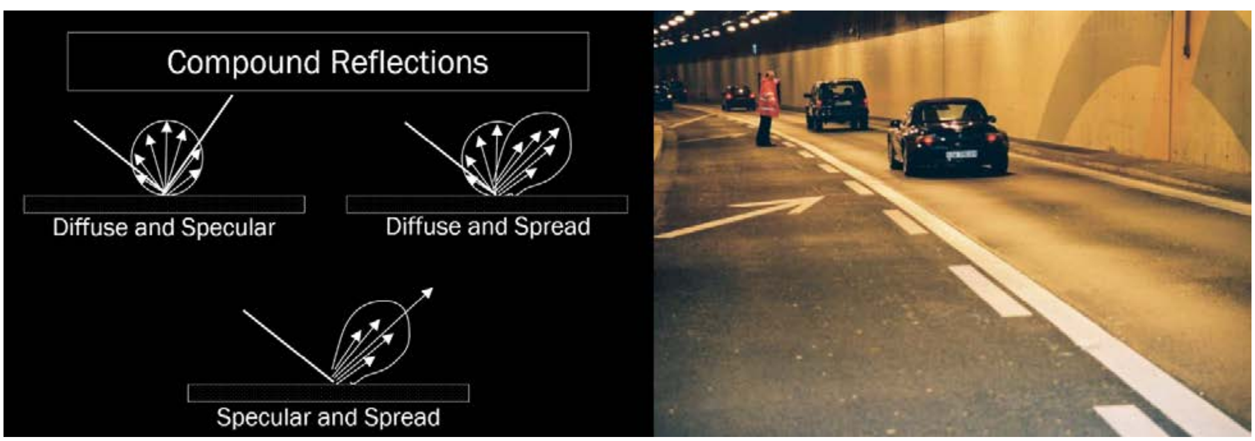

Figure 6-26. Pavement reflective differences (FHWA 2012).

[5] http://www1.eere.energy.gov/buildings/ssl/consortium.html

This concept of illumination is standardized in the pavement reflectivity classification numbers (R-numbers) used in IESNA RP-8 (IESNA 2000) to compute the required pavement illumination based on pavement surface luminance and roadway classification. A higher pavement luminance (e.g., R1) requires less illumination than pavements having less luminance (e.g., R3). This standard is used in the Minnesota DOT roadway lighting manual that prescribes more illumination for darker and more textured pavement surfaces (R2 and R3 which are asphalt/gravel and asphalt/rough texture) than for lighter, smoother textured pavement surfaces (R1 which is cement/concrete, and to a lesser degree R4 which is smooth textured asphalt); this standard is applied for all paved surfaces (including sidewalks) other than interstates (MnDOT 2010).

Many state DOTs (for example, California, Florida, and Texas) do not differentiate between surface types, partially because it is unknown what the long-term color and texture of the pavement will be. Thus, they are designed for a reduced luminance condition even though the newly constructed pavement may have a high luminance value, which results initially in overdesign. Although it is recognized that reductions in illumination can be warranted due to initial pavement surface luminance, reducing energy costs, and environmental impacts, it is difficult to design long-term lighting systems with the assumption that the pavement surface will always retain a given reflectance. The use of adaptive lighting, in which occupancy sensors, ambient light sensors, and adjustable lighting are employed, could address this limitation as the lighting level (and thus energy consumption) can be automatically adjusted as pavement luminance changes over time (FHWA 2014).

In addition to stationary roadway lighting, there are questions regarding the impact of pavement luminance on the effectiveness of vehicle headlights. Although lighter pavements may increase the efficiency of vehicle headlights, little documentation is available in terms of how they affect safety, and what was found reveals that this issue is unresolved. The problem is more complex than it may at first appear, as the contrast between an obstacle and the background is extremely important, as is the glare generated by oncoming traffic (Mace et al. 2001). Thus, in some scenarios, darker pavements may provide enhanced nighttime obstacle recognition for light colored obstacles, but further work needs to be done to better understand this issue (Dumont et al. 2009).

Future Directions and Emerging Trends

The impact of roadway lighting practices on the surrounding environment is of increasing concern to the public and highway agencies out of concern for impacts on wildlife and on energy efficiency and costs (AASHTO 2008). Overall, there is a general trend to reduce light pollution and unneeded lighting and its associated cost and environmental impact. As of about 2005, cities and states have responded with lighting ordinances and requirements regarding certain types of fixtures, minimum and maximum lighting levels, lumen/acre limits, and lighting elimination in some cases. Legislation has been adopted in Arizona, California, Connecticut, Colorado, Maine, New Mexico, Texas, Georgia, and New Jersey and has also been introduced in other states (AASHTO 2008).

Strategies for Improving Sustainability

Practices available to pavement managers, designers, and specification developers that might be used to address lighting issues are provided in table 6-7.

Table 6-7. Summary of strategies to address lighting issues and potential trade-offs.

Lighting Objective	Sustainable Approach and Trade-offs	Economic Impact	Environmental Impact	Societal Impact
Increase Energy Savings	Use of LED technology coupled with adaptive lighting.	High initial costs but with high energy savings, payback period is around 3 years.	Significant reduction in energy consumption and reduced emissions. Downward directionality helps migrating birds.	Provides clear, consistent, and more natural light and less lighting when not needed.
Provide Appropriate Amount of Artificial Lighting	Better design that accounts for the long-term pavement reflectivity. Adaptive lighting to only provide illumination when needed.	Lower economic costs for lighting	Reduced environmental impact due to reduce lighting.	Less light pollution.
Reduce Light Pollution	Better design of luminaries, consideration of lighting needs, and implementation of new technologies	Increase in cost due to investment in new luminaries and lighting technologies	Reduction in light pollution	Reduction in light pollution
Provide Better Understanding of the Impact of Pavement Reflectivity/Luminosity on Safety	Conduct research to determine what effect, if any, pavement reflectivity/ luminosity have on night and daytime safety	Investment is required to conduct research to determine significance	Unknown	Positive if safety can be enhanced

As an example of addressing the effects of light pollution on wildlife, the Florida Department of Transportation (FDOT) performed lighting research primarily because the state's beaches serve as important nesting habitat for several species of threatened and endangered sea turtles. Artificial light on or near nesting beaches can negatively affect the nesting process by interfering with normal nocturnal behaviors and spatial orientation of sea turtles, a problem to which streetlights contribute. Consequently, FDOT contributed to the development of the Florida Power and Light Company's Coastal Roadway Lighting Manual (AASHTO 2008; Ecological Associates 1998; Salmon, Wyneken, and Foote 2003).

The need to reduce electrical energy consumption has stimulated significant research and product development in the field of roadway lighting, the most relevant being the coupling of LED lights with adaptive lighting technology. Research is underway considering lighting types, directionality, placement, and warrants for placing lighting and adaptive lighting controls. Adaptive lighting controls allow lighting levels to be reduced during off-peak periods and to adjust to ambient lighting conditions (FHWA 2012). Simply put, a significant amount of power can be saved by varying the levels of lighting between peak and off-peak periods and as lighting needs change due to changes in ambient light conditions and pavement luminance over time.

Adaptive lighting can be even more responsive to demand using tools such as occupancy sensors and multilevel lighting (FHWA 2014). For example, a new project on the campus of the University of California–Davis wirelessly connects more than 1,400 energy efficient lights along pathways and roadways to a main control area, so that lights that once operated in solitude are now "talking" to each other as part of a seamless web. The lighting can be scheduled and adjusted for increased or decreased levels of activity, such as during sporting events, or to guide pedestrians along preferred routes. The system senses occupants, whether on foot, bicycle or automobile, predicts their direction of travel, and lights the path ahead. The smart network also senses when areas are vacant, then dims lights enough to save energy and reduce light pollution, without compromising safety. This system has an approximate 10-year payback period ($950,000 investment and $100,000 per year in energy savings). These types of controls are currently being piloted on a city street (CLTC 2012). Similar systems will likely become more widely available for street and highway lighting, and can be tuned to consider pavement luminance (FHWA 2014).

Safety

Safety is a key part of a sustainable transportation system. Figure 6-27 shows the trends in fatalities and fatality rates from 2002 to 2011 in the U.S., where it is observed that the number of fatalities has decreased by almost 25 percent since 2002 and the fatality rate per 100 million vmt (161 million vkt) has declined from 1.51 to 1.10 (NHTSA 2013). This is the result of the continuous improvements in transportation safety. One of the goals of the Federal Surface Transportation Policy and Planning Act of 2009 is to reduce the motor-vehicle related fatalities by 50 percent by 2030.

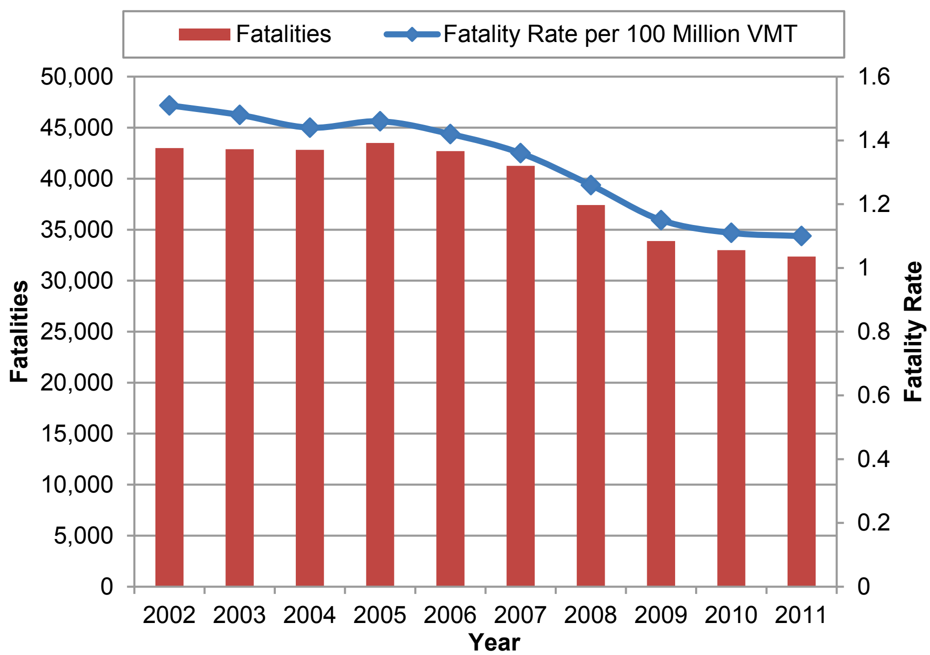

Figure 6-27. Fatality and fatality rates, 2002 – 2011 (NHTSA 2013).

A study conducted by Miller and Zaloshnja (2009) found that the roadway condition is a key contributing factor in vehicle crashes and that roadway-condition related crash costs are over $215 billion dollars annually (see figure 6-28). In order to have a sustainable and safe transportation system, keeping roadways in good condition is one of the most important factors. The MAP-21 Act signed into law in July 2013 supports FHWA's aggressive transportation safety goals. The Highway Safety Improvement Program (HSIP) is highlighted as one of the key programs in the MAP-21 act. The HSIP emphasizes a data-driven approach with each state required to identify key safety problems, establish a relative severity, and then adopt performance-based objectives to maximize transportation safety.

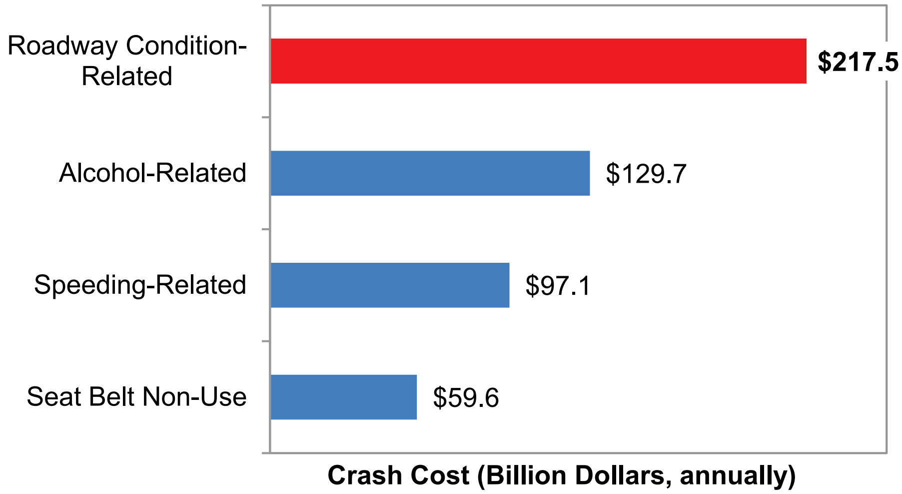

Figure 6-28. Crash costs by crash factor (Miller and Zaloshnja 2009).

From a pavement perspective, there are a number of major pavement-related factors that can influence safety, including the following:

- Traffic work zones. It is well documented that the number of crashes increases in work zones (Walls and Smith 1998). The utilization of pavement systems that minimize the number and duration of work zones over the life cycle reduce exposure to the increased crashes that occur in work zones.
- Surface friction. Adequate surface friction is critical to provide safe stopping distances. Friction levels should be based on friction demand, i.e., higher levels of friction required where there is a distinct need, such as on curves, ramps, and signalized intersections (Larson et al. 2008).
- Pavement macrotexture. Longitudinally grooved or tined concrete surfaces can add directional stability, reduce splash and spray, and provide drainage channels for surface water to reduce hydroplaning. Open-graded friction courses are effective at minimizing splash and spray from adjacent vehicles, which increases visibility while also reducing hydroplaning. Porous pavements also remove water from the surface, although they are generally not used on high-speed routes.
- Cross slopes. The pavement must have an adequate cross slope (typically a minimum of 2 percent) to promote surface drainage and help prevent hydroplaning. This includes maintenance of a continuous slope to the outside edge of the shoulder by avoiding wheelpath ruts and other transverse profile changes that can allow water to pond on the pavement surface.
- Rumble strips. These undulations that are paved, cast, or retrofitted into pavements emit a loud and abrupt noise when traversed, and have proven effective in shoulders (preventing roadway departure accidents by alerting wayward drivers to return to the roadway), at approaches to intersections and stop lights (preparing the driver to slow down or stop), and along the centerlines of two-lane roadways (helping to prevent head-on collisions).

- Pavement smoothness. Smoother pavements are comfortable and help reduce driver fatigue and minimize the potential for the driver to make unsafe maneuvers.

Obviously, there are a number of other roadway factors that also affect safety (e.g., geometrics, pavement markings, signage, shoulder condition/dropoff, ditch and roadway side slopes, right-of-way and clear zones, etc.), but these are not considered as part of the pavement decision.

Concluding Remarks

This chapter reviews important sustainability impacts of pavements in the use phase, including key factors related to rolling resistance and fuel consumption, tire-pavement noise, stormwater runoff, pavement thermal performance, lighting, and safety. For each of these factors, information is provided on their importance, quantification of their impact where available, current limitations, and trade-offs that must be considered. Only those use-phase effects that are influenced by pavement decisions are included.

The major highlights with regard to pavement characteristics and vehicle fuel use (and associated environmental benefits) are the following:

- Significant environmental benefits from reduced fuel consumption can be achieved by keeping high traffic pavements in smooth condition. There are trade-offs between negative effects of materials production and construction that occur when maintaining pavements in good condition versus benefits that may be realized in the use phase. Therefore, little or no environmental benefits from fuel economy improvements may be achieved from maintaining low-traffic pavements in smooth condition even though there are other reasons for doing so. Considering social aspects, roads should be kept in a functional condition to maintain access to the transportation system for efficient movement of people and goods by protecting pavement structures with appropriate preservation treatments.
- A high level of pavement smoothness should be sought whenever a pavement is built, rehabilitated, or maintained, particularly on high-volume routes. This can be accomplished by instituting rigorous smoothness specifications for new construction and rehabilitation, and by requiring that high-volume pavements are maintained at a high level of smoothness throughout their life.
- Structural responsiveness and its effect on vehicle fuel economy is the subject of several models that have been developed, and a number of field studies have been performed measuring vehicle fuel economy on different pavement structures under different conditions. These provide indications that under various conditions the structural responsiveness of different pavements to vehicle loading can have a measureable effect. However, unlike roughness, this effect is highly dependent on pavement temperatures and is much more sensitive to vehicle type and speed than roughness. The calibration of models that will allow definitive conclusions to be drawn based on general application of the models to a wide range of pavements under a broad range of traffic and climatic conditions in various locations has not yet been completed.
- The smoothness of pavements in locations where there are utilities should be preserved by avoiding utility cuts where possible, and by obtaining the best possible repairs to cuts where they must be performed.

The major conclusions with regard to pavement characteristics and tire-pavement noise are the following:

- Noise can have adverse effects on humans and wildlife. Although other factors are typically more important than the pavement in determining noise levels, noise attributable to the pavement surface characteristics should be controlled if it is determined to be detrimental to surrounding communities and habitat.
- Methods are available to measure tire-pavement noise. Research performed to date offers information regarding the noise benefits of different pavement surface types and textures, and initial indications of their long-term performance. For example, thin rubberized asphalt overlays have been found to be effective at mitigating pavement-generated noise in some locations such as Phoenix, Arizona. Diamond grinding is another strategy that has noticeably reduced noise emissions from some concrete pavement surfaces. The longevity of these noise mitigation strategies is still under investigation.
- New materials for asphalt surfaces and new textures for concrete surfaces have been developed to reduce noise and are being evaluated.

The major conclusions regarding the use of permeable pavements and stormwater management are:

- There are many options to construct permeable pavements including porous asphalt, pervious concrete, and permeable paver systems. Regardless of the pavement type, permeable pavements are currently better suited for low-speed, low-volume roadways and parking areas. Ongoing research is being done to investigate the applicability of permeable pavements to more heavily loaded facilities.
- Permeable pavement systems require more frequent cleaning and maintenance than do conventional pavements in order to maintain adequate permeability. This often requires the need to purchase specialized cleaning equipment and to schedule more frequent cleanings.
- Although rare, the runoff drained through permeable pavement surfaces may contain pollutants that could potentially contaminate groundwater sources. This must be evaluated for each specific application.

The major conclusions of the discussion on the thermal performance of pavements and their potential contribution to the UHIE are as follows:

- Methods are available to measure solar reflectance, but quality assurance and control procedures need to be more fully developed (NCPTC/NCAT 2013). Typically, concrete pavements have higher reflectivity than asphalt pavements but it is recognized that age and weathering generally result in asphalt pavements becoming more reflective over time (increasing albedo) whereas concrete pavements become less reflective over time (decreasing albedo). Application of preservation and rehabilitation treatments can alter the reflectivity of the pavement surface. These changes in pavement solar reflectance over time are not well understood and research is underway to better quantify them (NCPTC/NCAT 2013).
- In general, in locations where it is deemed important, high solar reflectance should be maintained over time, which may become a consideration for maintenance and

rehabilitation activities. For example, the frequent use of some asphalt surface treatments (e.g., slurry seals, microsurfacing) has a tendency to keep albedo low. Diamond grinding of concrete may also change the surface reflectivity, either increasing it or decreasing it depending on the color of the aggregate.

- Some materials used to create the most highly reflective surfaces, particularly highly reflective photocatalytic materials and some proprietary coatings, may have a high environmental footprint during manufacturing compared to conventional materials. Their use in pavements should be considered on a case-by-case basis. An LCA study can help to evaluate the net environmental effects of implementing more reflective surfaces for different applications.
- Pavement strategies that reduce pavement surface temperatures consist of more than just using pavements with high solar reflectance, and instead require a systems approach. The use of pervious pavements and shading should also be considered.
- At this time, it is unclear to what degree pavement solar reflectance impacts the development of the UHIE for different urban architectures, climate regions, and other variables. Research is underway to provide a more comprehensive understanding of the UHI phenomenon. Similarly, the overall impact of reflective surfaces and regional and global climate is a subject of current research, which is needed to provide a more complete understanding of the potential positive and negative impacts of increased pavement reflectivity.

Some of the major conclusions surrounding roadway lighting and pavement are as follows:

- The high energy demand of current lighting systems has a significant economic and environmental footprint. Thus, the goal is to provide an appropriate amount of artificial lighting for driver safety that is not excessive or wasteful. This will not only result in economic and environmental savings, but will also help reduce the amount of light pollution produced.
- Pavement surface luminance is known to influence the amount of artificial lighting required, but practical application of this knowledge is currently unclear as surface luminance changes with time. Adaptive lighting technologies featuring the use of LEDs offers an opportunity to account for pavement luminance by adjusting illuminance in response to changing ambient conditions.
- Understanding of the impact of pavement luminance on nighttime and daytime safety is still unclear, as trade-offs exist with respect to the improved lane demarcation that can exist between light-colored line markings and a dark pavement surface, with light colored pavement and dark backgrounds beyond the pavement edge, and with the increased efficiency of artificial lighting (such as headlights) on pavement surfaces with higher luminance.
- Development and implementation of new adaptive lighting systems, which provide lighting only when it is needed, is currently underway and has the strong potential to significantly lower economic, environmental, and societal costs associated with artificial lighting.

Finally, regarding safety, it is emphasized that adequate surface friction should be made available on all pavement facilities to ensure that safe stopping distances are achievable. Friction levels should be based on the demands of the facility or location, in that higher levels should be targeted where there is a distinct need, such as at curves, ramps, and intersections. Smoothness levels of pavements should also be maintained as it contributes to safer traveling conditions. Open-graded friction courses or porous pavements are effective at minimizing splash and spray from adjacent vehicles, which increases visibility. Similarly, grooved concrete surfaces can add directional stability, reduce splash and spray, and provide drainage channels for surface water to reduce hydroplaning.

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CHAPTER 7. MAINTENANCE AND PRESERVATION TREATMENTS TO IMPROVE SUSTAINABILITY

Introduction

Diminishing budgets and the recent recognition of the benefits of considering life-cycle costs have motivated changes in agency policies that advocate environmental and financial sustainability through the practice of pavement preservation. This is in stark contrast to the "worst-first" approach that was commonly practiced in the past, in which pavements were allowed to deteriorate to a highly distressed condition before performing major (and more intrusive) rehabilitation. In fact, the FHWA has been a strong proponent and supporter of the concept of cost effectively preserving the nation's pavement network. This has helped to spur a nationwide movement of pavement preservation and preventive maintenance programs, with an overall goal of improving safety and mobility, reducing congestion, and providing smoother, longer lasting pavements (Geiger 2005).

Incorporating Pavement Preservation into the AASHTOWare Pavement ME Design Software

A recently completed study for the National Cooperative Highway Research Program (Project 1-48) investigated different approaches for incorporating pavement preservation into the pavement design process, and specifically into the AASHTOWare Pavement ME Design software. The project identified several procedures and approaches for designing asphalt and concrete pavement structures so that they account for the effects of future scheduled preservation treatments (e.g., chip seals, thin overlays, diamond grinding, partial-depth repair) on pavement life. By designing a pavement to include preservation at key points in its life and carrying through with the application of those treatments once the pavement has been put into service, the pavement can be kept in better overall condition with less disruption to traffic because of delayed and less frequent rehabilitation treatments. This preservation-based design philosophy represents a sustainable approach to building and maintaining highway infrastructure, as it optimizes the use of pavement materials and minimizes the amount of energy and resources used in keeping the infrastructure in good condition.

Pavement preservation is inherently a sustainable activity. It often employs low-cost, low-environmental-impact treatments to prolong or extend the life of the pavement by delaying major rehabilitation activities. This conserves energy and virgin materials while reducing GHG emissions over the life cycle. Furthermore, as mentioned above, well-maintained pavements provide smoother, safer, and quieter riding surfaces over a significant portion of their lives, resulting in higher vehicle fuel efficiencies, reduced crash rates, and lower noise impacts on surrounding communities, which positively contributes to their overall sustainability. The philosophy of pavement preservation is often succinctly captured in terms of "applying the right treatment to the right pavement at the right time."

This chapter describes the impact that maintenance and preservation treatments have on the sustainability of pavement systems. It first describes the role that pavement management systems play in the pavement planning and decision making of highway agencies, and how they can incorporate preservation programs. This is followed by a review of common maintenance and preservation treatments for both asphalt and concrete pavements, and an assessment of how these various treatments impact sustainability. It is important to point out that only limited information exists in this regard, so much of the information is conjectural at this stage. This chapter does not delve into the details of the materials or the specific construction details of the various treatments, as there are a number of manuals and documents covering those aspects.

Pavement Preservation and Sustainability

Pavement Management Systems and Pavement Preservation

Since their conceptualization in the late 1960s and initial implementation by state highway agencies beginning in the late 1970s, the use of pavement management systems (PMS) has grown considerably. The benefits of pavement management are well documented, and include:

- Enhanced planning ability at all levels, including strategic, network, and project.
- Decision making based on observed and forecasted conditions rather than opinions.
- The ability to generate alternate scenarios for future pavement conditions based on different budget scenarios or management approaches.

Many state highway agencies have been using pavement management systems to demonstrate to legislators the benefits of pavement preservation in maintaining or improving the overall condition of the pavement network (Zimmerman and Peshkin 2003). Figure 7-1 shows a schematic that illustrates how pavement preservation can help extend the life of the pavement, delaying the need for major (and more costly) rehabilitation activities.

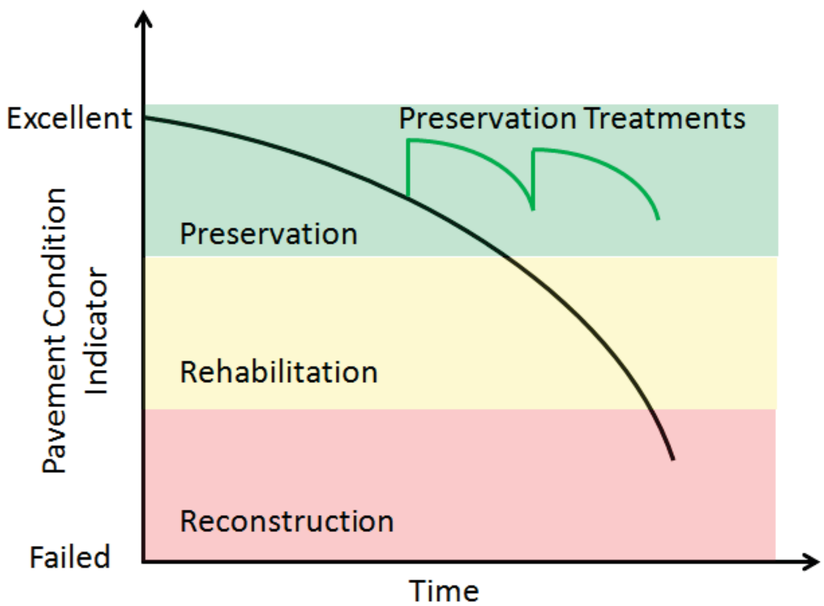

Figure 7-1. Illustration of the impact of pavement preservation.

Integrating PMS and Pavement Preservation

The integration of pavement preservation into pavement management requires a deliberate effort on the part of transportation agencies to reevaluate their existing data collection activities, to revise and update performance modeling approaches, and to improve overall program development activities. The desired outcome (and ultimate goal) is that the need for pavement preservation treatments, and their timing of application, can be identified within the pavement management system, and that the benefits realized from the application of the treatments can be accounted for in the system's optimization analysis. The critical steps involved in the integration of PMS and pavement preservation are summarized in figure 7-2.

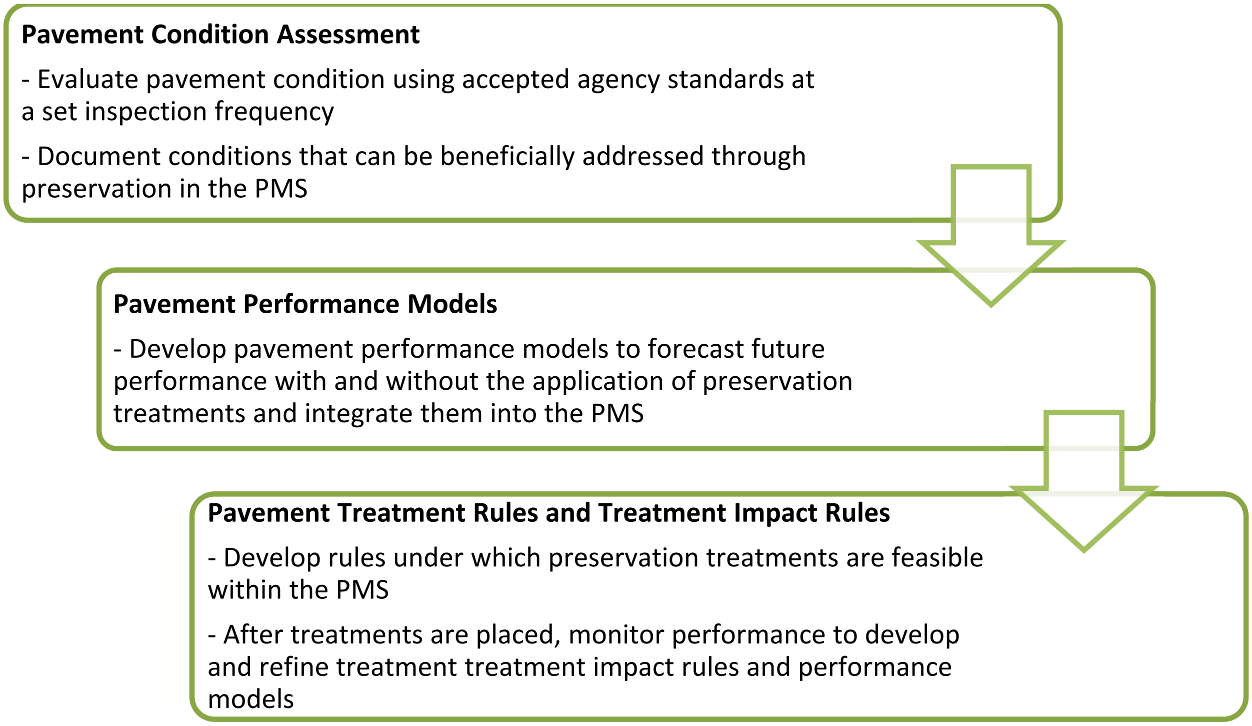

Figure 7-2. Steps in integrating PMS and pavement preservation (adapted from Zimmerman and Peshkin 2003).

General Pavement Preservation Strategies for Improving Sustainability

> ***Major Issues:***
>
> - ✓ *Lack of life cycle inventories specific to maintenance and preservation activities.*
> - ✓ *Cost effectiveness has been investigated and widely accepted.*
> - ✓ *Impact of traffic.*
> - ✓ *Treatment and material selection.*
> - ✓ *Construction quality.*

Pavement preservation is primarily concerned with minimizing the project-level life-cycle cost of the agency. To minimize the agency life-cycle cost, only the materials and construction phases of the pavement life cycle are considered, since use-phase costs (primarily vehicle operating costs) are mostly borne by pavement users and not by the agency. For low-volume roads, where the environmental impact of vehicle operations is small, improvements in the agency life-cycle cost and improvements in sustainability are generally compatible, since the objective for both is to minimize the frequency of treatment applications and the amount of material used for each treatment. Assuming that preservation treatments all generally use combinations of aggregate, water, cement, and asphalt as construction materials and that internal combustion engines are used in their placement (e.g., the transport, removal, and application of the treatment and associated waste), the environmental impact of pavement treatments is roughly linearly proportional to the total thickness of the treatment, whether it is a milling/grinding activity, a surface treatment, or an overlay. Therefore, for low-volume routes, the general strategy for improving sustainability is to minimize the amount of materials used and the number of construction cycles over the life cycle by optimizing the treatment selection and timing to avoid major structural damage while minimizing costs.

For higher traffic volume roadways, the environmental impact of the use phase becomes more important, often to the point that, for very high-volume routes, the materials and construction phase impacts of maintenance and preservation become very small relative to the influence of the pavement smoothness, deflection, and macrotexture on vehicle operations (primarily in terms of fuel economy). Depending on the route, the optimization of the environmental benefit will require balancing the impacts incurred to keep the pavement in good condition (in order to reduce vehicle operating costs) with the impacts resulting from materials production and construction of the treatment. An example of this is provided in chapter 6, in which the optimization of ride quality (in terms of IRI) to minimize CO_2 emissions is presented for routes with different levels of traffic and considering materials, construction, and vehicle use. The optimization of environmental benefits for high-volume routes is, therefore, much more complex than it is for low-volume routes because it may increase agency economic life-cycle cost as the need for more frequent treatment is increased to maintain good condition to reduce road user costs and vehicle-produced emissions.

An example of this situation for high-volume routes is illustrated in figure 7-3 for asphalt concrete overlays placed at different recurring intervals on a high-volume interstate highway. The placement of the asphalt concrete overlays at different recurring intervals results in varying amounts of cumulative agency GHG emissions (expressed in terms of CO_2e). In the figure, it can be seen that the cumulative agency GHG emissions from materials production and construction decrease as the overlay interval increases from 10 years (when the IRI is expected to be 136 in/mi [2.2 m/km]) to 30 years (when the IRI is expected to be 273 in/mi [4.4 m/km]), while the cumulative user GHG emissions increase from vehicles operating on a rougher pavement. For this example, it is also observed that the net emissions are minimized at an overlay interval of 22 years; however, the IRI is 211 in/mi (3.4 m/km) at this age interval and the GHG emissions due to increased roughness may potentially offset any benefits obtained. This is but one example and the results change considerably depending on the expected overlay performance, the traffic levels, and the emissions from materials, construction, and end-of-life scenarios. Nevertheless, the application of such multi-criteria decision-making tools and approaches can be used as a way of balancing trade-offs between environmental goals and life-cycle cost goals.

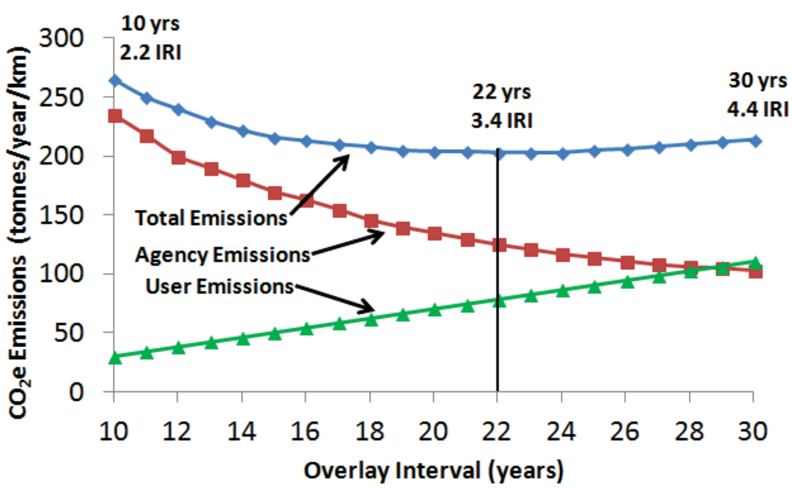

Figure 7-3. Effect of overlay interval on agency, user and total GHG (CO_2e) emissions (Lidicker et al. 2013*).

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To summarize, the selection of the right treatment for existing conditions is always important to improve sustainability. Most agencies are focused on minimizing agency economic life-cycle cost while preserving the pavement structure. For low-traffic-volume routes, minimization of agency life-cycle cost through the right timing of the right treatment also generally improves sustainability. The selection of the right treatment for existing conditions is also important for reducing agency life-cycle costs for higher traffic volume routes. However, as traffic levels increase, more frequent maintenance and preservation treatments can further reduce environmental impacts (in terms of its effect on the use phase), albeit at a higher agency cost.

Preservation Treatment Selection

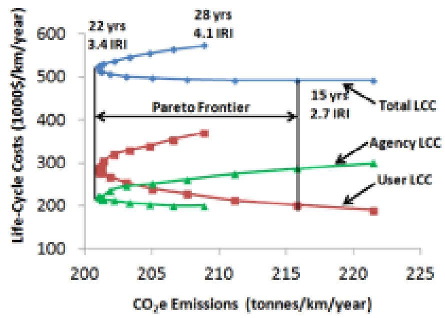
The selection of appropriate preservation treatments must consider the variables that are most important in the decision-making process. These variables may include factors that differ from those considered in identifying and selecting rehabilitation activities. The literature suggests that the following factors be considered in selecting appropriate pavement preservation treatments (Hicks, Seeds, and Peshkin 2000):

- Existing pavement type.
- Type and extent of distress.
- Climate.
- Cost of treatment.
- Availability of qualified contractors.
- Time of year of placement.
- Duration of lane closures.
- Traffic loading and expected life.
- Availability of quality materials.
- Pavement noise and surface friction.

A sequential approach for evaluating possible preservation treatments for an existing pavement and identifying the preferred alternative is provided in figure 7-4.

Reconciling Life-Cycle Costs and Environmental Impacts: A Quantitative Approach

One approach to evaluating both costs and environmental effects is to perform a Pareto analysis where the two criteria for decision making are plotted together. The example shown below illustrates the LCC and GHG emissions associated with several different overlay intervals/trigger roughness levels.



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Using this type of information, a final selection can be made from those alternatives that are on the "Pareto Optimal Frontier" where an increase in life-cycle cost results in a decrease in GHG emissions, or vice versa. In this example, this is the set of options on the lower portion of the life cycle cost (LCC) curves labeled "Pareto Frontier." The alternatives on the upper part of the curves are not optimal because there are alternatives with lower life-cycle costs with the same GHG emissions. The options on the lower portion of the Total LCC curve to the right of the Pareto Frontier (less than 15 years and 137 in/mi [2.7 m/km]) are not optimal because there is a slight minimum at that point. The point on the Pareto Frontier selected for overlay frequency for this pavement section would depend on the relative values placed on life-cycle cost and life-cycle CO_2e emissions by the agency, or specific cost or sustainability constraints placed on the project by the agency, which might narrow the range of acceptable values on the Pareto Optimal Frontier. Although simple tools for this type of analysis are not yet widely available, this example illustrates an approach for considering both life-cycle cost and sustainability (Lidicker et al. 2013).

*http://wwwcf.fhwa.dot.gov/exit.cfm?link=http://cedb.asce.org/cgi/WWWdisplay.cgi?302677

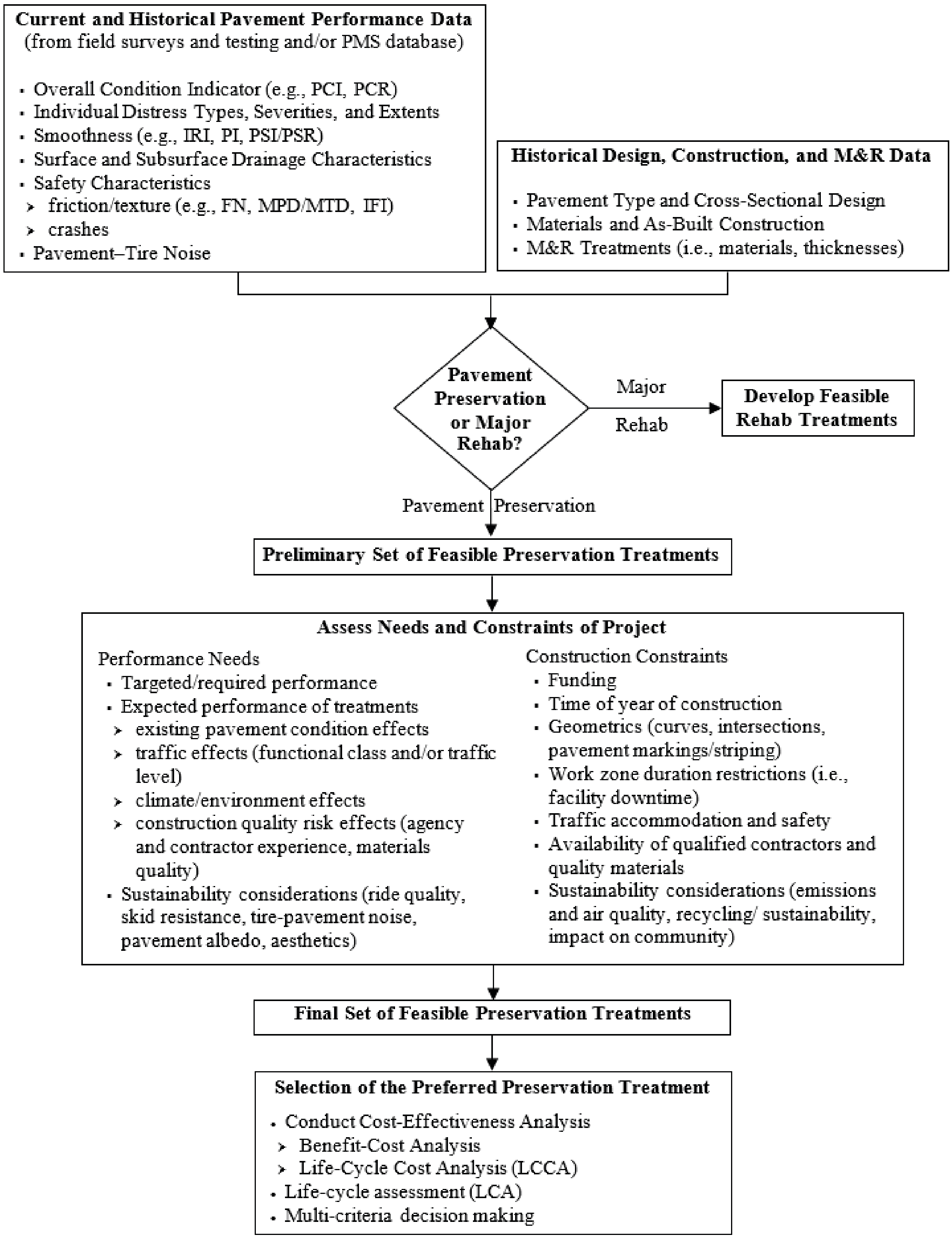

Figure 7-4. Process of selecting the preferred preservation treatment (adapted from Peshkin et al. 2011).

The rest of this chapter discusses various pavement maintenance and preservation techniques for asphalt and concrete pavements, particularly in terms of their associated benefits or costs with regards to enhancing sustainability. These benefits and costs are expressed in terms of the level of performance, performance longevity, congestion, lane closure durations, fuel consumption, as well as many others. Table 7-1 lists the maintenance and preservation treatments included in this discussion.

Table 7-1. Pavement maintenance and preservation techniques.

Asphalt	**Concrete**
Crack Filling/Sealing	Joint/Crack Sealing
Asphalt Patching	Slab Stabilization/Slab Jacking
Fog Seals/Rejuvenators	Diamond Grinding/Grooving
Chip Seals	Partial-Depth Repairs
Slurry Seals	Full-Depth Repairs
Microsurfacing	Dowel Bar Retrofit
Ultra-thin and Thin Asphalt Overlays	Slot/Cross Stitching
Hot In-Place Recycling	Retrofitted Edge Drains
Cold In-Place Recycling	Ultra-thin Bonded Wearing Course
Ultra-thin Bonded Wearing Course	Bonded Concrete Overlays
Bonded Concrete Overlays	

Whereas there is abundant literature available on the topics of how pavement materials, design, and construction influence sustainability, far less information is available on how pavement maintenance and preservation treatments and practices impact sustainability. One recent project (TRB 2012) concluded that environmental sustainability research related specifically to post-construction operations is an emerging field and that the consideration and quantification of the sustainability associated with pavement maintenance and preservation programs is not commonly practiced in the United States.

A concise summary of the potential applicability of RCWMs and other emerging techniques/materials for use in pavement maintenance and preservation treatments is shown in table 7-2 (TRB 2012). Although it is generally simply assumed that maintenance and preservation is inherently sustainable, the details of treatment type, placement frequency, and functional condition levels (especially roughness) affecting environmental impacts are not necessarily addressed.

Table 7-2. Potential use of non-traditional materials and techniques with potential pavement maintenance and preservation application (TRB 2012).

Material/ Technique	Literature Cited	Possible Preservation Uses	Possible Maintenance Uses	Remarks
Bio-Fluxing Agent	Denevillers (2010)	• Prime Coat • Chip Seal • Microsurfacing	• Overlay tack coat • Cold mix • Warm mix	Trade name is Vegeflux®
Bio Binder	Denevillers (2010)	• Chip Seal • Microsurfacing	• Cold in-place recycling • Chip seals • Road marking	Trade name is Vegecol®
Recycled Concrete Aggregate (RCA)	Gardner and Greenwood (2008)	• Bonded Concrete Overlay	• Full-depth patching • Partial-depth patching	RCA acts to sequester CO_2 in addition to recycling
Recycled Glass Gravel	Melton and Morgan (1996)	• Untried	• Unbound base courses	Potential use on gravel roads
Fly Ash	MnDOT (2005)	• Microsurfacing mineral filler • Slurry seal mineral filler • Concrete Overlays	• Concrete maintenance mixtures • Microsurfacing	Widely used in a variety of products
Bottom Ash	Carpenter and Gardner (2007)	• Microsurfacing mineral filler	• Subbase under gravel surfaces	
Flue Gas Desulfurization Gypsum	Benson and Edil (2009)	• Microsurfacing mineral filler • Slurry seal mineral filler	• Concrete maintenance mixtures	
Kiln Dust	MnDOT (2005)	• Prime coat • Microsurfacing	• Prime coat • Microsurfacing	
Baghouse Fines	Denevillers (2010)	• Microsurfacing mineral filler • Slurry seal mineral filler	• Untried	
Crushed Slag	Chappat and Bilal (2003)	• Chip seal aggregate	• Special binder road mixture	
Ultra-High Pressure Water Cutter	Pidwerbesky and Waters (2007)	• Restore macrotexture on chip seals	• Retexture chip-sealed roads prior to resealing	Uses no virgin material and the sludge can be recycled as precoating for chip seal aggregates
Shotblasting	Gransberg (2009)	• Restore microtexture on polished HMA and PCC pavements	• Restore skid resistance on resealed PCC bridge decks	Uses no virgin material and the steel shot is recycled for reuse in the process
Recycled Motor Oil	Waters (2009)	• Dust palliative • Otta Seals	• Otta seal as surface course	Motor oil is refined before use
Recycled Tire Rubber	Beatty et al. (2002)	• Chip seals • Thin overlay	• Chip seals • Thin overlays	Also found to reduce road noise

Asphalt-Surfaced Pavement Maintenance and Preservation Treatments

Introduction

Asphalt-surfaced pavements include any pavement surfaced with an asphalt material, whether asphalt concrete (i.e., HMA, WMA) or an asphalt surface treatment of some type. Although this represents a large family of different pavement types, the maintenance and preservation activities are identical.

Table 7-3 presents an overall summary of various maintenance and preservation treatments applicable to asphalt-surfaced pavements. First, it provides a brief description of the technique and then indicates its effect on a number of preventive and restorative benefits ("↑" indicates positive impact, "↓" indicates negative impact, and "↔" indicates both positive and negative impacts). This is followed by a general assignment of the relative life expectancy and cost, and the relative environmental and social impacts. It is noted that these relative comparisons are inherently non-specific, by definition, due to the general lack of available information and the broad number of variables that affect the performance, costs, life-cycle environmental impacts, and social impacts of each treatment. The relative comparisons will also vary depending on the traffic levels, climate region, and a host of other variables.

Various resources are available that discuss each treatment type, including the type of pavement conditions addressed, how each should be constructed, and their cost effectiveness. These include a series of three courses offered by the National Highway Institute (NHI Course Nos. 131115, 131103, and 131116), a series of webinars on key concepts and guidelines related to asphalt pavement maintenance, preservation, and recycling developed by the Asphalt Institute (http://www.asphaltinstitute.org/public/asphalt_academy/webinars/index.dot), and a manual on basic asphalt recycling and reclaiming concepts published by the Asphalt Recycling and Reclaiming Association (ARRA) and the FHWA, among others. As considerable information is readily available regarding the proper timing, cost effectiveness, and construction of the various treatments, the following sections specifically address the sustainability aspects of each treatment, focusing on the environmental and social impacts.

Crack Filling/Sealing

Crack filling (see figure 7-5) involves the process of placing an adhesive material (generally a lower quality, non-polymerized or polymerized cold-pour emulsion asphalt binder) into or over non-working cracks (cracks that are not expected to open and close with temperature changes) to reduce the infiltration of moisture and incompressible materials into the pavement structure (FHWA 1999; Peshkin et al. 2011). Typically very little preparation of the crack is performed prior to the installation of the filler material.

Figure 7-5. Installation of hot-applied sealant.

Table 7-3. Evaluation of sustainability impacts of treatments for asphalt-surfaced pavements.

Treatment	Description	Preventive		Restorative					Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Rejuvenate Surface	Addresses Surface Distress	Eliminate Stable Ruts	Improves Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Crack Filling	Placement of adhesive material into and/over non-working cracks, minimal crack preparation, lower-quality materials used	↑		↑ Cracking only		↓ Longitudinal overbanding can negatively impact friction	Overbanding may increase roughness; sealing cracks may slow development of roughness	↔ Overbanding increases noise	✓	$	Low	Reduced traffic delays, less pleasing aesthetics, potential roughness and noise issues
Crack Sealing	Placement of adhesive material into and/over working cracks, good crack preparation, high-quality materials used	↑		↑ Cracking only		↓ Longitudinal overbanding can negatively impact friction		↔ Overbanding increases noise, filling can reduce noise	✓	$	Low	Reduced traffic delays, less pleasing aesthetics, potential roughness issues
Asphalt Patching	Used to treat localized distresses; partial-depth patches address surface distresses and full-depth patches address structural distresses	↑		↑	↑				✓✓	$$	Variable Depends on amount of patching and improvement gained in structural life and ride quality	Reduced traffic delays compared to other treatments; negative impact on ride quality and noise, poor aesthetics (if patching is substantial)
Fog Seal/ Rejuvenators	Very light application of asphalt emulsion on pavement surface to seal the existing asphalt surface	↑	↑			↓ (May negatively impact skid resistance)			✓	$	Medium Depends in part on materials	Reduced traffic delays; improves aesthetics
Chip Seals	Sprayed application of asphalt (usually emulsion, heated asphalt cement and cutbacks also used) followed by aggregate chips roller to achieve 50 to 70% embedment. Cost and performance depends on whether it is single or multi-course, as well as binder type and aggregate quality	↑		↑		↑	↑ Depends largely on number of courses placed	↓ Depends on chip size	✓✓	$$	Medium to High Depends on number of courses and binder type	Increases safety by improving friction, reduced traffic delays due to faster construction and opening to traffic; reduced ride quality due to rough surface, potential vehicle damage due to loose aggregate chips
Slurry Seals	Mix of well-graded aggregate (fine sand and mineral filler) and asphalt emulsion spread over entire pavement surface	↑	↑			↑			✓✓	$$	Medium	Increases safety by improving friction, reduced traffic delays due to faster construction and opening to traffic; improves aesthetics. Lower albedo may negatively impact UHI effect

Table 7-3. Evaluation of sustainability impacts of treatments for asphalt-surfaced pavements (continued).

Treatment	Description	Preventive		Restorative					Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Rejuvenate Surface	Addresses Surface Distress	Eliminate Stable Ruts	Improves Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Microsurfacing	Mix of crushed, well-graded aggregate, mineral filler, and latex-modified emulsified asphalt spread over entire pavement surface. Cost and performance depends on whether single, double, or multiple-course	↑	↑	↑	↑	↑	↑	↑ Depends on system	✓✓✓	$$	Variable Highly dependent on system and materials used, longevity of treatment, and improvements gained in ride quality	Increases safety by improving friction and eliminating stable ruts; reduced traffic delays due to faster construction and opening to traffic; improves aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin and Thin HMA Overlay: Dense-Graded	Asphalt binder (may be polymerized) and dense-graded aggregate combined in central mixing placement and placed with paver in thickness ranging from 0.625 to 0.75 in. for ultra-thin and 0.75 to 1.5 in. for thin overlays. Cost and performance depends on binder type and whether milling is performed prior to treatment placement	↑		↑	↑	↑	↑	↑	✓✓✓✓	$$$	High Use of WMA may reduce construction impact (see Chapter 3)	Improved ride quality; improved safety through improved friction and drainage; improved aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin and Thin HMA Overlay: Open-Graded	Asphalt binder (often polymerized or rubberized) and open-graded aggregate combined in central mixing placement and placed with paver in thickness ranging from 0.625 to 0.75 in. for ultra-thin and 0.75 to 1.5 in. for thin overlays. Cost and performance depends on binder type and whether milling is performed prior to treatment placement			↑	↑	↑	↑	↑	✓✓✓	$$$	High Use of WMA may reduce construction impact (see Chapter 3)	Improved ride quality; improved safety through improved friction and drainage; reduces splash and spray; noise; improved aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin and Thin HMA Overlay: Gap-Graded	Asphalt binder and gap-graded aggregate, usually made with polymerized or rubberized binder and/or fibers, combined in central mixing placement and placed with paver in thickness ranging from 0.625 to 0.75 in. for ultra-thin and 0.75 to 1.5 in. for thin overlays. Cost and performance depends on binder type and whether milling is performed prior to treatment placement	↑		↑	↑	↑	↑	↑	✓✓✓✓	$$$	High Use of WMA may reduce construction impact (see Chapter 3)	Improved ride quality; improved safety through improved friction and drainage; highly rut resistant; improved aesthetics. Lower albedo may negatively impact UHI effect

Table 7-3. Evaluation of sustainability impacts of treatments for asphalt-surfaced pavements (continued).

Treatment	Description	Preventive		Restorative					Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Rejuvenate Surface	Addresses Surface Distress	Eliminate Stable Ruts	Improves Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Hot In-Place Recycling	Corrects surface distresses within top 2 in. of existing asphalt pavement by softening surface material through heat, mechanically loosening it, mixing with recycling agent, aggregate, rejuvenators, and/or virgin asphalt	↑		↑	↑	↑	↑		✓✓✓	$$$	Medium to High Re-use of existing materials reduces impact. Impact depends on whether it involves surface recycling, remixing, or repaving	Improved ride quality; improved safety through improved friction and drainage; improved aesthetics. Lower albedo may negatively impact UHI effect
Cold In-Place Recycling	Milling and sizing reclaimed asphalt pavement (RAP) and mixing in-place with recycling additive and new aggregate which is then relaid and compacted as new base course. CIR requires that a new surface be placed over it, usually an asphalt overlay or other surface treatment		↑	↑	↑	↑	↑		✓✓✓	$$	Variable Depends on additives used and type of surface applied; re-use of existing materials reduces impact	Increases safety through improved friction and drainage; improved ride quality; improved aesthetics. Lower albedo may negatively impact UHI effect
Ultra-thin Bonded Wearing Course	May be used as an alternative to chip-seals, microsurfacing, or thin overlays. Consists of a open-graded or gap-graded, polymer-or rubber-modified asphalt layer (0.4 to 0.8 in. thick) placed on a heavy tack coat	↑		↑		↑	↑	↑	✓✓✓✓	$$$	Medium Partly dependent on use of proprietary additives	Improved ride quality; improved safety through improved friction and drainage; improved aesthetics. Lower albedo may negatively impact UHI effect
Bonded Concrete Overlay	Placement of a thin (2 to 4 in.) PCC layer, with slab dimensions between 2 and 6 ft. over an existing asphalt-surfaced pavement	* Existing surface supports new concrete surface	* Existing surface supports new concrete surface	↑	↑ Also addresses unstable rutting	↑	↑	↔ Depends on surface texture and joint condition	✓✓✓✓	$$$$	Medium Virgin materials and concrete materials increase impact, thinner cross section reduces impact	Increases safety through improved friction and drainage; improved ride quality; improved aesthetics. Increase in albedo may positively impact the UHI effect

Note: Relative Environmental Impacts discussed in tale 7-3 provide rough comparisons; reliable estimates will be available only after new assessments are conducted.

Key:
↓ decreased
↑ increased
↔ no trend

In applications where significant crack movement is expected, crack filling is not expected to perform particularly well and crack sealing should be considered. Crack sealing is a more rigorous process than crack filling, and thus is more energy and emission intensive than crack filling. It begins with more preparation of the crack (e.g., routing, cleaning) before the placement of a higher quality adhesive and elastic material (typically polymerized or rubberized hot-poured asphalt materials) into or over prepared working cracks to minimize the infiltration of moisture and incompressible materials into the pavement structure.

Crack filling and crack sealing do not add any structural benefit to the pavement, but they do slow the rate of moisture ingress, which will slow the rate of pavement deterioration by preventing moisture from infiltrating and degrading the pavement layers (FHWA 1999; Peshkin et al. 2011).

Positive Sustainability Attributes of Crack Filling/Sealing

- Crack filling/sealing is expected to extend the life of the pavement by keeping the pavement sealed against water infiltration.
- Crack filling/sealing uses relatively small material quantities and thus does not have large material-related environmental impacts (but LCAs are not readily available).
- Crack filling/sealing generates little construction waste.
- Crack filling/sealing construction operations use relatively little energy.
- Crack filling/sealing can be conducted using moving traffic control operations, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Crack Filling/Sealing

- Crack filling/sealing has a relatively short life compared to the pavement and thus must be repeated multiple times over the pavement life cycle.
- Crack filling/sealing configurations that apply material on the surface of the pavement on either side of the crack (i.e., overband configurations) can negatively impact ride quality and tire-pavement noise.
- Crack filling/sealing can negatively impact the pavement aesthetics.
- Overutilization of filling/sealing of longitudinal cracks using an overband configuration can negatively impact surface friction, especially for motorcycles.
- Construction operations (specifically the crack routing and cleaning processes) are typically noisy and produce particulates that can be a potential issue in a community setting.

Asphalt Patching

Figure 7-6. Full-depth asphalt patch.

The placement of an asphalt patch (see figure 7-6) is a common maintenance procedure used to treat localized distresses. Patching can be performed with limited preparation and using a cold-mix material (such as under winter conditions) or may employ a more rigorous approach consisting of milling or saw cutting, application of a tack coat, and placement of a high-quality asphalt concrete patching material. Patching may be partial depth or full depth, depending on the type and severity of the distresses being addressed. Patching is typically used to fix potholes and severely cracked areas. Patching is also commonly done in preparation for (or in conjunction with) other forms of maintenance activities or preservation treatments, or as a pre-treatment for an asphalt overlay. The primary materials used for patching are asphalt concrete, cold-mix asphalt, aggregate/asphalt emulsions, and various proprietary patching mixtures.

Positive Sustainability Attributes of Asphalt Patching

- The replacement of localized pavement failures restores structural integrity and ride quality. If done correctly, this is a long-term repair that should last for the life of the pavement.
- For isolated repairs, patching uses relatively little material and thus does not have large material-related impacts.
- Construction operations associated with patching use relatively little energy (when compared to a more substantial treatment like asphalt overlays).
- Although some construction waste is generated from the removed material, it can be recycled as RAP.
- Patching can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Asphalt Patching

- Poorly constructed asphalt patching can negatively impact ride quality and tire-pavement noise.
- Patching becomes costly with increasing environmental impact as the density of patching increases.
- Large quantities of asphalt patching can negatively impact the overall aesthetics of the pavement.

Fog Seals/Rejuvenators

Fog seals or rejuvenators (see figure 7-7) are treatments used to add fresh asphalt binder or more volatile asphalt constituents to the surface of an existing pavement to seal the pavement surface, prevent or slow oxidation, and prevent further loss of aggregates from the pavement surface. Fog seals/rejuvenators are not effective in treating cracking or other surface distresses that may compromise the structural integrity of the pavement.

Figure 7-7. Fog seal application.

Positive Sustainability Attributes of Fog Seals/Rejuvenators

- Fog seals/rejuvenators restore the pavement surface with minimal application of material, effectively sealing it and preventing further loss of aggregate.
- Fog seals/rejuvenators improve pavement aesthetics creating the impression of a new pavement.
- Construction operations associated with the placement of fog seals/rejuvenators use relatively little energy.
- The application of fog seals/rejuvenators can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Fog Seals/Rejuvenators

- Poorly constructed fog seals/rejuvenators can negatively impact surface friction and safety.
- Some non-emulsion-based rejuvenators contain volatiles that can negatively impact the local community.
- The application of asphalt binder over the entire surface results in moderate overall environmental impact, especially due to the relatively short performance period of the treatment (which, therefore, would require the application of multiple treatments over the life of the pavement).
- Fog seals/rejuvenators will typically darken the surface, and will likely decrease the pavement albedo.

Chip Seals

Chip seals are typically used to seal the pavement, address minor, nonstructural surface distresses, and improve the friction of the wearing course. The construction of a chip seal (see figure 7-8) uses a non-polymerized, polymerized, or rubberized asphalt material as a binder, most commonly in emulsion form, but heated asphalt and cutbacks may also be used. The binder is applied to the pavement surface (typical application rates are between 0.35 and 0.50 gal/yd^2 [1.58 and 2.26 l/m^2]) followed by the application of aggregate chips (generally one stone thick; typical application rates are between 15 and 50 lb/yd^2 [27 kg/m^2]), and these are then rolled into the asphalt binder to achieve 50 to 70 percent embedment. Chip seals can be applied in single or multiple layers and in combination with other surface treatments (such as microsurfacing, which yields a "cape seal") to reduce concerns associated with loose aggregate chips and to improve ride quality. In many cases, chip seals can significantly extend pavement life at relatively low costs. Guidelines for constructing effective chip seal treatments are documented in an NCHRP synthesis document (Gransberg and James 2005).

Figure 7-8. Chip seal construction.

Positive Sustainability Attributes of Chip Seals

- Chip seals renew the pavement surface, effectively sealing and addressing minor surface defects.
- Chip seals restore surface friction.
- When multiple courses are used, chip seals can improve ride quality and surface profile.
- Chip seals improve pavement aesthetics by creating the impression of a new pavement.
- The use of light-colored aggregates in chip seals can increase surface albedo.
- The construction of chip seals can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.
- Chip seals have a much lower initial cost than thin asphalt overlays.

Potential Negative Sustainability Attributes of Chip Seals

- Poorly constructed chip seals can result in vehicle damage due to loose chips and can result in wasted aggregate resources when excessively applied or poorly bound.
- Chip seals can exhibit a rough ride and high noise levels at high speeds, particularly if large size stone is used or if there is non-uniform stone loss due to poor application of the binder.
- The application of asphalt binder and aggregate over the entire pavement surface results in a moderate overall environmental impact, especially where traffic and climate

conditions result in a relatively short performance period of the treatment (requiring multiple applications over the life of the pavement).

Slurry Seals

Slurry seals (see figure 7-9) consist of a mixture of well-graded aggregate (fine sand and mineral filler) and asphalt emulsion that is spread over the surface of the pavement using a squeegee or a spreader box fixed to the back of the truck that is depositing the mixture. Slurry seals are generally used to seal the pavement surface, address low-severity cracking on the pavement surface, or improve the friction of the pavement surface. Slurry seals can also help reduce noise due to tire-pavement interaction to an extent (Peshkin et al. 2011). Slurries typically have a short service life on high speed routes due to abrasion loss.

Figure 7-9. Slurry seal application.

Positive Sustainability Attributes of Slurry Seals

- Slurry seals help keep water out of the pavement structure, potentially extending pavement life.
- Slurry seals can improve the surface friction of the pavement, thereby enhancing safety.
- Slurry seals improve pavement aesthetics by creating the impression of a new pavement.
- Slurry seal construction can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Slurry Seals

- The application of asphalt binder and aggregate over the entire pavement surface results in a moderate overall environmental impact, especially due to the relatively short performance period associated with slurry seals (requiring multiple applications over the life of the pavement).
- Improperly constructed slurry seals can adversely affect surface friction.
- Slurry seals are often dark in color and will likely decrease pavement albedo.

Microsurfacing

Typical microsurfacing consists of a mixture of crushed, well-graded aggregate, mineral filler, and polymer-modified emulsified asphalt spread over the entire pavement surface. This represents a broad category of different treatments, many of which are proprietary. The primary use of microsurfacing is to seal surface cracks, inhibit raveling and oxidation of the existing asphalt surface, address minor surface irregularities and rutting, and improve surface friction. Microsurfacing may be applied in a single or double course, depending upon project requirements. A double course usually involves a rut-fill application followed by another course to cover the entire pavement surface (Peshkin et al. 2011).

The cost, performance, and environmental impacts of microsurfacing depend on whether single, double, or multiple courses are used and the nature of the binder (i.e., binder type and level of polymerization). Many studies have specifically identified microsurfacing as a very sustainable treatment with relatively low life-cycle economic and environmental impacts (Chehovits and Galehouse 2010; Kazmierowski 2012; Uhlman 2012).

Positive Sustainability Attributes of Microsurfacing

- Microsurfacing renews and seals the pavement surface.
- Microsurfacing can restore surface friction and fills ruts, thereby improving safety.
- Microsurfacing improves pavement aesthetics by creating the impression of a new pavement.
- Although new material is used in microsurfacing projects, it is often of less quantity than that used in asphalt concrete paving options.
- Microsurfacing has a relatively long life when compared to other preservation treatments, reducing material consumption and construction impacts that are associated with frequent and repeated applications of other treatments.
- Microsurfacing construction can be completed in a relatively short period of time, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Microsurfacing

- Some of the polymerized materials used in microsurfacing projects may have a relatively high environmental impact and this should be considered when determining life-cycle impacts.
- Microsurfacing is often dark in color and will likely decrease pavement albedo (although some microsurfacing techniques actually are designed to increase albedo).

Environmental Impact of Preservation Treatments

The environmental impacts of two pavement preservation treatment scenarios were evaluated by Uhlman (2012). The first scenario compared a polymer-modified emulsion microsurfacing to a 2-inch (51-mm) mill and replacement with a polymer-modified HMA overlay. The overall environmental impact of the microsurfacing was determined to be significantly lower because of specific aspects of the HMA alternative, namely its elevated production and application temperatures, the milling operation performed prior to HMA placement, and the increased fuel requirements. In a second scenario, various chip seal options (including a hot-applied chip seal incorporating ground tire rubber [GTR] and two different polymer-modified cold-applied emulsion chip seals with and without fibers) were compared. The chip seal made with GTR had the lowest impact for solid waste emissions due to the diversion of tires from landfill, yet it also exhibited the greatest environmental impact in all categories considered except toxicity potential. This was because of the extra requirements for precoating the aggregates, the higher manufacturing and application temperatures for the GTR chip seal, and the production and storage requirements for the GTR binder. Thus, although at face value the use of recycled products appears to be a "sustainable" practice, the results in this case indicate that the use of cold-applied polymer-modified emulsions provided lower environmental impacts over the life cycle. However, it is important to recognize that the findings from this study are not absolute, as different results might be obtained for projects constructed under different situations (e.g., traffic, climate, pavement condition, material sources, system boundaries for analysis).

Ultra-Thin and Thin Asphalt Concrete Overlays

This is a very broad category of overlays made with asphalt concrete in a central mixing plant and placed with a paver in thicknesses ranging from 0.625 to 0.75 inches (16 to 19 mm) for ultra-thin and 0.75 to 1.50 inches (19 to 38 mm) for thin overlays (see figure 7-10). Life-cycle cost, performance, and environmental impacts depend on traffic, binder type, bonding to the existing surface, the extent of cracking in the existing surface, and whether milling is performed prior to treatment placement.

Figure 7-10. Ultra-thin asphalt overlay.

Ultra-thin and thin overlays are effective in sealing the pavement, addressing minor surface cracking and rutting, and improving surface friction. They will generally be quieter and smoother than chip seals, but will have higher initial costs. The incorporation of polymer-modified binders may improve overall performance. These overlays may be constructed using dense-graded, open-graded, or gap-graded mixtures:

- **Dense-graded**—A well-graded, relatively impermeable mixture, for general application.
- **Open-graded**—An open-graded, permeable mixture containing crushed aggregate and a small fraction of manufactured sand. Open-graded mixtures are effective in addressing splash/spray issues and also in reducing noise due to tire-pavement interaction. Polymer and rubberized binders can extend pavement life in terms of cracking and raveling.
- **Gap-graded**—A gap-graded mixture with either rubberized gap-graded mixtures or stone matrix asphalt (SMA) containing polymerized binder and fibers. These mixtures are designed to maximize cracking and rutting resistance and durability through stone-on-stone contact and high binder film thicknesses. Rubberized gap-graded mixtures are specifically designed to be highly resistant to reflection cracking.

Positive Sustainability Attributes of Ultra-Thin and Thin Asphalt Concrete Overlays

- Ultra-thin and thin overlays address minor surface distress, restore surface friction, fill ruts, improve ride quality, and improve texture that results in improved safety. Open-graded overlays can reduce both splash/spray (thus improving safety in wet-weather conditions) and noise emissions.
- Ultra-thin and thin dense-graded overlays improve pavement aesthetics by providing a new pavement surface.
- Ultra-thin and thin dense-graded overlays exhibit a relatively long life if placed on a pavement that is not significantly cracked and if good bonding is achieved with the existing surface, which reduces material consumption and construction impacts due to repeated applications.

- Construction of ultra-thin and thin overlays can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.
- Ultra-thin and thin overlays are generally quieter and smoother than chip seals.

Potential Negative Sustainability Attributes of Ultra-thin and Thin Overlays

- Ultra-thin and thin overlays require acquisition, processing, and transporting of material from central mixing facilities.
- Poor construction of ultra-thin and thin overlays, or their misapplication on badly deteriorated pavements, can result in early failures that negatively impact economic and environmental performance.
- Ultra-thin and thin overlays are initially dark in color and will likely decrease pavement albedo.
- In some cases, open-graded ultra-thin and thin overlays with conventional binders have exhibited notably shorter lives due to raveling.

Hot In-Place Recycling (HIR)

HIR is used to correct surface distresses limited to the top 2 inches (51 mm) of the existing asphalt surface by softening the binder using heat treatment, mechanically loosening it, and mixing it with recycling additives, rejuvenators, or virgin asphalt binder before placing and compacting the modified mixture. The National Highway Institute offers a training course (Course No. 131050) on asphalt pavement in-place recycling techniques where this topic is covered in further detail (see https://www.nhi.fhwa.dot.gov).

HIR includes three different techniques (Peshkin et al. 2011):

- **Surface recycling**—The wearing surface (typically 0.50 to 1.50 inches [13 to 38 mm]) is heated, loosened, and mixed with new asphalt binder and relaid and compacted. For low-volume roadways, a single-pass recycling operation is used where the recycled mixture is relaid and compacted and serves as the wearing surface. For high-volume roads, the recycled and relaid mixture serves as the base course on top of which an asphalt overlay or surface treatment may be placed.
- **Remixing**—The wearing surface is heated, loosened, and mixed with virgin aggregates and new asphalt binder and relaid and compacted for significant improvement and minor pavement strengthening. The recycled surface may serve as the wearing course (for low-volume roads) or as the base layer for a subsequent asphalt overlay or a surface treatment (for higher volume roads).
- **Repaving**—This technique essentially involves surface recycling followed by the placement of a thermally bonded asphalt overlay (see figure 7-11) in order to strengthen the pavement and restore the surface profile.

Figure 7-11. Hot in-place recycling with application of overlay (Kandhal and Mallick 1997).

Positive Sustainability Attributes of Hot In-Place Recycling

- HIR seals and restores the pavement surface.
- HIR addresses minor surface distress, restores surface friction, removes rutting, improves ride quality, and improves texture, all contributing to improved safety.
- HIR improves pavement aesthetics by providing a new pavement surface.
- If not resurfaced with an asphalt overlay, HIR requires very little use of virgin materials, thus reducing transportation of materials to the site.
- HIR exhibits a relatively long life, reducing material consumption and construction impacts.
- The construction of HIR can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.
- HIR followed by an asphalt overlay can have a positive impact on tire-pavement noise emissions.

Potential Negative Sustainability Attributes of Hot In-Place Recycling

- The use of heat in the HIR process to soften the existing pavement surface and subsequently to combine with new material is energy and emission intensive.
- The HIR operation can generate fumes that can be objectionable in a community setting.
- The new surface produced by the HIR is initially dark in color and will likely have a lower albedo.
- A chip seal or asphalt overlay is often required as part of the HIR treatment, adding cost and environmental burden.
- The improper application of HIR can result in early failures that negatively impact economic and environmental performance.
- HIR followed by a chip seal can have a negative impact on tire-pavement noise emissions.

Cold In-Place Recycling (CIR)

CIR is primarily used to restore the profile/cross slope and address other minor surface distresses. CIR consists of cold milling, sizing the RAP, and mixing the RAP with asphalt emulsion, recycling additives, and new aggregate to produce a recycled cold mix; this cold mix is relaid and compacted to serve as the base course for a new surface (see figure 7-12). For low-volume roads, the surface resulting from the recycled cold mix is typically treated with a fog seal/rejuvenator to delay surface raveling. On higher volume roads, the recycled cold mix is treated with a more substantial treatment such as a chip seal or a thin asphalt overlay. The National Highway Institute offers a training course (Course No. 131050) on asphalt pavement in-place recycling techniques where this topic is covered in greater detail (see https://www.nhi.fhwa.dot.gov).

Figure 7-12. Cold in-place recycling (photo courtesy of D. Matthews).

Positive Sustainability Attributes of Cold In-Place Recycling

- CIR seals and restores the pavement surface.
- CIR addresses surface distress, removes rutting, and corrects minor profile deficiencies.
- Depending on the final surface, CIR can restore surface friction, improve ride quality, and improve surface texture, all contributing to improved safety.
- CIR improves pavement aesthetics by providing a new pavement surface.
- CIR uses existing materials in place, thus reducing the impacts of procuring and transporting new materials.
- CIR offers the potential for a relatively long life, thereby reducing material consumption and construction impacts due to repeated applications.
- CIR followed by an asphalt overlay can have a positive impact on tire-pavement noise levels.

Potential Negative Sustainability Attributes of Cold In-Place Recycling

- The sustainability of CIR is heavily dependent on the type of surface material applied on top of it.
- The new surface on a CIR project is often dark in color and will likely have a lower albedo.
- The construction of CIR projects is often performed in stages, which can result in traffic disruptions and delays.
- The improper application of CIR can result in early failures that negatively impact economic and environmental performance.
- CIR followed by a chip seal can have a negative impact on tire-pavement noise levels.

Ultra-Thin Bonded Wearing Course

This treatment is effective in addressing minor surface distresses and improving the frictional characteristics of the riding surface. It consists of a gap-graded or open-graded polymer- or rubber-modified asphalt layer (typically 0.4 to 0.8 inches [10 to 20 mm] thick) placed on a thick tack coat or membrane, and is commonly used as an alternative to chip seals, microsurfacing, or thin asphalt overlays.

Positive Sustainability Attributes of Ultra-Thin and Thin Bonded Wearing Course

- An ultra-thin bonded wearing course effectively seals the pavement surface.
- An ultra-thin bonded wearing course addresses minor surface distress, restores surface friction, improves ride quality, and improves texture, all contributing to improved safety.
- An ultra-thin bonded wearing course improves pavement aesthetics by providing a new pavement surface.
- An ultra-thin bonded wearing course can reduce noise generated through tire-pavement interaction.
- Ultra-thin bonded wearing courses can exhibit relatively long life, thereby reducing material consumption and construction impacts otherwise associated with repeated applications of other treatments.
- The construction of an ultra-thin bonded wearing course can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Ultra-Thin Bonded Wearing Course

- An ultra-thin bonded wearing course requires the use of new material transported from a central mixing facility.
- The improper application of an ultra-thin bonded wearing course can result in early failures that negatively impact economic and environmental performance.
- An ultra-thin bonded wearing course is initially dark in color and will likely decrease pavement albedo.

Bonded Concrete Overlays

Bonded concrete overlays (sometimes referred to as thin or ultra-thin whitetopping) are placed on existing asphalt pavements to eliminate surface distresses and correct pavement deformations (rutting, corrugation, and shoving). This treatment is characterized by the placement of a thin (2- to 6-inch [51 to 152 mm] thick) concrete (sometimes fiber reinforced) layer onto a cold-milled asphalt pavement (Harrington and Fick 2014). The cold milling is necessary to establish a strong bond between the two materials. Typical slab dimensions range from about 2 to 6 ft (0.61 to 1.8 m) for thinner overlays to about 6 to 12 ft (1.8 to 3.6 m) for thicker (6-inch [152-mm]) slabs. Figure 7-13 shows the short panels associated with many thin overlays. A comprehensive document describing the use, application, and construction of bonded concrete overlays is available (Harrington and Fick 2014).

Figure 7-13. Short panels for bonded concrete overlay.

Positive Sustainability Attributes of Bonded Concrete Overlays

- A completely new concrete surface is bonded onto the existing asphalt pavement, effectively sealing it while addressing minor surface distress, rutting, and continued instability in the asphalt layer.
- The concrete surface can be shaped and textured as desired, restoring surface friction, eliminating profile deficiencies, and reducing tire-pavement noise.
- Bonded concrete overlays improve pavement aesthetics by providing a new pavement surface.
- The pavement can be easily colored or textured to enhance aesthetics.
- Bonded concrete overlays typically are initially light in color and will likely increase pavement albedo.
- Bonded concrete overlays exhibit relatively long life, reducing material consumption and construction impacts that would be otherwise caused by repeated applications of other treatments.

Potential Negative Sustainability Attributes of Bonded Concrete Overlays

- Bonded concrete overlays require the use of new material transported from a central mixing facility, so the environmental impact of those materials must be considered.

- The improper construction of bonded concrete overlays (primarily through poor joint layout, construction and sealing practices or poor bonding) can result in early failures that negatively impact economic and environmental performance.
- The construction of bonded concrete overlays may require a longer period of time, leading to the development of traffic disruptions and delays.

Energy Use and Emissions for Asphalt-Surfaced Pavement Treatments

Limited information is available on the life-cycle energy consumption and emissions generated by asphalt-surfaced pavement maintenance and preservation treatments. This is partly because the diversity of these treatments is such that they are not easily categorized for analysis. In addition, most of the early focus in investigating environmental impacts has been on new construction and major rehabilitation. It has not been until fairly recently that the life-cycle impacts of preservation have been investigated by the pavement community.

For example, table 7-4 presents energy consumption and GHG emissions data for some typical asphalt-surfaced pavement preservation treatments, along with assumptions related to the extension of service life (Chehovits and Galehouse 2010). Table 7-5, which is from the same study, presents similar data for typical new construction and major rehabilitation. In developing the values shown in tables 7-4 and 7-5, energy use and GHG emissions were calculated for each treatment on the basis of the unit area of the pavement surface being treated and using typical quantities of raw materials for each treatment (agency costs only, no user costs). Those values were then divided by the pavement life extensions for each treatment to produce annualized results to allow more meaningful comparisons of the energy use and GHG emissions associated with the different treatments. In this context, relative comparisons can be made between the different treatments.

What is evident from these data is that the energy consumption and GHG emissions per year are considerably lower for many of the preservation and maintenance treatments compared to new construction or major rehabilitation, although not universally so. For instance, thin HMA overlays and hot in-place recycling both exhibit energy and GHG emissions that are similar to those of new construction. This suggests that these alternatives are similar for the factors considered, but other environmental and social factors not included in the analysis (e.g., solid waste generation, noise, safety, particulate matter) could also impact the results. Furthermore, the boundary conditions for the analysis were quite limited, and did not include such items as traffic delays resulting from construction operations and improved vehicle fuel efficiencies associated with smoother pavements. Regardless of the limitations associated with the data, it clearly demonstrates the reduced energy consumption and GHG emissions associated with many preservation and maintenance treatments.

A study conducted in Ontario (Chan et al. 2011) on various asphalt pavement treatment alternatives found that microsurfacing had the lowest annualized energy consumption and emission levels when compared to the other treatment alternatives (see table 7-6). However, that study suffers from some simplifications in the analysis. For one, it assumes that all of the treatments exhibit similar benefits over their entire life. In addition, it does not consider the broader impact of creating additional traffic disruptions for short-lived treatments. Still, it illustrates that less material-intensive preservation treatments have positive environmental impacts than more material-intensive options, reinforcing the concept that the environmental impact of materials production and construction is generally well correlated with the thickness of the treatment.

Table 7-4. Energy consumption and GHG emissions data for some typical asphalt-surfaced pavement preservation treatments (Chehovits and Galehouse 2010).

Treatment	Details	Pavement Life Extension (Years)	Energy Use per Year BTU/yd²	Energy Use per Year MJ/M²	GHG Emissions per Year lb/yd²	GHG Emissions per Year kg/m²
Hot-Mix Asphalt	Thickness 1.5 in (3.8 cm)	5-10	4,660 – 9,320	5.9 – 11.8	0.9 – 1.8	0.5 – 1.0
Hot-Mix Asphalt	Thickness 2.0 in (5.0 cm)	5-10	6,080 – 12,160	7.7 – 15.4	1.2 – 2.4	0.7 – 1.3
Hot In-Place Recycling	Thickness 1.5 in (3.8 cm) 50/50 Recycle/New	5-10	3,870 – 7,740	4.9 – 9.8	0.7 – 1.4	0.4 – 0.80
Hot In-Place Recycling	Thickness 2.0 in (5 cm) 50/50 Recycle/New	5-10	5,130– 10,260	6.5 – 13.0	0.9 – 1.5	0.5 – 1.0
Chip Seal	Emulsion 0.44 g/yd² (2.0 L/m²) Aggregate 38 lb/yd² (21 kg/m²)	3-6	1,170 -2,340	1.5 – 3.0	0.15 – 0.3	0.08 – 0.10
Chip Seal	Emulsion 0.35 g/yd² (1.6 L/m²) Aggregate 28 lb/yd² (15 kg/m²)	2-5	1,026 – 2,565	1.3 – 3.3	0.14 – 0.35	0.08 – 0.20
Slurry Seal/ Micro-surfacing	Type III 12% Emulsion, 24 lb/yd² (13 kg/m²)	3-5	1,026 – 1,710	1.3 – 3.3	0.12 – 0.2	0.06 – 0.10
Slurry Seal/ Micro-surfacing	Type II 14% Emulsion, 16 lb/yd² (8.7 kg/m²)	2-4	968 – 1,935	1.2 – 2.4	0.10 – 0.2f0	0.05 – 0.10
Crack Seal	1 lin ft/yd² (0.37 m/m²), 0.25 lb/ft (0.37 kg/m²)	1-3	290 - 870	.05 – .14	0.05 – 0.14	0.03 – 0.08
Crack Fill	2 lin ft/yd² (0.74 m/m²), 0.50 lb/ft (0.74 kg/m²)	1-2	930 – 1,860	1.0 – 2.0	0.13 – 0.25	0.07 – 0.14
Fog Seal	0.05 gal/yd² (0.23 L/m²) 50/50 Diluted Emulsion	1	250	0.4	0.04	0.02
Fog Seal	0.10 gal/yd² (0.46 L/m²) 50/50 Diluted Emulsion	1	500	0.8	0.07	1.04
Fog Seal	0.15 gal/yd² (0.69 L/m²) 50/50 Diluted Emulsion	1	750	1.2	0.12	0.07

Table 7-5. Energy consumption and GHG emissions data for new construction and major rehabilitation activities (Chehovits and Galehouse 2010).

Treatment	Details	Pavement Life or Life Extension (Years)	Energy Use per Year BTU/yd²	Energy Use per Year MJ/M²	GHG Emissions per Year lb/yd²	GHG Emissions per Year kg/m²
New Construction	4 in (102 mm) HMA over 6 in (152 mm) Aggregate Base	20	7840	9.9	1.2	0.7
Major Rehab Hot-Mix Asphalt	4 in (102 mm) Overlay	15	7500	9.4	1.3	.08
Major Rehab Hot-Mix Asphalt	3 in (76 mm) Overlay	12	7050	8.9	1.3	0.7
Major Rehab Warm-Mix Asphalt	4 in (102 mm) Overlay	15	7210	9.2	1.3	.08
Major Rehab Warm-Mix Asphalt	3 in (76 mm) Overlay	17	6780	8.5	1.3	0.7

Table 7-6. Comparison between microsurfacing and other treatment alternatives for asphalt-surfaced pavement (Chan et al. 2011).

Treatments	Service Life	Energy	CO_2	NO_x	SO_x
Mill 1.95 in (50 mm) Pave 1.95 in (50 mm)	10 Yrs	65 million BTU (67,493 MJ)	3.9 ton (3.5 mt)	67.6 lbs (30.7 kg)	2110 lbs (958 kg)
Mill 1.95 in (50 mm) Pave 1.95 in (50 mm) WMA	10 Yrs	45 million BTU (47,782 MJ)	2.2 ton (2.0 mt)	35.5 lbs (16.1 kg)	1478 lbs (671 kg)
1.95 in (50 mm) HIR	10 Yrs	54 million BTU (56,694 MJ)	3.0 ton (2.7 mt)	52.6 lbs (23.9 kg)	1645 lbs (747 kg)
0.39 in (10 mm) Microsurfacing	7 Yrs	7.6 million BTU (8,064 MJ)	0.33 ton (0.3 mt)	14.1 lbs (6.4 kg)	619 lbs (281 kg)

Strategies for Improving Sustainability

The general strategies for improving sustainability discussed at the beginning of this chapter are applicable, namely that thinner cross sections, the use of local or in-place materials, maintaining high levels of smoothness, and increased construction quality all reduce environmental burden and contribute to more sustainable treatments. It is emphasized that significant differences may exist in the approaches that are used to reduce environmental impacts, depending on a number of project-specific characteristics (perhaps most notably the traffic volumes and associated burdens created in the use phase).

Future Opportunities

As interest in improving the sustainability of asphalt-surfaced pavement maintenance and preservations techniques continues to evolve and move forward, future opportunities exist in the following areas:

- Improved maintenance materials that require the use of less material or last longer. However, some of the materials now being developed and marketed are proprietary and the environmental impacts of the component materials used is not known.
- Improved approaches for optimizing treatment selection and timing through the use of more sophisticated pavement management systems and more proactive "leading" indicators of performance.
- Improved construction, particularly improvements in paving machines that place the tack coat just ahead of the laydown of the hot mix, and improved compaction from the use of warm mix.
- Other improvements identified in chapter 3 on materials.

Concrete-Surfaced Pavement Maintenance and Preservation Treatments

Introduction

Concrete-surfaced pavements are any pavement structures surfaced with concrete, including JPCP, CRCP, and older jointed reinforced concrete pavement (JRCP) designs. In general, these pavements consist of a concrete surface on one or more granular or bound layers, but concrete-surfaced pavement also includes various concrete overlays that can be placed on existing concrete pavements (unbonded and bonded concrete overlays) or on existing asphalt pavements (again, either bonded or unbonded). Although this represents a range of different pavement types, the maintenance and preservation activities are largely identical (although there are some variations in how the treatments are executed).

Table 7-7 presents an overall summary of various maintenance and preservation treatments applicable to concrete-surfaced pavements. First, it provides a brief description of the technique and then indicates its effect on a number of preventive and restorative benefits ("↑" indicates positive impact, "↓" indicates negative impact, and "↔" indicates both positive and negative impact). This is followed by a general assignment of the relative life expectancy and cost, and the relative environmental and social impacts.

As noted before in the discussions of the treatments for asphalt-surfaced pavements, these relative comparisons are inherently non-specific, which is due to the general lack of available information and the large number of variables that affect the performance, cost, life-cycle environmental impact, and social impact of each treatment. The relative comparisons will also vary depending on the traffic levels, climate region, and a host of other variables. In general, treatments that require more material or materials that have higher environmental impacts will have higher environmental impacts through construction. Those that last longer and have the greatest impact on preserving functional surface characteristics (e.g., ride quality, surface friction, and high albedo) will have reduced environmental impacts over the life cycle, especially in high-traffic applications where the economic and environmental impacts of vehicles are the greatest.

Table 7-7. Evaluation of sustainability impacts of treatments for concrete-surfaced pavements.

Treatment	Description	Preventive		Restorative				Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Prevent Intrusion of Incompressibles	Eliminate/ Control Faulting	Improve Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Joint Resealing/ Crack Sealing	Joint resealing consists of removing existing longitudinal/transverse joint sealants, preparing and installing new sealant material. Crack Sealing consists of cleaning, preparing and sealing longitudinal/transverse cracks	↑	↑		↓ Longitudinal overbanding can negatively impact friction		↔ Overbanding increases noise, filling can reduce noise	✓	$	Low	Reduced traffic delays; less pleasing aesthetics and potential roughness issues with crack sealing
Slab Stabilization/Slab Jacking	Slab stabilization involves the restoration of support to slabs by filling voids, thereby reducing deflections. Slab jacking involves raising slabs to their desired elevation by pressure inserting material beneath settled slabs			↑ In combination with other CPR treatments		↑ In combination with other CPR treatments		✓✓	$$$	Low to Medium Depends on amount of slab stabilization required	When combined with other treatments, results in long-term Improvement in ride quality
Diamond Grinding	Removal of thin concrete layer (0.12 to 0.25 in.) from pavement surface using special equipment.			↑	↑	↑ Significant improvements on faulted pavement	↑	✓✓✓	$$	Medium to High Depends on how much surface is being removed, hardness of the aggregate, level of smoothness obtained, and traffic level	Increases safety by improving friction, reduces noise from tire-pavement interaction
Diamond Grooving	Cutting narrow, discrete grooves (typically longitudinal) into pavement surface to increase friction and reduce noise				↑			✓✓✓	$$	Low	Improved wet weather safety and reduced noise. Some issues regarding negative impact on vehicle tracking (particularly motorcycles) have been cited
Partial-Depth Repairs	Localized removal and replacement of deteriorated concrete, most often in vicinity of joints) in the upper third of the slab using approved repair materials	↑ In combination with other CPR treatments	↑ In combination with other CPR treatments			↑		✓✓	$$$	Variable Depends on type of material used and amount of patching required	Rapid-setting repair materials used for partial-depth patching reduce traffic delays. Restoration of ride quality is significant for badly damaged pavement if slabs are ground. Aesthetics can be negatively affectively if repair material does not match existing pavement

Table 7-7. Evaluation of sustainability impacts of treatments for concrete-surfaced pavements (continued).

Treatment	Description	Preventive		Restorative				Performance and Cost		Relative Environmental Impact based on life cycle energy use and GHG emissions, materials (Low, Medium, High, Variable)	Societal Impact
		Seal Pavement	Prevent Intrusion of Incompressibles	Eliminate/ Control Faulting	Improve Texture for Friction	Improves Ride Quality and Surface Profile	Improve Texture for Noise	Relative Treatment Life (✓ to ✓✓✓✓)	Relative Cost ($ to $$$$)		
Full-Depth Repairs	Removal and replacement of deteriorated concrete through the full depth of the slab using approved repair materials; may be cast in-place of precast	↑ In combination with other CPR treatments	↑ In combination with other CPR treatments	↑ At affected joint(s)		↑		✓✓✓	$$$$	Medium to High Depends on amount of patching and type of material used; also depends on whether repairs are cast in-place or pre-cast	Pre-cast panels reduce traffic delays. Aesthetics can be negatively affectively if repair material does not match existing pavement
Dowel Bar Retrofit	Placement of dowel bars across joints or cracks in existing jointed concrete pavement			↑ In combination with other CPR treatments		↑ In combination with other CPR treatments		✓✓✓✓	$$$	Variable If globally applied, high initial negative impact but restoration of load transfer, in combination with diamond grinding, will make the smoothness last longer and have positive impact throughout the life cycle.	Improves ride quality by controlling faulting, which is eliminated when combined with diamond grinding. Aesthetics can be negatively affectively if repair material does not match existing pavement
Cross Stitching	Technique used to maintain load transfer across non-working longitudinal cracks that are in relatively good condition			↑					$$$	Low	Improves long-term performance by keeping longitudinal cracks tight. Eliminates the need for slab removal and replacement
Retrofitted Edge Drains	Technique used to collect water that has infiltrated into the pavement structure and discharges it to the ditches through regularly spaced outlet drains. Can have negative impact if creates "bathtub" through poor design or construction					↑		✓✓✓	$$$$	Variable Can have a large impact if poor drainage is primarily responsible for poor performance, but must be properly designed, constructed and maintained or can trap water in the pavement	Can improve long-term performance by reducing moisture induced distress
Ultra-Thin Wearing Course, typically open-graded with rubberized or polymerized binders	Used to improve the functional surface characteristics of the concrete pavement including enhancing friction and reducing noise. Consists of open or gap-graded aggregates and rubberized or polymer-modified asphalt layer (0.4 to 0.8 in. thick) well bonded to the concrete surface	↑	↑		↑	↑	↑	✓✓	$$$	Variable Depends on type of material used and life of treatment	Primarily used to enhance functional surface characteristics of the pavement, most notably noise reduction and improved friction
Bonded Concrete Overlay	Placement of a relatively thin (2 to 6 in.) concrete layer, with slab over an existing concrete-surfaced pavement	↑	↑		↑	↑		✓✓✓✓	$$$	Medium Virgin materials and concrete materials increase impact, thinner cross section reduces impact	Increases safety through improved friction and drainage; improved ride quality; improved aesthetics. Increase in albedo may positively impact the UHI effect

Note: Relative Environmental Impacts discussed in tale 7-3 provide rough comparisons; reliable estimates will be available only after new assessments are conducted.

Key: ↓ decreased
↑ increased
↔ no trend

Various resources are available that discuss concrete pavement preservation/maintenance strategies as well as each treatment type, including the types of pavement conditions addressed, how each treatment should be constructed, and their cost effectiveness. These include a web-based training series developed by the National Concrete Pavement Technology Center and offered by the National Highway Institute (NHI Course No. 131126) and a number of treatment-specific references available from the American Concrete Pavement Association, the FHWA, and others. As considerable information is readily available regarding the application, cost effectiveness, and construction of the various treatments, the following sections specifically address the sustainability aspects of each treatment, focusing on the environmental and social impacts.

Although any given concrete-surfaced pavement treatment can be applied alone (for example full-depth patching can be used to repair a localized slab failure), it is far more common to use several treatments together in an approach often referred to as concrete pavement restoration (CPR) to restore a structurally sound but distressed concrete pavement to a higher level of serviceability. Thus the sustainability impact of any one treatment is very difficult to assess, as ultimately the economic, environmental, and social impacts of the entire strategy should be assessed together. A recommended sequence for the placement of various treatments during a CPR project is illustrated in figure 7-14 (ACPA 2006). In the following discussion, each treatment is considered individually with the linkage to other treatments established in the narrative.

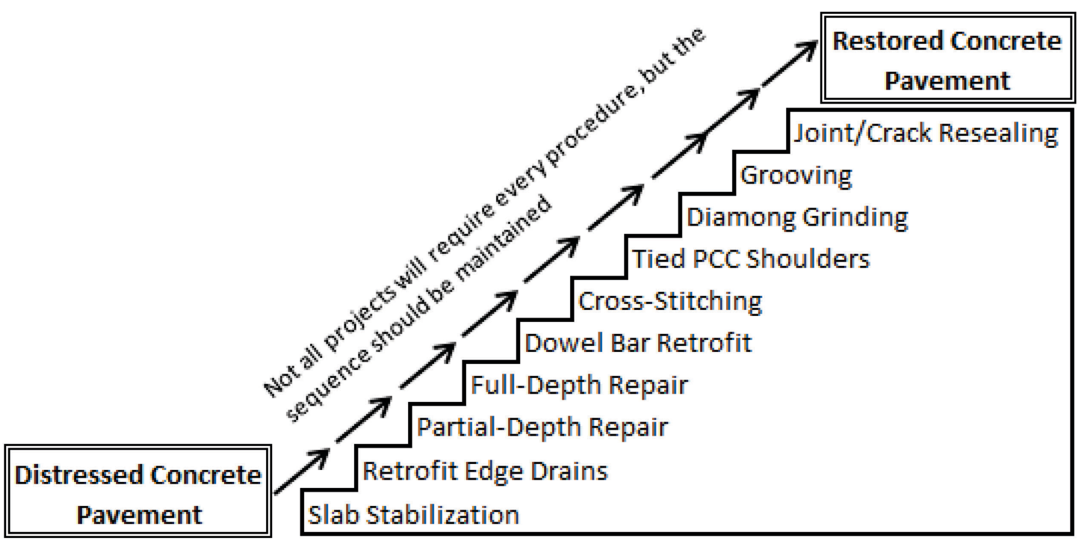

Figure 7-14. Typical sequence of concrete-surfaced pavement treatments as part of CPR (ACPA 2006).

Joint Resealing/Crack Sealing

Joint and crack sealing is a commonly performed pavement maintenance activity that serves two purposes: reduce the amount of moisture infiltration into the pavement structure, thereby reducing moisture-related distresses such as pumping, joint faulting, base and subbase erosion, and corner breaks; and prevent the intrusion of incompressibles to prevent pressure-related distresses such as spalling, blowups, buckling, and shattered slabs (Smith et al. 2014).

Joint resealing involves the removal of existing deteriorated sealant material (if present), preparation of the joint sidewalls, and installation of the new sealant material (see figure 7-15). Crack sealing is typically done only on longitudinal and transverse cracks and corner break cracks that are wider than 0.125 inch (3 mm) and involves routing, cleaning, and sealing cracks using a high-quality sealant material (Peshkin et al. 2011).

Figure 7-15. Joint sealing.

Joint resealing and crack sealing should be the last activities in the sequence of treatments performed on a given restoration project. Intended for pavements in relatively good condition, joint resealing can also be performed independently on a project with an original sealant that has failed or become ineffective.

Positive Sustainability Attributes of Joint Resealing and Crack Sealing

- Joint/crack sealing helps minimize the amount of moisture infiltrating the pavement, potentially extending the life.
- Joint/crack sealing uses relatively little material and, thus, does not have large material-related environmental impacts.
- Joint/crack sealing generates little construction waste.
- Joint/crack sealing operations use relatively little energy.
- Joint/crack sealing can be performed using a moving traffic control operation, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Joint Resealing and Crack Sealing

- Joint/crack sealing can have a relatively short life when compared to that of the concrete pavement and thus must be repeated multiple times over the life cycle (with associated more frequent disruptions to traffic).
- Multiple joint resealing operations widen the joint reservoir and can negatively impact ride quality and increase tire-pavement noise emissions.
- Crack sealing can negatively impact pavement aesthetics over time.
- The sealant removal and cleaning portions of joint/crack sealing operations are typically noisy and can produce particulate that may be problematic in a community setting.

Slab Stabilization/Slab Jacking

Slab stabilization is a technique used to restore support beneath the concrete pavement by filling voids that developed under service, thereby reducing deflections (Smith et al. 2014). Slab stabilization should be performed in areas where loss of support is known to exist. For optimum performance, it is critical that this technique be used prior to the onset of damage caused by loss of support (ACPA 1994).

Slab jacking involves the injection of a cement grout or expansive polyurethane material beneath the slab to gradually elevate a settled slab back to its original profile. This technique is used to correct localized areas of settlement or depression, and not to address common transverse joint faulting (Smith et al. 2014).

Slab stabilization is rarely used alone, instead often being the first step in a restoration project. Slab jacking, on the other hand, can be applied independently of other treatments as its sole purpose is to elevate a slab that has settled due to underlying conditions (such as often occurs at bridge approach slabs or over culverts).

Positive Sustainability Attributes of Slab Stabilization/Slab Jacking

- Slab stabilization restores slab support, thereby reducing deflections and reducing the likelihood of corner breaking. However, in order for slab stabilization to be effective in the long term, the underlying causes of pumping and loss of support (such as poor drainage and poor load transfer) must be addressed.
- Slab stabilization and slab jacking use relatively little material and, thus, do not have large material-related environmental impacts.
- Slab stabilization and slab jacking generate little construction waste.
- The construction operations associated with slab stabilization and slab jacking use relatively little energy.
- Slab stabilization and slab jacking are expected to provide long-term positive impacts if the voids are filled and the root causes of the loss of support are addressed.

Potential Negative Sustainability Attributes of Slab Stabilization/Slab Jacking

- Slab stabilization must be appropriately applied to slabs in which loss of support has occurred. The inappropriate application of this treatment can result in waste and early pavement failure.
- Slab stabilization and slab jacking can be labor-intensive operations that may result in traffic disruptions and delays, but innovative construction practices and materials can be used to minimize that impact.
- Although material usage is low, the environmental impact of the materials (cement grout, polyurethane) must be evaluated.

Diamond Grinding/Grooving

Figure 7-16. Surface texture produced by diamond grinding (courtesy ACPA)

Diamond Grinding involves the removal of a thin (0.12 to 0.25 inch [3 to 6 mm]) layer of material from the concrete surface using special grinding equipment equipped with gang-mounted, closely-spaced diamond saw blades. This technique has traditionally been used to address faulting and other surface irregularities (Peshkin et al. 2011). Diamond grinding contributes to improved sustainability by providing a smooth riding surface (which increases vehicle fuel efficiency) and also by providing a safe pavement surface (through increased surface friction) (Smith et al. 2014). Diamond grinding has also been used on new pavements and older pavements with no apparent distress simply to improve ride quality, provide frictional characteristics, and reduce tire-pavement noise emissions. Diamond grinding also creates an aesthetically pleasing surface that exposes the underlying aggregates (see figure 7-16).

Positive Sustainability Attributes of Diamond Grinding

- Diamond grinding renews the pavement surface without the need for additional material other than the water used in the grinding operation and the wear of the diamond blades. This provides a significant sustainability advantage over treatments that rely on the application of new material.
- Diamond grinding produces a riding surface that is functionally (ride quality, surface friction, noise) as good, or better, than what was originally constructed. This significantly reduces user impacts as long as the high level of functionality is maintained.
- Diamond grinding generates little construction waste, although the disposal of the slurry that is produced during the operation must be addressed.
- Diamond grinding can be conducted under a moving traffic control operation, thus minimizing traffic disruptions and delays.
- Diamond grinding is expected to provide a long-term, positive impact if the pavement is structurally sound and the root causes of the roughness issues (i.e., faulting) are addressed.

Potential Negative Sustainability Attributes of Diamond Grinding

- The effectiveness of diamond grinding to restore surface friction is largely a function of the polishing susceptibility of the coarse aggregate. If the aggregate is susceptible to polishing, the positive effects of diamond grinding on surface friction will be short lived.
- Although material usage is low, the environmental impact of disposal of the slurry must be considered.

- If the coarse aggregates are dark in color, diamond grinding will result in a darker surface color, likely reducing the pavement albedo.
- Diamond grinding operations are typically noisy, which may be a potential issue in a community setting.

Diamond Grooving (see figure 7-17) involves cutting narrow, discrete grooves (longitudinal or transverse) to help improve safety by reducing hydroplaning potential, splash and spray, and wet-weather-related crashes. Transverse grooving, which is common on bridges, may have an adverse impact on tire-pavement noise, which is why longitudinal grooving is more commonly used on highways as it reduces tire-pavement noise while still reducing hydroplaning potential. A hybrid surface texture, called the Next Generation Concrete Surface, employs a combination of diamond grinding and diamond grooving and has demonstrated excellent restoration of the pavement functional characteristics (ride quality, friction, and noise reduction) (IGGA 2011).

Figure 7-17. Diamond grooving operation.

Positive Sustainability Attributes of Diamond Grooving

- Diamond grooving is specifically applied to reduce hydroplaning potential and the noise emissions associated with tire-pavement interaction. There is no need for additional material other than the water used in the grooving operation and the wear of the diamond blades. This provides a significant sustainability advantage over treatments that rely on the application of new material.
- Diamond grooving generates little construction waste, although the disposal of the slurry that is produced must be addressed.
- Diamond grooving can be conducted under a moving traffic control operation, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Diamond Grooving

- Although material usage is low, the environmental impact of disposal of the slurry created by diamond grooving must be considered.
- Diamond grooving operations are typically noisy, which may be a potential issue in a community setting.

Partial-Depth Repairs

Partial-depth repairs (see figure 7-18) are used to address joint spalling and other surface distresses that are limited to the top third to top half of the slab through the use of approved repair materials. This treatment is effective in restoring the ride quality and structural integrity of localized areas while allowing joints to be effectively sealed. Improper repair finishing can result in poor ride quality, so diamond grinding is typically recommended to blend the repaired surface with the adjoining pavement (Smith et al. 2014).

Figure 7-18. Partial-depth repair.

Although they can be used alone to repair isolated damaged joints, partial-depth repairs are most typically conducted before full-depth repairs are completed and after slab stabilization is performed.

Positive Sustainability Attributes of Partial-Depth Repairs

- Partial-depth repairs use relatively little material and, thus, do not have large material-related environmental impacts.
- Partial-depth repairs generate a small amount of construction waste.
- Partial-depth repairs are expected to have long-term positive impacts if properly constructed in conjunction with other needed treatments.

Potential Negative Sustainability Attributes of Partial-Depth Repairs

- Partial-depth repairs must be appropriately applied to appropriate distresses and on slabs in which the limits of the damaged area are correctly identified and removed. The inappropriate application of partial-depth repairs can result in waste and early pavement failure.
- The construction of partial-depth repairs has historically been a labor-intensive, time-consuming operation with a high potential for traffic disruptions and delays; however, newer construction processes (including milling) and rapid-setting materials are being used to reduce these impacts.
- Partial-depth repairs can compromise pavement aesthetics if the repair material does not match the existing pavement material or if installed at a high density.
- The installation of partial-depth repairs is typically noisy and produces particulates, which may be problematic in a community setting.

Full-Depth Repairs

Figure 7-19. Full-depth repair.

Full-depth repairs (see figure 7-19) are effective in addressing structural distresses that extend through more than one-half of the slab thickness. Full-depth repairs extend through the entire thickness of the existing slab and involve the removal and replacement of full lane-width areas with cast-in-place or precast concrete. The additional joints created through full-depth repairs have the potential to decrease the ride quality. Hence, diamond grinding should be considered after full-depth repair installation to blend the repairs with the adjoining pavement and provide a smooth-riding surface (Smith et al. 2014). These repairs may not be a sustainable solution from an environmental and societal standpoint if they are performed over a large area of the project.

Positive Sustainability Attributes of Full-Depth Repairs

- Full-depth repairs are most often used to replace deteriorated joints or entire slabs, thereby restoring ride quality and pavement structural integrity.
- Full-depth repairs applied on a moderate scale have less environmental impact and lower costs than more extensive alternatives such as overlays or reconstruction.
- Full-depth repairs are expected to have a long-term positive impact on pavement longevity if properly constructed in conjunction with other needed treatments.

Potential Negative Sustainability Attributes of Full-Depth Repairs

- The installation of full-depth repairs is a labor-intensive operation that can result in significant traffic disruptions and delays. Various innovative construction practices and materials can be used to minimize this impact, but these are sometimes at a greater cost and a higher risk of early failure. Full-depth repair using precast concrete panels is an innovative option that can result in a reduction in environmental impact through reduced material-related impacts and expedited construction to minimize traffic delays.
- Full-depth repairs can compromise pavement aesthetics if the repair material does not match the existing pavement material or if installed at a high density.
- The installation of full-depth repairs is typically noisy and produces particulates, which may be an issue in a community setting.

Dowel Bar Retrofitting

Dowel bar retrofitting (also called load transfer restoration) involves the placement of dowel bars across joints or cracks with poor load transfer (see figure 7-20). The operation involves cutting slots, removing the existing concrete and preparing the slots, installing the dowels in the slot seated on a small chair, and backfilling the slot with repair grout. This technique helps reduce deflections by improving the load transfer across joints and cracks, thereby reducing the potential for the development of pumping, faulting, void formation, and corner breaks.

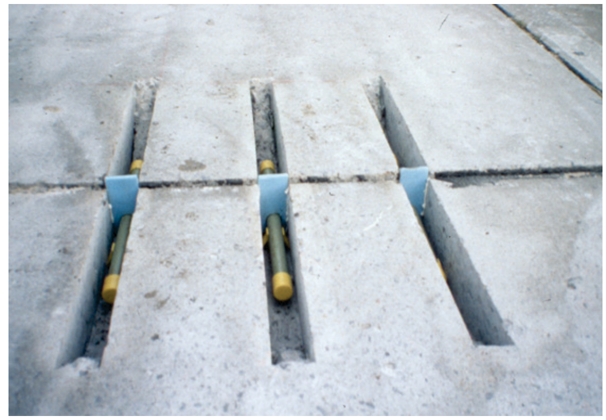

Figure 7-20. Placement of dowel bars in a dowel bar retrofitting operation.

This treatment is often performed along with diamond grinding, which removes faulting and reduces noise levels. It is a common practice to use dowel bar retrofit to provide load transfer in jointed pavements that were originally constructed without dowels, or to provide improved transfer at mid-panel cracks.

Positive Sustainability Attributes of Dowel Bar Retrofitting

- Dowel bar retrofitting is used to provide/restore joint load transfer and reduce load-related stresses and deflections at joints and cracks, thereby helping to control the development of faulting and corner breaks.
- Dowel bar retrofitting uses relatively little material and thus does not have large material-related environmental impact. The use of dowels with a high recycled steel content provides further sustainability benefits.
- A relatively small amount of construction waste is generated by the dowel bar retrofitting operation.
- Dowel bar retrofit is expected to have a long-term positive impact if properly constructed in conjunction with other needed treatments.

Potential Negative Sustainability Attributes of Dowel Bar Retrofitting

- Dowel bar retrofitting must be appropriately applied to slabs; the inappropriate application or poor construction can result in early pavement failure at a high cost.
- Dowel bar retrofitting is a labor-intensive operation that can result in traffic disruptions and delays. The process can be expedited to some degree through the use of innovative construction practices and materials to minimize this impact, but at a greater cost and a higher risk of early failure.
- Dowel bar retrofitting can compromise pavement aesthetics if the repair material does not match the existing pavement material.
- The construction operations associated with dowel bar retrofitting are typically noisy and produce particulates, which may be problematic in a community setting.

Cross Stitching

Cross stitching is a technique used to maintain load transfer across non-working longitudinal cracks that are in relatively good condition (Smith et al. 2014). This treatment helps keep the cracks tight (or keeps them from opening further) by preventing vertical and horizontal movement, thereby maintaining adequate load transfer and reducing the rate of deterioration.

Positive Sustainability Attributes of Cross Stitching

- If done correctly, cross stitching provides a good long-term alternative to full-depth replacement of the affected slabs. This results in significant economic and environmental savings.
- Cross stitching uses relatively little material and thus has a small material-related environmental impact, made even less impactful if the steel has a high recycled content.
- Cross stitching generates little construction waste.

Potential Negative Sustainability Attributes of Cross Stitching

- Cross stitching must be appropriately applied to non-working cracks. Inappropriate application or poor construction can result in early pavement failure at a high cost.

Retrofitted Edge Drains

Retrofitted edge drains are sometimes used on concrete pavements that exhibit early indications of moisture-related distresses such as pumping and joint faulting. This technique involves the excavation of narrow trenches longitudinally at the outside edge of the pavement, the placement of a pipe or “fin” drain in the trench, and backfilling with drainable material to collect water that has infiltrated into the pavement structure and discharge it into the ditches through regularly spaced outlet drains (Smith et al. 2014). In some regions, retrofitted edge drains have been successful in slowing pavement degradation.

Retrofitting of edge drains is done near the beginning of the pavement restoration process, usually after slab stabilization has been completed.

Positive Sustainability Attributes of Retrofitted Edge Drains

- Retrofitted edge drains are intended to extend pavement life by removing excess moisture beneath the pavement.
- The installation of retrofitted edge drains can be completed in a relatively short time period and with relatively short work zones, thus minimizing traffic disruptions and delays.
- Retrofitted edge drains use no new paving materials, but do incorporate polyethylene or polyvinyl chloride piping materials whose environmental impacts must be assessed.

Potential Negative Sustainability Attributes Retrofitted Edge Drains

- Retrofitted edge drains must be appropriately installed, as the inappropriate application or poor construction can result in early pavement failure.
- The installation of retrofitted edge drains is a labor-intensive operation that can result in traffic disruptions and delays.
- Continued maintenance of the edge drain system is essential to its long-term effectiveness.

Ultra-Thin Wearing Course

This type of treatment on concrete pavement is used exclusively to improve the functional surface characteristics (friction and noise) of an existing pavement. These are very similar to the treatment of the same name discussed under asphalt-surfaced pavements, consisting of specially graded aggregates and a polymer-modified asphalt layer (0.4 to 0.8 inch [10 to 20 mm] thick) placed on a polymer-modified asphalt membrane. The life expectancy for ultra-thin wearing courses on jointed concrete pavements is shorter than when used on asphalt pavements due to the occurrence of joint reflection cracking in the wearing course (Tayabji, Smith, and Van Dam 2010). Ultra-thin wearing courses are applied to concrete pavements to achieve improved surface friction or to reduce noise emissions (or both).

Positive Sustainability Attributes of Ultra-Thin Bonded Wearing Course

- Ultra-thin wearing courses effectively seals the pavement, including joints and cracks.
- Ultra-thin wearing courses improve wet-weather safety by increasing texture and reducing splash and spray.
- Ultra-thin wearing courses improve pavement aesthetics by providing a new pavement surface.
- Ultra-thin wearing courses reduce noise generated through tire-pavement interaction.
- The construction of ultra-thin wearing courses can be completed in a relatively short time period, thus minimizing traffic disruptions and delays.

Potential Negative Sustainability Attributes of Ultra-Thin Bonded Wearing Course

- Ultra-thin wearing courses are dark in color and will likely decrease pavement albedo.
- Ultra-thin wearing courses require the use of new material transported from a central mixing facility.
- The life of ultra-thin wearing courses is relatively short when compared to the underlying concrete pavement, and thus will need to be reapplied multiple times during the pavement life.

Bonded Concrete Overlays

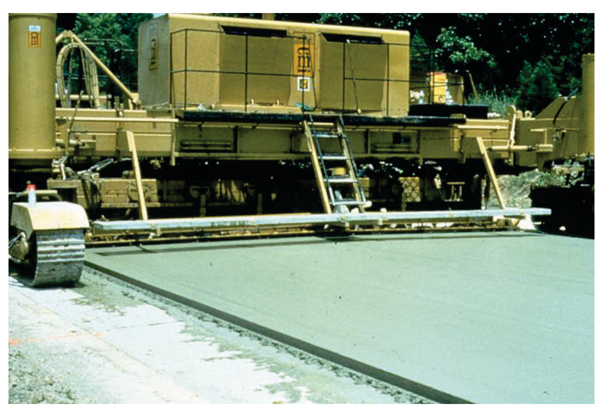

Figure 7-21. Bonded concrete overlay construction (courtesy ACPA).

Bonded concrete overlays (see figure 7-21) are characterized by the placement of a relatively thin (2 to 4 inch [51 to 102 mm] thick) concrete layer over an existing concrete pavement after isolated areas of deterioration on the existing pavement have been repaired and proper surface preparation practices have been followed to ensure adequate bonding. Bonded concrete overlays can be placed on existing concrete pavements to eliminate surface distresses and improve surface friction, ride quality, and noise emissions. A strong bond between the new overlay and existing pavement is required so that the resultant pavement behaves as a monolithic structure. Bonded concrete overlays require that the existing pavement be in (or be restored to) good or better structural condition. A comprehensive document on the use, application, and construction of concrete overlays is available from the National Concrete Pavement Technology Center (Harrington and Fick 2014).

Positive Sustainability Attributes of Bonded Concrete Overlays

- The concrete surface can be shaped and textured as desired, restoring surface friction, eliminating profile deficiencies, and reducing tire-pavement noise.
- Bonded concrete overlays improve pavement aesthetics by providing a new pavement surface.
- The pavement can be easily colored or textured to enhance aesthetics.
- Bonded concrete overlays are initially light in color and will likely increase pavement albedo.
- If properly designed and constructed, bonded concrete overlays exhibit relatively long life, reducing material consumption and construction impacts that would be otherwise caused by repeated applications of other treatments.

Potential Negative Sustainability Attributes of Bonded Concrete Overlays

- Bonded concrete overlays require the use of new material transported from a central mixing facility, so the environmental impact of those materials must be considered.
- Bonded concrete overlays can be difficult to construct, and improper construction (particularly the failure to achieve good bond between the overlay and the original pavement) can result in early failures that negatively impact economic and environmental performance.
- The construction of bonded concrete overlays may require a longer period of time, leading to the development of traffic disruptions and delays.

Energy Use and Emissions for Concrete-Surfaced Pavement Treatments

The information available regarding energy use and emissions for preservation and maintenance treatments placed on concrete-surfaced pavements is even more limited than that available for asphalt-surfaced pavements. Past studies of environmental impact have largely used LCI values for standard materials and computed hours of equipment use for a given treatment, assuming treatment life based on agency experience. Similar to asphalt-surfaced pavement treatments, the early focus has been on investigating the environmental impact of new construction and major rehabilitation. Only recently has the life-cycle value of preservation been investigated by the sector of the pavement community applying sustainability concepts.

One recent study (Wang et al. 2012) evaluated a limited number of concrete-surfaced pavement maintenance treatments and concluded that pavement maintenance can produce important net reductions in GHG emissions and energy use for high-volume routes. For segments with low-traffic volumes, the potential benefits take much longer to accrue, and payback may not occur before the end of the treatment life.

To elaborate, the study by Wang et al. (2012) examined the impacts of different material types for early-opening-to-traffic full-depth repairs (i.e., a high-cementitious mixture comprising AASHTO M 85 Type III cement with a high dose of accelerator, compared to a standard

Caltrans-specified calcium-sulfo-aluminate cement [CSA] mixture) as well as the benefits of diamond grinding. The construction efforts and performance periods for the two materials were considered identical; thus, the differences in energy consumption and GHG emissions were largely related to the material choices. As a result, the environmental impact of the more traditional Type III cement mixture was found to be significantly higher than that of the CSA mixture due to the following three factors:

- The Type III mixture had a cement content of 801 lbs/yd^3 (475 kg/m^3) versus 657 lbs/yd^3 (380 kg/m^3) for the CSA mixture.
- Although data on differences in embodied energy for the two cement types varies, the CSA cement is far less GHG intensive to produce than Type III cement as no calcination of limestone takes place.
- The Type III mixture used a very high dosage of accelerator (63 lbs/yd^3 [37 kg/m^3]). At that dosage rate, the accelerator had a significant environmental impact.

Figure 7-22 illustrates the impact of the material choice on the calculated energy consumption for the high-traffic-volume case study. As can be seen, although the cementitious binder had the single largest impact on the energy consumption, the accelerating admixture had a very significant impact as well. The same trend was observed for GHG emissions, but to a slightly lesser degree. Aggregates and mixing plant effects are minimal. This illustrates the importance of using mixture-specific information in any environmental analysis.

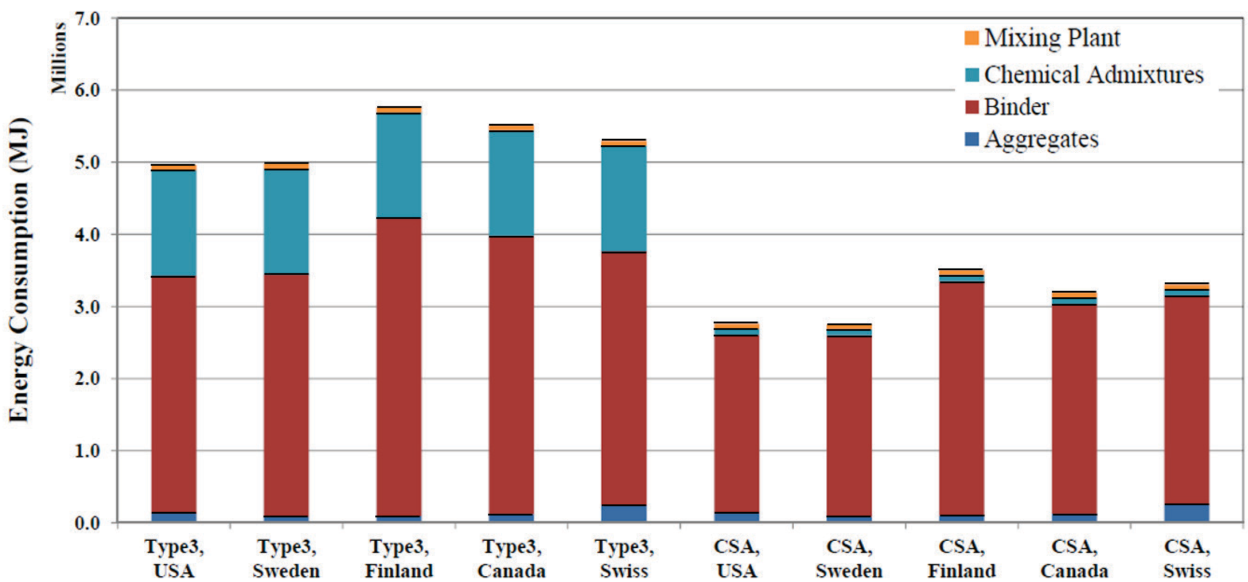

Figure 7-22. Details for the high-traffic case study of the material production phase showing the energy consumption for different LCI data sets (Wang et al. 2012).

In this same study, Wang et al. (2012) evaluated the use of diamond grinding to create three different levels of smoothness. It was concluded that the as-constructed pavement smoothness has an important effect on GHG emissions and energy use in the use phase and, therefore, on the total GHG emissions and energy use over the life cycle. It was also found that if the treatment does not result in a smooth pavement, then the environmental benefit is greatly reduced. Furthermore, although the emphasis on most work to date has been on materials and construction, the differences in net energy consumption, GHG emissions, and payback time between materials for a given treatment (i.e., repairs constructed using CSA cement or Type III portland cement) were small compared with the effects of smoothness over the life of the treatment. The authors noted that the impact of materials was probably reduced due to the limited number of slabs being replaced (3 percent) in the case studies.

Considerable work remains to be done in order to document and validate the effects of preservation and maintenance with regards to life-cycle environmental impacts. Nevertheless, this early work on concrete-surfaced pavements suggests that treatments that use less material and create smooth pavements that remain smooth for long periods of time will have distinct environmental benefits, particularly on more heavily traveled routes.

Strategies for Improving Sustainability

The general strategies for improving sustainability of preservation and maintenance treatments for concrete-surfaced pavements discussed at the beginning of this chapter are applicable. Thus, factors such as limited new material use, thinner cross sections, maintaining high levels of smoothness, and increased construction quality all reduce environmental burden and contribute to more sustainable treatments. As noted before, significant differences may exist in the approaches that are used to reduce environmental impacts, depending on a number of project-specific characteristics (perhaps most notably traffic volumes and associated burdens created in the use phase). As traffic volume increases, maintaining smooth surfaces becomes even more critical as the economic and environmental costs during the use phase begin to dominate the analysis. Although there is a clear distinction between agency costs and user costs with regards to economics, no such distinction exists when considering environmental impacts such as GHG and other emissions.

Future Opportunities

As interest in improving the sustainability of concrete-surfaced pavement maintenance and preservation techniques continues to evolve and move forward, future opportunities exist in the following areas:

- Improved materials that use less material and last longer. However, many of these innovative materials are (or will be) proprietary, so their environmental impacts are unknown or difficult to determine.
- Improved approaches for optimizing treatment selection and timing through the use of more sophisticated pavement management systems and more proactive “leading” indicators of performance.
- Improved construction, particularly improvements in equipment that can expedite some of the more labor-intensive and time-consuming activities.
- The use of precast solutions to reduce traffic disruptions and lane closures.

- Increased emphasis and refinement of renewable surfaces (e.g., diamond grinding).
- Alternative repair materials that can be opened to traffic more quickly without compromising future performance.
- Alternative load transfer devices that expedite construction yet have exceptional long-term performance.
- Increased sophistication of pavement evaluation equipment to determine suitability of various treatments.
- Other improvements as identified in chapter 3 for materials.

Concluding Remarks

This chapter reviews the effects of various maintenance and preservation treatments on the sustainability of pavement systems. There is a considerable lack of information on this topic, but clearly there are environmental and social impacts associated with the application of the broad range of preservation treatments on either asphalt-surfaced or concrete-surfaced pavements.

Although the cost effectiveness of these treatments has been investigated in recent years and they are widely accepted, the environmental and societal benefits still need to be explored. Specifically:

- Life-cycle inventories have not generally been done for pavement maintenance/ preservation treatments. Although preliminary work has demonstrated significant environmental value for some techniques, considerably more work needs to be done.
- Lower life-cycle costs are often highly correlated with lower environmental burden, with both being affected by:
  - Treatment selection.
  - Materials selection.
  - Timing of treatment.
- On higher-traffic routes, the higher economic cost of more frequent treatment may be offset by large reductions in environmental impact due to vehicle operation on smoother pavement.
- Treatment and materials selection.
  - Treatments with thinner cross sections having the same service life result in reduced environmental impacts.
  - The use of local materials reduces transportation costs, but must be balanced with the need to meet performance requirements.
  - Reducing traffic delays on high-volume routes must be balanced with the need to maintain high levels of smoothness.
  - New materials that enhance performance or lower energy consumption and emissions should be investigated.
  - The environmental footprint during the manufacture of some materials may be high. The development and implementation of Environmental Product Declarations (EPD) (discussed in chapter 10) will help provide useful information to decision makers.

- Construction quality.
  - Increased construction quality extends pavement life and reduces environmental burden.
  - The additional effort required to achieve additional quality is generally very low.
  - Pavements that are initially constructed smooth and that are maintained in a smooth condition over their life will result in reduced energy use and GHG emissions.

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CHAPTER 8. END-OF-LIFE CONSIDERATIONS

Introduction

Chapter 2 defines pavement end-of-life as the "final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its useful life." When the pavement reaches its end-of-life, it may: 1) remain in place and be reused as part of the supporting structure for a new pavement, 2) be recycled, or 3) be removed and landfilled. Each of these activities has economic and environmental costs that should be considered (e.g., consumption of raw materials, energy input, emissions), just as there are economic and environmental costs to the other more highly visible portions of the pavement life cycle (i.e., production of pavement materials, initial pavement construction, and the use phase). Therefore, end-of-life activities can impact sustainability factors such as waste generation and disposition, air and water quality, and materials use, and must be considered in a comprehensive LCA.

Asphalt Pavement End-of-Life (EOL) Options:

- ✓ *Central Plant Recycling (hot and cold)*
- ✓ *Full-Depth Reclamation*
- ✓ *Landfilling*

Concrete Pavement End-of-Life (EOL) Options:

- ✓ *Recycling*
- ✓ *Reuse*
- ✓ *Landfilling*

This chapter introduces the methods and definitions associated with the EOL phase, drawing from ISO standards and practices and from case studies in the literature. Various EOL considerations for asphalt and concrete pavements and the associated challenges to quantify the EOL contribution in the pavement life cycle are also presented.

Recycling and Reuse Statistics of Pavements

As quality aggregate sources are depleted, there is growing importance given to incorporating RCWMs even more aggressively in new and rehabilitated pavements. An ideal goal would be to use recycled materials to produce a long-lived, well-performing pavement, and then at the end of its life be able to use those materials again into a new pavement, effectively achieving a zero waste highway construction stream. This would not only produce distinct cost advantages, but it would also provide significant reductions in energy consumption and GHG emissions, eliminating the need for landfill disposal.

Asphalt and concrete pavements are commonly recycled and reused construction materials (EPA 2009), with an overall description of reclaimed asphalt and concrete pavements and their reuse in highway applications provided by Chesner, Collins, and MacKay (1998). According to industry data, in 2012 less than 1 percent of RAP was sent to landfills, with 68.3 million tons (62.0 million mt) of RAP being used in new asphalt concrete mixtures. This is a 22 percent increase in the use of RAP in 2012 compared to 2009 (Hansen and Copeland 2013). The total amount of recycled concrete used in the U.S. is estimated to be 140 million tons (127 million mt) in 2014, including materials recycled from both pavements and other sources (CDRA 2014). These recycled materials can be used back in new asphalt or concrete mixtures or used as aggregates in base layers, or even in a number of other uses such as fill, riprap, and ballast. A distribution of the use of recycled asphalt and concrete materials is shown in figure 8-1.

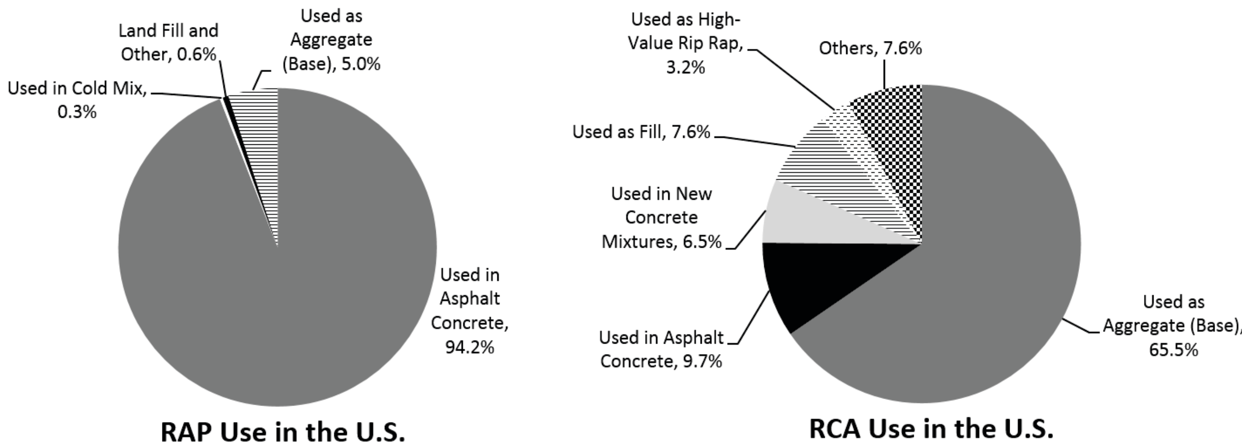


Figure 8-1. Recycling and reuse statistics of asphalt and concrete materials (data compiled from Hansen and Copeland (2013) for RAP and Wilburn and Goonan (1998) and USGS (2000) for RCA).

Economic and Environmental Considerations of EOL Options

Using materials from a pavement at the end of its life is accepted as one of the most effective ways to improve pavement sustainability. However, a comprehensive economic and environmental analysis for recycling and reusing pavement materials must be done in order to fully quantify the effects of the various EOL options. For example, pavement recycling is highly affected by material transportation costs as compared to the cost of new virgin material delivered to the construction site (Horvath 2004).

Different options are available for recycling asphalt and concrete pavement materials. However, in order to assess realistic benefits of recycling, all recycling options and their associated costs should be evaluated. Figure 8-2 illustrates a detailed characterization of the environmental cost determinants, including the potential factors contributing to the cost of pavement recycling and environmental implications. The important factors are technology (on site or off site), disposal costs (if the pavement is going to be landfilled), transportation, and the quality of the recycled material. These are expanded upon below:

- *Technology* – This can be an important driving determinant for on-site and off-site recycling. This includes the construction equipment used for on-site recycling, such as cold in-place recycling, hot in-place recycling, and full-depth reclamation. On the other hand, if the pavement is recycled in a central plant, the environmental costs include demolition at the job site, crushing, screening, and stockpiling at the plant.
- *Disposal costs* – If the recycled pavement materials are disposed of at a landfill, the total disposal costs include demolition, transportation, and landfill tipping fees. According to Horvath (2004), landfill tipping fees can be $10 to $70 per ton ($11 to $78 per mt) of material, varying widely even over relatively small distances. A very important consideration for landfill disposal is the diminishing number of landfills.

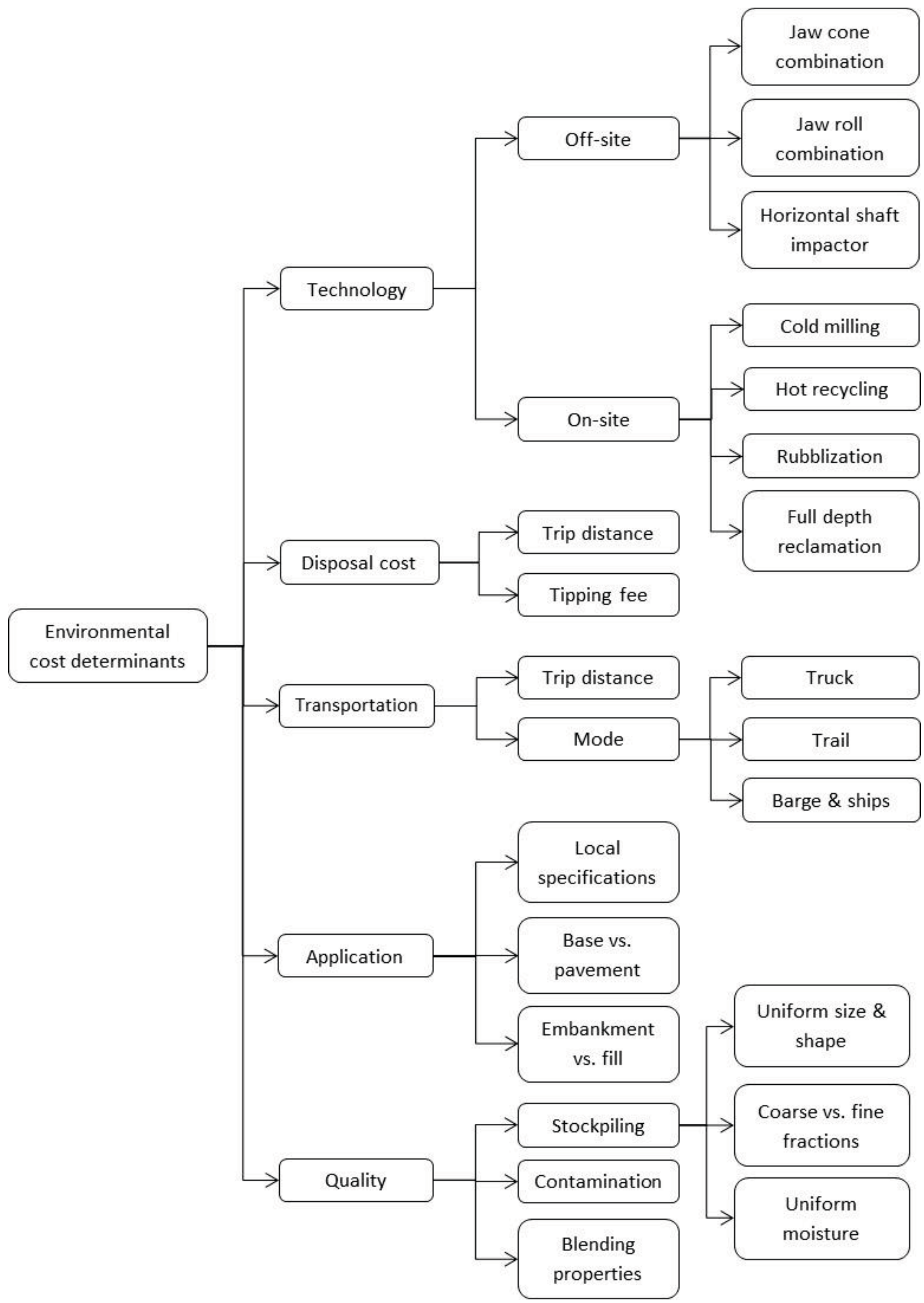


Figure 8-2. Environmental cost determinants for pavement EOL considerations (adapted from Horvath 2004).

- *Transportation* – For recycled materials, transportation can have a major impact on the environmental burden. This results from transportation from job site to a landfill, from job site to a central plant for processing, or from the plant back to the job site.
- *Application* – Recycled pavement can be reused in pavements as base layers or surface layers, in addition to embankments, fills, and scores of other potential uses.
- *Quality* – The original quality of recycled pavement, its process, storage, and local specifications determine its final application. The quality requirements of using recycled pavement can be different for asphalt and concrete pavements, including surface and base layers. The potential contamination risk of recycled pavement can also limit its use and application.

A Strategy for Optimizing the Use of Recycled Materials

Chapter 3 discusses approaches for highest use of recycled materials in pavements. While experience shows that using recycled aggregate in a base can be cost effective, other costs must be considered including material handling, preparation for reuse, and transportation. Transportation is usually a relevant aspect from both a cost and environmental perspective; in general, on-site recycling or transporting recycled materials within a small radius is feasible. However, it may not be optimal to transport recycled materials over a long distance when a local primary source or sometimes subprime materials are available. An LCA provides the means to determine the optimized distance for transporting recycled materials compared to using local virgin materials to ensure efficiency and sustainability. Hence, applying all four concepts of sustainability assessment (functional performance, LCCA, LCA and rating systems, as described in chapter 10) would provide a quantitative measure of the optimized use of recycled materials. It should be noted that the highest use is usually context defined, and may change over time as technologies continue to evolve and alternative recycling material implementation methods are developed.

Closed-Loop or Zero-Waste Thinking for Pavement Systems

There is a growing interest among infrastructure professionals, such as urban planners, architects, and engineers, in the application of *zero-waste* or *closed-loop* concepts. In closed-loop systems, a high proportion of energy and materials will need to be provided from reused waste and water from wastewater. This can be realized by transforming existing urban development design and construction philosophy to create or upgrade recycling infrastructure. Such thinking is encouraged for application at small scales of urban development such as planning for city districts. For instance, one of the critical planning considerations for more sustainable city districts is to have recycling facilities in close proximity to avoid transporting materials for longer distances. For pavements, closed-loop or zero-waste thinking will promote standardization of the recycling processes and improve the overall quality, the result of which will improve the overall sustainability of pavements.

Closed-loop system thinking can deliver a series of advantages (compiled from Lehmann 2013):

- Avoids waste being generated in the first place.
- Creates closed-loop economies with additional employment opportunities in recycling industries.
- Transforms industries toward a better use of resources, cleaner production processes, and, importantly, extends the initial producer's responsibility.

- Delivers economic benefits through more efficient use of resources.
- Conserves landfill space and reduces the need for new landfill spaces.

It is very important to place some level of responsibility of the pavement's future on the initial producer (this can be the contractor or the owner/agency) instead of the last owner only. This will lead to practices where an increasing number of contractors or agencies consider future recovery and processing of the materials at the end of its useful life (Lehmann 2013). Economic incentives in the last decades have been the major driver of the increased use of recycled pavement and recycled materials or co-products (for example, shingles, slag, fly ash, tire rubber) from other industries. A detailed discussion of some of these materials is given in chapter 3.

It is critical in a closed-loop pavement system to quantify and measure the benefits to incentivize contactors and owner/agencies. Some of the relevant questions that need to be addressed to generate robust, realistic, and scalable assessment of pavement recycling include (Horvath 2004):

- How much environmental "credit or burden" should be given to recycled materials (i.e., what is the environmental impact of recycled materials)?
- Where should these credits be counted?
- How should transportation be counted in the model?
- Which life-cycle stage should it be assigned to?

LCA deals with these issue through allocation rules. Allocation is defined by ISO 14044 (ISO 2006) as the partitioning the input or output flows of a process or a product system between the product system and one or more product systems. Several allocation rules and procedures are applicable to reuse and recycling.

ISO 14044 defines a closed loop as being when a material from a product is recycled into the same product system, while defining the open loop as being when a material from one product system is recycled in a different product system (ISO 2006). As far as the allocation procedures, similar categorization exists for both open- and closed-product systems. Closed-loop allocation procedures apply to materials from a product recycled into a material of the same product system (closed loop) or to a material in a different product system (open loop) without inherent property changes. On the other hand, open-loop allocation procedures apply to only open-loop product systems where the material is recycled into other product systems with substantial change in the inherent properties.

According to another definition of open- and closed-loop recycling and allocation procedures by Boguski, Hunt, and Franklin (1994), open-loop recycling can be defined as recycling of a post-consumer product into another useful product that will be disposed of or recycled only for limited number of cycles due to material degradation. An example for this is the recycling of old newspapers to the cereal box system where the cereal boxes are ultimately discarded. Boguski, Hunt, and Franklin (1994) go on to define closed-loop recycling as recycling of a material from a virgin product into another product that can be recycled over and over, theoretically endlessly. For example, used aluminum containers can be recycled into containers or other aluminum products virtually to no end. The key difference in the recycling definitions is the degradation of the recycled material, which can limit the number of recycling cycles. If the properties of the recycled product are not degrading, it can be recycled endlessly in the same or different product system (closed-loop recycling).

There is no trivial answer to the question of allocation for pavement materials. When pavement materials (asphalt concrete and concrete) are recycled, they can be reused in another pavement application. The two critical questions that need to be answered to determine the type of recycling definition applies to RAP and RCA: Do the properties of pavement materials degrade, and is there infrastructure to collect RAP and RCA? The answer to both of these questions is generally yes. However, there is always some measurable value left in the recycled pavement that can make it reusable multiple times. Therefore, pavement recycling is more analogous to closed-loop recycling due to its potential for being reused many times.

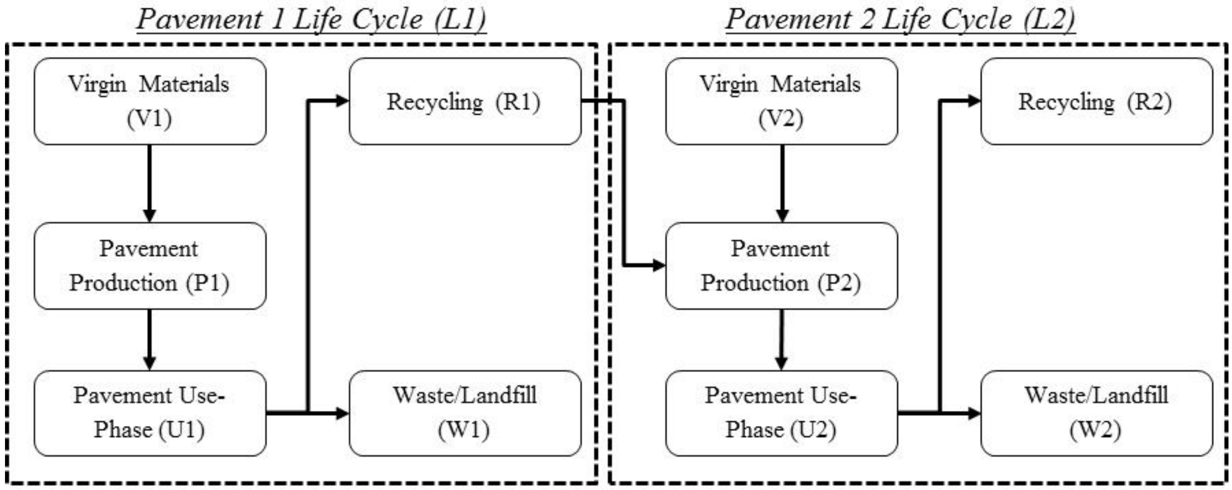
A comprehensive definition of a different class of allocation rules for different industrial products is discussed by Boguski, Hunt, and Franklin (1994); Ekvall and Tillman (1997); Ekvall and Finnveden (2001); and Nicholson et al. (2009). A schematic description of the three allocation rules is shown in figure 8-3.

The most commonly used allocation method is the cut-off and substitution method for pavements (Horvath 2004; Nicholson et al. 2009; Huang, Spray, and Parry 2013). According to the cut-off method, each product is assigned only the burdens directly associated with it; in other words, all benefits of recycling are given to using recycled materials. The cut-off method is usually applied when a "waste" material (negative economic value) turns into a product (positive economic value). The life of the recycled materials starts with its removal from the old pavement followed by transportation to a depository place for processing and transportation to a job site to be reused. All benefits are given to the pavement using the recycled materials by reduction in the use of virgin materials without any *a priori* knowledge about the rate of recycling at the end of its life.

Allocation Issues Related to Recycling at the End-of-Life of Pavements

Recycled materials can be produced during pavement rehabilitation (for example when a top layer of asphalt concrete is milled before adding a new layer). However, most recycled material is produced during a full pavement reconstruction or possibly from the demolition of some other civil structures (e.g., recycled asphalt shingles and crushed concrete from buildings). When the material is recycled, a system boundary is crossed from one pavement life cycle to another. For example, RAP can be recycled back into new asphalt concrete where it can function as aggregate and also as a source of binder, reducing the need for virgin aggregate and asphalt binder. Another example is recycling crushed concrete for use as aggregate in the base or as an aggregate in a new concrete pavement. Hence, it is important to determine the allocation of processing and handling to the producing and receiving life cycles.

Several approaches have been and are being investigated to ensure that the "benefits" of using secondary materials or fuel resources are properly reflected in LCA for pavements. Most EPD approaches use a strict and conservative approach in that all processes and transportation needed to reuse or recycle the material are assigned to the product utilizing the recycled content. The allocation of environmental impact to the new application is cut off from the previous use at the start of the processes and transport to prepare it for use in the new application.



Cut-off Method:

Benefits and burdens of recycling to downstream (Pavement 2 is responsible for the impacts of R1 and no credit for pavement producing recyclable material)

50/50 Method:

Half impact to using recycled pavement life cycle (L2) and half impact to producing recycled materials (L1)

Substitution Method:

The first pavement producing recycled product (R1) is given full benefits.

V1: Primary material burden for pavement L1

V2: Primary material burden for pavement L2 (V1 < V2 due to using recycling content from L1)

R1: Recycling burden

W1: Waste management burden

P1, P2: Burden associated with production (plant + construction) of each pavement

U1, U2: Burden associated with use-phase of each pavement

Note: Impacts associated with one product only should be allocated to that product such as P1, P2, U1, and U2 (Ekvall 1998).

Figure 8-3. An illustration of EOL allocation rules potentially applicable for pavements (cut-off method, 50/50 method, and substitution method).

The substitution method, on the other hand, gives new pavement full benefits of recycling at EOL. In other words, since the pavement is recyclable at the end of its life, it will replace the use of virgin material in another pavement. Therefore, the pavement under study can be rewarded *a priori* if the rate of recycling is known at present time. This approach requires appropriate accounting rules for the percentages of recycled content used in the pavement itself and the recycling at EOL. Double counting of benefits should be prevented. Another important consideration is the material to be substituted, whether it is virgin aggregate, binder, or a combination, and to what extent.

The cut-off method and the substitution method are the two extremes of allocation rules. A third option is the 50/50 method in which one-half of the benefits of recycling are allocated to the pavement using recycled materials and the other half are allocated to the pavement producing the recyclable material. Some of the available strategies most applicable to pavement EOL scenarios are summarized by Santero, Masanet, and Horvath (2011).

EOL Considerations for Asphalt Pavements

Asphalt pavement recycling has played a significant role in the pavement rehabilitation and preservation strategies employed by highway agencies since the energy crisis of the 1970s. With the more recent emphasis on sustainability considerations in pavement design and construction, effective pavement recycling strategies are sought even more by agencies interested in reducing energy usage, lowering material and transportation costs, and reducing GHG emissions. Asphalt pavement recycling can be done through central plant or in-place recycling techniques. Both of these EOL techniques are discussed in the following section along with best practices, procedures, and opportunities to improve sustainability at this stage of pavement life cycle.

Central Plant Recycling

Central plant recycling (CPR) is the process of producing hot or cold asphalt mixtures in a central plant by combining virgin aggregates with new asphalt binder and recycling agents along with a certain amount of RAP. RAP is most commonly generated through cold milling or by ripping and crushing of existing pavements and then transported to asphalt plants. RAP from different source is usually kept in different stockpiles, and is usually screened into two, or sometimes three, different sizes at the asphalt plant.

In hot central plant recycling (HCPR), heat transfer is used to soften RAP for mixing instead of direct heating. This means it is important that the moisture content of RAP be kept to a practical minimum as high moisture contents can significantly hamper the plant production as the heat will turn the moisture into steam instead of softening the RAP. Heat transfer is carried out by overheating the virgin aggregates before introducing the RAP into the drum, and may lead to additional fuel and energy use, which may offset the economic and environmental benefits of using RAP. Heat radiation has also been used to heat RAP.

Cold central plant recycling (CCPR) combines RAP with emulsified asphalt/recycling agent without the use of heat; new aggregates can also be added if needed. Although not a common practice (Chesner, Collins, and Mackay 1998; Hansen and Copeland 2013), these mixtures can be used for surface, base, or subbase courses. Specifications for cold plant recycled mixtures are found in ASTM D4215.

Best Practices for Construction of Asphalt Concrete with RAP

Processing and fractionating RAP at the central plant increases product uniformity and, consequently, produces more consistent asphalt concrete containing RAP. However, there are costs involved in processing and fractionating RAP, and greater stockpiling areas (multiple sizes vs. one) are required, which may present issues in some urban plant locations. Moreover, the amount of RAP that ends up in a given fractionated stockpile is usually a function of the parent material and the sizes chosen for fractionation. This, in turn, dictates how much each fractionated size is available for use in the new asphalt concrete. Thus, while processing helps improve consistency, the amount of RAP that ends up (on average) in each fractionated stockpile drives how much it can be used. Al-Qadi, Elseifi, and Carpenter (2007) provide a comprehensive review of RAP use in central plant recycling.

Dust control is a critical issue with the use of RAP in a central plant facility. Plant production of mixtures with high RAP results in high dust contents and difficulties in meeting specifications (VMA and Dust/Effective Binder primarily). Very few plants are equipped to properly waste dust and even fewer have an outlet for that dust even if the plant is capable of wasting it. Without being able to address the increasing dusts, the use of a clean/washed aggregate material becomes more important in order to achieve VMA. Unfortunately, this type of product is not readily available in many locations.

Environmental and Economic Impact of RAP

The proponents of using high RAP contents in asphalt claim the benefit of resource conservation and waste reduction; however, it is necessary to corroborate such claims in a quantified way over the pavement life cycle. Horvath (2004), Ventura, Moneron, and Julien (2008), and, more recently, Aurangzeb and Al-Qadi (2014) and Aurangzeb et. al. (2014) discuss environmental benefits and trade-offs of using RAP in pavements from a pavement life-cycle perspective.

Pavements incorporating RAP should be evaluated using LCCA and LCA and should include the materials production and maintenance stages. For example, when asphalt binder mixtures with 30 percent, 40 percent, and 50 percent RAP are used, LCCA showed a net savings up to $94,000/mi ($58,000/km), whereas LCA showed energy savings of 800 to 1400 MBTU and GHG reductions of 70 to 117 ton (64 to 106 mt) when 30 percent to 50 percent RAP was added to the asphalt mixtures (Aurangzeb and Al-Qadi 2014). However, when the loss of inherent properties of recycled pavement materials is considered, it can be argued that the pavement with recycled mixtures may deteriorate faster in the field than pavements with less (or without any) RAP. The possible substandard performance of recycled mixtures will necessitate more maintenance and rehabilitation activities, thereby offsetting the economic and environmental benefits of using RAP. Figure 8-4 illustrates the potential for increasing costs and emissions as the percentage of RAP increases in the pavement. An "optimum performance level" is defined where the economic and environmental benefits of using RAP are counterbalanced by the project costs and environmental burden incurred from increased frequency of maintenance and rehabilitation activities (Aurangzeb and Al-Qadi 2014). For example, based on the total cost, the mixture with 50 percent RAP can have a performance margin of 11.5 percent (100 − 88.5 = 11.5).

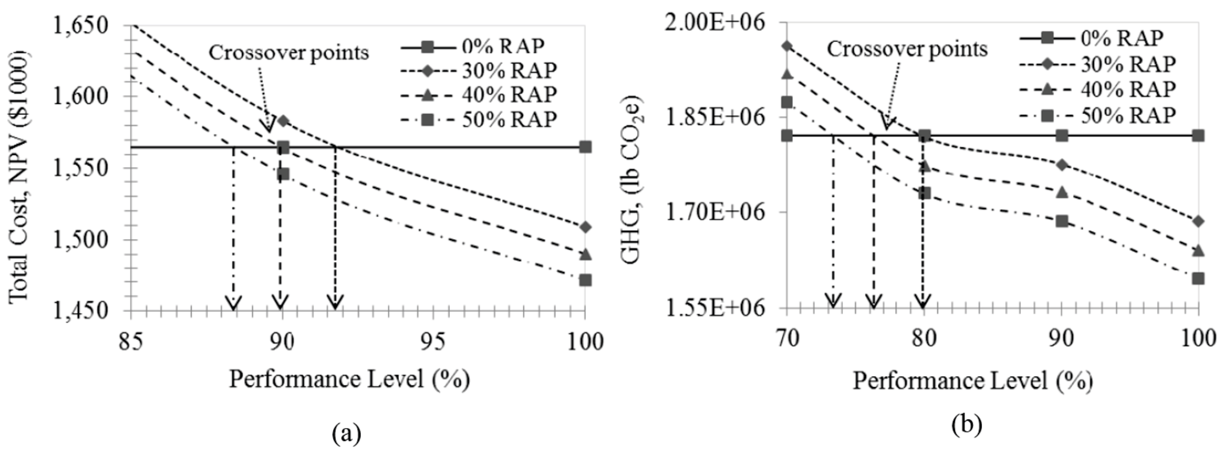


Figure 8-4. Optimal performance levels based on (a) total cost and (b) GHG emissions (Aurangzeb and Al-Qadi 2014).

One environmental concern about the use of reclaimed pavement is associated with leachate when RAP is stockpiled, placed in a landfill, or used in a surface layer exposed to water infiltration. Brantley and Townsend (1999) investigated this issue of leachate produced by RAP, and concluded that RAP samples in the study were not hazardous waste and did not leach chemical greater than allowed by typical groundwater standards. Horvath (2003) reported average metal concentrations for various recycled and co-product materials used in construction including RAP. The hazardous limits were slightly exceeded only for two metals (barium and lead) out of fifteen metals examined. Legret et al. (2005) also concluded that insignificant leaching occurred from RAP.

Full-Depth Reclamation (FDR)

FDR is a technique in which the full thickness of the existing asphalt pavement and a predetermined portion of the underlying materials (base, subbase, and subgrade) are uniformly pulverized and blended to provide a homogeneous material. The pulverized material is mixed with or without additional binders, additives, or water, and is placed, graded, and compacted to provide an improved base layer before placement of the final surface layers. Full-depth reclamation can be performed through single-unit trains, two-unit trains, or multi-unit trains (Thompson, Garcia, and Carpenter 2009). The FDR trains may include combinations of a reclaimer (milling, reclaimer, and stabilizer), pugmill mixer/paver, or a portable crushing and screening unit. Figure 8-5 illustrates a full-depth reclamation train, with more detailed information provided elsewhere (ARRA 2001b; Wirtgen 2004; Asphalt Academy 2009).

FDR is distinguished from other commonly used rehabilitation techniques, such as cold in-place recycling and hot-in place recycling, by its ability to recycle thicker pavement layers and to address specific problems rooted in different layers. FDR can recycle pavement depths up to 12 inches (305 mm), with depths of 6 to 9 inches (152 to 229 mm) more common (ARRA 2001b; Stroup-Gardiner 2011).

The FDR process varies between projects depending on needs of the owner/agency, the in situ material properties, and the required structural capacity after recycling. Three basic components of FDR processing are:

- *Pulverization* – Pulverization is the first stage of the FDR process where existing HMA and part of the granular layers are transformed into uniform granular material with a target gradation that can be used as base layer. Once the layers are pulverized, a compacted base layer can be obtained by adding proper moisture.
- *Stabilization* – Additives and stabilizers are commonly added to the pulverized materials to improve the strength and structural capacity of the compacted layers. Stabilization can be classified into four groups (ARRA 2001b).
  - Mechanical stabilization involves the incorporation of imported granular materials such as crushed aggregates, RAP, or RCA to achieve desired density and gradation and compaction.
  - Asphalt stabilization using asphalt emulsion or foamed asphalt binder (Wirtgen 2004; Jooste and Long 2007; Jones, Fu, and Harvey 2008; Fu, Jones, and Harvey 2011).
  - Chemical stabilization by adding additives such as fly ash, calcium chloride, magnesium chloride, lime, and portland cement. These additives can be added alone or in combination with other chemical additives.
  - Combination of asphalt and chemical additives is also a possibility to improve the properties of recycled layers. For example, Wirtgen (2004) indicates that cement is routinely used with emulsions to improve moisture resistance.
- *Overlay or Surface Treatment* – A structural asphalt concrete overlay is commonly used as the final wearing surface for a FDR project, although a number of surface treatments (chip seal, microsurfacing, slurry seal) may also be placed. These treatments are described in chapter 7.

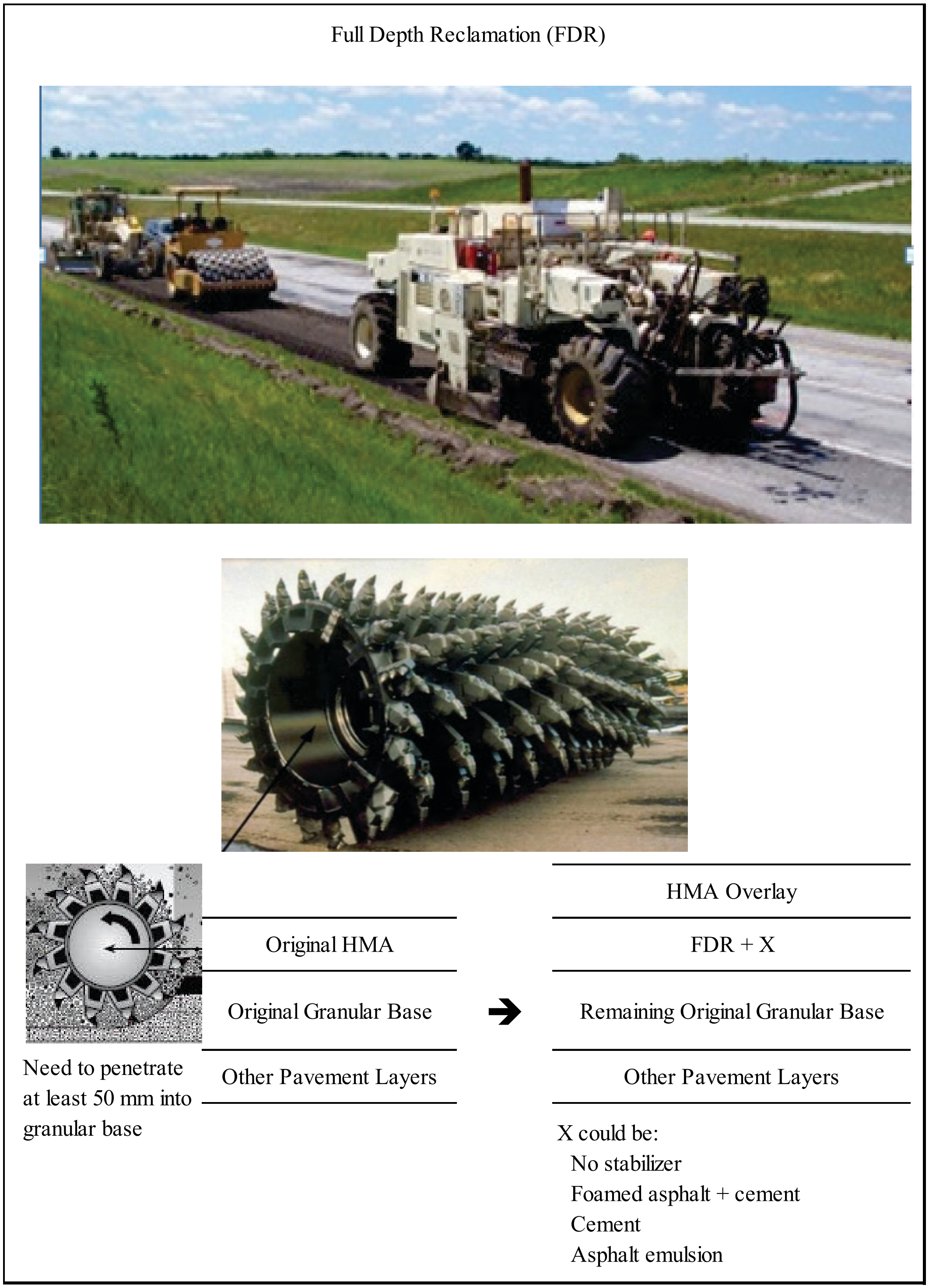


Figure 8-5. Full-depth reclamation train (courtesy of John Harvey).

Project selection, using the proper stabilizing agent, mixture design, and curing considerations, are critical for the performance of any recycling project. Some of these considerations for improving quality of FDR mixture design and construction are discussed next.

There are several comprehensive references that document best practices for FDR construction (e.g., Stroup-Gardiner 2011; Wirtgen 2004; ARRA 2001b). At the same time, the successful installation and performance of FDR projects has been well documented in the literature, including in Minnesota (Dai et al. 2008), Canada (Berthelot et al. 2007); Georgia (Smith, Lewis, and Jared 2008); Nevada (Bemanian, Polish, and Maurer 2006); and Indiana (Nantung, Ji, and Shields 2011). A summary of advantages, limitations, and candidate pavements for FDR projects is presented in table 8-1.

Table 8-1. Summary of FDR advantages, candidate pavements, and limitations.

Summary	Description
Advantages	• Provides significant structural improvement. • Can address most pavement distresses at different layers. • Can improve ride quality. • Minimizes hauling costs. • Reduction in energy use and emissions in material production. • Can correct smoothness deficiencies.
Candidates for FDR	• Pavements with severe longitudinal and transverse cracking. • Pavements with poor ride quality. • Pavements with permanent deformation problems. • Pavements with raveling problems and potholes. • Inadequate structural capacity.
Limitations	• Not recommended for high-volume roads (i.e., > 20,000 ADT). • Not recommended for roads with high percentage of trucks. • Not suitable for areas with drainage problems. • Soils with high plasticity can result in swelling.

Best Practices for FDR

Project selection, mixture design, the selection of appropriate additives for the project, and effective compaction are all critical to the effective construction of FDR. These are described in the following sections.

- *Project Selection* – Understanding key project details such as traffic, roadway geometry and features, and the ability of the existing pavement structure to support the equipment recycling train are all critical in identifying suitable FDR projects. According to a recent survey done with contractors, the lack of project selection criteria was a strong factor limiting the use of in-place recycling techniques (Stroup-Gardiner 2011). Commonly used project selection criteria include pavement condition (distress type and severity, ride quality), pavement thickness, roadway geometry, and identification of the needed surface type for structural capacity, the prevention of moisture infiltration, and protection from thermal cracking.
- *Mixture Design* – A mixture design is required for each FDR project. However, a unique mixture design could be impossible because the design depends on the properties of the in situ pulverized materials, which is often variable. The ultimate objective of mixture design is to determine the quantity and type of additive, water, and compactive effort. A standard mixture design specification does not currently exist for FDR mixtures, but guidelines have been developed by some states and agencies to aid the development of

good quality FDR layers (SEM Materials 2007; Caltrans 2012). Sieve analysis, extraction for binder content, soil plasticity, moisture susceptibility, critical low temperature cracking, resilient modulus, and triaxial compressive strength tests are usually conducted as part of the mixture design process. Material evaluation is primarily focused on the wet and dry strength of FDR mixtures and determination of the compaction curve for optimum moisture and additive content at a specified curing time. Compaction equipment and procedures and curing times can also vary depending on the additives and in situ climatic conditions. Table 8-2 summarizes the commonly used test methods used in the mixture design in addition to the standard ones. An on-going NCHRP study (Project 09-51) is currently studying the selection of material properties and the preparation of mixture designs for cold in-place recycling and full-depth reclamation of asphalt concrete for pavement design.

- *Additives* – The cost effectiveness of additives can vary based on the characteristics of the project. However, one study demonstrated that emulsion, cement, or a combination of emulsion and lime improves moisture susceptibility of FDR mixtures (Mallick et al. 2002). The same study indicated that emulsion-lime combination appears to be more cost-effective compared to water, emulsion, and cement stabilization. The critical issue for stabilized layers is the classification of the mixtures as “improved granular materials” (Anderson and Thompson 1995) or as bound materials such as HMA. The distinction between two material types governs the mixture design process as testing required will vary for each type of materials. Depending on the type and amount of additives, FDR mixtures can span a range of material behavior from very stiff (highly cemented) to very flexible (high emulsion content). The most commonly used additives are summarized in table 8-3 with their commonly reported and accepted advantages and limitations.
- Compaction – The importance of compaction and achieving target density is as critical as selecting the right amount and type of additive. Mallick et al. (2002) emphasize the selection of design number of gyrations and achieving the target density in the field. It was reported that 97 percent of the laboratory density or 92 percent to 98 percent of the theoretical maximum specific gravity is suitable for wide range of FDR mixtures (Thompson, Garcia, and Carpenter 2009).

Economic and Environmental Impact

A number of potential benefits can be listed for in-place recycling techniques that can be attributed to the increasing attention by agencies. Some of the major benefits are conservation of virgin materials; reduction in the cost of pavement preservation, maintenance, and rehabilitation; reduced lane closures; reduced fuel consumption; and reduced emissions. Of course, these are listed as potential benefits and they can only be realized when impacts over the complete life cycle of the pavement are considered.

Table 8-2. Commonly used test methods in the mixture design of FDR projects.

Test Method	Specification	Purpose
Extraction of Binder Content	ASTM D2172	Determine existing binder content in the HMA layers
Sieve Analysis	ASTM C136 or AASHTO T27-11	Determine gradation of pulverized materials
Plasticity	ASTM D4318 or AASHTO T90-00	Suitability for pavement layer and additive selection
Fines	ASTM C117 or AASHTO T11-05	Determine materials finer than 75 µm in the granular layer
Wet and Dry Indirect Tensile Strength	Similar to ASTM D4867 or AASHTO T283-07 (curing time may vary)	Moisture susceptibility of mixture design
Resilient Modulus	ASTM D4123 or AASHTO T307	Resilient modulus for thickness determination
Thermal Cracking	AASHTO T322	Determine critical cracking temperature
Cohesiometer Test	ASTM D1560 or AASHTO T246	Determine early mixture
Raveling Test	ASTM D7196	Determine resistance to raveling
Confined and Unconfined Triaxial	Similar to AASHTO T296	Determine cohesion and shear strength parameters

Table 8-3. Common additives used in FDR projects (recommended additive percentages from ARRA 2001a).

Additive	Advantages	Limitations
Liquid calcium chloride (1% by weight)	Improves freeze-thaw resistance	
Portland cement (3 to 6% by weight)	Increases compressive strength, improves moisture resistance	Works best with soils plasticity index less than 10% (Thompson, Garcia, and Carpenter 2009), increases risk of shrinkage cracking
Lime (calcium hydroxide) (2 to 6% by weight)	Works best with reactive clay (plasticity index > 8) and fine content > 10% (Mathews 2008; Franco et al. 2009); reduces plasticity of base material, improves moisture resistance	Too much lime can result in shrinkage cracking
Quicklime (calcium oxide)	Improves early strength	Can result in shrinkage cracking
Fly ash (8 to 14% by weight)	Improves strength and moisture resistance	
Asphalt emulsions (1 to 4% by weight)	Improves strength and soften aged asphalt binder in RAP, reduce shrinkage cracking	Less resistance to permanent deformations, vulnerable to moisture related stripping
Foamed asphalt (1 to 3% by weight)	Stockpile material for longer period (up to 1 month), deeper road stabilization (up to 14 inches), open roads to traffic faster	
Lime and cement	Improves stiffness, moisture resistance, and strength (Naizi and Jalili 2009)	
Fly ash and lime	Improves strength	Increased shrinkage cracking
Emulsion and lime slurry	Provides flexibility for low temperature cracking and shrinkage cracking	
Cement and emulsion	Improves strength, fatigue resistance, moisture resistance, accelerates curing time	

Strategies for Improving Sustainability

Some general approaches to improving sustainability with regard to pavement recycling at the end of its life along with associated environmental benefits and trade-offs are summarized in table 8-4. The specific strategies are discussed in the following sections.

Strategy No 1: Improve Plant Technology

There exist few asphalt plants that are equipped with positive dust control (PDC) systems. The PDC system allows the producer to "waste dust" by returning less dust to the mixture than is being generated and the system is able to account for the aggregate weight change and translate that to adding the "correct" amount of virgin binder. Other energy efficient technologies should be explored.

Strategy No 2: Increase Initial Quality of Pavement Materials and Construction

Improvement in the initial quality of paving materials and construction will increase the level of performance and the overall pavement life. The increase in pavement life will reduce the total cost of the pavement and the number of recycling phases, directly impacting the emission resulting from the total recycling process.

Strategy No 3: Use Rejuvenators or Softening Agents

Recycled asphalt concrete materials, including plant and hot in-place recycling, have different characteristics than the original materials. The recycled materials usually have relatively high stiffness due to the aged binder. Effective rejuvenators are needed to reduce the brittleness of these materials, and these also affect the fatigue and thermal cracking of the new pavements with recycled materials. A suitable rejuvenator added at an optimized amount would increase the new pavement life, thereby reducing life-cycle costs, the impacts on the environment, and the number of recycling phases within a specific period of time. However, the upstream environmental impacts of any rejuvenator or softening agent must also be considered.

Strategy No 4: Maintain and Manage RAP Stockpiles Fractionated and Moisture Free

It is important that the mixture design of asphalt concrete with RAP be developed to meet the design volumetrics. RAP fractionation is needed to accomplish that, which requires management of multiple stockpiles. This would allow achieving initial quality of the mixture that would result in extended performance. In addition, to reduce the cost of energy needed to process the RAP, the RAP stockpiles should be covered to protect them from exposure to moisture.

Strategy No 5: Selection of Proper Type and Amount of Additives or Stabilizers

It is critical to use the proper type and amount of additives or stabilizers. The selection should be made on geotechnical inspection of in situ properties of the granular materials. This strategy may have minimal impact on the environmental burden of construction and material procurement phase; however, the expected improvement in performance and service life of the FDR can easily offset the initial environmental burdens and costs.

Table 8-4. Approaches for improving sustainability of asphalt pavement recycling for pavement sustainability.

Asphalt Pavement Recycling Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Increase Central Plant Recycling Rate of Pavements	Improve plant technology (including heating time, positive dust control, double barrel etc.)	Requires initial capital investment for the producer. Can potentially reduce pavement production costs.	Can reduce GHG emissions if transportation burden will not offset.	Preserves virgin natural sources. Reduces need for landfills.
	Increase initial quality of pavement products and construction.	Can increase initial costs but may decrease life-cycle costs.	Can increase material production energy use but overall life-cycle energy and emissions may reduce.	Decline in natural resources.
	Use softening agents or rejuvenators	Can increase material production costs.	Can reduce GHG emission in overall life cycle if pavement quality is improved.	Preserves virgin natural sources. Reduces need for landfills.
	Maintain and manage RAP stockpiles (reduce moisture, fractionation)	Can increase material production costs slightly but may decrease life-cycle costs.	Can increase material production energy use but overall life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
Increase In-Place Recycling Rate of Pavements	Use the proper type and amount of additive or stabilizers	Can increase material production costs but may decrease life-cycle costs.	Life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
	Use structural asphalt overlays to improve weathering, cracking and fatigue resistance	Can increase material production costs but may decrease life-cycle costs.	Life-cycle energy and emissions may reduce.	Preserves virgin natural sources. Reduces need for landfills.
	Develop standards for mixture design and QA to improve quality	No costs.	Life-cycle energy and emissions may reduce since the quality is improved.	Preserves virgin natural sources. Reduces need for landfills

Strategy No 6: Structural Overlays

The type and thickness of an asphalt overlay can have considerable impact on the environmental burden of initial construction. However, their placement can protect the recycled layers from direct exposure to weathering and slow down the deterioration rate. LCCA and LCA can be used to demonstrate the potential benefits of different structural overlay alternatives.

Strategy No 7: Improve Construction Quality

Similar to any other highway construction works, the quality of construction is also critical for the long-term performance of recycled pavements using FDR. Inexperienced contractors and the relative complexity of FDR jobs are some of the factors that may increase risks for quality construction. Stringent quality assurance protocols are critical to improve the long-term performance of pavements constructed with FDR.

Future Directions and Emerging Technologies

Continued evaluation and eventual adoption of zero-waste strategy for all reconstruction projects should be considered, providing the primary benefit that none of the existing pavement materials is ever wasted. This will require innovative equipment and approaches to make sure that all the materials can be recovered and effectively recycled. In addition, in order to minimize the recycled materials transportation cost and environmental impact, innovative equipment and processes that recycle the pavement completely in place should be considered.

EOL Considerations for Concrete Pavements

Introduction

There are three primary end-of-life options for concrete pavement surfacing: reuse, recycling, and disposal. The sustainable aspects of each of these (and the impact that sustainable choices have on the necessary production and use processes of each) are introduced in this section and discussed in detail in following sections.

Recycling

Natural aggregate resources are vast, but finite; many high-quality, conveniently located aggregate resources are being depleted rapidly. In addition, environmental regulations, land use policies, and urban/suburban construction and settlement are further limiting access to known aggregate resources. As a result, natural aggregate costs can be expected to rise with scarcity and increased haul distances. Concrete pavement recycling is a proven technology that offers an economical and sustainable solution to these problems.

Concrete recycling is a relatively simple process. It involves breaking, removing, and crushing hardened concrete from an acceptable source to produce RCA, which a granular material that can be produced for use as a substitute for natural aggregate in almost any application.

Typical Uses of Recycled Concrete Products

Concrete recycling has been used extensively in Europe since the 1940s and in the U.S. since the 1970s (NHI 1998), with one of the first U.S. applications of RCA in pavement construction taking place in the 1940s on U.S. Route 66 (Epps et al. 1980). Production of RCA in the U.S. currently averages about 140 million tons (127 million mt) per year from all sources (CDRA 2014). USGS has reported that aggregate producers were responsible for approximately 100 million tons of all crushed concrete production in 2000 (USGS 2000). The primary applications of RCA have been base and subbase materials, but it also has been used in both concrete and asphalt concrete paving layers, as well as in high-value riprap, general fill and embankment, and other applications.

The recycling of paving materials (including concrete pavement) into new paving applications is supported by the Federal Highway Administration, which states that "reusing the material used to build the original highway system makes sound economic, environmental, and engineering sense" (FHWA 2002; Hall et al. 2007). FHWA further states that "The engineering feasibility of using recycled materials has been demonstrated in research, field studies, experimental projects and long-term performance testing and analysis. When appropriately used, recycled materials can effectively and safely reduce cost, save time, offer equal or, in some cases, significant improvement to performance qualities, and provide long-term environmental benefits" (FHWA 2002).

The suitability of RCA products may be limited by the quality of the source concrete from which it is derived. For example, poorly controlled or highly variable sources (such as might be produced from building demolition stockpiles) or sources that include significant amounts of known materials-related distress (e.g., freeze-thaw durability cracking or alkali-aggregate reactivity [AAR] distress) will generally not be suitable for use in producing aggregate for new concrete mixtures; however, these products can often still be recycled into aggregate for subbase and backfill applications.

Benefits of Concrete Recycling

One major incentive for concrete pavement recycling is economics. Aggregate costs (for fill, foundation and surface layers) constitute one of the greatest costs of highway construction, comprising between 20 and 30 percent of the cost of materials and supplies (Halm 1980). Concrete pavement recycling saves much of these costs. The cost of producing RCA can be considered to be limited to the costs of crushing the demolished concrete and screening and backhauling the RCA (along with quality assurance costs). The costs of concrete demolition, removal, and hauling are required whether the pavement is recycled or simply discarded. RCA production costs may be offset by savings in hauling and disposal costs, especially if the RCA is produced on site.

The USGS reported that the average cost of RCA in 2005 was $6.93/ton ($7.62/mt), ranging from $3.41/ton ($3.75/mt) in New Jersey to more than $8.09/ton ($9/mt) in California, Louisiana, and Hawaii. Virgin aggregate was reported to cost an average of $6.52/ton ($7.16/mt), ranging from $3.54/ton ($3.89/mt) in Michigan to more than $10.01/ton ($11/mt) in Mississippi and Hawaii (Kuennen 2007). In considering these numbers, it must be remembered that the volume of any given mass of RCA is 5 to 20 percent greater than the volume of natural aggregate, so a ton of RCA "goes farther" than a ton of virgin aggregate. Cost savings from concrete pavement recycling vary but have been reported to be as high as $5 million on a single project (CMRA 2008).

In addition, concrete pavement recycling is a smart and environmentally sustainable choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy, reduces greenhouse gas emissions, and captures CO_2 from the atmosphere. Concrete recycling can eliminate the need for mining or extracting new virgin aggregates, and can reduce haul distances and fuel consumption associated with both aggregate supply and concrete slab disposal.

Best practices for concrete pavement recycling and guide specifications for using RCA in new concrete and base materials can be found in many sources, including ACPA (2009).

Reuse

The reuse of a material can be considered to include applications where the material is used in its current form, often in its current placement or location, with minimal (if any) processing.

Typical Applications for Concrete Pavement Reuse

The most common example of reuse of concrete pavement is when it is used without significant processing as a base or subbase layer for an overlay or new pavement structure. Rubblization of concrete pavement in preparation for the placement of an asphalt overlay can be considered to be reuse of the concrete because the processing (rubblization) is not inherently necessary for the application but is one of several approaches for minimizing the potential for reflection cracking of concrete pavement joints and cracks in the asphalt (other options include the placement of various fabrics, membranes, and interlayer materials).

The suitability of a concrete pavement for reuse may be limited by the type, severity, and extent of the distresses that are present. Pavements that do not present relatively uniform quality (e.g., pavements with significant amounts of joint deterioration and other distresses that would result in "soft spots" or areas with significantly higher deflections) may require in-place processing (e.g., rubblization) in order to be reused successfully. Alternatively, such pavements may be better suited for recycling into an appropriate application or, in extreme cases, disposal.

Benefits of Concrete Pavement Reuse

The economic, environmental, and societal benefits of appropriately reusing the existing pavement structure are generally the highest of all end-of-life options for concrete pavements. There is great potential for material savings and conservation of resources, in terms of both the materials and energy required to produce and haul new materials, as well as reductions in the costs and energy associated with landfill disposal of old materials. In addition, construction duration is generally significantly shorter, resulting in reduced impacts to local users and businesses.

These benefits may be partially (or even wholly) offset by shorter performance life or more frequent maintenance requirements in some cases, particularly when a reconstruction alternative would address foundation or drainage deficiencies in the existing structure. LCA, LCCA, and pavement performance analyses are useful in determining whether reuse of the concrete pavement is appropriate for any given situation.

Disposal

Disposal refers solely to the removal and hauling of a paving material to a landfill where it serves no purpose or value. As was noted earlier in this chapter, disposal costs are associated with demolition, transportation (which varies with haul distance), and landfill tipping fees, which vary widely, even over relatively short distances, and are increasing rapidly as available landfill space decreases. The National Solid Wastes Management Association reports that tipping fees increased from an average of \$8/ton (\$8.79/mt) in 1985 to \$34.29/ton (\$37.68/mt) in 2004, with averages as high as \$70.53/ton (\$77.51/mt) in the Northeast region (Kuennen 2007). One can also consider the potential value of RCA product (which can vary significantly with the quality of the source concrete and the availability of local natural aggregate) as a lost value or opportunity cost of disposal.

Clearly, the economic and environmental costs of disposal are generally quite high and disposal is not an end-of-life option that will not often be preferred over the recycling and reuse options. Therefore, this option will not be discussed further in this chapter.

Concrete Recycling

RCA can be used as a replacement for natural aggregate in many situations and applications, but it is a composite material comprising natural aggregate and hardened mortar. As such, RCA can have significantly different physical, mechanical, and chemical properties than natural aggregate, and these differences must be addressed in the material processing, pavement design, and construction phases of road projects. Some of the most important issues to consider are highlighted below, along with strategies for improving the sustainability of concrete pavement recycling activities.

Source Material

The quality and overall properties of the source concrete must be evaluated to determine the potential uses of the RCA. High-quality, durable concrete may be suitable for producing RCA for use in structural concrete or pavement surface layers. Lower quality materials may be best suited for subbases, fill, or other applications. Additional factors, such as availability of local materials and haul distances, will also be necessary to determine the highest *feasible* use for the RCA.

Original construction and mixture design records can be an excellent source of information concerning the component material sources and their qualities and proportions. If the pavement to be recycled is still in place, a condition survey should be performed to determine the type and extent of any distresses present and to retrieve samples for visual inspection and laboratory evaluation (FHWA 2007). If any material-related distresses (e.g., D-cracking or AAR) are observed in the source concrete, evaluations and tests should be conducted to ensure that mitigation measures will be effective in preventing recurrence of these distresses if the RCA is to be used in new concrete applications or the development of degradation-related problems in foundation or other applications. Techniques that may be effective in preventing recurrent ASR[1] for RCA to be used in new concrete applications include the introduction of lithium-based admixtures, the use of Class F fly ash or slag cement in place of a portion of the cement, a reduction in the total alkali loading in the concrete, or other ASR mitigation strategies applicable for virgin aggregate to be used in concrete. Recurrent D-cracking may be prevented by reducing the coarse RCA top size to 0.75 inches (19 mm) or less.

Stockpile Runoff and Drainage Effluent

The runoff from RCA stockpiles is initially highly alkaline, with one study finding median pH values of 9.3 and 9.8 for fine and coarse RCA stockpiles, respectively (Sadecki et al. 1996). The high alkalinity is the result of the leaching of calcium hydroxide from the freshly exposed mortar faces of the recycled aggregate. In addition, studies have shown the presence of trace amounts of

[1]Note that there is no effective way to mitigate alkali-carbonate reactivity (ACR) and RCA obtained from a pavement affected by ACR must not be used as aggregate in new concrete.

heavy metals and other naturally occurring contaminants in RCA stockpile runoff, although generally not at levels considered hazardous (Sadecki et al. 1996).

Similarly, the effluent from RCA foundation layers is initially highly alkaline (an effect that diminishes with time in service), and it is not uncommon to see very small regions of vegetation kill in the immediate area of associated pavement drain outlets for a short time after construction (Snyder 1995). Nevertheless, stockpile runoff and drainage effluent alkalinity usually decrease rapidly within a few weeks as the exposed calcium hydroxide is depleted through neutralization, dissolution, and reaction with carbon dioxide in the air; in addition, the concentrations of other contaminants in the runoff or effluent can also be expected to decrease rapidly with time (Snyder 1995).

Runoff and effluent alkalinity is generally not considered to be an environmental hazard because it is effectively diluted and partially neutralized at a very short distance from the stockpile or drain outlet with much greater quantities of rainwater runoff (Sadecki et al. 1996; Reiner 2008), which is typically slightly acidic (in the range of 5.2 to 5.4 inches some regions of the U.S). Furthermore, the effects of soil buffering and equilibration with atmospheric CO_2 during transport from the RCA source to local surface waters may further reduce pH levels. Washing and selectively grading the RCA (as described in the next section) is also generally effective in reducing initial pH levels in RCA stockpile runoff and drainage effluent (Snyder and Bruinsma 1996).

The bottom line is that there appear to be no negative environmental effects from using RCA that significantly offset the positive environmental effect of reduced use of virgin aggregate and landfills (Reiner 2008).

Impact of RCA on Pavement Design and Construction

Because RCA typically has different physical, mechanical, and chemical properties than most natural aggregates, the properties and behavior of materials and layers comprising RCA can be significantly different from those of similar materials and layers comprising only natural aggregate. It is important to consider these differences in the design and construction of systems containing RCA components. Some of the key impacts of RCA on the design and construction of pavement foundation and concrete surface layers are described herein, along with generally accepted techniques for mitigating the effects.

Mitigation of Calcareous Tufa in RCA Base Materials

One major concern with using RCA in drained pavement layers is the potential for calcium carbonate precipitate in edge drainage structures and on associated filter fabrics. The mechanism of precipitate formation is presented completely in Bruinsma, Peterson, and Snyder (1997), where it is described as the dissolution of calcium hydroxide (an important cement hydration phase) into water from freshly exposed crushed mortar surfaces and the subsequent precipitation of calcium carbonate as the dissolved calcium hydroxide reacts with atmospheric CO_2. The availability of calcium hydroxide increases with increasing surface area of recycled concrete (i.e., with finer particle sizes) and decreases over time as the available calcium hydroxide is depleted.

Bruinsma (1995) and Tamarisa (1993) also determined that as much as 50 percent of the material deposited in drainage structures and on associated filter fabrics may be dust and insoluble residue produced by the crushing operation. Bruinsma (1995) found that washing the product prior to use minimized the presence of this material.

There have been many lab and field studies to characterize and identify solutions to this potential problem. The following conclusions, drawn from these reports, are useful in preventing problems with pavement drainage systems when using RCA in drained pavement layers:

- Consider using "daylighted" subbase designs that provide broad paths for drainage (rather than concentrating all residue in outlet structures) (ACPA 2009).
- Unbound RCA layers that can pass water to pavement edge drainage systems or are "daylighted" should contain no more fine material than is necessary for stability. This will minimize the movement of dust and the formation of calcium carbonate precipitate. Blending with virgin aggregate will also reduce precipitate potential, but may not represent a best sustainable practice. Unstabilized fine RCA may be suitable for placement in layers below the pavement drainage system.
- Wash RCA prior to its use in a drained layer to minimize the contribution of "crusher dust" to drainage system problems.
- Select filter fabrics with initial permittivity values that are at least double the minimum required so that adequate flow will be maintained even if some clogging takes place (Snyder 1995).
- When filter fabrics are used in pipe drain trenches, leave the top of the trench unwrapped to reduce deposits of residue on the fabric.
- Accumulations of precipitate and residue in drainage pipes can be significant and can reduce discharge capacity, but are rarely (if ever) observed to significantly impede drainage flow.
- RCA intended for use in cement- or asphalt-stabilized layers require none of the special treatment or handling required for unstabilized RCA layers.

Effects of Material Properties on Pavement Design and Construction

The use of RCA can significantly affect the properties and behavior of the materials and layers in which it is used. As a result, it may be necessary to modify certain pavement design and mixture proportions in order to obtain the desired behavior of the materials and performance of the pavement. Key considerations and possible design and construction modifications are provided below.

- <u>Effects of Unbound RCA Layers on Pavement Design</u>. When unbound RCA is used in pavement subbase layers, it may initially behave similarly to layers comprising unbound natural aggregate (although studies suggest that the angular, rough-textured nature of the particles may provide modest increases in layer stiffness). However, after time, the hydration of freshly exposed and previously unhydrated cement grains (sometimes referred to as "secondary hydration") can result in a layer that behaves like a stabilized layer. The increased stiffness of this layer may allow for a slight reduction in the thicknesses of surface layers. However, it may also result in increased slab curling and warping stresses and the need to reduce panel dimensions to mitigate the effect.

- Effects of RCA on PCC Mixture Properties. Fresh concrete mixtures containing RCA may exhibit higher water demand and have poorer workability or finishing characteristics, depending upon the amount and properties of RCA used. These difficulties are related to the inclusion of reclaimed mortar (which is generally angular and relatively porous) and can be especially acute for high replacement levels of fine natural aggregate with fine RCA. Mixture design and proportioning modifications (for example, using chemical and mineral admixtures or using lower levels of RCA substitution) can partially offset or eliminate many of these issues. ACPA (2009) and FHWA (2007) provide specific guidance on the proportioning of concrete mixtures containing RCA.

  PCC mixtures comprising RCA may also be more susceptible to drying shrinkage problems due to the absorptive nature of the reclaimed mortar. These issues can be minimized with good RCA stockpile moisture management, mixture design modifications, and good construction and curing practices.

- Effects of RCA on Hardened PCC Properties and Related PCCP Design Parameters. When all other factors are held constant (i.e., no compensating mixture adjustments are made), hardened RCA concrete can be expected to have somewhat lower (but still acceptable) strength and elastic modulus values, significantly more permeability, drying shrinkage and creep potential, slightly lower specific gravity, and somewhat higher CTE values (ACPA 2009). The physical and mechanical properties of RCA concrete must be determined and considered in the development of RCA concrete pavement design details.

  For example, increased shrinkage and thermal response of concrete containing RCA can cause larger joint movements, requiring different sealant materials and reduced panel dimensions. They also may increase slab curling and warping deformations. Strength and elastic modulus reductions can impact stress distributions and fatigue damage and may cause increases in required pavement thickness. Some of these effects can be offset with mixture proportioning modifications (e.g., lower *w/cm*) to reduce shrinkage and increase strength) or modifications in the properties of the RCA (e.g., reductions in the use of fine RCA and using impact crushing processes that remove most of the mortar from the reclaimed natural aggregate particles).

  In some cases, the use of large amounts of coarse and fine RCA can have a beneficial effect on pavement behavior. Won (2007) describes the design and reconstruction of I-10 near Houston, TX in 1995 using 100 percent recycled concrete aggregate in a CRCP. The resulting pavement had a 28-day compressive strength of 4600 lb/in^2 (32 MPa), but an elastic modulus of only 2.6 million lb/in^2 (17,900 MPa); in other words, it was strong, but relatively compliant and not brittle, which is theorized to be at least partially responsible for the good behavior and excellent performance of the section to date.

Table 8-5 summarizes pavement design modifications that should be considered when using RCA concrete in new pavement construction.

Table 8-5. Design recommendations for RCA concrete pavements (ACPA 2009).

Concrete Pavement Design Element	Design Recommendations
Pavement Type	Use JPCP with panel length of 15 ft (4.6 m) or less to minimize potential for mid panel cracking. JRCP and CRCP may be considered if aggregate interlock is enhanced with larger aggregate top size or blending virgin and recycled, coarse aggregate. Additional reinforcement may be desirable to ensure that cracks are held tight.
Slab Thickness	Generally the same as for conventional concrete pavement provided that the RCA concrete mixture design provides adequate strength. For two-course construction using RCA concrete, the overall slab thickness might need to be greater than what is required for a conventional concrete pavement design, depending on the materials and mixture proportions used in each lift.
Joint Spacing	Panel length should be selected to minimize the incidence of mid panel cracks in JPCP or to keep crack width to a minimum in JRCP.
Load Transfer	The criteria used for using dowels in RCA concrete pavements should be identical to those used for pavements constructed using virgin aggregate. Reinforcing steel recommendations for crack load transfer are presented below.
Joint Sealant Reservoir Design	Dimensions must consider both the selected sealant material and expected joint movements caused by temperature and shrinkage effects, which may be higher for RCA concrete.
Subbase Type	Subbase material should be selected in consideration of the structural requirements of the pavement type selected (as for conventional concrete designs). Free-draining subbase layers should be considered for RCA concrete pavements produced from D-cracked or ASR-damaged concrete.
Reinforcement	Higher amounts of longitudinal steel reinforcing may be required in JRCP and CRCP to hold cracks tight so that aggregate interlock load transfer can be maintained.
Shoulder Type	Same as for conventional concrete pavement.

Concrete Pavement Reuse

In some situations, concrete pavements can be reused (without recycling) at the end of their natural service lives by treating them as a base layer for a new pavement that is constructed directly over them (i.e., an overlay). Unbonded concrete overlays are prime examples of this end-of-life strategy because they are typically placed over concrete pavements that have no other options besides reconstruction. Asphalt overlays of badly distressed concrete pavements are another example, although it may be necessary to rubblize the concrete in situ (or provide an interlayer of some type) to provide a more uniform support condition for the asphalt pavement and to prevent joint/crack reflection. Some of the most important issues to consider in reusing concrete pavements are highlighted below.

Evaluation of Existing Pavement Structure

The in situ reuse of a concrete pavement may not be a sustainable end-of-life option if there are significant structural or drainage issues in the underlying foundation that must be addressed. Like any other pavement structure, the sustainability of a new pavement structure being built on a reused concrete pavement foundation will depend in part upon the quality, strength, and durability of that pavement foundation. Failing to correct known structural deficiencies may result in a shorter life cycle with higher economic and societal costs, and increased environmental impacts. In addition, the reuse of concrete pavements may require that additional geometric and safety considerations be addressed in the new pavement design due to the increased elevation of the new pavement surface (e.g., reductions in overhead clearances, changes in foreslope and ditch bottom location, adjustment of guardrail).

Uniformity of Material

One of the most important aspects of concrete pavement reuse is the uniformity of support that the old pavement will provide to the new, particularly for new asphalt pavements, which are sensitive to foundation support. If the old pavement suffers from significant material-related distress (e.g., D-cracking, joint spalling), it may be necessary to construct or place interlayer materials (e.g., geotextile fabrics and constructed interlayers) or to rubblize the pavement (to reduce the stiffness of the entire pavement to levels comparable to those of the deteriorated areas).

If non-uniform pavement conditions necessitate interlayer or rubblization treatments (or the construction of thicker pavement overlay structures), then reuse of the original pavement may not be the most sustainable approach. The sustainability assessment techniques described in chapter 10 are useful in making such determinations and decisions.

Strategies for Improving Sustainability

The use of recycled concrete aggregate in lieu of natural aggregates is inherently sustainable when all other factors are equal. The following subsections describe strategies for improving the sustainability of concrete recycling by optimizing the production and use of the material, and these are also summarized in table 8-6. The ultimate goal for improving concrete pavement sustainability is the achievement of a zero-sized waste stream at the pavement end-of-life (as well as for rehabilitation operations).

Strategy #1: Optimize Use of Recycled Materials through Testing and Characterization

As was noted previously, the quality and overall properties of the source concrete must be evaluated to determine how best to use the resulting RCA products as completely as possible and in the highest feasible applications. RCA particles tend to be highly angular and are comprised of reclaimed virgin aggregate and reclaimed mortar. Reclaimed mortar generally has higher absorption, lower strength, and lower abrasion resistance than most virgin aggregates. As a result, RCA generally has lower specific gravity and higher absorption than virgin aggregate, particularly for smaller particle sizes, which tend to be comprised largely of mortar. The properties of a specific recycled concrete aggregate depend upon many factors, including the properties of the original concrete and the processes used to produce the RCA, particularly the crushing processes. Therefore, even when a preliminary assessment of product potential has been made, laboratory tests of product samples should be performed to further qualify the RCA for the selected applications, bearing in mind that higher type applications may require the use of higher test result thresholds.

Table 8-6. Approaches for improving sustainability of concrete pavement recycling.

Concrete Pavement Recycling Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Increase Use of Recycled Materials and Minimize Wastage	Optimize use of recycled materials through testing and characterization	Initial investments in research and development, will help understand material properties better	Optimized material usage will help reduce emissions and wastage	Preserves virgin natural sources. Reduces need for landfills
	Adjust RCA production operations	Initial investments to adjust production protocols	Reduced fuel consumption and minimizes wastage	Preserves virgin natural sources. Reduces need for landfills
	Customize preparation and breaking of source concrete: removal of asphalt overlays and patches and pavement breaking	Potential increase in production costs, higher production rate may reduce overall material costs	Minimizes material wastage	Preserves virgin natural sources. Reduces need for landfills
Reduce CO_2 Emissions over the Life Cycle	Sequestration of CO_2 by RCA	No economic impact.	Potential to offset CO_2 emissions from the raw materials used in cement production (not including fuels used in production)	Reduced impact on climate change.
Reduce Virgin Material Usage and Material Transportation needs	On-site recycling	Reduction in fuel and potentially labor costs, increased cost to setup up portable crusher at job site	Reduced GHG emissions due to reduction in haul traffic	Reduction in haul truck traffic and traffic congestions, reduces need for landfills

A good example of the use of several tests and varying criteria for use in different situations can be found in the final report for NCHRP Project 4-31 (Saeed 2008), which identifies several properties of recycled aggregate subbase materials that influence the performance of the overlying pavement, including aggregate toughness, frost susceptibility, shear strength, and stiffness. Table 8-7 is a matrix that was developed by Saeed (2008) to summarize their recommendations for critical test values to ensure good RCA subbase performance for specific traffic, moisture, and temperature conditions.

Table 8-7. Recommended RCA subbase quality tests and threshold values for various applications (Saeed and 2008).

Tests and Test Parameters	Medium-High Traffic Low or High Moisture Freeze climate	Low, Medium or High Traffic Low-High Moisture Freeze or Non-freeze climate	Low-Medium Traffic High Moisture Non-freeze climate	Low Traffic Low Moisture Non-freeze climate
Micro-Deval test (percent loss)	< 5 percent	< 15 percent	< 30 percent	< 45 percent
Tube Suction test (dielectric constant)	≤ 7	≤ 10	≤ 15	≤ 20
Static Triaxial Test (Max. Deviator Stress) OMC, s_c = 5 psi (35 kPa)	>100 psi (0.7 MPa)	>60 psi (0.4 MPa)	>25 psi (170 kPa)	Not required
Static Triaxial Test (Max. Deviator Stress) Sat., s_c = 15 psi (103 kPa)	≥180 psi (1.2 MPa)	≥135 psi (0.9 MPa)	≥60 psi (410 kPa)	Not required
Repeated Load Test (Failure Deviator Stress) OMC, s_c = 15 psi (103 kPa)	≥180 psi (1.2 MPa)	≥160 psi (1.1 MPa)	≥90 psi (620 kPa)	Not required
Repeated Load Test (Failure Deviator Stress) Sat., s_c = 15 psi (103 kPa)	≥180 psi (1.2 MPa)	≥160 psi (1.1 MPa)	≥60 psi (410 kPa)	Not required
Stiffness Test (Resilient Modulus)	≥60 ksi (0.4 MPa)	≥40 ksi (275 kPa)	≥25 ksi (170 kPa)	Not required

Note: Low traffic: < 100,000 ESALs/year, Medium traffic: 100,000 to 1,000,000 ESALs /year, High traffic: 1,000,000 ESALs/year

Strategy #2: Adjustment of RCA Production Operations

The intended use of the RCA products should drive production operations in ways that maximize production efficiency, which means maximizing product yield (i.e., producing as much of the desired particle sizes as possible and minimizing waste) and doing so with a minimum expenditure of effort and consumption of fuel). For example, the production of RCA for use in new concrete mixtures often requires additional care to prevent the inclusion of contaminants (e.g., joint sealant material, reinforcing steel, and perhaps asphalt materials) and should be produced using breaking and crushing equipment that maximizes the production of useful size fractions. Conversely, the use of RCA in base or backfill operations will be less sensitive to the inclusion of minor amounts of contaminants and may permit the use of different types of breaking and crushing equipment to produce properly graded materials.

Strategy 2A: Customize Preparation and Breaking of Source Concrete

Removal of Asphalt Overlays and Patches – Concrete pavements with asphalt concrete patches and overlays can be processed to produce RCA for use in new concrete mixtures or other applications. Historically, the asphalt and concrete components have been recycled separately in the U.S., but some European countries routinely recycle concrete with up to 30 percent coarse RAP into new concrete paving mixtures without any apparent detrimental effects (Hall et al. 2007), and the Illinois Tollway has recently begun utilizing fractionated reclaimed asphalt pavement (FRAP) as a partial replacement for virgin coarse aggregate in the lower course of two-layer concrete pavement construction. The sustainability of these practices must be evaluated for any given situation to determine whether it is better to recycle the asphalt materials separately (thereby making high use of the RAP) or to simply recycle the asphalt and concrete together and save the costs of separate recycling.

Pavement Breaking – The main purpose of pavement breaking is to size the material for ease of handling and transport to the crushing plant. Slabs are typically broken into pieces small enough to be easily lifted, transported, and processed by the primary crusher (typically 18 to 24 inches [457 to 610 mm] in diameter). Breaking processes that produce an excessive amount of fines (e.g., drop balls and vibrating beam breakers or resonant breakers) are not recommended for off-site processing operations because they tend to produce a greater amount of excessively small fragments that are not easily salvaged. Pavement breaking equipment and slab cracking patterns should be selected after considering the intended crushing operation and desired product yield and gradation. For example, impact crushers typically can handle larger broken concrete pieces than compression (jaw or cone) crushers, allowing the use of a larger crack pattern and often resulting in higher breaking production rates.

Strategy 2B: Customize Crushing and Sizing Operations

The yield of coarse RCA from the recycling operation depends upon many factors, including the crushing processes used. Crushing for larger aggregate particles generally produces higher coarse RCA yields because less crushing is necessary and fewer fines are produced. For example, 55 to 60 percent coarse RCA yield is common when crushing to 0.75 inches (19 mm) top size, while 80 percent yield is common when crushing to 1.5 inches (38 mm) top size (NHI 1998).

Jaw crushers tend to produce fewer fines than impact or cone crushers, resulting in higher yields of coarse RCA, which often is more useful than fine RCA, particularly in new concrete mixtures. Figure 8-6 shows the results of one study of the impact of crusher type on RCA particle size distribution for a particular concrete source.

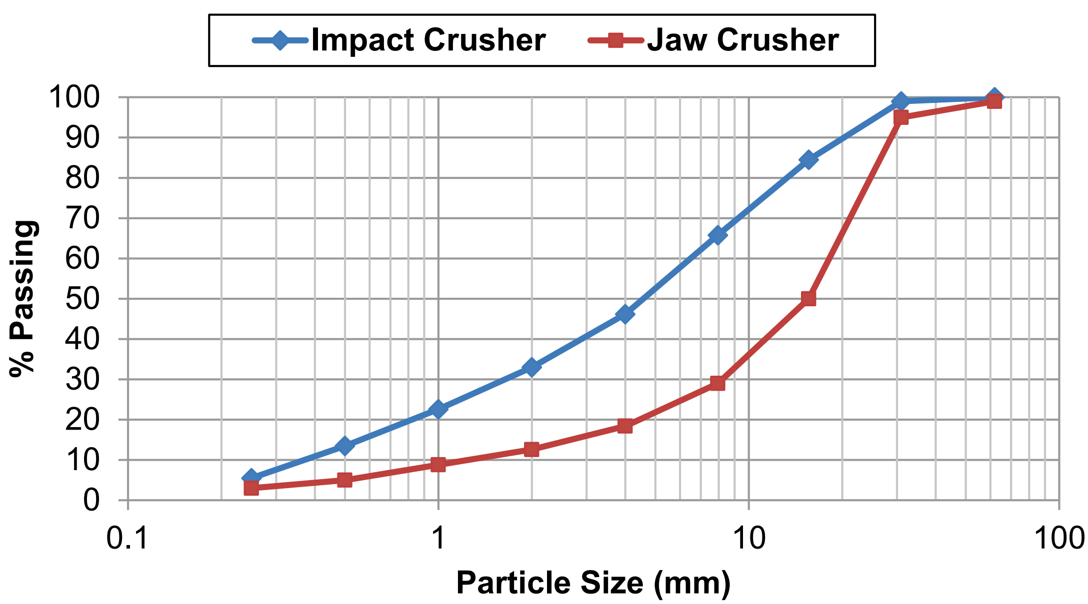


Figure 8-6. Example effect of type of crusher on RCA particle size distribution.

Impact and cone crushers often are more effective in removing most of the reclaimed mortar, producing RCA that looks and behaves similarly to the original virgin aggregate in the source concrete (although the yield of coarse RCA will be reduced). Impact crushers also can supply particle size distributions that are well suited for constructing unbound foundation layers (ACI 2001).

Strategy #3: Sequestration of CO2

Research has shown that RCA has significant value as a sink for CO_2 when atmospheric CO_2 reacts with calcium hydroxide ($Ca(OH)_2$), one of the principal phases resulting from cement hydration that is present in the concrete mortar, to produce calcium carbonate (Gardner, Leipold, and Peyranere 2006). The potential for carbon dioxide sequestration is equal to all of the CO_2 that was originally evolved from calcination of the raw materials used in the production of the cement (but not from the fuels used in production). Figure 8-7 shows an example of laboratory test results documenting CO_2 removal over time for various moisture conditions. This study suggests that the use of RCA in unstabilized applications (e.g., unstabilized subbases, embankment stabilization) has the potential to "scrub" the local atmosphere of significant quantities of CO_2.

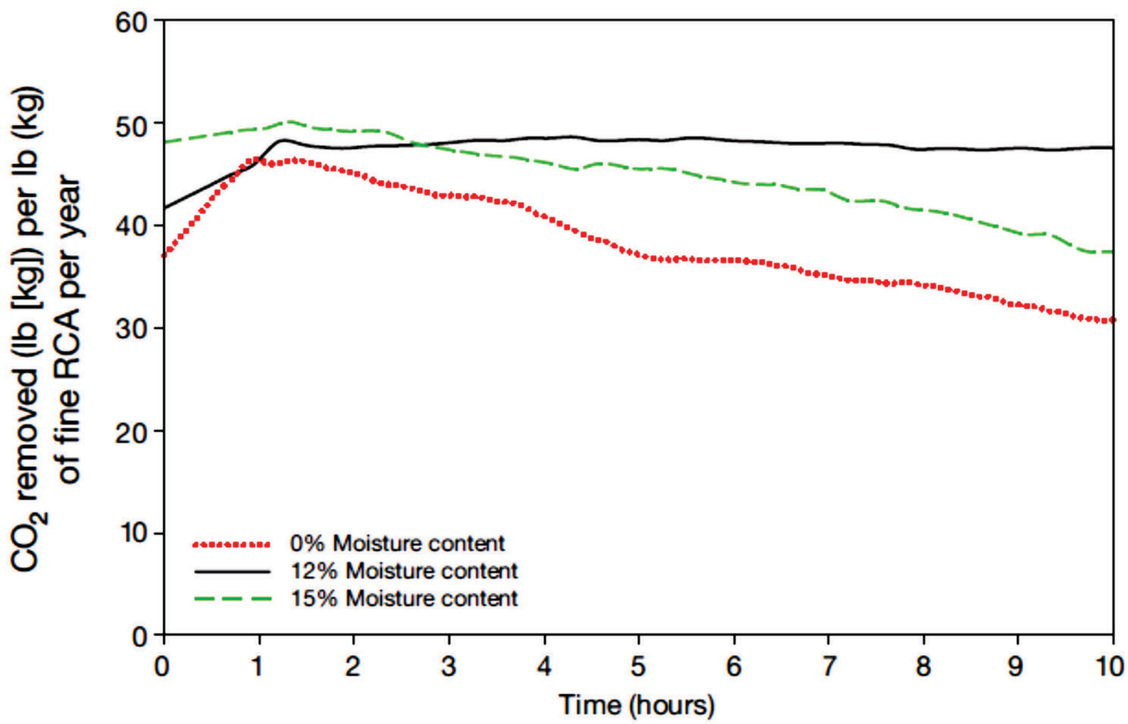


Figure 8-7. Carbon sequestration by fine RCA in laboratory column studies (Gardner, Leipold, and Peyranere 2006).

Strategy #4: On-Site vs. Off-Site Processing

When RCA is to be used in some component of the same project from which it was produced, substantial reductions in fuel consumption and emissions (as well as labor costs) can be achieved by processing the material at the construction site (as shown in figure 8-8) rather than by using an off-site facility. On-site processing also offers societal benefits (reductions in haul truck traffic and related traffic congestion and delays) and the potential for economic savings (which will be at least partially offset by the costs of setting up a portable crusher at the job site).

Figure 8-8. On-site concrete recycling operation.

When the RCA will be used in a foundation layer of the reconstructed pavement, additional sustainability benefits can be achieved through the use of a mobile crusher (an in-place concrete recycling train) that includes primary and secondary crushers that have been specially adapted for in-place recycling and are mounted on crawler tracks. Figure 8-9 shows a concrete recycling train working on a pavement recycling project.

Future Directions/Emerging Technologies

Current trends of increased and improved utilization of recycled concrete are expected to accelerate and continue for the foreseeable future, as highlighted in the following sections.

Increased Recycling (Reduced Disposal in Landfills)

Recent statistics on concrete recycling are difficult to find, but Wilburn and Goonan (1998) indicated that, while it is accepted that concrete pavement is 100 percent recyclable, only 50 to 60 percent of the 200 million tons (181 million mt) of concrete debris generated annually was being recycled in practice. This percentage has likely increased since 1998 due to national pushes by the FHWA and the development of a standard AASHTO specification for the use of RCA in new paving concrete. However, it is unlikely that 100 percent of all concrete paving demolition debris is currently being recycled or reused, so there is still room for concrete recycling initiatives to help in moving towards a zero-waste goal.

Figure 8-9. Recycling existing concrete pavement in place (photo courtesy of Jim Grove).

Improved Utilization of RCA Products

USGS (2000) reports that in 1997 only 15 percent of all recycled concrete aggregate were being used as aggregate in new concrete or asphalt concrete mixtures, which probably represents the highest type of application for recycled concrete aggregate. Seventy-eight percent was being used in base or landfill applications, which represents a relatively low value used for RCA.

It is understandable that many engineers are not comfortable with using RCA in higher type applications because of the ramifications of premature failures in a surface layer are usually more critical than when defects develop in lower pavement layers. In addition, there has not been widely accepted guidance on the use of recycled concrete aggregate in new asphalt and concrete mixtures. However, guidance on the production, characterization and use of recycled concrete aggregate has recently been developed in several forms, including:

- A technical bulletin from the American Concrete Pavement Association (ACPA 2009).
- A technical report by the American Concrete Institute (ACI 2001).
- Specifications from AASHTO.
  - AASHTO M319, "Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course."
  - AASHTO MP16, "Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete"
- Newer policies and technical advisories from the U.S. Federal Highway Administration (FHWA 2002 and FHWA 2007).

The advent of this level of technical support, combined with increased pressure for sustainable pavement construction, are certain to result in continued and improved high-type utilization of recycled concrete.

Concluding Remarks

This chapter describes the EOL phase of the pavement, particularly focusing on recycling, reuse, and disposal options for both asphalt and concrete pavements. Portions of the information presented in this chapter are also touched on in other chapters, including chapter 3 (materials), chapter 4 (design), chapter 5 (construction), and chapter 7 (maintenance and preservation).

Major issues associated with asphalt pavement EOL considerations are listed below:

- According to a survey conducted as part of an NCHRP Synthesis 421 (Stroup-Gardiner 2011), 33 out of 45 states have some experience with FDR. The implementation of in-place recycling—which includes cold in-place and hot in-place recycling in addition to FDR—is relatively low. Annual in-place recycling is less than 50 lane miles (80 lane km) in most of the states. However, central plant recycling is very common.
- Lack of mixture designs, specifications, and standards for project selection are some of the barriers for FDR applications.
- Uncertainty of future EOL consideration in the life-cycle assessment of pavements is a barrier for LCA calculations. Because of this uncertainty, pavements are not usually given credits for producing recyclable materials at the end of their life time.
- The quality of the recycled material remains a challenge for the pavement using recycled materials. The major question with pavement recycling is, how many times can a pavement be recycled without loss in the inherent properties?

Major issues associated with concrete pavement EOL considerations include:

- Source material: quality and overall properties of the source concrete must be evaluated to determine the potential uses of the RCA.
- Stockpile runoff and drainage effluent.
- Impact of RCA on pavement design and construction.
- Evaluation of existing pavement structure for concrete pavement reuse.

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CHAPTER 9. PAVEMENT SUSTAINABILITY WITHIN LARGER SYSTEMS

Introduction

Pavements can always be viewed as components of a larger system. Consider, for example, that transportation systems, highway corridors, neighborhoods, port terminals, pedestrian networks, stormwater treatment, and the local ecosystem are all larger systems that can influence or are influenced by a pavement system. The health, maintenance, improvement, restoration, or construction of these larger systems all have associated sustainability goals (which may or may not be explicitly stated) that will necessarily affect the sustainability goals of pavement subsystems. This could either encourage or exclude certain pavement sustainability practices. For instance, a larger corridor project may have a goal of minimizing GHG emissions from construction but may also specify a particular pavement type to match adjacent corridor sections for ease of maintenance and rehabilitation. In this case, recycled material use in pavements would be consistent with the project goals, but the pavement type with the lowest initial emissions may not be consistent with project goals.

This chapter describes how pavement systems can interact with larger system sustainability goals by highlighting several larger system efforts and metrics. Specific sustainability considerations that can arise from these interactions and example treatments are also presented.

Larger System Goals and Metrics

Larger systems within which pavements reside increasingly have sustainability goals and objectives to which the pavements subsystem contributes in some manner. This section provides examples to illustrate this concept and how it relates to the social and environmental components of sustainability, which are often undervalued or ignored when the focus is strictly on the pavement as the system in question.

> ***Major Issues:***
>
> - ✓ *Inherent uncertainty in performance of materials specifically designed to meet aesthetic, environmental, or social criteria.*
> - ✓ *Higher cost of non-traditional approaches used to accommodate environmental and societal considerations.*
> - ✓ *Quality and performance of utility cuts.*
> - ✓ *Timing and quality of construction versus working in a prescribed window of operation.*

Sustainable Communities

Very generally, society is recognized by most as a large system that needs to function and grow in a sustainable manner. This includes how individuals, groups, industry, and infrastructure function together. This concept of an interacting population is often labeled “community.” There are a number of efforts nationwide aimed at strengthening the role of community (and community values) in the development, operation, and maintenance of infrastructure (including roads). An example effort at the federal government level is the Partnership for Sustainable Communities, which is a partnership between the U.S. Department of Housing and Urban Development (USHUD), U.S. Department of Transportation (USDOT), and the Environmental Protection Agency (EPA), that aims to “…coordinate federal housing, transportation, and other infrastructure investments to protect the environment, promote equitable development, and help to address the challenges of climate change” (EPA 2012). According to the partnership agreement, the HUD, USDOT, and EPA commit to coordinate and identify strategies that (USHUD, USDOT, and EPA 2009):

- **Provide more transportation choices**. Develop safe, reliable and economical transportation choices in order to decrease household transportation costs, reduce the nation's dependence on foreign oil, improve air quality, reduce GHG emissions, and promote public health.
- **Promote equitable, affordable housing**. Expand location and energy efficient housing choices for people of all ages, incomes, races, and ethnicities to increase mobility and lower the combined cost of housing and transportation.
- **Increase economic competitiveness**. Enhance economic competitiveness through reliable and timely access to employment centers, educational opportunities, services, and other basic needs by workers as well as through expanded business access to markets.
- **Support existing communities**. Target federal funding toward existing communities to increase community revitalization, to improve the efficiency of public works investments, and to safeguard rural landscapes.
- **Leverage federal investment**. Cooperatively align federal policies and funding to remove barriers, leverage funding, and increase the accountability and effectiveness of all levels of government to plan for future growth.
- **Value communities and neighborhoods**. Enhance the unique characteristics of all communities by investing in healthy, safe, and walkable neighborhoods—rural, urban or suburban.

Within this partnership context, pavements can play a significant role. Specifically, pavement construction, preservation, use, and reconstruction can be inferred to be a part of the strategies to (1) provide more transportation choices, (2) reduce GHG emissions, (3) increase mobility and lower the combined cost of housing and transportation, (4) expand business access to markets, (5) increase community revitalization, (6) increase the efficiency of public works investments, and (7) invest in walkable neighborhoods (USHUD, USDOT, and EPA 2009). These items also imply that pavement characteristics such

Pavement Integrated into a Sustainable Street: City of Chicago's Cermak/Blue Island Sustainable Streetscape.

The Chicago Department of Transportation (CDOT) advertises the first phase of a 2-mile stretch of Blue Island Ave. and Cermak Rd. in the Pilsen neighborhood as the "greenest street in America." It is a good example of how pavement is integrated into an overall approach to roadway sustainability. The $14 million project (completed in 2012) is helping to transform an industrial mixed-use stretch of street into one that can serve as a community focal point providing a sense of place, beautification, and ecological services.

The overall drivers for the project involve more than just pavements, although pavement features play a significant role.

Achievements of this project include:

- Reduced energy use by 42 percent.

- Wind/solar powered pedestrian lights.

- 76 percent local materials (manufactured within 500 mi (800 km) of the site).

- 131 percent increase in tree canopy cover.

- Education kiosks and an English/Spanish guidebook.

- New bike lanes.

Pavement contributions include:

- Warm-mix asphalt.

- Photocatalytic cement, largely used for its self-cleaning properties.

- Permeable pavements helping divert 80 percent of stormwater.

- Use of RCWMs including slag, shingles, and ground tire rubber.

More information is available at:
http://www.cityofchicago.org/dam/city/depts/cdot/CBISS_flier_2010.pdf

as materials, geometry, design, and location can be influenced or controlled by things like aesthetics, historical context, and cultural identity. Other examples of larger system efforts to which pavements may contribute are:

- **National Complete Streets Coalition**. Part of Smart Growth America, the National Complete Streets Coalition is an advocacy group that assists organizations in creating and adopting policies that advocate for connected networks of multimodal access streets (Smart Growth America 2010) (http://www.smartgrowthamerica.org/complete-streets).
- **Walk Score**. A private company that uses algorithms to provide scores related to the walkability, transit service, and bike friendliness. Among other things, scores are linked closely with apartment and home searches (http://www.walkscore.com/).
- **National Scenic Byways Program**. This program, part of the FHWA, formally recognizes certain roads for their archeological, cultural, historic, natural, recreational, and scenic qualities (NSBP 2013) (http://byways.org/).
- **United States National Register of Historic Places**. The official list of U.S. historic places worthy of preservation. Authorized by the National Historic Preservation Act of 1966, the list is maintained by the National Park Service and contains over 6,800 transportation-related listings among its over 80,000 properties. For instance, listings include the first concrete street in Bellefontaine, OH; a proprietary R.S. Blome Granitoid Pavement in Grand Forks, ND; a Hessler Court Wooden Pavement in Cleveland, OH; and on original brick portion of the 1913 "Yellowstone Road" (NPS 1974) that went from Boston to Seattle (http://www.nps.gov/nr/).

Ecosystems

Very generally, ecosystems are communities of living organisms interacting with their surrounding non-living environment. This interaction involves complex systems such as nutrient cycles, food chains, and energy flows. As the full impact of human development on these systems becomes better recognized, a large number of national and international efforts have been undertaken to better understand these impacts and preserve complex ecosystems. An example effort by the U.S. DOT, called "Eco-Logical," defines what is called an "ecosystem approach to developing infrastructure projects" (Brown 2006).

Eco-Logical provides guidance on an approach to mitigating the effects of infrastructure with the larger surrounding ecosystem as the focal point of the effort. Instead of regulatory driven individual mitigation efforts done within narrowly defined project boundaries, an ecosystems approach seeks to define and optimize solutions for the larger impacted ecosystem. Generally, this requires coordination among multiple agencies and can ultimately lead to more efficient and meaningful mitigation efforts. Goals that drive the Eco-Logical effort include (Brown 2006):

- **Conservation**. Protect and even restore large-scale ecosystems.
- **Connectivity**. Reduce habitat fragmentation from infrastructure (including roads and their constituent pavements) projects.
- **Predictability**. Commitments made by all participating agencies will be recognized and honored.
- **Transparency**. Leverage better stakeholder (including the general public) involvement to improve public trust, credibility and streamline planning and development.

An ecosystems approach to mitigating infrastructure impacts on ecosystems can create a set of goals and objectives for the ecosystem that has significant interplay with pavement systems. For instance, a particular area's wildlife action plan can identify areas with high conservation needs, which may, in turn, influence the location of a temporary quarry for a roadway project. As a result, it may be that lesser quality aggregate is selected based on priorities of a wildlife action plan.

Other examples of efforts with an ecosystem focus include those by the Federal Lands Highway (FLH) Program's interaction with its partner agencies such as the National Park System, the U.S. Forest Service, and the U.S. Fish and Wildlife Service. These partner agencies are generally charged with the stewardship of larger ecosystems (e.g., Yosemite, Deschutes National Forest, Vieques Island National Wildlife Refuge) and tend to view roads and pavements within such ecosystems as secondary to the ecosystem itself. Consequently, when the FLH does work on roads and pavements with these partners, they frequently make design and construction decisions that conform to ecosystem goals and objectives that may not be optimized for pavements. For instance, many national parks and forests have aggressive invasive species programs that require imported aggregate be devoid of seeds from invasive weeds. This may require running the aggregate through the aggregate dryer portion of an asphalt plant to burn off weed seeds, resulting in a more energy-intensive pavement. Yet such a result is acceptable in light of the larger goal of controlling invasive species.

Strategies for Improving Sustainability

This section identifies some specific pavement features that have not been described previously in other sections of this document yet may be influenced by larger system goals. These pavement features are often not quantifiable by LCCA or LCA and may or may not be explicitly recognized in sustainability rating systems.

Aesthetics

"Aesthetics" refers to the nature and appreciation of beauty. In the context of infrastructure it refers to general appearance (typically meaning "visual appearance" but not necessarily excluding other senses) and usually implies a measure of beauty and harmony with the surrounding environment. There are limited opportunities to address the aesthetics of a pavement. To a large degree pavements are designed and materials selected for engineering reasons rather than artistic ones. However, there are situations where pavement aesthetics influence design; usually these influences are based on color or texture.

Color can be controlled by choice of aggregate and binder materials, either alone or in combination with stains, dyes, or pigments. An example of color-related aesthetics is the red cinder chip seal used in and around Zion National Park by the National Park Service and

Pavement Aesthetics

The Eastern Federal Lands Highway Division (EFLHD) used a transparent, amber-colored synthetic binder combined with salmon-colored granite and pink quartzite aggregate to achieve desired aesthetics for paving the portion of Pennsylvania Avenue in front of the White House in 2004 (EFLHD 2004).

Another example of aesthetics impacting pavement design is documented along the Gatlinburg Spur of the Great Smokey Mountains National Park Foothills Parkway. For this project, EFLHD was tasked with creating stabilized soil highway pull-offs for emergency use by motorists. Park aesthetics required that these pull-offs be grass surfaced (not paved) so EFLHD experimented with several different stabilization techniques that all proved successful (Hatcher 2004).

Central Federal Lands Highway Division (CFLHD) (see figure 9-1). Pavement materials and type can also be changed in specific areas to create increased visibility, separating pedestrian and bicycle features based on color and texture (see figure 9-2).

Figure 9-1. Zion Park Blvd. in Utah (SR 9) with a chip seal surfacing that uses local red volcanic cinders to match the aesthetics of the surrounding environment and to be consistent with historical road surfacing (photo courtesy of Steve Muench).

Figure 9-2. Brick crosswalk in Charlotte, NC implemented as part of an intersection improvement (Hughes, Chappell, and Chen 2006).

For concrete pavements, their normal grey color can be made nearly white through the use of white cement, slag cement, pigments, or stains. Projects have also been constructed where white cement is coupled with photocatalytic titanium dioxide to help keep the surface clean, thus maintaining the light color while also treating nitrous and sulfur oxides in air pollution. Concrete can also be patterned to add aesthetic appeal. A similar effect can also be achieved through the use of interlocking concrete pavers. Figure 9-3 shows how a combination of colored interlocking concrete pavers and colored concrete is being used to add aesthetic appeal on U.S. 41 in a pedestrian-friendly historic downtown area of Houghton, Michigan.

Figure 9-3. Vehicular interlocking concrete pavers being placed in a pedestrian-friendly downtown area in Houghton, MI. Note the use of colored concrete for the pavers to provide a visual offset for the cross walk (photo courtesy of Thomas Van Dam).

Historical and Cultural Identity

Historical and cultural identities are often closely associated with aesthetics since aesthetics can help create such identities, enhance feelings of community, or maintain ties to the past. Several of the examples previously given (paving of Pennsylvania Avenue in front of the White House [see sidebar in page 9-4], Zion Park Boulevard in Utah, and U.S. 41 in Houghton, Michigan) are all aesthetic treatments done for historical or cultural identity. Indeed, one of the most common ways pavement contributes to such identity is the preservation of an old pavement type or material in an historical area (see, for example, figures 9-4, 9-5 and 9-6).

Figure 9-4. Old cobblestone pavement preserved and still in use on East Republican St., Seattle, WA (photo courtesy of Steve Muench).

Figure 9-5. Lombard Street in San Francisco during construction in 1922 (FoundSF 2013).

Figure 9-6. Lombard Street as it looks today with its brick pavement, kept for historical and cultural reasons (Wikipedia, public domain).

Utility Cuts

Utility cuts in pavements present a sustainability challenge because they breech the integrity of the pavement surface and their subsequent patches can result in weak points in the pavement structure through the existence of added joints, substandard pavement (figure 9-7), or inadequate subgrade repair. Some empirical work has been done to document these effects (e.g., City of Seattle 2000).

Figure 9-7. Poor quality patch in an existing concrete pavement (photo courtesy of Steve Muench).

Coordination Issues

In many instances paving and utility work schedules are not coordinated, which can result in utility cuts being made on newly paved surfaces. Many road owners have policies that forbid utility cuts for a specified time after paving (e.g., City of Spokane 2005; County of San Diego 2008); however, coordination between street paving and utility work can be difficult. Generally, those jurisdictions that actively coordinate such work use some form of electronic database that registers all projects and checks for conflicts (Trombka and Rubin 2013). Some jurisdictions even charge a "pavement degradation fee" associated with utility cuts, which is intended to recover the cost of associated long-term pavement damage (Trombka and Rubin 2013).

Repair Guidance

Most guidance on utility cut repair is directed at local agencies and focuses on traditional means including locating and marking existing utilities, traffic control, pavement cutting, excavation, backfill, surface restoration, and site cleanup (FHWA 1996). A key element to restoring long-term ride quality is to ensure that the backfill is adequately compacted. This is challenging in a long, narrow utility cut and thus the use of controlled low-strength materials (CLSM) to fill trenches is highly recommended.

Ongoing work continues in the development of modular/precast pavements specifically designed to provide ready access to underground utilities, allowing panel removal and replacement after utility work is completed. Considerable work has been done showing how interlocking concrete pavers can be reused to create relatively seamless and repeatable repairs, as shown in figure 9-8 (ICPI 2009). A French system using hexagonal panels is shown in figure 9-9 (Larrard, Sedran, and Balay 2012). While these methods are not new (see figure 9-10) they show promise in many instances.

Figure 9-8. Illustration of how existing concrete pavers can be removed to repair a gas line (a), and then the bedding recompacted (b), joint sand reapplied (c), and the final product which shows little sign of disturbance (d) (ICPI 2009).

Figure 9-9. Removal of French hexagonal modular pavement to access utility (Larrard, Sedran, and Balay 2012).

Figure 9-10. A utility cut in Rome, Italy shown with the excavation open and sampietrini (individual rounded black basalt stones) removed. Upon completion the cut is filled and sampietrini reinstalled (photo courtesy of Steve Muench).

Odor, Soot, and Particulate Matter

Although of greatest concern to construction workers, odors, soot, and particulate matter (PM) generated during construction and shortly thereafter are also of concern to the adjacent communities. All paving construction operations have the potential to negatively impact worker health and local communities through plant and construction equipment emissions and PM generated from soil disturbance and demolition activity (SMAQMD 2013). For example, a recent study cited increased level of exposure to submicron PM for workers in both paving and milling operations, listing multiple strategies to improve worker safety including improved maintenance of paver ventilation systems, diesel fume engineering controls, reduced idling, provision of cabs for the operators, and improved dust suppression systems on milling machines (Freund et al. 2012). Practices that can be used to help control construction generated emissions include (SMAQMD 2010):

- Fugitive dust can be controlled by watering all exposed unpaved surfaces twice daily, covering or maintain 2 ft (0.61 m) of free board space on haul trucks transporting loose material (all haul trucks using freeways or major roads should be covered), wet power vacuum paved surfaces daily, limiting vehicle speed on unpaved roads to 15 mi/hr (24 km/hr), and paving surfaces as soon as possible.
- Soot and other emissions from diesel-powered fleets can be reduced by minimizing idle time and maintaining all construction equipment in proper working condition.

In addition, as documented in chapter 3, the use of WMA technologies will reduce emissions and odors associated with the placement of asphalt materials.

Allowable Hours of Construction

It is very common in urban areas to have specified times in which delivery of materials and construction activities are allowed, being limited to certain times of the day, days of the week, or times of year. This is primarily to mitigate noise (e.g., in residential neighborhoods it is common for night construction to be prohibited) and minimize congestion during prime travel times. For example, in specifications used by the City of Azusa, California, construction is allowed between the hours of 7:00 a.m. to 6:00 p.m. Monday through Saturday and can be extended to 10:00 p.m. if approved by the City. For Sunday and national holidays, construction is only allowed if approved by the City, and is allowed only between the hours of 9:00 a.m. and 5:00 p.m.

Such restrictions are put in place to reduce the impact of construction on the community, yet they can impose difficult on contractors who often are working under tight schedules to complete the work as expeditiously as possible. Further, some construction activities are very sensitive to timing, and delays can cause serious damage and premature pavement failure. For example, concrete contraction joints must be sawed within a “sawing window” that is directly related to the properties of the mixture, the ambient temperature, and the length of time since mixing, among other factors. In general, joint sawing should be initiated within 4 hours and completed within 12 hours of paving, although specialized early-entry sawing equipment may allow sawing to begin within 1 to 2 hours of paving (Smith 2007). If paving is delayed and the sawing window falls at a time in which construction (e.g., sawing joints) is not allowed, the pavement can suffer random cracking and may require removal and replacement.

Strategies for Improving Sustainability

Most important to this chapter is that larger system goals, and specifically sustainability goals, can drive pavement sustainability choices. Most prominently, social and environmental goals of larger systems contain elements to which pavements can contribute. In some instances, the more sustainable solution for the larger system requires pavement choices that are less than optimal when viewed from the perspective of pavement alone. Some general approaches to improving pavement sustainability within larger systems are summarized in table 9-1.

Table 9-1. General strategies to improve pavement sustainability within larger systems.

Larger System Objective	Pavement Contribution	Economic Impact	Environmental Impact	Societal Impact
Enhance Roadway Aesthetics	Color, texture, and historical materials	Increased cost, single-sourced or scarce materials	Minimal	Improved sense of place, beauty, and integration with surroundings
Minimize/Eliminate Impacts of Utility Cuts Through Coordination and Repair	Better repair techniques, use of pavements that allow utility cuts without degrading pavement structure once repaired	Lower repair costs, less traffic disruption, longer pavement life	Reduction in needed material due to better repairs providing longer pavement life	Less disruption of transportation and services
Improve Worker and Community Health Through Reduction of Odors, Soot, and Particulate	Dust control, minimized idle time, warm-mix asphalt	Time and effort to train and implement new procedures	Less pollution that could adversely affect the environment	Improved worker and community health
Balance Approach to Allowable Hours of Construction	Faster construction and proper phasing of construction to conform to working hours	Increased construction costs (offset by impact savings) to accommodate community working hours	Improved environmental performance (e.g., reduced noise) during hours of non-work	Better accommodation of surrounding community needs and desires

Future Directions/Emerging Technologies

A few of the future directions and emerging technologies in this broad topic area are presented below:

- Photocatalytic pavement. Photocatalytic pavement can be made using photocatalytic cement or through the use of photocatalytic coatings. This innovation potentially offers an opportunity to create a surface that remains clean while treating air pollution through a photocatalytic reaction involving nanoparticles of titanium dioxide (TiO_2). In addition to its pollution-reducing quality, these materials are often lightly colored, having high albedo (reflectance). The technology has recently been implemented on a limited basis in the U.S. Additional information on photocatalytic cement can be found in chapters 3 and 6.

However, titanium dioxide has recently been classified by the International Agency for Research on Cancer (IARC) as a possible carcinogen to humans (IARC 2006). The effects of nanostructured titanium dioxide on the environment are also not fully known; some initial studies show significant effects on microbial communities in surface waters (Battin et al. 2009).

- Energy production. Pavements may provide a venue to produce electric power through use of pressure, vibration, embedded solar photovoltaic (PV) devices, or simply by harvesting heat from sun exposed surface with embedded tubing. Research is ongoing in this arena, with numerous promising ideas populating the worldwide web. No idea has yet taken root, but it is likely that at some point energy harvesting from pavement will become a reality.
- Translucent concrete. Translucent concrete may be a viable material in urban environments for use in delineating crosswalks or bicycle crossings (PCA 2013). Made from orientated optical fibers, the concrete literally glows and if accompanied with sensors, can light up a crosswalk as a pedestrian approaches the intersection. The technology can be used to show predefined messages.
- Precast pavement systems. This technology continues to evolve, and new methods are being developed that offer the potential to allow ready removal and replacement of the surface to access underground utilities. This "snap in, snap out" approach is still in early stages of development, but if implemented, will provide an answer to municipal agencies that are confronted with seeing the integrity of newly placed pavement being compromised as it is cut into pieces for utility access. An overview of precast concrete pavement systems is provided by Tayabji, Ye, and Buch (2012).

Concluding Remarks

This chapter describes how pavements interact with larger system sustainability goals and objectives, and highlights a number of key pavement-related sustainability considerations not directly covered elsewhere. There are a number of potential issues and trade-offs that are inherent when considering sustainable pavements within the context of these larger systems, including:

- Uncertainty in performance of materials specifically designed to meet aesthetic, environmental, or social criteria.
- Cost is often higher for non-traditional approaches to pavement design, materials, and construction including meeting historical or cultural identity.
- Depending on local policy, utility cuts are often executed by utilities that are not focused on the quality or long-term performance of the repair. This will require education and accountability to improve the state-of-the-practice.
- Timing and quality of construction versus being allowed to work only within prescribed hours of operation. This is most acute in urban areas where construction often is prohibited during nighttime hours (e.g., 6:00 p.m. to 7:00 a.m.).
- Specific features designed to accommodate wildlife can be expensive, and their effectiveness not well demonstrated.

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CHAPTER 10. ASSESSING PAVEMENT SUSTAINABILITY

Introduction

In general, there are four broadly categorized measurement tools, or methods, that are typically used either in isolation or in concert to quantify various aspects of sustainability: performance assessment, life-cycle cost analysis, life-cycle assessment, and sustainability rating systems. These methods were introduced in chapter 2 and are discussed in more detail here. Because performance assessment is a long-standing method of evaluation and is essentially built into current standards, it is not addressed in detail as a measurement tool. Notably, there are few, if any, generally accepted metrics able to measure equity/social impacts associated with pavement systems, although a few are recognized to some degree in sustainability rating systems.

Pavement Sustainability Aspects Can Be Evaluated Using:

- ✓ *Performance assessment.*
- ✓ *Life-cycle cost analysis.*
- ✓ *Life-cycle assessment.*
- ✓ *Rating systems.*

Life-Cycle Cost Analysis (LCCA)

Background

According to the Transportation Equity Act for the 21st Century (TEA-21), LCCA is "…a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment." Because LCCA is an essential component of most pavement type selection processes, many other definitions incorporate descriptions of typical LCCA applications (e.g., "LCCA is an analytical tool to provide a cost comparison between two or more competing design alternatives producing equivalent benefits for the project being analyzed" [NHI 2008]). However, whether used to compare competing alternatives or simply to assess the total expected cost of a single strategy, the basic analytical process remains the same. In simplest terms, LCCA can be considered to be a generally accepted accounting practice that "…offers sophisticated methods to determine and demonstrate the economic merits of the selected alternative in an analytical and fact-based manner" (FHWA 2013).

The basic pavement LCCA process requires that the analyst define the schedule of initial and future activities involved in implementing a specific alternative (whether new construction or rehabilitation). Next, the costs of each of these activities are estimated. The predicted schedule of activities and their associated costs comprise the projected life-cycle cost stream, an example of which is depicted in figure 10-1. Using an economic analysis technique known as "discounting," all projected costs are converted into present dollars and summed to produce a net present value (NPV) or net present cost (NPC). If multiple alternatives with similar benefits are being considered over identical analysis periods, the net present values or costs can be compared to determine which alternative is the most cost effective. More thorough descriptions of the LCCA process can be found in numerous publications (e.g., Walls and Smith 1998; Riggs and West 1986; FHWA 2002; FHWA 2004; NHI 2008; FHWA 2010; ACPA 2011).

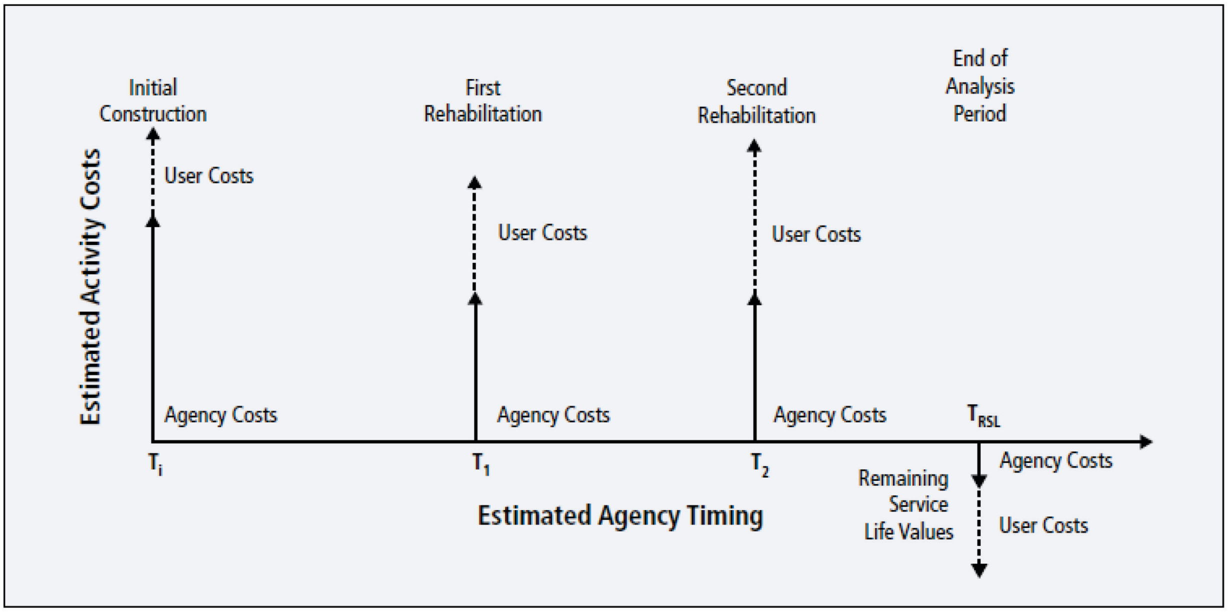


Figure 10-1. Example projected life-cycle cost stream diagram (FHWA 2002).

LCCA provides a means of measuring the economic consequences of design, materials, construction techniques, maintenance schemes, and end-of-life treatments. If the economic inputs for these are reasonable, LCCA is a tool that can account for their economic impact over the life cycle and is thus able to measure that component of sustainability.

Like most analytical tools, LCCA is not without limitations and, if used incorrectly, can provide false support for poor choices. While the accurate estimation of the timing and costs of life-cycle activities is the most important factor in conducting a good pavement LCCA (see Hallin et al. [2011] for guidance on developing reasonable maintenance and rehabilitation strategies), there are several additional considerations that are also important, as described in the next section.

Key Issues in LCCA

As noted previously, LCCA is useful for determining the economic impact of potential changes in design, construction, materials, etc. that are intended to improve the environmental or societal impacts of a pavement project. NPV or NPC is also commonly used to select from among various design or rehabilitation alternatives that are believed to provide the same level of performance or benefits to the project's users during normal operations over the same analysis period.

If the benefits are the same but the analysis periods differ, then equivalent uniform annual cost (EUAC) analysis is useful in identifying the preferred alternative. Implicit in an EUAC analysis is the assumption that the strategies are repeated at the end of the analysis periods. An alternate approach (and the one that is recommended by FHWA) is to use the same analysis period (generally the shortest of those being considered) for all candidate alternatives and to include the remaining value of each alternative at the end of the analysis period (i.e., salvage value of materials or value of remaining service life) as a "benefit" or "negative cost" at the end of the analysis period.

If the benefits vary among the candidate alternatives (e.g., if they provide different levels of service), then the alternatives cannot be compared solely on the basis of cost and, consequently, LCCA alone may not be an appropriate means of comparison. If all benefits can be expressed monetarily, then the benefits can be considered in the same analysis as the costs, discounted similarly, and a decision can still be made based on the results of the analysis and the overall objective (e.g., to maximize net benefits or minimize net costs).

Another option for analyzing monetarily expressed costs and benefits that is sometimes favored by public agencies is benefit-cost analysis (BCA), in which the ratio of discounted benefits to discounted costs is computed. Unfortunately, simple BCA can lead to incorrect strategy selections in some cases, although incremental BCA, a more complex analysis, will yield consistently correct strategy selections (Riggs and West 1986). Because of its relative simplicity, NPV analysis is often preferred over BCA for economic analyses.

It must also be noted that, because there are usually other decision factors in the selection process that cannot be easily quantified monetarily (e.g., work zone safety, environmental impacts, impact of local development), LCCA alone is rarely sufficient for selecting from among competing alternatives. Utility theory and other forms of value engineering are sometimes useful in evaluating the preferred alternative when monetary and nonmonetary considerations must be balanced. In such cases, the option with the lowest LCC may not be implemented. Nevertheless, LCCA provides valuable information to the overall decision-making process.

The following subsections briefly describe additional considerations in the proper conduct of LCCA.

Discount Rate

It is generally accepted that all future cost streams should be estimated in constant (current) dollars and discounted to present dollar values using a real discount rate, which represents the combined effects of interest and inflation rates. For pavement project LCCAs, the selected discount rate used should reflect both historical trends over long periods of time and near-term projections. The U.S. Office of Management and Budget (OMB) provides federal agencies with guidance concerning many of the technical aspects of conducting economic analyses, including the selection of a discount rate. FHWA recommends that highway agencies use OMB Circular A-94, Appendix C (OMB 2012) in selecting a discount rate, and many agencies use rates that are based on the "real interest rates on Treasury Notes and Bonds" found in that document, which is updated annually.

The choice of discount rate is very important and thus it is useful to understand the impact of discount rate on LCCA. Higher discount rates reduce the present value of future costs by a greater amount than do lower discount rates; a zero discount rate values future costs the same as current costs; and negative discount rates increase the present value of future costs above those of current costs.

End-of-Analysis (Residual) Value: Salvage Value vs. Remaining Service Life Value

It is often necessary to assign a value (generally a benefit or negative cost) to the pavement at end of the LCC analysis period to capture either the value of the remaining pavement life (assuming that the pavement's service life has not been fully consumed at the end of the analysis period) or the "salvage" value of the materials that will be derived from the pavement structure if it will have no remaining service life (e.g., if the pavement is to be removed and replaced at the end of the analysis period). Alternatively, the "salvage value" may be computed as the value of the existing pavement as a support layer for an overlay at the end of the analysis period (i.e., recycling or "repurposing" the pavement in place).

These options are mutually exclusive for any given LCCA; that is, no analysis should include both a salvage value and a remaining service life value. Whichever end-of-analysis value is selected (if any), it should reflect what the agency realistically expects will be done with the pavement structure at the end of the analysis period. ACPA (2011) and West et al. (2012) provide summaries of U.S. state highway agency practices concerning the inclusion of salvage and remaining service life values in their LCCAs.

It should be noted that consideration must be given to the proper allocation of pavement salvage values to avoid "double counting" their contributions to the LCCA. For example, it may be appropriate to consider the value of salvaged materials as a positive cash flow at the end of the analysis period if the agency retains the ownership of the material for use on another project. In such cases, the salvage value might be considered to be equal to the cost savings associated with using the material on another project. On the other hand, if the contractor retains ownership of the material, then the agency receives no immediate benefit from the salvage operation and no benefit should be reflected at the end of the LCCA analysis period. However, it is reasonable to expect that the contractor will use the material on a different project and that the bid price for the material on that project will reflect the contractor's low cost in obtaining the material. In this way, the agency benefit for the salvage value of the old pavement should be reflected (at least partially) in the lower initial costs of future projects. In any event, it is extremely important that the analyst place the salvage value benefit of any given material at the end of the analysis period <u>or</u> as a reduction in cost at the beginning of the next project, but not fully in both places. If different materials from the same project are used in different ways, then portions of the salvage value may be allocated to both places.

User Cost Estimates

User costs originate primarily from vehicle operating costs (i.e., vehicle wear and tear, fuel consumption, repairs and maintenance), delay costs (e.g., from increases in time required to travel between two points as a result of work zones, congestion, etc.), and crash costs (which are often a result of driver error and other factors not related to the roadway conditions and, as a result, are generally not factored into LCCA) (Walls and Smith 1998).

The value of road users' time is a subject of great debate. User delay costs are generally computed in consideration of vehicle class, trip type (urban or rural), and trip purpose (business or personal). Details concerning the computation of user costs can be found in NCHRP (2004), and free software for computing these costs is a part of the FHWA *RealCost* LCCA program (FHWA 2010) or the CA4PRS software (Caltrans 2011).

While there is no doubt that user costs should be considered in decision-making processes, it is widely recognized that these costs should not be included in the same LCCA cost stream as agency costs because: 1) although there is much literature on the topic, the quantification of user costs is subject to debate and uncertainty (FHWA 2002), 2) user costs "do not debit agency budgets as do agency costs" (FHWA 2002); and 3) computed user costs on some projects can be so large as to swamp the decision process or to drive it toward options that the agency cannot afford. Therefore, it is common for user costs to be weighted differently than agency costs in the decision process or (as current FHWA policy recommends) for user costs to be computed and analyzed separately from agency costs. The consideration of user costs in LCCA is described in more detail later in this chapter.

Deterministic LCCA vs. Probabilistic LCCA

The use of fixed values for all LCCA inputs (e.g., activity timing, costs, discount rate) to produce a single output value is referred to as the *deterministic* approach to LCCA. While this approach is relatively simple and requires few inputs, it fails to adequately account for either the variability in actual initial costs and discount rates over time or the uncertainty in the timing and costs of planned maintenance and rehabilitation activities. Furthermore, the output of a single value (i.e., NPV or NPC) without some statement to qualify that value may imply a degree of certainty in the conclusion that is inappropriate (FHWA 2010). Sensitivity analyses (i.e., varying input values, often one at a time, and rerunning the analysis to determine how sensitive the output value is to variations in specific inputs) can give the analyst a better sense of confidence in the accuracy of deterministic LCCA results.

The *probabilistic* approach to LCCA is more realistic in that it uses statistical descriptions of the probable distribution of values for each input (e.g., a mean and standard deviation for each normally distributed input value) to account for the input-associated variability that creates uncertainty in the outputs of the analysis, which helps quantify the risk in any decisions that are made on the basis of the outputs. A distribution of output values (often derived from numerical simulations involving input variables that have been randomly selected from populations of values that represent the input variable distributions) is produced to provide users with information for understanding the variability of the results and the confidence that can be placed in the analysis. Figure 10-2 provides an example illustration of the results of a probabilistic analysis.

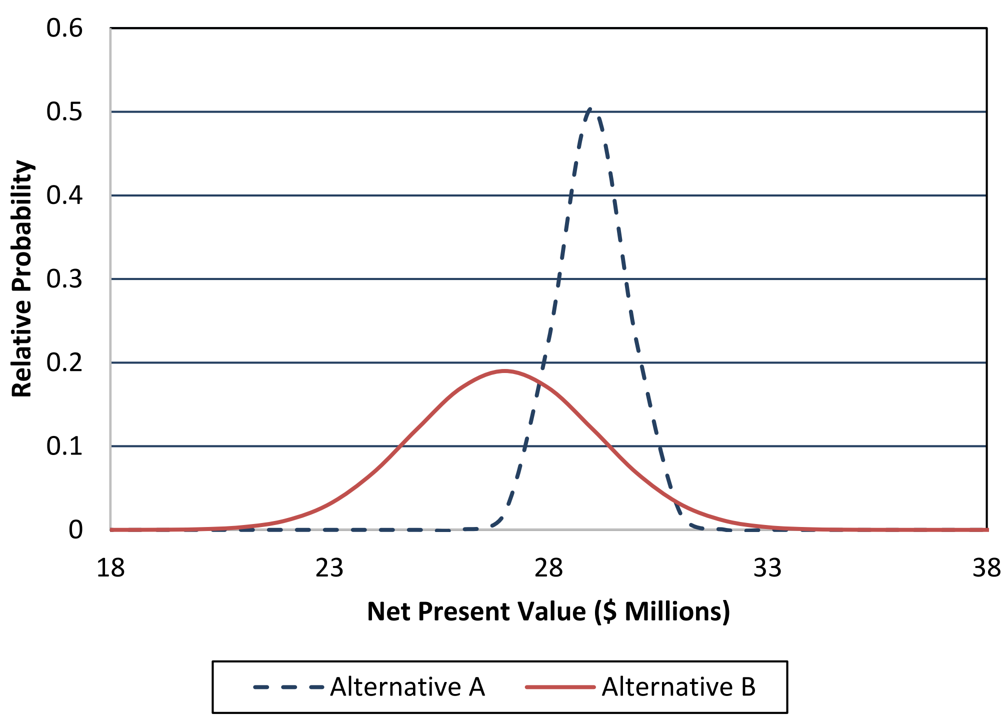


Figure 10-2. Probabilistic analysis of two design alternatives (Walls and Smith 1998).

The development of appropriate input-value distributions can be time-consuming, particularly if the data required to develop the input distributions are not routinely collected or available. The collection and use of good pavement cost, performance, and maintenance activity information is essential for the conduct of a good LCCA. The probabilistic LCCA approach typically requires the use of sophisticated computer software (such as the FHWA's *RealCost* tool), but is generally considered to have the potential for providing the most accurate "real-world" economic analysis and assessment of risk.

Use of LCCA in Various Pavement Delivery Approaches

LCCA can be used to improve decisions made in different types of pavement delivery approaches. For example, in traditional design-bid-build (DBB) programs, LCCA (along with other criteria) is typically used by the owner/agency to aid in determining the pavement type and principal design features (e.g., full-depth HMA vs. deep-strength HMA or JPCP vs. CRCP designs) based on very preliminary project assumptions and design inputs. Knowledge of the selected pavement type and principal design is used by planners, designers, right-of-way (ROW) acquisition teams, and others to develop the detailed designs, purchase ROW, and prepare bid documents that are specific to the project and the selected pavement type.

As mentioned previously, user costs are commonly excluded from DBB project LCCA, but they may be recognized in the bidding process through "A + B" bidding. In this type of bidding, contractors submit both a bid price (A) and a number of days to complete the project construction (B), which is multiplied by some value that represents the impact on users caused by the duration of the construction activity and associated congestion and delays. Longer planned construction windows effectively increase the contractors' bid prices, making them less competitive. There are typically substantial financial penalties for exceeding the contracted number of work days, and often incentives for completing the work early.

"A + B" bidding recognizes only the impact of initial construction on user costs, and it is assumed that future agency maintenance costs and associated user costs (for work zone delays during future M&R activities) will be constant, regardless of which contractor builds the project. However, in "alternate design, alternate bid (ADAB)" projects, where the contractor can choose to bid on the construction of a specific design from among different design options, the future agency and user costs may differ significantly between the design options. In these cases, "A + B" bidding takes on a different meaning, where A is defined as the price of each contractor's bid and B is the present value of future agency maintenance and rehabilitation costs for each alternative (note: B can also be computed as a difference in future costs between alternatives that is only applied to the alternatives with the higher NPV of future costs). Given the uncertainty in estimating future activity costs and timing, alternatives with NPVs that differ by less than 10 percent are often considered to have similar costs to the agency. Since user costs are not considered directly in the analyses, the NPV of user costs for competing alternatives should be approximately equal for ADAB project alternatives. When the difference in NPV of user cost streams exceeds 20 percent, "the suitability of the project for (ADAB) should be carefully evaluated" (FHWA 2012).

The use of LCCA in design-build (DB) contracting is similar to its use in DBB contracting in that the analysis can be used to estimate future agency (and user) costs for a particular type of pavement design. The owner/agency can then use this information in evaluating the preliminary designs and construction bid packages prepared by competing engineer-contractor consortiums to determine the overall best value to the agency (considering both the initial costs and the expected future costs).

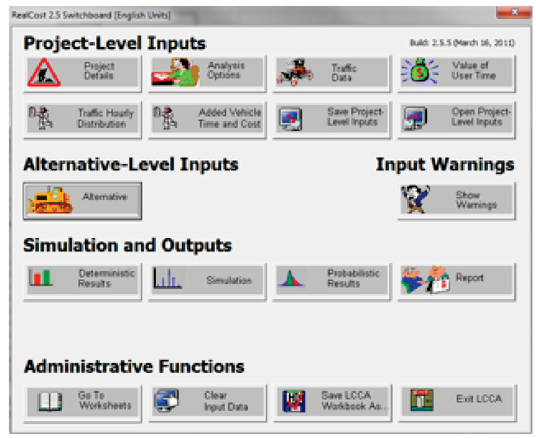
In design-build-maintain (DBM) contracting, the successful contractor is responsible for designing, constructing, and maintaining the pavement at a specified level on behalf of the owner for a predetermined period of time that generally approaches the expected pavement life. The contractor bids typically reflect both a construction cost and an annual maintenance cost over the contract. The agency can use LCCA to determine the present value of these costs and can also factor in anticipated user costs (both during initial construction and future maintenance activities) to help in identifying the best value proposal (in consideration of other nonmonetary factors as well).

Available LCCA Tools

Since basic LCCA can be performed simply using pencil and paper, calculator, or spreadsheet programs, it is no surprise that there are probably many such tools available. In fact, many state highway agencies have developed and adopted their own software (generally computer-based spreadsheets) that incorporate their own predetermined unit costs, discount rates, assumed maintenance cycles, and other policy-based or standard parameters to facilitate uniform LCCAs by their staff and consultants. These LCCAs are usually deterministic and provide the users with relatively little flexibility in inputs.

RealCost LCCA Software

RealCost is essentially an MS-Excel® spreadsheet based automated version of the LCCA methodology contained in the FHWA's LCCA Technical Bulletin (Walls and Smith 1998). The program can be used to compute life-cycle costs for agency and work zone user costs associated with new construction, maintenance, and rehabilitation activities using both deterministic and probabilistic approaches. The menu options available in the software's user interface are show in the figure below.



RealCost, however, does not compute agency costs or service lives for individual construction, maintenance, and rehabilitation activities. These values are typically established by the owner/agency prior to the analysis. While RealCost presents comparisons between agency and user life-cycle costs of programmed alternatives, these values alone are not sufficient in making a selection on the ideal option for a particular project. Other environmental, societal, and agency specific factors also need to be considered in arriving at the final decision. As with any other analytical tool, RealCost provides useful economic metrics that help in the overall decision-making process.

The most widely accepted and adopted LCCA tool for pavement applications currently in use in the U.S. is the FHWA's *RealCost* Software. Originally developed as a relatively simple proof-of-concept, spreadsheet-based program for use in LCCA workshops in 1997, it has undergone numerous improvements and enhancements over the years and is routinely used by pavement design practitioners throughout the country.

Examples

Numerous LCCA examples exist in agency and industry technical, reports, bulletins and training course materials (e.g., ACPA 2011; FHWA 2002; NHI 2008; West et al. 2012). For the most part, the examples included in those documents provide examples of LCCA for the purpose of pavement type selection and the selection of rehabilitation strategies.

Documentation of the use of LCCA for applications more closely related to sustainability include the following:

- Ram et al. (2011) studied a series of Michigan concrete pavement projects using both LCCA and LCA, concluding that higher levels of sustainability are achieved with increased pavement longevity.
- Embacher and Snyder (2001) used LCCA to investigate actual maintenance and rehabilitation costs and strategies for concrete and asphalt pavements in two Minnesota counties, documenting the impact of differing maintenance strategies on the normalized costs (adjusted for varying traffic levels) of comparable pavements.
- Hicks and Epps (1996) used LCCA to examine the cost effectiveness of using asphalt rubber as an alternative to traditional HMA. They concluded that, for the scenarios evaluated, asphalt rubber is a cost-effective alternative for many (but not all) highway pavement applications. When variability of the inputs was considered (e.g., cost, expected life), the asphalt rubber alternates were the best choices in most of the applications considered.

These three studies are presented as examples of the application of LCCA in making decisions that are related to pavement sustainability (beyond pure economics). The conclusions drawn from these studies are project specific and are not presented as universally applicable findings. It is important that the specific details of each analysis be considered in evaluating the conclusions drawn in these studies.

Life-Cycle Assessment (LCA)

Awareness of the importance of environmental protection, and the possible impacts associated with the production, use, and retirement of products, has generated considerable interest in the use of assessment methods to better understand and address those impacts. Life-cycle assessment (LCA) is one of the techniques developed for this purpose. This section includes an introduction to the purpose, approach, intended outcomes, and limitations associated with the use of LCA.

Purpose of an LCA

LCA is a structured evaluation methodology that quantifies the environmental impacts over the full life cycle of a product or system, including impacts that occur throughout the supply chain. LCA can be used for a variety of purposes, including:

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle.
- Informing and guiding decision makers in industry, government, and non-governmental organizations for a number of purposes, including strategic planning, priority setting, product or process design selection, and redesign.

- Selecting relevant indicators of environmental performance from a system-wide perspective.
- Quantifying information on the environmental performance of a product or system (e.g., to implement an eco-labeling scheme, make an environmental claim, or produce an environmental product declaration statement).

Differences in results from an LCA can guide decision makers into making choices that have a lower or reduced environmental impacts.

LCA is one of several environmental assessment techniques, and may not be the most appropriate technique for use in all situations. For example, environmental impact statement (EIS) or risk assessment may be more appropriate in some cases. An EIS is a detailed analysis that serves to ensure that the policies and goals defined in NEPA, the National Environmental Policy Act, are infused into the ongoing programs and actions of the federal agency. EISs are generally prepared for projects that the proposing agency views as having significant prospective environmental impacts. The EIS should provide a discussion of significant environmental impacts and reasonable alternatives that would avoid or minimize adverse impacts or enhance the quality of the human environment, whereas an LCA is focusing more on the environmental impacts associated with the material and energy flows throughout the pavement life cycle.

The LCA Process

LCA quantifies environmental flows that occur throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (in other words, from cradle to grave). In LCA, these are referred to as life-cycle stages (or phases), and these were introduced in chapter 2 for pavement systems.

As shown in figure 10-3, there are four phases in an LCA study:

1. The goal and scope definition phase.
2. The inventory analysis phase.
3. The impact assessment phase.
4. The interpretation phase.

The first phase of an LCA determines key features of the analysis including the depth and the breadth of an LCA, which can differ considerably depending on the overall goal. The scope of an LCA defines the system boundary of analysis (essentially, what life-cycle stages and processes are included in the LCA), the geographic and temporal boundaries of analysis, the functional unit of analysis, and also determines the required quality of data. Again, all of these depend on the subject and the intended use of the LCA.

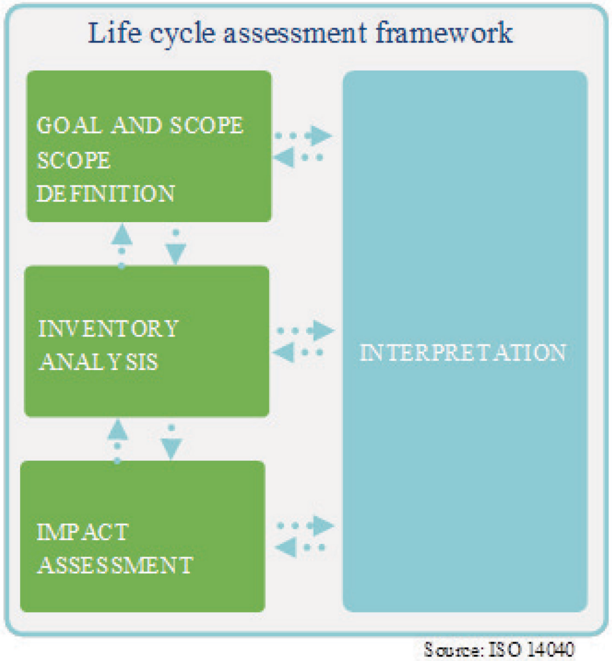


Figure 10-3. Life-cycle assessment framework (ISO 2006a).

This figure is adapted from ISO 14040:2006, Figure 1 on page 8, with the permission of ANSI on behalf of ISO. (c) ISO 2013 - All rights reserved.

The second phase of an LCA, the life-cycle inventory analysis phase (LCI phase), is the accounting stage where environmental flows (inputs of material, energy, and resources, and outputs of waste, pollution, and co-products) are tracked for the system being studied. Figure 10-4 illustrates the types of data that are collected.

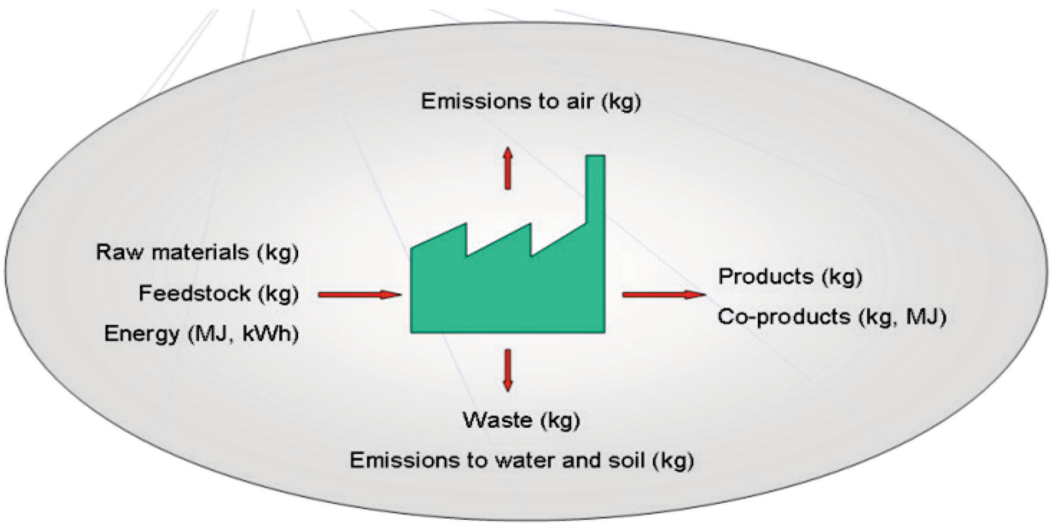


Figure 10-4. Data types relevant to a typical LCA (courtesy of theRightenvironment).

The life-cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to better understand the environmental significance of the LCI by translating environmental flows in to environmental impacts that are presented in different impact categories, typically:

- Impacts to people (humans).
- Impacts to nature (ecosystems).
- Depletion of resources.

A list of typical impact categories is included in table 10-1. LCA studies usually include a selection of impact categories that are most relevant to the specific project goal and scope, and can range from narrowly focusing on energy and energy-related emissions to a full set of impact categories. The most commonly used impact categories in the U.S. are based on the TRACI impact assessment methodology developed by the EPA, the most recent version of which (TRACI v2.0) was released in 2012 (Bare 2011; EPA 2012b). The most widely used global impact assessment method is the CML methodology (Guinée et.al. 2002), with the most recent update from April 2013.

Table 10-1. Typical LCA impact categories.

Group	Impact Category	Geographical scale	Comment on Available Impact factors
Energy use	Fuel, non-renewable[1] Resources, non-renewable Resources, non-renewable, secondary Fuel, renewable Resource, renewable Resource, renewable, secondary	Global	Small uncertainty, both energy use and feedstock energy should be quantified
Resource use	Resource, renewable Resources, non-renewable[2]	Global	Small uncertainty
Emissions	Climate Change[1, 2]	Global	Small uncertainty, typical 100 year time horizon, biogenic CO_2 requires special attention
	Ozone layer depletion[1, 2]	Global	Small uncertainty
	Acidification[1, 2]	Regional	Small uncertainty
	Tropospheric ozone[1, 2]	Local	Medium uncertainty
	Eutrophication[1, 2]	Local	Small uncertainty, local
Toxicity	Human toxicity[2], respiratory[1] Human toxicity, carcinogenic[1] Human toxicity, non-carcinogenic[1] Ecotoxicity[1], fresh water[2] Ecotoxicity, marine water[2] Ecotoxicity, soil[2]	All scales	High uncertainty, incomplete
Water	Fresh water use	Local	Small uncertainty
Waste	Hazardous Non-hazardous	Local	Small uncertainty

[1] part of TRACI
[2] part of CML

The life-cycle interpretation is the last phase of the LCA procedure, in which the results are summarized and discussed as a basis for conclusions, recommendations, and decision making in accordance with the goal and scope definition.

Types of LCA Studies

There are cases where the goals of an LCA may be satisfied by performing only an inventory analysis and an interpretation. This is usually referred to as an LCI study. Generally, the information developed in an LCA or LCI study can be used as part of a much more comprehensive decision process. Comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent. To address this, the ISO 14044 standard contains several requirements and recommendations to ensure transparency on these issues (ISO 2006b).

Most Pavement LCAs are Process Based and "Attributional"

Most pavement-oriented LCA studies are process based, meaning that data are collected for every process that is covered in the LCA. This is a bottom-up approach, and while data intensive it does allow for specific, regionalized, and representative results. Several commercial database and software tools are available that are based on this type of LCA.

Other LCA studies are based on data generated from a top-down approach, called input-output LCA. These LCAs produce estimates of total supply chain impacts for economic sectors using economic input-output tables (which trace dollar flows across sectors) linked with resource use information and pollution flows for economic sectors. Products within a sector are assigned a portion of a sector's supply chain impact based on their value. LCAs sometimes follow a hybrid approach where input-output data are used for secondary data and process LCI data are used for the primary processes, materials, and life-cycle phases that are under consideration.

Regardless of whether the LCA is process based or input-output, pavement-oriented LCA studies most often are attributional, meaning they focus on describing the overall environmental properties of a life cycle and its subsystems. This is very useful in understanding the overall impact of a pavement project, for example. On the other hand, some pavement LCA studies that have been conducted are consequential, meaning that they aim to describe the environmental impacts of changes to an evaluated system. This can be useful in evaluating system wide impacts and is often used for studies that evaluate the impact of a proposed change in policy. Additionally, consequential LCA can be useful for infrastructure and traffic planning studies that evaluate decisions that have longer term and more far-reaching consequences.

Available Tools

Although there are no generally accepted LCA tools for pavements in the U.S., there are a number of LCA software programs (e.g., Athena, Gabi, SimaPro) that include relevant LCI datasets (many of which are proprietary) that can be used to develop LCA models. There are some pavement modeling tools available as well, such as PaLATE, which uses a hybrid LCA approach and considers energy use, air emissions, and leachate; information on this tool can be found at http://www.ce.berkeley.edu/~horvath/palate.html, but the tool is no longer maintained. This renders the database outdated and not fit-for-purpose. An update of the database would be required to make this a useful tool. This could leverage the results from LCI databases that rely less on input-output based LCI models.

More recently, the Project Emissions Estimator (PE-2) tool has been developed and provides a GHG emissions model for construction, maintenance, and use of pavements[1] (Mukherjee, Stawowy, and Cass 2013). Additionally, AASHTO has also released a tool, GreenDOT, that estimates carbon dioxide emissions from the operations, construction, and maintenance activities of state highway agencies; it is designed to calculate emissions for geographical areas ranging from a single project to an entire state, and over time periods ranging from 1 day to several years (Gallivan, Ang-Olson, and Papson 2010). The two most likely uses of the GreenDOT tool are to calculate annual agency-wide emissions or to calculate emissions related to a specific project, covering a period of days or years[2].

Most of these models rely on publicly available CO_2 emissions factors such as those derived from MOVES, NONROAD and GREET. The EPA's MOVES (Motor Vehicle Emission Simulator) (EPA 2012a) and NONROAD (EPA 2005) are air emissions inventory models and thus can be used to estimate on-road or non-road mobile source emissions (i.e., tailpipe emissions) associated with vehicles and equipment, but not life-cycle emissions. The GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model) model, developed by the Argonne National Laboratory, includes life-cycle emission and energy factors for different fuels, electricity, and other energy sources (ANL 2013).

The Canadian Athena Institute released the most comprehensive North American LCA tool, a Highway Impact Estimator that relies on generic LCI data that the user cannot alter (Athena 2013). There are many other examples of pavement LCA tools from Europe, including the decision-weighting model for roads, where the material life cycle of pavement can be modeled for environmental, economical, and user-defined project-specific sustainability aspects (Van Leest, Van Hartskamp, and Meijer 2008), and the RWS model DuboCalc[3], which is an LCA model for the Dutch DOT that is mandated for use in all highway infrastructure. Other entities have developed their own models, often tailored for specific research projects or regional decision making including models developed at universities or by regional authorities.

Key Issues

Pavement LCA methods and models continue to evolve. To illustrate some of the challenges that lie ahead, a short summary of the key issues that must be addressed to advance the use and implementation of LCA for pavements is provided below:

- A general pavement LCA framework has not yet been agreed upon by practitioners. When pavement LCA studies are executed, LCA practitioners have to make many assumptions and make methodological choices that can lead to confusing and contradictory results among studies. The development of a generic pavement LCA framework could create a template that would define the most relevant starting points (i.e., for scope, goal, system boundaries, etc.) for any pavement LCA going forward. This would not only make LCAs easier to perform, but would also make them easier to interpret and compare.
- There is a need for a centralized database of non-proprietary LCIs for materials, equipment, vehicles, and other elements that can serve as a reference database for

[1] http://www.construction.mtu.edu/cass_reports/webpage/plca_estimator.php

[2] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(58)_GreenDOTv1-5b.xls

[3] http://www.rijkswaterstaat.nl/zakelijk/duurzaam/duurzaam_inkopen/duurzaamheid_bij_contracten_en_aanbestedingen/dubocalc/index.aspx

pavement LCA. This database would be used in conjunction with primary project data, and would include generic data covering all upstream data or "cradle-to-gate" data. A significant amount of data needs to be developed, preferably in a harmonized framework, such as an EPD framework for materials.

- A pavement life cycle can extend over a period of 60 to 75 years, and modeling a complete life cycle means making a number of assumptions based on design parameters, anticipated performance, maintenance and rehabilitation timing and frequency, and so on. It is extremely difficult to predict all these parameters today for the years to come. Transparently reporting the uncertainty in these assumptions is one step to improving LCAs.
- When the use phase is included, traffic-related impacts often dominate other life-cycle stages. Some key traffic-related elements are traffic composition, volume, traffic delays, future traffic, vehicle fuel efficiency, rolling resistance, and pavement smoothness. The LCA models for these elements are still in development, and some still require basic research, especially with regards to vehicle and pavement interactions including the effect of pavement condition on vehicle fuel efficiency.

Example Studies

A number of relevant pavement LCA studies have been performed in the last few years, with some of the significant findings and conclusions from selected studies summarized below.

- Generally, most pavement LCA studies find that the materials for construction and overlays dominate the results when vehicle traffic is excluded from the analysis. This is true for both asphalt and concrete pavements. The combination of manufacturing the binder and producing the resultant mixture is a relevant contributor to the results for both pavement types. Aggregates constitute the majority of the mass of the pavement, making transportation and logistics particularly relevant for recycling and virgin aggregates.
- The energy used and the emissions generated from the traffic that uses the pavement facility typically outweigh the emissions produced during the production of the materials and construction of the pavement. Steps towards cleaner fuels, higher fuel efficiency of the vehicles, and better traffic flow are relevant and potentially significant. This last point also favors nighttime work when traffic disruptions are minimized (Santero, Masanet, and Horvath 2010).
- Ram et.al. (2011) studied a series of concrete pavement projects in Michigan using LCCA and LCA tools, and concluded that increased pavement longevity was associated with reduced environmental impacts. Additionally, it was noted that if longevity is achieved, the use of SCM and RCA results in further improvements in both the economic and environmental life-cycle indicators.
- Wang et.al. (2012) applied LCA of pavement to research the impact of pavement smoothness over time and the relation between pavement maintenance and preservation on the fuel efficiency of vehicles for California state highways. The study found that the application of preservation treatments that enhance smoothness has a net positive effect on the overall energy and GHG emissions for facilities carrying high traffic volumes.
- The time period that is covered by the LCA model is a very important factor. Typically, pavements are modeled using existing design criteria, construction practices and planned maintenance, rehabilitation, and replacement cycles, even though it is acknowledged that

these practices are constantly changing. Studies tend to use estimates for typical practices and use considerations such as traffic volume, traffic delays, and fuel efficiency over this long period of time, but these estimates become more and more uncertain as they are projected further into the future (Santero, Masanet and Horvath 2010).

Methodological Framework in Greater Detail

The general framework for LCA is defined in the ISO 14040 series, with the most prominent one the ISO 14044 standard that defines the general requirements and guidelines (ISO 2006a). The standard provides a framework that encourages transparency and some consistency in approaches and reporting. However, because the ISO standard applies to LCAs for all products and systems, it does not prescribe an approach tailored to specific categories of analysis, such as for an LCA of pavements. Still, even though there is no generally accepted LCA framework for pavements, there are some important developments that should be noted. For example, a basic framework for pavement LCA was developed in 2010 that builds on the ISO guidelines and provides pavement-specific methodological guidelines (UCPRC 2010).

The European industry is organized in a technical working group that is defining pavement specific guidelines under the Construction Products Directive. It details the LCA process for products, buildings, and construction works. The CEN 15804 lays down a structure for product LCA and Environmental Product Declarations (CEN 2012). The focus of the CEN/TC 350/WG 6 is to develop a framework for Civil Engineering Works, and it is estimated that a standard will be developed by 2016.

ISO 14044 includes an important section that is meant to ensure that LCAs are methodologically sound and adhere to accepted practices. In section 6, rules and requirements are laid down for critical review, especially when comparisons are made with the aim of external publication. Depending on the goal and scope of the LCA, a critical review by an independent LCA expert is sufficient. For competitive LCAs, a critical review panel (consisting of at least three members, one of which needs to be an LCA expert and two that need to be independent industry experts) needs to be instituted.

Although reviews are currently not common practice in pavement LCA, except when published as peer-reviewed articles, some recent studies have incorporated a review component. It is recommended that future work incorporate a critical review process and greater stakeholder involvement, which should lead to increased standardization and enhanced LCA practices.

What Lies Ahead: Environmental Product Declarations

An EPD, as defined in the ISO 14025 standard (ISO 2006c), is a declared LCA for a product and is a form of certification. If all products had an EPD, a pavement LCA using those products would benefit tremendously in terms of quality and lower cost. EPDs can be issued on a specific product from a specific producer, but may also be issued for a generic product from a group of manufacturers (such as an association). Figure 10-5 shows a sample EPD for a concrete mix design.

Summary of
Environmental Product Declaration

Central Concrete

Mix 340PG9Q1

San Jose Service Area

EF V2 Gen Use P4000 3" Line 50% SCM

Performance Metrics

28-day compressive strength	4,000 psi
Slump	4.0 in

Environmental Impacts

Impact name	Unit	Impact per m3	Impact per cyd
Total primary energy consumption	MJ	2,491	1,906
Concrete water use (batch)	m3	6.66E-2	5.10E-2
Concrete water use (wash)	m3	8.56E-3	6.55E-3
Global warming potential	kg C02-eq	271	207
Ozone depletion	kg CFC-11-eq	5.40E-6	4.14E-6
Acidification	kg S02-eq	2.26	1.73
Eutrophication	kg N-eq	1.31E-1	1.00E-1
Photochemical ozone creation	kg 03-eq	46.6	35.7

A sample EPD for a concrete mix design by Central Concrete Supply Co.

Credit: Central Concrete Supply

Figure 10-5. Sample EPD for a concrete mix design (courtesy of Central Concrete Supply Company).

The basis for an EPD is a Product Category Rule (PCR) document generated through a stakeholder procedure and including rules for specific product categories. Two recent examples of industry involvement in this area are: 1) the Product Category Rules Task Group produced a draft PCR for portland and blended cements in 2012 and is close to releasing a publication, and, 2) the National Ready Mixed Concrete Association (NRMCA) is certifying EPDs for cement (Carbon Leadership Forum 2010) and concrete (Carbon Leadership Forum 2013) as a program operator. In addition, the National Asphalt Pavement Association (NAPA) has formed a task group to develop PCRs and EPDs for the asphalt pavement industry.

Product Category Rules

- *The Product Category Rule (PCR) document defines the rules for a product LCA, is industry accepted, and defines the Environmental Product Declaration (EPD) format. It is owned by a Program Operator.*
- *The LCA can be drafted against the PCR document.*
- *The EPD follows the PCR requirements and uses the results from the LCA.*
- *An independent third party performs a verification of the LCA and EPD against the PCR after which the Program Operator issues the EPD.*

An Example of an Important Methodological Element: Allocation

There are several important methodological elements to an LCA, but one that is keeping the LCA community engaged is the aspect of allocation. This topic is not limited to just pavement LCA, but is relevant to all LCA studies. This section is included to highlight some of the ongoing discussions that are relevant to pavement LCA. All elements of the pavement life cycle are germane to allocation, but this discussion on allocation is focused on material sources that are discussed in chapter 3 and on material recycling performed at the end of the life of the pavement that are discussed in chapter 8. Those chapters include several callout boxes that relate to allocation, and this section aims to tie it together.

Whenever a system of production yields multiple products or services, the environmental inputs and outputs of the system have to be assigned to each product and service, referred to as co-products. The ISO 14040 standards for LCA prescribe a hierarchical preference for how to assign, or *allocate*, environmental flows that occur in the modeling of the LCA. These allocations must be assigned whenever a production system boundary is crossed. For example, when one pavement life cycle ends and another begins, allocation must be utilized when assigning environmental impact to the material that is recycled from the pavement.

A general consensus among LCA practitioners and those involved in evaluating products and systems is that allocation rules should be set up to:

- Incentivize practices that reduce environmental impact.
- Prevent double counting of credits or the omission of important items.
- Provide fairness between industries by reflecting as closely as possible what is actually happening.
- Be transparent so that all parties can understand how allocation is applied and how it influences the results.

In addition, ISO standards, such as ISO 14044 for LCA, require sensitivity analysis to evaluate the impact of allocation rules to determine how they might change the final results of the assessment. According to ISO standards, the preference for treating co-products is to first try to avoid allocation by either 1) subdividing the production system into processes that can be assigned wholly to a single co-product, or 2) expanding the scope of interest to include the processes that seem to need allocation, thereby removing the need for allocation (this is referred to as system expansion). System expansion is more or less equivalent to displacement or substitution, where co-products are modeled as if they are displacing equivalent products in the marketplace. Thus, the system of production is credited with avoiding the need for producing these equivalent products. This approach is often used in consequential LCA approaches, as described earlier.

In most pavement LCA studies, the boundaries for the system of production are crossed (and thus allocation is necessary) in three situations:

1. Multi-output situations like manufacturing processes with co-products (e.g., oil refineries).
2. Reuse of components and recycling of materials after initial use, such as steel rebar, reclaimed asphalt pavement, coal combustion co-products from power generation, or use of discarded tires in asphalt binder.
3. Multi-input situations like waste treatment processes, such as incineration and landfilling.

All three situations are described below with examples of some actual processes and materials in pavement LCA.

Manufacturing Processes with Co-Products

The preferred way to deal with assigning impacts to multi-outputs is to reflect the physical properties of the outgoing flows, such as mass or energy content. If a relationship can be established that is more suitable than mass, it should be used. This means that the physical basis for allocation can be different in different situations and for different materials. The economic value of co-products can also be used for allocation; however, Bernard, Blomberg, and Southern

(2012) suggest that allocation based on physicochemical properties (e.g., mass or energy content) is preferred to economic allocation. With that being said, Ayer et al. (2007), Basset-Mens and van der Werf (2005), and Guinee et al. (2002), among others, have stated a preference for economic allocation above other approaches, largely because economic value is typically the primary driver of business.

Allocation requires a somewhat arbitrary partitioning of the co-producing processes without considering the interactions between subprocesses; thus, an objective justification is warranted between the chosen allocation parameter, such as mass or economic value, and the share of environmental loads (Weidema 2001). This makes co-product allocation sometimes contentious. Good LCA practice in this case requires justification of the grounds for allocation, transparency in reporting, showing the impact of allocation choices on the results, and performing sensitivity analyses to assess the significance of the allocation choice on the overall LCA conclusions. Some examples are provided in chapter 3 for specific materials (e.g., asphalt as a co-product from the petroleum refinery). An example of an economic allocation for a multi-output process is show in figure 10-6.

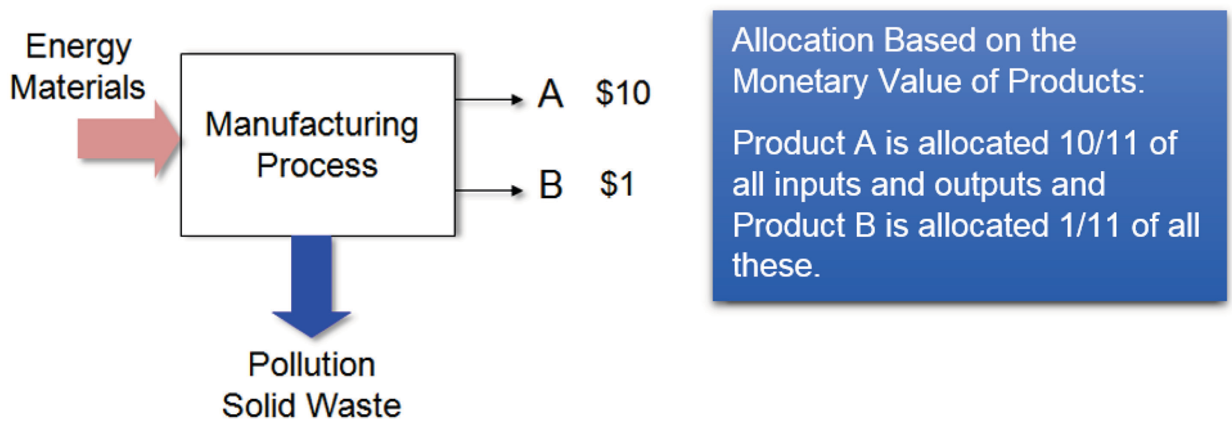


Figure 10-6. Example of economic allocation for a multi-output process.

Reuse of Components and Recycling of Materials after Initial Use

When using a material from another product, pavement or system, several approaches for allocation have been and are being tried to ensure that the "benefits" of using secondary materials or fuel resources are properly reflected in an LCA.

Most EPD approaches use a strict and conservative approach: all processes and transportation needed to reuse or recycle the material are assigned to the product utilizing the recycled content, but the production of the original product is assigned to the first product's life cycle. The same is true of reused or recycled materials that are used in pavement projects, such as the secondary content in steel, recycled aggregate from building waste, rubberized asphalt binder containing recycled tires, recovered binder from asphalt shingles, and SCMs derived from other industrial processes. Furthermore, materials that become available for reuse or recycling at the end of the pavement life cycle, such as RAP, RCA, and reinforcing steel, are also allocated in this manner.

An important element in this discussion is whether a material is defined as a waste or a product. If an economic approach is used to define a resource as a waste or a co-product, the following reasoning can be used:

- Where a waste flow material has value, it is considered a co-product and needs to have "production" processes allocated to it for the life cycle that is using the material. In essence, as soon as a waste flow has positive economic value, it is considered a co-product and should be treated as such.
- Where a waste flow material has a negative cost but becomes an economically valuable product through processing, the impact of processing and handling is allocated based on the difference between the cost (assigned to the producing life cycle where the waste occurred) and the positive value (assigned to the receiving life cycle where the co-product is used). An example of this is concrete waste that requires an acceptance fee at a crushing facility where it is processed (crushed and sized), and then sold back to the market at a price.
- Where the waste remains a cost regardless of processing, all environmental burdens of the processes are assigned to the producing life cycle; in this case, it essentially stays a waste and never becomes a co-product. The life cycle that uses materials like this are essentially part of the waste treatment process and receive the material "for free."

Other approaches assign a "value" to the recycled materials and include credits for preventing the need for new primary materials for the new application. This is referred to as substitution, and must be considered cautiously and aligned with the approach for the receiving product system. Double counting of credits should be prevented.

One variation of assigning credits for recycling is the modeling of multiple life cycles to reflect repeated recycling benefits. This approach is typically used to assign future recycling credits to the current product. There are examples reported where an infinite number of life cycles are modeled to show the benefits of recycling, which can extend time periods that are irrelevant on a human scale. This is not considered good LCA practice, particularly given that modeling a pavement over a period in the range of 50 to 75 years is methodologically challenging enough as it is.

Waste Treatment Processes

The preferred way to deal with assigning impacts to multi-input processes is to reflect the physical properties of the incoming flows. If a relationship can be established that is more suitable than mass, it should be used. An example is the relation between the chemical composition of a waste that is available for landfill and the associated emissions to air and water from the landfill. However, this is not very relevant for most pavement LCA materials since most of them are inert. Another example is the relation between the chemical composition of a waste that is available for incineration and the associated emissions to air and energy recovery as heat or electricity. Both situations occur in pavement LCA but are not very relevant to the outcome of most pavement LCA materials since most of them are inert or have little or no economic value as a combustion energy source.

Final Thoughts

Allocation is clearly a complex and contentious issue, and of particular importance to those conducting pavement LCAs given their wide range of processes and the significant amount of recycling that occurs. While it is expected that allocation will remain an ongoing topic of debate, it is recommended that the key goals for allocation should be to incentivize practices that reduce environmental impact, prevent double counting and omission of key inputs/outputs, provide fairness between industries, and be transparent about the procedure utilized.

Sustainability Rating Systems

Transportation and associated industries offer a range of guidance on the sustainability of transportation infrastructure. This guidance ranges from generally advocated strategic directions, to more comprehensive guide documents, to rating systems that call out specific practices. Each level of guidance has value; the choice on which to use depends upon the goals and requirements of the governing agency or organization.

Background

A sustainability rating system is essentially a list of sustainability best practices with an associated common metric. This metric, usually points, quantifies each best practice in a common unit. In this way the diverse measurement units of sustainability best practices (e.g., pollutant loading in stormwater runoff, pavement design life, tons of recycled materials, energy consumed/saved, pedestrian accessibility, ecosystem connectivity, and even the value of art) can all be compared. In its simplest form, a rating system can count every best practice equally (e.g., all worth one point), in which case the rating system amounts to a tally of the number of best practices used. In more complex forms, rating systems weight best practices (usually in relation to their impact on sustainability or priority), which can assist in choosing the most impactful best practices to use given a limited scope or budget.

Currently there are a number of national and international rating system efforts within the transportation community. These systems vary in scope and complexity but are generally designed to provide guidance, scoring, and potential rewards for the use of sustainability best practices. Rating systems usually concentrate on practices that are compatible with current regulations but are above and beyond existing minimum regulatory requirements. Rating systems are particularly appealing because they:

- Provide a common metric (points) for the entire range of sustainable solutions.
- Measure sustainability and thus make it manageable.
- Allow for straightforward communication of sustainability goals, efforts, and achievement.
- Provide a reasonable context within which designers, contractors, and material suppliers can be innovative in their solutions.

While there has been and continues to be much debate over the scientific merit and basis for rating systems, such debate can miss the point. The essential purpose of most sustainability rating systems is not a scientifically defensible taxonomy of sustainability, but rather a tool to (1) encourage sustainability practices beyond the regulatory minimum, and (2) to communicate sustainability in a comprehensible manner. In particular, rating systems provide an understandable way to communicate sustainability whether it is within an agency or project, to design and construction professionals, or to the general public. Furthermore, rating systems are often turned to when other means of quantification (e.g., LCA) fail to capture the full range of sustainability best practice impacts. For instance, while LCA is capable of accounting for GHG emissions associated with pavement construction, it is not able to capture more abstract, yet important, sustainability features such as ecological connectivity and aesthetics.

Rating systems are often criticized because (1) they tend to sacrifice detail for simplicity, (2) it is difficult to generate consensus on which items to include/exclude, (3) they do not capture the entire scope of sustainable solutions, and (4) their use in blindly pursuing points as part of a rating system could trump good design/construction. However, a well-designed rating system used within a proper organizational approach to sustainability can overcome these issues and provide value to the agency or organization.

Rating Systems in Context

It is important to view a rating system in the right context. For instance, project-based rating systems address sustainability within the context of an individual project. Therefore, they should be considered specialized tools that fit within a broader agency approach to sustainability but do not address all agency sustainability efforts. In this context, the adoption or use of a rating system does not supply sustainability but rather complements other agency-wide efforts.

Potential Industry Impacts of Rating Systems

Beyond a single agency, well-designed and marketed rating systems can have broad-reaching sustainability impacts within an industry. For instance, the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED®) rating system addressing building sustainability (often termed "green buildings") has been in use since 1998 and is by far the most popular sustainability rating system worldwide. It can be argued that LEED has allowed sustainable infrastructure to gain a commercial foothold in the building industry because of its success. For instance, as of April 2013 there were 16,611 LEED certified projects, 39,712 LEED registered projects, and the annual USGBC conference, GreenBuild®, attracts over 30,000 attendees and 1,000 exhibitors (USGBC 2013). Growth of the green building industry is evidenced by *Engineering News-Record's* (*ENR's*) annual survey of green contractors, most of which are working on projects pursuing LEED certification. In September 2013, *ENR*' s identified "Top 100 Green Contractors" in the U.S. received $42.75 billion in contracting revenue from green projects in 2012, which represented 34.4 percent of their total revenue (Tulacz 2013). They also identified 13,019 accredited staff in those 100 companies. While one might still argue the details of LEED rating systems, the number of certifications, registrations, and conference attendees makes a strong case for the overwhelming success of the communication aspect of the USGBC's suite of rating systems.

Rating Systems Relevant to Pavements

While there are many rating system efforts that apply in some way to pavements worldwide, the following sections briefly outline those systems that are (1) the most prevalent on the national stage in the U.S., and (2) most relevant to pavements. Note that although all of these rating systems are relevant to pavements in some way, none of them are focused on pavements as the primary system under consideration. All focus on larger systems (e.g., road project, agency sustainability efforts, neighborhood design, infrastructure systems) and account for pavement as a contributing subsystem. Therefore, none of them should be used to rate or grade pavement sustainability in isolation because pavement tends to exist as a subsystem that contributes to larger systems (e.g., neighborhood, highway corridor, downtown street network, community, ecology).

The following sections provide overviews of several sustainability rating systems that are reasonably well developed and are being used at the national level (either actively rating projects or engaged in a pilot phase).

INVEST (Infrastructure Voluntary Evaluation Sustainability Tool)

INVEST (FHWA 2011; Bevan et al. 2012) is a sustainability rating system for roadways that encompasses planning and policy, project development, and operations and maintenance. It is point based and voluntary and applicable to all U.S. road projects with a focus on state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs). A summary of its characteristics is provided below.

- **Owner**: FHWA.
- **Scope**: Transportation system and project planning, design, construction, operations and maintenance.
- **Status**: (as of April 2013): Version 1.0 is available at www.sustainablehighways.org.
- **Background**: INVEST was created by the FHWA as a self-evaluation tool. There are no plans to make it required in any context. INVEST has three different subsystems that can be used independently: Systems Planning, Project Development, and Operations and Maintenance. INVEST is intended to function as a self-certification program (i.e., the project owner can also perform the review).
- **Relevance to pavements**: Systems Planning: no criteria are directly relevant to pavement sustainability concepts discussed in this document. Project Development: 14 criteria (48 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document. Operations and Maintenance: 5 criteria (36 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

Greenroads®

Greenroads (Muench et al. 2011) is a sustainability rating system for roadway design and construction. It is point based and voluntary and applicable to all U.S. road projects. Relevant characteristics are given below.

- **Owner**: Greenroads Foundation (501 c3 non-profit organization).
- **Scope**: Roadway design and construction. Does not directly address planning or operations and maintenance, although a number of credits influence those items.
- **Status**: (as of April 2013): Version 1.5 is available to review projects at http://www.greenroads.org/. Six projects certified and 23 projects registered representing about $2.8 billion of construction value.
- **Background**: Greenroads was originally created by the University of Washington and CH2M HILL in partnership, now independently owned and operated by the Greenroads Foundation, and also includes an individual accreditation program. Greenroads is a third-party certification program (i.e., the Greenroads Foundation functions as an independent third party review).
- **Relevance to pavements**: 7 of 11 Project Requirements (64 percent) and 19 Voluntary Credits (49 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

Envision™

Envision (ISI and Zofnass 2012) is a sustainability rating system for civil infrastructure. It is point based, voluntary, and applicable to all civil infrastructure. Important characteristics are listed below.

- **Owner**: A joint collaboration between the Zofnass Program for Sustainable Infrastructure at the Harvard University Graduate School of Design and the Institute for Sustainable Infrastructure (ISI), a joint venture of the ASCE, American Council of Engineering Companies (ACEC), and the American Public Works Association (APWA).
- **Scope**: All civil infrastructure (including roads).
- **Status**: (as of February 2014): Version 2.0 manual is available to review projects at http://www.sustainableinfrastructure.org/.
- **Background**: Envision™ has some features in common with CEEQUAL (a U.K.-based system). Also includes individual training and accreditation.
- **Relevance to pavements**: 17 credits (31 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

GreenLITES

GreenLITES (Leadership In Transportation and Environmental Sustainability) is a rating program for transportation infrastructure (NYSDOT 2010). It has the following key characteristics:

- **Owner**: NYSDOT.
- **Scope**: NYSDOT project design and operations. There are two manuals, one for Project Design certification and one for Operations certification.
- **Status**: (as of April 2013): Version 2.1.0 (April 2010) for the Project Design Certification Program, and a draft version for the Operations Certification Program are available.
- **Background**: The Project Design Certification Program is used as a design review for NYSDOT projects (NYSDOT 2012). The Operations Certification Program began piloting in 2009. Both are self-certification programs meaning the NSYDOT does the project work and the certification review.
- **Relevance to pavements**: 16 credits (10 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document.

Leadership in Energy and Environmental Design (LEED®)

LEED is a series of rating systems (nine currently) focused on buildings. Characteristics of the system are provided below.

- **Owner**: USGBC (501 c3 non-profit organization).
- **Scope**: Buildings, neighborhoods (there are nine separate rating systems).
- **Status**: (as of April 2013): Fully deployed as LEED 2009 (this equates to Version 3) at http://www.usgbc.org/. Over 16,000 projects certified worldwide and 40,000 projects registered (USGBC 2013). The next full version, LEED v4, was launched in 2013.

- **Background**: LEED has been in existence since 1998. Claims over 12,000 member organizations, more than 160,000 accredited professionals and 491 government organizations with LEED legislation, executive orders, resolutions, ordinances, policies and incentives (USGBC 2012).
- **Relevance to pavements**: For LEED ND (LEED for Neighborhood Development) (USGBC 2012), 4 credits (6 percent of the available points) are directly relevant to pavement sustainability concepts discussed in this document. All 9 LEED rating systems are focused on buildings; only a small portion of each LEED rating system is relevant to pavements. Typically, this relevance is limited to credit for recycled content, high albedo surfaces, and porous pavement.

Tables 10-2 through 10-6 show more detail about how INVEST version 1.0, Greenroads version 1.5, GreenLITES Project Design version 2.1.0, Envision version 2.0, and LEED ND 2009, respectively, address and relate to the pavement sustainability concepts described in this reference document.

Table 10-2. Summary of INVEST sustainability criteria and scoring (FHWA 2011).

Criterion	SYSTEM PLANNING CRITERIA Title	Points Possible	Pavement Related
SP-1	Integrated Planning: Economic Development and Land Use	15	
SP-2	Integrated Planning: Natural Environment	15	
SP-3	Integrated Planning: Social	15	
SP-4	Integrated Planning: Bonus	10	
SP-5	Access and Affordability	15	
SP-6	Safety Planning	15	
SP-7	Multimodal Transportation and Public Health	15	
SP-8	Freight and Goods Movement	15	
SP-9	Travel Demand Management	15	
SP-10	Air Quality	15	
SP-11	Energy and Fuels	15	
SP-12	Financial Sustainability	15	
SP-13	Analysis Methods	15	
SP-14	Transportation Systems Management and Operations	15	
SP-15	Linking Asset Management and Planning	15	
SP-16	Infrastructure Resiliency	15	
SP-17	Linking Planning and NEPA	15	
	Total Points	**250**	**0**
	Percentage of points directly relevant to pavement		**0%**

Table 10-2. Summary of INVEST sustainability criteria and scoring (FHWA 2011) (continued).

Criterion	**PROJECT DEVELOPMENT CRITERIA Title**	**Points Possible**	**Pavement Related**
PD-1	Economic Analysis	5	
PD-2	Lifecycle Cost Analysis	3	✓
PD-3	Context Sensitive Project Development	5	
PD-4	Highway and Traffic Safety	10	✓
PD-5	Educational Outreach	2	
PD-6	Tracking Environmental Commitments	5	✓
PD-7	Habitat Restoration	3	
PD-8	Stormwater	9	
PD-9	Ecological Connectivity	3	
PD-10	Pedestrian Access	2	
PD-11	Bicycle Access	2	
PD-12	Transit and HOV Access	5	
PD-13	Freight Mobility	7	
PD-14	ITS for System Operations	5	
PD-15	Historical, Archaeological, and Cultural Preservation	3	
PD-16	Scenic, Natural, or Recreational Qualities	3	
PD-17	Energy Efficiency	8	
PD-18	Site Vegetation	3	
PD-19	Reduce and Reuse Materials	8	✓
PD-20	Recycle Materials	8	✓
PD-21	Earthwork Balance	3	
PD-22	Long-Life Pavement Design	5	✓
PD-23	Reduced Energy and Emissions in Pavement Materials	3	✓
PD-24	Contractor Warranty	3	✓
PD-25	Construction Environmental Training	1	✓
PD-26	Construction Equipment Emission Reduction	2	✓
PD-27	Construction Noise Mitigation	2	✓
PD-28	Construction Quality Assurance Plan	5	✓
PD-29	Construction Waste Management	3	✓
	Total Points	**126**	**58**
	Percentage of points directly relevant to pavement		**46%**
Criterion	OPERATIONS AND MAINTENANCE CRITERIA Title	Points Possible	Pavement Related
OM-1	Internal Sustainability Plan	15	
OM-2	Electrical Energy Efficiency and Use	15	
OM-3	Vehicle Fuel Efficiency and Use	15	
OM-4	Reuse and Recycle	15	✓
OM-5	Safety Management	15	
OM-6	Environmental Commitments Tracking System	15	
OM-7	Pavement Management System	15	✓
OM-8	Bridge Management System	15	
OM-9	Maintenance Management System	15	✓
OM-10	Highway Infrastructure Preservation and Maintenance	15	✓
OM-11	Traffic Control Infrastructure Maintenance	15	
OM-12	Road Weather Management Program	15	
OM-13	Transportation Management and Operations	15	
OM-14	Work Zone Traffic Control	15	✓
	Total Points	**210**	**75**
	Percentage of points directly relevant to pavement		**36%**

Table 10-3. Summary of Greenroads credit categories and scoring (Muench et al. 2011).

Credit	Title	Points Possible	Pavement Related
	Project Requirements		
PR-1	Environmental Review Process	NA	
PR-2	Lifecycle Cost Analysis	NA	✓
PR-3	Lifecycle Inventory	NA	✓
PR-4	Quality Assurance Plan	NA	✓
PR-5	Noise Mitigation Plan	NA	✓
PR-6	Waste Management Plan	NA	✓
PR-7	Pollution Prevention Plan	NA	
PR-8	Low-Impact Development	NA	✓
PR-9	Pavement Management System	NA	✓
PR-10	Site Maintenance Plan	NA	
PR-11	Educational Outreach	NA	
	Environment and Water		
EW-1	Environmental Management System	2	✓
EW-2	Runoff Flow Control	3	
EW-3	Runoff Quality	3	
EW-4	Stormwater Cost Analysis	1	
EW-5	Site Vegetation	3	
EW-6	Habitat Restoration	3	
EW-7	Ecological Connectivity	3	
EW-8	Light Pollution	3	
	Access and Equity		
AE-1	Safety Audit	2	
AE-2	Intelligent Transportation Systems	5	
AE-3	Context Sensitive Solutions	5	
AE-4	Traffic Emissions Reduction	5	
AE-5	Pedestrian Access	2	
AE-6	Bicycle Access	2	
AE-7	Transit & HOV Access	5	
AE-8	Scenic Views	2	
AE-9	Cultural Outreach	2	
	Construction Activities		
CA-1	Quality Management System	2	✓
CA-2	Environmental Training	1	✓
CA-3	Site Recycling Plan	1	✓
CA-4	Fossil Fuel Reduction	2	✓
CA-5	Equipment Emission Reduction	2	✓
CA-6	Paving Emission Reduction	1	✓
CA-7	Water Use Tracking	2	✓
CA-8	Contractor Warranty	3	✓
	Materials and Resources		
MR-1	Lifecycle Assessment	2	✓
MR-2	Pavement Reuse	5	✓
MR-3	Earthwork Balance	1	
MR-4	Recycled Materials	5	✓
MR-5	Regional Materials	5	✓
MR-6	Energy Efficiency	5	
	Pavement Technologies		
PT-1	Long-Life Pavement	5	✓
PT-2	Permeable Pavement	3	✓
PT-3	Warm-Mix Asphalt	3	✓
PT-4	Cool Pavement	5	✓
PT-5	Quiet Pavement	3	✓
PT-6	Pavement Performance Tracking	1	✓
	Total Points	**108**	**53**
	Percentage of points directly relevant to pavement		**49%**

Table 10-4. Summary of ENVISION sustainability criteria and scoring (ISI and Zofnass 2012).

Credit	Title	Points Possible	Pavement Related
	Quality of Life		
QL1.1	Improve Community Quality of Life	25	
QL1.2	Stimulate Sustainable Growth and Development	16	
QL1.3	Develop Local Skills and Capabilities	15	✓
QL2.1	Enhance Public Health and Safety	16	✓
QL2.2	Minimize Noise and Vibration	11	✓
QL2.3	Minimize Light Pollution	11	
QL2.4	Improve Community Mobility and Access	14	
QL2.5	Encourage Alternative Modes of Transportation	15	
QL2.6	Improve Accessibility, Safety and Wayfinding	15	
QL3.1	Preserve Historic and Cultural Resources	16	
QL3.2	Preserve Views and Local Character	14	
QL3.3	Enhance Public Space	13	
	Leadership		
LD1.1	Provide Effective Leadership And Commitment	17	
LD1.2	Establish A Sustainability Management System	14	
LD1.3	Foster Collaboration And Teamwork	15	
LD1.4	Provide for Stakeholder Involvement	14	
LD2.1	Pursue By-Product Synergy Opportunities	15	✓
LD2.2	Improve Infrastructure Integration	16	✓
LD3.1	Plan for Long-Term Monitoring and Maintenance	10	✓
LD3.2	Address Conflicting Regulations and Policies	8	
LD3.3	Extend Useful Life	12	✓
	Resource Allocation		
RA1.1	Reduce Net Embodied Energy	18	✓
RA1.2	Support Sustainable Procurement Practices	9	
RA1.3	Use Recycled Materials	14	✓
RA1.4	Use Regional Materials	10	✓
RA1.5	Divert Waste from Landfills	11	✓
RA1.6	Reduce Excavated Materials Taken Off Site	6	
RA1.7	Provide for Deconstruction and Recycling	12	✓
RA2.1	Reduce Energy Consumption	18	
RA2.2	Use Renewable Energy	20	
RA2.3	Commission and Monitor Energy Systems	11	
RA3.1	Protect Fresh Water Availability	21	
RA3.2	Reduce Potable Water Consumption	21	
RA3.3	Monitor Water Systems	11	
	Natural World		
NW1.1	Preserve Prime Habitat	18	
NW1.2	Preserve Wetlands and Surface Water	18	
NW1.3	Preserve Prime Farmland	15	
NW1.4	Avoid Adverse Geology	5	
NW1.5	Preserve Floodplain Functions	14	
NW1.6	Avoid Unsuitable Development on Steep Slopes	6	
NW1.7	Preserve Greenfields	23	
NW2.1	Manage Stormwater	21	✓
NW2.2	Reduce Pesticides and Fertilizer Impacts	9	
NW2.3	Prevent Surface and Groundwater Contamination	18	
NW3.1	Preserve Species Biodiversity	16	
NW3.2	Control Invasive Species	11	
NW3.3	Restore Disturbed Soils	10	
NW3.4	Maintain Wetland and Surface Water Functions	19	

Table 10-4. Summary of ENVISION sustainability criteria and scoring (ISI and Zofnass 2012) (continued).

Credit	Title	Points Possible	Pavement Related
	Climate and Risk		
CR1.1	Reduce Greenhouse Gas Emissions	25	✓
CR1.2	Reduce Air Pollutant Emissions	15	✓
CR2.1	Assess Climate Threat	15	
CR2.2	Avoid Traps and Vulnerabilities	20	
CR2.3	Prepare for Long-Term Adaptability	20	✓
CR2.4	Prepare for Short-Term Hazards	21	
CR2.5	Management Heat Island Effects	6	✓
	Total Points	**809**	**247**
	Percentage of points directly relevant to pavement		**31%**

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010).

Credit	Title	Points Possible	Pavement Related
	Alignment Selection		
S-1a	Avoidance of previously undeveloped lands (open spaces or "greenfields")	2	
S-1b	Selecting an alignment that establishes a minimum 100-ft (30.5-m) buffer zone	2	
S-1c	Alignments which minimize overall construction "footprint"	2	
S-1d	Design vertical alignments which minimize total earthwork	1	
S-1e	Adjust alignment to avoid or minimize impacts to social/environmental	1	
S-1f	Alignments that optimize benefits among competing constraints	1	
S-1g	Micro-adjustments that do not compromise safety or operation	1	
S-1h	Clear zones seeded with seed mixtures that help to reduce maintenance	1	
S-1i	Provide a depressed roadway alignment	1	
S-1j	Use of launched soil nails as a more cost effective option to stabilize a slope	1	
	Context Sensitive Solutions		
S-2a	Adjust or incorporate highway features to respond to the unique character	2	
S-2b	Incorporate local or natural materials for substantial visual elements	2	
S-2c	Visual enhancements (screening objectionable views)	2	
S-2d	Period street furniture/lighting/appurtenances.	1	
S-2e	Inclusion of visually-contrasting (colored or textured) pedestrian	1	
S-2g	Incorporates guidance from Section 23 - Aesthetics of the NYS Bridge	1	
S-2h	Site materials selection & detailing to reduce overall urban "heat island" effect	1	
S-2i	Permanently protect viewsheds via environmental or conservation easements	1	
S-2j	Color anodizing of aluminum elements (ITS cabinets, non-decorative light	1	
S-2k	Decorative bridge fencing (in lieu of standard chain link).	1	
S-2l	Use of concrete form liners (for bridge approach barriers, parapet walls, etc.)	1	
S-2m	Imprinted concrete/asphalt mow strips, gores or snow storage areas	1	✓
	Land Use/Community Planning		
S-3a	Use of more engaging public participation techniques (e.g., charette, task force)	2	
S-3b	Enhanced outreach efforts (e.g., newsletters, project-specific Web page	2	
S-3c	Projects better enabling use of public transit (e.g., bus shelters, 'Park &Ride')	2	
S-3d	Projects applying "Walkable Communities" or "Complete Streets"	2	
S-3e	Projects that increase transportation efficiencies for moving freight	2	
S-3f	Project-specific formal agreement with public or private entities	2	
S-3g	Project is consistent with local and regional plans	2	
S-3h	Project reports and community outreach materials available online	1	
S-3j	Establishment of a new recreational access facility (e.g., trailhead parking)	2	
S-3k	Establishment of a new recreational facility (pocket park, roadside overlook)	2	
S-3l	Enhancement of an existing recreational facility	1	
	Protect, Enhance or Restore Wildlife Habitat		
S-4a	Mitigation of habitat fragmentation	3	
S-4b	Providing for enhancements to existing wildlife habitat (e.g., bird/bat houses)	2	
S-4c	Partial mitigation of habitat fragmentation through techniques	2	
S-4d	Use of natural-bottomed culverts	2	
S-4e	Wildlife crossings that are structures that allow for safe passage of wildlife	2	
S-4f	Wetland restoration, enhancement, or establishment	2	
S-4g	Minimize use of lands that are part of a significant contiguous wildlife habitat	1	
S-4h	Use of wildlife mortality reduction measures	1	
S-4k	Stream restoration/enhancement	1	
S-4l	Installation of mowing markers to protect natural areas and wetlands	1	
S-4m	Inclusion of scheduling and logistic requirements to avoid disrupting wildlife	1	
S-4n	Permanently protects the new or expanded habitat	1	

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010) (continued).

Credit	Title	Points Possible	Pavement Related
	Protect, Plant or Mitigate for Removal of Trees & Plant Communities		
S-5a	Avoidance/protection of established trees/veg communities	2	
S-5b	Designs that demonstrate a net increase in tree canopy	2	
S-5c	Re-establishment or expansion of native vegetation into reclaimed work areas	2	
S-5d	Use of trees, large shrubs or other suitable vegetation as living snow fences	2	
S-5e	Use of native species for seed mixtures and other plantings	1	
S-5f	Avoidance/protection of individual significant trees/desired vegetation	1	
S-5g	Designs that demonstrate no net loss of tree canopy or mitigation	1	
S-5h	Planting trees, shrubs or plant material in lieu of traditional turf grass	1	
S-5i	Removal of undesirable plant species	1	
S-5j	Preserving, replacing, or enhancing vegetation associated with historic property	1	
	W-1 Stormwater Management (Volume & Quality)		
W-1a	Improve water quality or nearby habitat	2	
W-1b	Detecting and eliminating any non-stormwater discharges	2	
W-1c	Demonstrate a reduction of pollutant loadings to adjacent water sources	2	
W-1d	Reduction in overall impervious area	2	
W-1f	Requirements for staged construction to minimize bare soil exposure	1	
W-1g	Detecting/documenting non-stormwater discharges from unpermitted sources	1	
	W-2 Best Management Practices (BMPs)		
W-2a	Design features that make use of highly permeable soils	2	
W-2b	Use of other structural BMPs (e.g., wet or dry swales, sand filters, filter bags)	2	
W-2c	Inclusion of “permeable pavement” such as grid pavers where practical	2	✓
W-2d	Minimize the project's overall impervious surface area increase	1	
W-2e	Include grass channels, where appropriate	1	
W-2f	Designate qualified environmental construction monitor to provide oversight	2	
	M-1 Reuse of Materials		
M-1a	Specify that 75 percent or more of topsoil removed for grading is reused on site	2	
M-1b	Design the project so that “cut-and-fills” are balanced to within 10 percent	2	
M-1c	Reuse of excess fill (“spoil”) within the project corridor	2	
M-1d	Specify rubblizing or crack and seating of portland cement concrete	2	✓
M-1e	Reuse of previous pavement as subbase during full-depth reconstruction	2	✓
M-1f	Arranging for the reuse of excavated material, asphalt millings, old concrete	2	✓
M-1g	Specify the processing of demolished concrete to reclaim scrap metals	2	✓
M-1h	Salvaging removed trees for lumber or similar uses	2	
M-1i	Use surplus excavated material on nearby state highways for slope flattening	2	
M-1j	Use surplus excavated material, demolished concrete, or millings at nearby abandoned quarry	2	
M-1k	Specify that 50 percent or more of topsoil removed for grading is reused on site	1	
M-1l	Design the project so that cut and fills are balanced to within 25 percent	1	
M-1m	Reuse (i.e., remove and reset versus remove and replace) of granite curbing	1	
M-1n	Reuse of elements of the previous structure (stone veneer, decorative railing)	1	
M-1o	Designing an on-site location for chipped wood waste disposal	1	
M-1p	Specifying the recycling of chipped untreated wood waste for use as mulch	1	
M-1q	Project documents make scrap metals available for reuse or recycling	1	
M-1r	Identify approved, environmentally acceptable and permitted sites for disposal	1	
M-1s	Obtain and implement a project specific DEC Beneficial Use Determination for re-use of otherwise waster material from a location with New York State	1	
M-1t	Specify the salvage/moving of houses rather than demo for disposal in landfill	1	
M-1u	Reuse of major structural elements such as bridge piers, bridge structure, etc.	2	

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010) (continued).

Credit	Title	Points Possible	Pavement Related
	M-2 Recycled Content		
M-2a	Use tire shreds in embankments	2	
M-2b	Use recycled plastic extruded lumber or recycled tire rubber	2	
M-2c	Specify hot-in-place or cold-in-place recycling of hot-mix asphalt pavements	2	✓
M-2d	Specify use of recycled glass in pavements and embankments	2	✓
M-2e	Specify asphalt pavement mixtures containing recycled asphalt pavement	2	✓
M-2f	Specify PCC pavement mixtures containing recycled concrete aggregate	2	✓
M-2g	Use crumb rubber or recycled plastic for noise barrier material	2	✓
M-2h	Use of porous pavement systems in light duty situations (e.g., sidewalks)	2	✓
	M-3 Local Materials		
M-3a	Specify locally available natural light weight fill	2	
M-3b	Specify local seed stock and plants	2	
	M-4 Bio-engineering Techniques		
M-4a	Project designs that utilize soil bioengineering treatments	2	
M-4b	Project designs utilizing soil biotechnical engineering treatments	2	
M-4c	Projects using targeted biological control methods to reduce invasive species	2	
M-4d	Project designs utilizing soil biotechnical engineering treatments	1	
M-4e	Project designs that utilize soil bioengineering/soil biotechnical treatments	1	
	M-5 Hazardous Material Minimization		
M-5a	Project design substantially minimizes the need to use hazardous materials	2	
M-5b	Project design specifies less hazardous materials or avoids their generation	2	
M-5c	Removing and disposing of contaminated soils	2	
	E-1 Improved Traffic Flow		
E-1a	Special use lane (HOV/Reversible/Bus Express)	3	
E-1b	Innovative interchange design or elimination of freeway bottlenecks	3	
E-1c	Specify new roundabout(s)	3	
E-1d	Implementation of Traffic Management Center / Traveler Information System	3	
E-1e	Installation of a closed-loop coordinated signal system	2	
E-1f	Installation of a transit express system (queue jumper, pre-emptive signals, etc.)	2	
E-1g	Expansion of a Traffic Management Center / Traveler Information System	2	
E-1h	Implementation of a corridor-wide access management plan	2	
E-1i	Limiting/consolidating access points along highway	1	
E-1j	Improving a coordinated signal system and other signal timing and detection	1	
E-1k	Adding bus turnouts	1	
E-1l	Installing higher capacity controllers to improve flow/reduce delay	1	
E-1m	Infill or preparation for Traffic Management/Traveler Information System	1	
E-1n	Inclusion of integrated traffic/incident management/traveler information system	1	
E-1o	Installation of isolated systems to provide for spot warning	1	
E-1p	Road Diet (reduction in lanes to add turn lane & accommodate bike traffic)	2	
	E-2 Reduce Electrical Consumption		
E-2a	Solar/battery powered street lighting or warning signs	2	
E-2b	Replace overhead sign lighting with higher type retro-reflective sign panels	2	
E-2c	Use of LED street lighting	2	
E-2d	Solar bus stops	2	
E-2e	Use of LED warning signs/flashing beacons	1	
E-2e	Retrofit existing street/sign lighting with high efficiency types	1	
	E-3 Reduce Petroleum Consumption		
E-3a	Provide new Park & Ride lots	3	
E-3b	Provide new intermodal connections	3	
E-3c	Increase bicycle amenities at Park & Rides and transit stations	2	

Table 10-5. Summary of GreenLITES sustainability criteria and scoring (NYSDOT 2010) (continued).

Credit	Title	Points Possible	Pavement Related
E-3e	Operational improvements of an existing Park & Ride lot	1	
E-3f	Improve an existing intermodal connection	1	
E-3g	Reduce mowing areas outside of the clear zone	1	
E-3h	Use of warm-mix asphalt	1	✓
E-3i	Documented analysis proving the project design reduced carbon footprint	1	✓
E-3j	Documented analysis proving the work zone requires the least fuel usage	1	✓
E-3k	Improved shading through vegetation at Park & Ride lots to reduce UHI	1	
	E-4 Improve Bicycle & Pedestrian Facilities		
E-4a	New grade-separated (bridge or underpass) bike/pedestrian crossing structure	3	
E-4b	Separate bike lane at intersection	2	
E-4c	New separated bike path or shoulder widening to provide for on-road bike lane	2	
E-4d	Create new or extend existing sidewalks	2	
E-4e	New pedestrian signals	2	
E-4f	Align roadway and other highway features/structures within ROW for future development	2	
E-4g	Work with local communities to create parallel bike routes	2	
E-4h	Sidewalk or bikeway rehabilitation, widening, realignment or repair	1	
E-4i	Upgrading pedestrian signals	1	
E-4j	Installation of bikeway signs, "Share the Road" signs, or shared lanes markings	1	
E-4k	Shoulder restoration for bicycling	1	
E-4l	Inclusion of five-rail bridge rail system for bicyclists	1	
E-4m	Installation of permanent bicycle racks	1	
E-4n	New crosswalks	1	
E-4o	New curb bulb-outs	1	
E-4p	New raised medians/pedestrian refuge islands	1	
E-4q	New speed hump/speed table/raised intersection	1	
E-4r	New curbing (where none previously existed), to better define the edge of road	1	
E-4s	New or relocated highway barrier or repeating vertical elements	1	
E-4t	Installation of bicycle detectors (quadrupoles) at signalized intersections	1	
E-4u	"All Stop" phase programmed into a traffic signal	1	
E-4v	Permanent digital "Your Speed is XX" radar speed reader signs	1	
E-4w	Overhead flashing beacon, lighted "Crosswalk" sign, or pedestrian signal	1	
E-4x	Advanced warning of crosswalk with signs and yield pavement markings	1	
E-4y	In street plastic pylon "State Law - Yield to Pedestrians within Crosswalk" sign	1	
E-4z	Use of durable cast iron detectible warning units embedded in concrete	1	
E-4aa	Add/replace crosswalks with high visibility cross walks	1	
	E-5 Noise Abatement		
E-5a	Construction of a new noise barrier	2	
E-5b	Incorporate traffic system management techniques to reduce prior noise	2	
E-5c	Provide a buffer zone for adjacent receptors	2	
E-5d	Provide sound insulation to public schools	2	
E-5e	Diamond grinding of existing portland cement concrete (PCC) pavement	1	✓
E-5f	Rehabilitation of an existing noise wall	1	
E-5g	Berms designed to reduce noise	1	
E-5h	Provide planting to improve perceived noise impacts	1	
	E-6 Stray Light Reduction		
E-6a	Retrofit existing light heads with full cut-offs	2	
E-6c	Use cut-offs on new light heads	1	
	Total Points	**271**	**27**
	Percentage of points directly relevant to pavement		**10%**

Table 10-6. Summary of LEED-ND sustainability criteria and scoring (USGBC 2012; 2013).

Credit	Title	Points Possible	Pavement Related
	Smart Location and Linkage		
SLLp1	Smart Location	NA	
SLLp2	Imperiled Species and Ecological Communities	NA	
SLLp3	Wetland and Water Body Conservation	NA	
SLLp4	Agricultural Land Preservation	NA	
SLLp5	Floodplain Avoidance	NA	
SLLc1	Preferred Locations	10	
SLLc2	Brownfield Development	2	
SLLc3	Access to Quality Transit	7	
SLLc4	Bicycle Facilities	2	
SLLc5	Housing and Jobs Proximity	3	
SLLc6	Steep Slope Protection	1	
SLLc7	Site Design for Habitat or Wetland and Water Body Conservation	1	
SLLc8	Restoration of Habitat or Wetlands and Water Bodies	1	
SLLc9	Long-Term Conservation Management of Habitat or Wetlands and Water Bodies	1	
	Neighborhood Pattern and Design		
NPDp1	Walkable Streets	NA	
NPDp2	Compact Development	NA	
NPDp3	Connected and Open Community	NA	
NPDc1	Walkable Streets	9	
NPDc2	Compact Development	6	
NPDc3	Mixed-Use Neighborhoods	4	
NPDc4	Housing Types and Affordability	7	
NPDc5	Reduced Parking Footprint	1	
NPDc6	Connected Circulation Network	2	
NPDc7	Transit Facilities	1	
NPDc8	Transportation Demand Management	2	
NPDc9	Access to Civic and Public Spaces	1	
NPDc10	Access to Recreational Facilities	1	
NPDc11	Visitability and Universal Design	1	
NPDc12	Community Outreach and Involvement	2	
NPDc13	Local Food Production	1	
NPDc14	Tree-Lined and Shaded Streetscapes	2	
NPDc15	Neighborhood Schools	1	
	Green Infrastructure and Buildings		
GIBp1	Certified Green Building	NA	
GIBp2	Minimum Building Energy Performance	NA	
GIBp3	Indoor Water Use Reduction	NA	
GIBp4	Construction Activity Pollution Prevention	NA	✓
GIBc1	Certified Green Buildings	5	
GIBc2	Optimize Building Energy Performance	2	
GIBc3	Indoor Water Use Reduction	1	
GIBc4	Outdoor Water Use Reduction	2	
GIBc5	Building Reuse	1	
GIBc6	Historic Resource Preservation and Adaptive Use	2	
GIBc7	Minimize Site Disturbance	1	
GIBc8	Rainwater Management	4	✓
GIBc9	Heat Island Reduction	1	✓
GIBc10	Solar Orientation	1	
GIBc11	Renewable Energy Production	3	
GIBc12	District Heating and Cooling	2	
GIBc13	Infrastructure Energy Efficiency	1	
GIBc14	Wastewater Management	2	
GIBc15	Recycled and Reused Infrastructure	1	✓
GIBc16	Solid Waste Management	1	
GIBc17	Light Pollution Reduction	1	
	Total Points	**100**	**6**
	Percentage of points directly relevant to pavement		**6%**

Use of Assessment Methods

Agencies that use the various assessment methods tend to do so by choice because they recognize a benefit in doing so. A general discussion on the use of these different methods is presented in the following sections.

Use Depends on Owner/Agency and Project Priorities

LCCA, LCA, and rating systems can be used alone or in concert to measure sustainability. In general, using them in concert provides a more holistic assessment of sustainability since each system tends to either (1) address one specific component of sustainability in detail, or (2) address all components in less detail. Ultimately, the priorities of the owner/agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems, should determine what assessment methods are used and what priority is given to each. For instance, a desire to implement lowest life-cycle solutions has driven many state DOTs to use LCCA in their pavement type selection process for major projects. On the other hand, a statewide GHG reduction goal may make it sensible to use LCA as a pavement system metric both for accounting and process improvement purposes. Or, a strategic DOT goal to improve or communicate sustainability (however the DOT chooses to define it) may make it sensible to use a rating system that takes a broad view of sustainability. As a footnote to this, it is worth noting that some rating systems require the use of LCCA and LCA within their framework.

Application at Various Levels

Goals for addressing sustainability can be defined on an agency level, on a pavement system level, and on a pavement project level. The types of sustainability performance tools described in this chapter can be used and tailored to address these different goals. Figure 10-7 provides a schematic of how LCCA, LCA, and rating systems can be applied at these different levels.

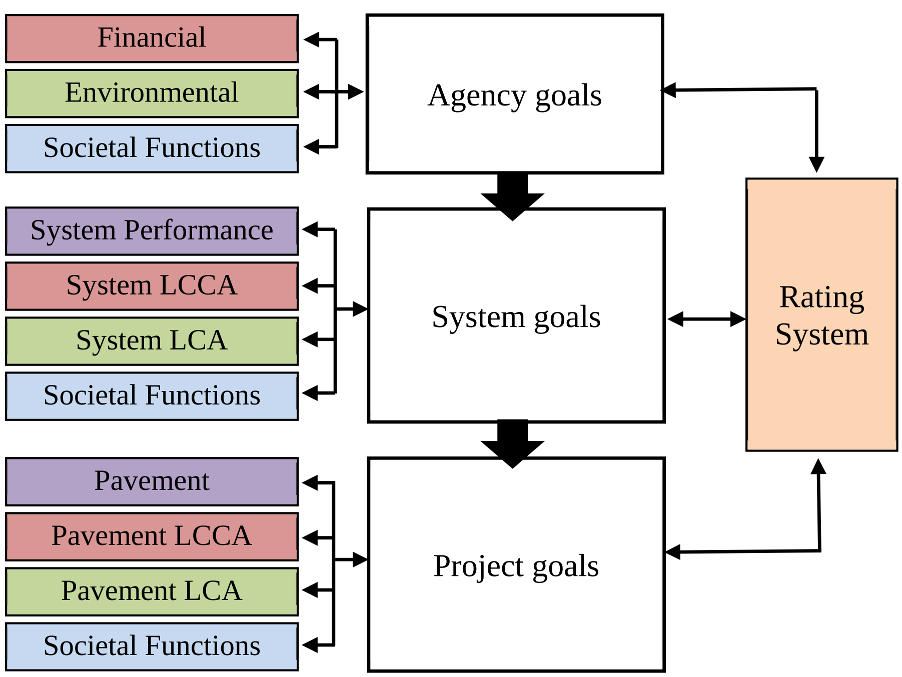


Figure 10-7. Assessing sustainabilty with LCCA, LCA, and rating systems on different levels.

It can be seen in figure 10-7 that rating systems aim to be more comprehensive in terms of topics that are covered and they typically include requirements on all levels. It also shows that LCCA and LCA can be applied at different levels. Through all of this, it is important to understand that the LCCA and LCA applications at the different levels are different types of studies; that is, depending on the specific goals and questions to be addressed the right use can be defined. As a general rule of thumb, system LCAs tend to be more generic and pavement LCAs tend to be more specific.

Level of Standardization

Currently, LCCA is the most mature of the three assessment methods in the pavement industry. Guidance from Walls and Smith (1998) has been generally accepted by the industry and incorporated into numerous official methods and software, the most prominent of which is *RealCost*.

LCA has a commonly accepted standard method (delineated by ISO 14040 and 14044); however, specifics within this method vary greatly from one application to another. Attempts at standardization within the pavement industry are underway (e.g., UCPRC 2010), but it may be some time before LCA reaches the same level of standardization that LCCA has in the pavement industry.

Rating systems are relatively new to the pavement industry and are not subject to any standard method. The more mature ones that are beginning to be used in practice generally focus on transportation infrastructure as a whole rather than just specifically on pavements. These tend to address some of the same core pavement sustainability concepts; however, there are differences and exclusions that should be investigated.

Concluding Remarks

Pavement sustainability can be evaluated using several different methods or tools, including performance assessment, life-cycle cost analysis, life-cycle assessment, and pavement rating systems. This chapter focuses on the latter three items, and describes the basis, inherent assumptions, and overall capabilities and limitations of each approach. Specifically:

- LCCA is an analysis technique that uses economic analysis to evaluate the total cost of an investment option over its entire life (Walls and Smith 1998). As such, it is principally used to address the economic component of sustainability.
- LCA is a technique that can be used for analyzing and quantifying the environmental impacts of a product, system, or process. It focuses on the environmental impacts throughout the pavement life cycle (from raw material acquisition to final disposal).
- Sustainability rating systems are essentially a list of sustainability best practices with an associated common metric (typically points). Rating systems are one way of quantifying the diverse set of sustainability best practices.

These methods can be used independently or in concert to quantify various aspects of sustainability, but ultimately, the priorities of the owner/agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems will determine which approach (or set of approaches) is most appropriate. It is important to note that there are currently few, if any, generally accepted metrics able to measure equity/social impacts associated with pavement systems.

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CHAPTER 11. CONCLUDING REMARKS

Sustainability is a journey, not a destination. This document provides guidance to the pavement community on how to begin this journey by incorporating sustainability considerations throughout the pavement life cycle. Even today there are a number of technologies and innovations that can be exploited to help facilitate that journey, and several of those key items are summarized in this chapter, along with the current and expected trends in each area. This is followed by a number of recommended implementation activities for helping to advance the adoption of more sustainable practices within the pavement community.

Review of Technologies, Innovations, and Trends

Throughout this reference document, a number of technologies and innovations that hold the potential for improving some aspect of pavement sustainability are described; summarized below are just a few of the more prominent ones that are making significant contributions.

- **Recycled material use at higher rates of replacement**. While the standard use of recycled materials (e.g., RAP, RAS, RCA) has been a long-standing practice, the rates of use have often been limited by design procedures, technology, performance risk (perceived or real), and availability. Recent and likely continuing budget cuts associated with the general cost of construction have driven owners, designers, and contractors to explore ways of incorporating locally available recycled material at greater replacement levels. Rethinking mixture design processes, manufacturing requirements, specification limits, and construction practices from the ground up has already led to higher rates of use and better acceptance of recycled materials. As an added benefit, the reduced virgin material use and associated reductions in processing and transport can and has led to significant reductions in energy consumption and GHG emissions, which are now also becoming drivers for the greater use of recycled materials.
- **Adoption of WMA technologies as standard practice**. For asphalt pavements, WMA has received much attention in both technology improvement and implementation. Documented benefits of reduced energy consumption, reduced emissions (GHG and others), and improved construction quality have been primary drivers in the expanded use of WMA.
- **Use of SCMs to reduce cement GHG emissions**. The cement industry has put forth a substantial effort in reducing GHG emissions by reducing the cement content per unit volume while providing equal or better performance. Cement producers are producing a greater variety and amount of blended cements using SCMs or interground limestone to further reduce GHG emissions. Mixtures containing less than 50 percent cement of the total cementitious content are available and have shown good performance. As SCMs, limestone cements, and mixtures containing less cement per unit volume gain more acceptance by highway agencies, significant reductions in GHG emissions associated with concrete pavement construction will be realized.
- **Mechanistic based pavement design procedures**. Improved pavement designs are being implemented as state transportation agencies adopt mechanistic-empirical pavement design methodologies, which are based on a better understanding of pavement responses to traffic and environmental loadings and how those responses are linked to pavement performance.

- **Optimization of use of materials**. Two-lift concrete pavements and perpetual asphalt pavements are examples of design approaches that optimize the use of paving materials to meet specific needs. For example, two-lift pavements use higher recycled or marginal aggregate content in a thicker bottom lift while reserving more durable material for the thinner surface lift, thereby reducing the environmental impact of the overall structure without compromising performance.
- **Porous pavements for stormwater management**. As concerns continue regarding the volume and quality of stormwater runoff from paved surfaces, permeable asphalt (porous asphalt) and concrete (pervious concrete) pavements are becoming more widely used. These materials can not only be used to reduce stormwater runoff, but they can also be effective in reducing contaminants in waterways and renewing groundwater supplies. Other permeable pavement surfaces also exist, including those made with permeable interlocking concrete pavers.
- **Precast pavements and interlocking pavers**. Precast pavement systems, either intermittent or continuous, offer a unique solution to certain pavement challenges, particularly where short work windows are demanded or when maintaining overall traffic flow is critical. Interlocking concrete pavers provide an aesthetically pleasing appearance while providing utility access without compromising the pavement structure, thereby making them an attractive alternative in urban settings.
- **Construction technologies**. A number of emerging construction technologies are resulting in the production of higher quality, longer lasting pavements that can have significant environmental, economic, and social benefits. Intelligent compaction, stringless paving, and real-time smoothness measurements are providing real-time data to contractors. These data allow them to better control their processes to achieve improved in-place material properties and higher levels of initial pavement smoothness.
- **Expanded use of preservation treatments**. Preservation treatments that use little material yet maintain pavements in a smooth condition for longer periods of time have great environmental benefit, especially on higher traffic volume roadways. This realization is making the use of ultra-thin asphalt surfaces and diamond grinding of concrete pavements particularly attractive.

In addition to these technologies, several trends are emerging within the sustainability arena that are expected to play a significant role in future activities and developments, including:

- **Recognition of the importance of the use phase.** The use phase is beginning to be recognized as having one of the most important impacts on pavement sustainability over the life cycle. Vehicle fuel consumption, noise, safety, stormwater runoff, and urban temperature can be impacted by pavement characteristics such as structural response, macrotexture, roughness, permeability, and surface reflectivity. Studies are ongoing to define the effects of these variables for possible inclusion in future pavement LCA tools, potentially shifting the perspective to focus on pavement attributes that are most critical to minimize environmental and social impacts over the pavement life cycle.
- **Recognition that pavement systems are a small part of larger systems.** Pavements do not stand alone, but are part of larger systems that include both communities and ecosystems possessing their own sustainability goals. Advances are occurring in the development of pavement specific tools that integrate economic, environmental, and

societal impacts within the pavement system and in the broader context of these larger systems.

- **Development/enhancement of sustainability tools**. Advances are occurring in the development of tools that integrate pavement LCCA, LCA, and elements of pavement sustainability rating systems. Considerable work remains on building a consensus LCA framework, populating the LCI database with accurate and regionalized data, and developing improved models that accurately reflect the contribution of the use phase. It is envisioned that the emergence of these tools will positively impact the paving community in the next decade.

It is again emphasized that sustainability is context sensitive, and the development of sustainable strategies will depend on the characteristics of the specific project, the materials and technologies that are readily available, and the specific economic, environmental, and societal goals of the agency. Closely linked to this is that the selection of sustainable solutions often requires the consideration of trade-offs between several competing sustainability goals or objectives. The development of an LCA framework is one key area required to be able to assess relative environmental impacts and to monitor overall progress that is being made in the sustainability area.

Implementation: The Next Step

The information presented in this document forms the foundation for moving ahead in adopting sustainability principles in pavement systems. Key factors and activities that are essential to implement pavement sustainability best practices include:

- **Leadership at the national level**. FHWA should work to make sustainability a strategic priority in all areas of pavement design, materials, and construction and in communicating the principles, strategies, and techniques outlined in this document. As part of this, the development of a sustainable pavements framework can help provide a measured, detailed approach on how to advance the concepts, provide the implementation, and promote the research of sustainable pavement systems.
- **Leadership at the state level**. This is necessary to incorporate elements of pavement sustainability in the design and construction of state highway systems. This includes having strategic directions for sustainability established within an agency that include pavement systems. In addition, highway agencies can also contribute to the adoption of more sustainable practices by revisiting their design standards and material and construction specifications to ensure that they are not barriers to implementing more sustainable solutions. This can also have a positive "trickle down" effect to local governments that often rely on state design standards and material and construction specifications. Finally, agencies should identify a short list of items related to sustainability that make sense to adopt or implement within their organization.
- **Partnership between stakeholders**. Collaborative relationships are needed in which industry, academia, and highway agencies work together to implement sustainability principles and address issues and problems that emerge during the ongoing sustainability journey.
- **Education and outreach**. Educational materials and outreach programs must be developed to provide information on basic sustainability principles as well as on specific examples of "low-hanging fruit" in which the implementation of innovative materials and

technologies can have immediate economic, environmental, and societal benefits. Given that the available information is overwhelming, it must be simplified and properly directed as part of the implementation effort. The development of useful resources—such as guide documents, technical briefs, case study examples, a user-friendly web page, simple computer-based tools, and mobile applications—are considered essential to this effort. Furthermore, sharing case studies, findings, and recommendations through workshops, webinars, and targeted conferences is also a fundamental part of that outreach effort.

- **Identify knowledge gaps and develop a focused research map**. The research should be fundamental and basic as well as practical. Broad stakeholder support is needed if research results are to be accepted and implemented. Potential topics requiring additional research include rolling resistance, urban heat island effects, maintenance and preservation impacts, and energy consumption and GHG emissions associated with a pavement over its entire life cycle.
- **Educate, encourage, and implement LCA tools**. Sustainable practices can only be implemented if the environmental impact of decisions over the pavement life cycle can be quantified to a high degree of certainty. The only tool capable of accomplishing this is LCA, and therefore the application of LCA principles are critical for evaluating many of the trade-offs encountered through the pavement life cycle. Efforts should be made to educate the pavement community on LCA concepts and tools, encourage the community to adopt changes in policy based on knowledge garnered from LCA studies, and ultimately implement pavement-based LCA tools developed and vetted through a peer-reviewed process representing all stakeholders.

GLOSSARY OF TERMS

The following presents a summary of terms that are used in this document. Sources of information for this glossary include the Asphalt Institute[1], the National Concrete Pavement Technology Center[2], and the Transportation Research Board[3].

AADT. The average annual daily traffic, expressed as the 24-hour traffic volume counts collected over a number of days greater than 1 day but less than 1 year, at a given location. AADT can also be approximated by adjusting the ADT count for daily (weekday versus weekend) and seasonal (summer versus winter) variations

Absorption. The amount of water absorbed under specific conditions, usually expressed as a percentage of the dry weight of the material; the process by which the water is absorbed.

Accelerator. An admixture which, when added to concrete, mortar, or grout, increases the rate of hydration of hydraulic cement, shortens the time of set, or increases the rate of hardening or strength development.

Admixture. A material other than water, aggregates, and portland cement (including air-entraining portland cement, and portland blast furnace slag cement) that is used as an ingredient of concrete and is added to the batch before and during the mixing operation.

Aggregate. Granular material, such as sand, gravel, or crushed stone used with a hydraulic cementing medium to produce either concrete or mortar; or used with asphalt cement to produce asphalt concrete; or used in the base and/or subbase layers of a pavement structure.

Aggregate Blending. The process of intermixing two or more aggregates to produce a different set of properties, generally, but not exclusively, to improve grading.

Aggregate Gradation. The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings). See also Grading.

Agitation. The process of providing gentle motion in mixed concrete just sufficient to prevent segregation or loss of plasticity.

Air Content. The amount of air in mortar or concrete, exclusive of pore space in the aggregate particles, usually expressed as a percentage of total volume of mortar or concrete.

Air-Entraining. The capabilities of a material or process to develop a system of minute bubbles of air in cement paste, mortar, or concrete during mixing.

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[1] Asphalt Institute (AI). *n.d. Asphalt Industry Glossary of Terms.* (Web Link)

[2] Taylor, P. C., S. H. Kosmatka, G. F. Voigt, M. E. Ayers, A. Davis, G. J. Fick, J. Grove, D. Harrington, B. Kerkhoff, H. C. Ozyildirim, J. M. Shilstone, K. Smith, S. Tarr, P. D. Tennis, T. J. Van Dam, and S. Waalkes. 2006. *Integrated Materials and Construction Practices for Concrete Pavements: A State-of-the-Practice Manual*. FHWA-HIF-07-004. Federal Highway Administration, Washington, DC.

[3] Transportation Research Board (TRB). 2013. *Glossary of Transportation Construction Quality Assurance Terms: Sixth Edition*. Transportation Research Circular E-C173. Transportation Research Board, Washington, DC. (Web Link)

Air Void. A space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 0.04 in (1 mm) or more in size and irregular in shape; an entrained air void is typically between 0.004 inches and 0.04 inches (10μm and 1 mm) in diameter and spherical (or nearly so).

Albedo. Solar reflectance.

Alkali-Silica Reaction. The reaction between the alkalis (sodium and potassium) in portland cement binder and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Allocate. Distribution of available resources among programs or geographic districts/regions.

Alternatives. Available choices or courses of action that can be considered at each stage of resource allocation or utilization.

Asphalt Cement. A bituminous material that, when used as a binder with aggregate, creates hot-mix asphalt.

Asphalt Cutback. Asphalt cement that has been liquefied by blending with petroleum solvents (diluents). Upon exposure to atmospheric conditions the diluents evaporate, leaving the asphalt cement to perform its function.

Asphalt Emulsion. An emulsion of asphalt binder and water that contains a small amount of an emulsifying agent. Emulsified asphalt droplets may be of either the anionic (negative charge), cationic (positive charge) or nonionic (neutral).

Asphalt Rubber (AR). Conventional asphalt cement to which recycled ground tire rubber has been added, that when reacted with the hot asphalt cement causes a swelling and/or dispersion of the tire rubber particles.

Asset. The physical infrastructure (e.g., right-of-way, pavements, structures, roadside features). Assets can also include other agency resources capable of providing added value (e.g., human resources, real estate, equipment and materials).

Asset Management. Business processes for resource allocation and utilization with the objective of better decision-making based upon quality information and well-defined objectives.

Asset Management Plan. Tactical plan for managing an agency's infrastructure (and/or other assets) to deliver an agreed upon level of service. Typically, the asset management plan encompasses more than one asset (e.g., a system approach).

Base. The layer of material immediately beneath the pavement surface or binder course.

Base Course. A layer of specified select material of planned thickness constructed on the subgrade or subbase below a pavement to serve one or more functions such as distributing loads, providing drainage, minimizing frost action, or facilitating pavement construction.

Batch Plant. Equipment used for batching concrete materials.

Batch Plant Mix Water. The mixing water added to a concrete or mortar mixture before or during the initial stages of mixing.

Benchmark. Process for comparing cost, performance life, productivity, or quality of a specific process or method to a standard or best practice. Benchmarking is used in strategic management to evaluate various process aspects in relation to best practice. Agencies then use the benchmarking results to develop plans for process improvement or adoption of best practices, usually with the aim of increasing performance.

Benefit/Cost. A comparison analysis of the economic benefit of an investment to its cost. The benefit/cost analysis should include all costs and benefits to both the agency and the users of the facility over an appropriate life cycle period. In asset management, benefit/cost can be applied for prioritizing projects, evaluation of the benefits and costs for all projects in a program, and determination of program tradeoffs.

Binder. An adhesive composition of asphalt cement, modified asphalt cement, or other bituminous materials which is primarily responsible for binding aggregate particles together. Also used to refer to the layer of asphalt directly below the surface course (i.e., binder course).

Bitumen. A class of black or dark-colored (solid, semisolid, or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, pitches, and asphaltites are typical.

Bituminous. Any asphalt material used in the construction of maintenance of a roadway.

Blast-Furnace Slag. The non-metallic byproduct, consisting essentially of silicates and aluminosilicates of lime and other bases, which is produced in a molten condition simultaneously with iron in a blast furnace.

Bleeding. The self-generated flow of mixing water within, or its emergence from, freshly placed concrete or mortar.

Blistering. The irregular rising of a thin layer of placed mortar or concrete at the surface during or soon after completion of the finished operation.

Bond. The adhesion of concrete or mortar to reinforcement or other surfaces against which it is placed; the adhesion of cement paste to aggregate.

Bonded Concrete Overlay. Thin layer of new concrete 2 to 4 inches (51 to 102 mm) placed onto slightly deteriorated existing concrete pavement with steps taken to prepare the existing surface to promote adherence of new concrete.

Broom. The surface texture obtained by stroking a broom over freshly placed concrete. A sandy texture obtained by brushing the surface of freshly placed or slightly hardened concrete with a stiff broom.

Capital. Type of investment that generally involves construction or major repair and can include: new construction, reconstruction, structural and functional improvements, and rehabilitation.

Cement, Blended. A hydraulic cement consisting essentially of an intimate and uniform blend of granulated blast-furnace slag and hydrated lime; or an intimate and uniform blend of portland cement and granulated blast-furnace slag cement and pozzolan, produced by intergrinding portland cement clinker with the other materials or by blending portland cement with the other materials, or a combination of intergrinding and blending.

Cement, High-Early Strength. Cement characterized by producing earlier strength in mortar or concrete than regular cement, referred to in the United States as Type III.

Cement, Hydraulic. Cement that is capable of setting and hardening under water, such as normal portland cement.

Cementitious Materials. Substances that alone have hydraulic cementing properties (set and harden in the presence of water); includes ground, granulated blast-furnace slag, natural cement, hydraulic hydrated lime, and combinations of these and other materials.

Chip Seal. A surface treatment in which a pavement surface is sprayed with asphalt (generally emulsified) and then immediately covered with aggregate and rolled. Chip seals are used primarily to seal the surface of a pavement with non-load-associated cracks and to improve surface friction (skid resistance). Also referred to as "seal coat."

Clinker. A fused or partially fused by-product of the combustion of coal. Also includes lava and portland cement and partially vitrified slag and brick.

Coal Tar. A dark brown to black cementitious material produced by the destructive distillation of bituminous coal.

Cohesiveness. The property of a concrete mix which enables the aggregate particles and cement paste matrix therein to remain in contact with each other during mixing, handling, and placing operations; the "stick-togetherness" of the concrete at a given slump.

Cold In-Place Recycling (CIR). A process in which a portion of an existing bituminous pavement is pulverized or milled, the reclaimed material is mixed with new binder and new materials, and the resultant blend is placed as a base for a subsequent overlay.

Cold Milling. A process of removing pavement material from the surface of the pavement either to prepare the surface to receive overlays (by removing rutting and surface irregularities), to restore pavement cross slopes and profile, or to re-establish the pavement's surface friction characteristics.

Compaction. The process whereby the volume of asphalt, aggregate, soil, or freshly placed mortar or concrete is reduced to the minimum practical space, usually by vibration, centrifugation, tamping, or some combination of these; to mold it within forms or molds and around embedded parts and reinforcement, and to eliminate voids other than entrained air. See also Consolidation.

Condition Index. A numeric score determined from pavement condition data and used to represent the performance of the pavement.

Consistency. The degree of fluidity of asphalt cement at any particular temperature. The consistency of asphalt cement varies with its temperature; therefore, it is necessary to use a common or standard temperature when comparing the consistency of one asphalt cement with another.

Consolidate. Compaction usually accomplished by vibration of newly placed concrete to minimum practical volume, to mold it within form shapes or around embedded parts and reinforcement, and to reduce void content to a practical minimum.

Consolidation. The process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of voids, usually by vibration, centrifugation, tamping, or some combination of these actions; also applicable to similar manipulation of other cementitious mixtures, soils, aggregates, or the like. See also Compaction.

Continuously Reinforced Concrete Pavement (CRCP). A concrete pavement characterized by no regularly spaced transverse joints and continuous longitudinal reinforcement.

Cost Plus Time Bidding. Also called **A+B Bidding.** A bidding procedure that selects the low bidder based on a monetary combination of the traditional bid price (A) and the time (B) needed to complete the project or a critical portion of the project. A cost-plus-time contract can be devised to actually pay the contractor either only the A portion of the bid or the A portion plus or minus an agreed-upon incentive–disincentive amount for early or late completion; this latter form of the contract is sometimes referred to as a **cost-plus-time with incentives or disincentives (A + B + I/D) contract.** [The intent of either form is to provide an incentive for the contractor to minimize delivery time for high-priority roadways.]

Course. In pavement construction, a horizontal layer of asphalt, concrete, or aggregate, usually one of several making up a lift. See also Lift.

Crack and Seat. A fractured slab technique used in the rehabilitation of PCC pavements that minimizes slab action in a jointed concrete pavement (JCP) by fracturing the PCC layer into smaller segments. This reduction in slab length minimizes reflective cracking in new asphalt overlays.

Deflection Basin. The idealized shape of the deformed pavement surface as a result of a cyclic or impact load as depicted from the peak measurements of five or more deflection sensors.

Deformed Reinforcement. Metal bars, wire, or fabric with a manufactured pattern of surface ridges that provide a locking anchorage with surrounding concrete.

Dense-Graded. Aggregates graded to produce low void content and maximum weight when compacted.

Design–Bid–Build (DBB). A project delivery system in which the design is completed either by in-house professional engineering staff or a design consultant before the construction contract is advertised. [The DBB method is sometimes referred to as the traditional method.]

Design–Build (DB). A project delivery system in which both the design and the construction of the project are simultaneously awarded to a single entity. [The main advantage of the DB method is that it can decrease project delivery time.]

Design–Build–Maintain (DBM). A project delivery system in which the design, construction, and maintenance of the project are awarded to a single entity.

Diamond Grinding. The process used to remove the upper surface of a concrete pavement to remove bumps and restore pavement rideability; also, equipment using many diamond-impregnated saw blades on a shaft or arbor to shave the surface of concrete slabs.

Dolomite. A mineral having a specific crystal structure and consisting of calcium carbonate and magnesium carbonate in equivalent chemical amounts (54.27 and 45.73 percent by weight, respectively); a rock containing dolomite as the principal constituent.

Dowel. A device located across transverse joints at mid-depth of a PCC slab to provide load transfer from one slab to the adjoining slab. These are commonly smooth, round, and coated to resist corrosion.

Early-Entry Dry Saw. Lightweight saw equipped with a blade that does not require water for cooling and that allows sawing concrete sooner than with conventional wet-diamond sawing equipment.

Empirical model. A model developed from performance histories of pavements. [An empirical model is usually accurate only for the exact conditions and ranges of independent variables under which it was developed.]

Emulsifying Agent or Emulsifier. The chemical added to the water and asphalt that keeps the asphalt in stable suspension in the water. The emulsifier determines the charge of the emulsion and controls the breaking rate.

Entrained Air. Round, uniformly distributed, microscopic, non-coalescing air bubbles entrained by the use of air-entraining agents; usually less than 0.04 inches (1 mm) in size.

Entrapped Air. Air in concrete that is not purposely entrained. Entrapped air is generally considered to be large voids (larger than 0.04 inches [1 mm]).

Facility. A general term referring to a street, roadway, or highway.

Fatigue Cracking. Cracking of a roadway surface (either asphalt or concrete) caused by repetitive loading.

Faulting. Differential vertical displacement of abutting concrete pavement slabs at joints or cracks creating a step-like deformation in the pavement.

Flexible Pavement. An asphalt pavement.

Flow. 1) Time dependent irrecoverable deformation. 2) A measure of the consistency of freshly mixed concrete, mortar, or cement paste in terms of the increase in diameter of a molded truncated cone specimen after jigging a specified number of times.

Fly Ash. The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the fire box through the boiler by flu gasses; used as mineral admixture in concrete mixtures.

Fog Seal. A light application of diluted asphalt emulsion. It is used to renew old asphalt surfaces, seal small cracks and surface voids, and inhibit raveling.

Full-Depth Asphalt Pavement. The term FULL-DEPTH (registered by the Asphalt Institute with the U.S. Patent Office) certifies that the pavement is one in which asphalt mixtures are employed for all courses above the subgrade or improved subgrade. A Full-Depth asphalt pavement is placed directly on the prepared subgrade.

Full-Depth Reclamation. A technique in which the full thickness of the existing asphalt pavement and a predetermined portion of the underlying materials (base, subbase, and/or subgrade) are uniformly pulverized and blended to provide a homogeneous material.

Gap-graded. Aggregate so graded that certain intermediate sizes are substantially absent.

Grading. The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings).

Heat of Hydration. Heat evolved by chemical reactions of a substance with water, such as that evolved during the setting and hardening of portland cement.

Hot In-Place Recycling (HIPR). A process which consists of softening the existing bituminous surface with heat, mechanically removing the surface material, mixing the material with a recycling agent, adding new asphalt or aggregate to the material (if required), and then replacing the material back on the roadway.

Hot Mix Asphalt (HMA). A plant-produced, high-quality hot mixture of asphalt cement and well-graded, high-quality aggregate thoroughly compacted into a uniform dense mass.

Incentive–Disincentive Provision (for quality). A pay adjustment schedule that functions to motivate the contractor to provide a high level of quality. [A pay adjustment schedule, even one that provides for pay increases, is not necessarily an incentive or disincentive provision, as individual pay increases or decreases may not be of sufficient magnitude to motivate the contractor toward high quality.]

Inlay. A form of reconstruction where new concrete is placed into an area of removed pavement; the removal may be an individual lane, all lanes between the shoulders or only partly through a slab.

International Roughness Index (IRI). A measurement of the roughness of a pavement, expressed as the ratio of the accumulated suspension motion to the distance traveled obtained from a mathematical model of a standard quarter car traversing a measured profile at a speed of 50 mi/hr (80 km/h).

Jointed Plain Concrete Pavement (JPCP). A concrete pavement system characterized by short joint spacings and no reinforcement. Smooth dowels may be placed across the transverse joints to facilitate load transfer.

Jointed Reinforced Concrete Pavement (JRCP). A concrete pavement system characterized by longer joint spacings and containing steel mesh reinforcement distributed throughout the slab to hold any cracks tightly together.

Level of Service (LOS). Measures related to the public's perception of asset condition or of agency services; used to express current and target values for maintenance and operations activities.

Life Cycle. A length of time that spans the stages of asset construction, operation, maintenance, rehabilitation, and reconstruction or disposal/abandonment; when associated with analyses, refers to a length of time sufficient to span these several stages and to capture the costs, benefits, and long-term performance impacts of different investment options.

Life Cycle Assessment (LCA). A technique that can be used for analyzing and quantifying the environmental impacts of a product, system, and/or process.

Life Cycle Cost Analysis (LCCA). A method of reducing all of the significant costs of an asset over its lifetime to either a present worth (today's cost) or equivalent uniform annual cost (annual cost). As such, LCCA accounts for initial (or in-place) costs, subsequent maintenance and rehabilitation costs, and salvage value. In addition to all of these costs, inputs to an LCCA include the analysis period and the discount rate (reflecting the time value of money.

Life Cycle Inventory (LCI). LCI involves collecting, validating, and aggregating input and output data to quantify material use, energy use, environmental discharges, and waste associated with each life cycle stage.

Lift. The material placed between two consecutive horizontal placements, usually consisting of several layers or courses.

Load Transfer Restoration (LTR). The placement of load transfer devices across joints or cracks in an existing jointed PCC pavement.

Longitudinal Tining. Surface texture achieved by a hand held or mechanical device equipped with a rake-like tining head that moves in a line parallel to the pavement centerline.

Maintenance. Activities that enable a transportation system to continue to perform at its intended level; comprises a range of services in preservation, cleaning, replacing worn or failed components, periodic or unscheduled repairs and upkeep, motorist services (incident response, hazardous materials response), snow and ice control, and servicing of traffic devices and aids; does not add to structural or operational capacity of an existing facility.

Maintenance Mix. A mixture of asphalt emulsion and mineral aggregate for use in relatively small areas to patch holes, depressions, and distressed areas in existing pavements. Appropriate hand or mechanical methods are used in placing and compacting the mix.

Mean Profile Depth (MPD). A measurement of pavement surface texture that strongly affects wet pavement friction.

Mechanistic Model. A model developed from the laws of mechanics, in which the prescribed action of forces on bodies of material elements are related to the resulting stress, strain, deformation, and failure of the pavement.

Mechanistic–Empirical Model. A model developed from a combination of mechanistic and empirical considerations. The basic advantage is that it provides more reliable performance predictions.

Microsurfacing. A mixture of polymer modified asphalt emulsion, crushed dense graded aggregate, mineral filler, additives and water. It provides a thin resurfacing of 0.38 to 0.75 inches (10 to 19 mm) to the pavement.

Mineral Filler. A finely divided mineral product, at least 70 percent of which will pass a 0.075 mm (No. 200) sieve. Pulverized limestone is the most commonly manufactured filler, although other stone dust, hydrated lime, portland cement, and certain natural deposits of finely divided mineral matter are also used.

Multi-Parameter Bidding. Also called **A + B + C bidding.** A bidding procedure that selects the low bidder based on a monetary combination of the traditional bid price (A), the completion time (B), and other elements (C) such as construction quality, safety, and life-cycle costs. Quantification of the elements and bidder evaluation methodology are included in the procedure.

Natural (Native) Asphalt. Asphalt occurring in nature, which has been derived from petroleum through natural processes of evaporation of volatile fractions, leaving the asphalt fractions. The native asphalt of most importance is found in the Trinidad and Bermudez Lake deposits. Asphalt from these sources is often called lake asphalt.

Network. System of assets to provide transportation services to customers.

Nominal Maximum Size. In specifications for and descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass; sometimes referred to as “maximum size (of aggregate).”

Open-Graded. Aggregate in which the voids are relatively large when the aggregate is compacted.

Open-Graded Friction Course (OGFC). A bituminous paving layer consisting of a mix of asphalt cement and open-graded (also called uniformly graded) aggregate. An open-graded aggregate consists of particles of predominantly a single-size aggregate.

Optimization. Process for determining the best available value (e.g., cost, performance life) within a given set of constraints.

Oven Dry. The condition resulting from having been dried to essentially constant weight, in an oven, at a temperature that has been fixed, usually between 221 and 239 ºF (105 and 115 ºC).

Oxidation. Chemical reaction between the asphalt in an asphalt pavement and air, causing the bituminous surface to become discolored and stiffer.

Particle-Size Distribution. The division of particles of a graded material among various sizes; for concrete materials, usually expressed in terms of cumulative percentages larger or smaller than each of a series of diameters or the percentages within certain ranges of diameter, as determined by sieving.

Pavement Maintenance. Work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service.

Pavement Management. All the activities involved in the planning, programming, design, construction, maintenance, and rehabilitation of the pavement portion of a public works program. A system which involves the identification of optimum strategies at various management levels and maintains pavements at an adequate level of serviceability. These include, but are not limited to, systematic procedures for scheduling maintenance and rehabilitation activities based on optimization of benefits and minimization of costs.

Pavement Management System (PMS). A set of tools or methods that assists decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time.

Pavement Preservation. A program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extend pavement life, improve safety and meet motorist expectations.

Pavement Rehabilitation. Structural enhancements that extend the service life of an existing pavement and/or improve its load-carrying capacity. Rehabilitation techniques include restoration treatments and structural overlays.

Pay Factor. A multiplication factor, often expressed as a percentage, used to determine the contractor's payment for a unit of work, based on the estimated quality of work. [Typically, the term "pay factor" applies to only one quality characteristic.]

Performance-Based. Characteristic of an asset that reflects its functionality or its serviceability as perceived by transportation users; often related to condition.

Placement. The process of placing and consolidating concrete; a quantity of concrete placed and finished during a continuous operation; also inappropriately referred to as "pouring."

Plastic. Condition of freshly mixed cement paste, mortar, or concrete such that deformation will be sustained continuously in any direction without rupture; in common usage, concrete with slump of 3 to 4 inches (76 to 102 mm).

Pneumatic-Tire Roller. A compactor with a number of tires spaced so their tracks overlap delivering a kneading type of compaction.

Polymer Modified Asphalt. Conventional asphalt cement to which one or more polymer compounds have been added to improve resistance to deformation at high pavement temperatures and often cracking resistance at low temperatures.

Porosity. The ratio, usually expressed as a percentage, of the volume of voids in a material to the total volume of the material, including voids.

Portland Cement Concrete. A composite material consisting of portland cement, coarse aggregate, fine aggregate, water, air, and possibly other additives that, when mixed together, hardens through a chemical reaction to form a hard solid mass. Physically, portland cement is a finely pulverized clinker produced by burning mixtures containing lime, iron, alumina, and silica at high temperature and in definite proportions, and then intergrinding gypsum to give the properties desired.

Pozzolan. A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Preventive Maintenance. Proactive approach that applies maintenance treatments while the asset is still in good condition; extends asset life by preventing the onset or growth (propagation) of distress.

Profile Index. Smoothness qualifying factor determined from profilograph trace. Calculated by dividing the sum of the total counts above the blanking band for each segment by the sum of the segment length.

Proportioning. Selection of proportions of ingredients for mortar or concrete to make the most economical use of available materials to produce mortar or concrete of the required properties.

Pumping. The forceful displacement of a mixture of soil and water that occurs under slab joints, cracks and pavement edges which are depressed and released quickly by high-speed heavy vehicle loads; occurs when concrete pavements are placed directly on fine-grained, plastic soils or erodible subbase materials.

Punchout. In continuously reinforced concrete pavement, the area enclosed by two closely spaced transverse cracks, a short longitudinal crack, and the edge of the pavement or longitudinal joint, when exhibiting spalling, shattering, or faulting. Also, area between Y cracks exhibiting this same deterioration.

Quality Assurance. Planned and systematic actions by an owner or his representative to provide confidence that a product or facility meet applicable standards of good practice. This involves continued evaluation of design, plan and specification development, contract advertisement and award, construction, and maintenance, and the interactions of these activities.

Quality Control. Actions taken by a producer or contractor to provide control over what is being done and what is being provided so that the applicable standards of good practice for the work are followed.

Raveling. The wearing away of a bituminous pavement surface caused by the dislodging of aggregate particles and loss of asphalt binder.

Reclaimed Asphalt Pavement (RAP). Excavated asphalt pavement that has been pulverized, usually by milling, and is used like an aggregate in the recycling of asphalt pavements.

Recycled Asphalt. A mixture produced after processing existing asphalt pavement materials. The recycled mix may be produced by hot or cold mixing at a plant, or by processing the materials cold and in-place.

Recycled Concrete Aggregate. A granular material manufactured by removing, crushing, and processing hydraulic-cement concrete pavement for reuse with a hydraulic cementing medium to produce fresh paving concrete.

Release Agent. Material used to prevent bonding of concrete to a surface.

Reservoir. The part of a concrete joint that normally holds a sealant material. Usually a widening saw cut above the initial saw cut.

Residual Asphalt. Amount of asphalt left in an emulsion after water has evaporated.

Restoration. The process of reestablishing the materials, form, and appearance of a structure to those of a particular era of the structure. See also Pavement Preservation, Pavement Rehabilitation.

Retardation. Reduction in the rate of hardening or strength development of fresh concrete, mortar, or grout; i.e., an increase in the time required to reach initial and final set.

Rigid Pavement. A pavement constructed with hydraulic cement concrete.

Roughness. Distortions of the road surface that contribute to an undesirable, unsafe, uneconomical, or uncomfortable ride.

Rubblization. The pulverization of a portland cement concrete pavement into smaller particles, reducing the existing pavement layer to a sound, structural base that will be compatible to an asphalt overlay.

Rutting. A surface depression in the wheelpath caused by a permanent deformation in any of the pavement layers or subgrade.

Sand Seal. An application of asphalt emulsion covered with fine aggregate. It may be used to improve the skid resistance of slippery pavements and to seal against air and water intrusion.

Scaling. Flaking or peeling away of the near-surface portion of hydraulic cement concrete or mortar.

Screed. 1) To strike off concrete lying above the desired plane or shape. 2) A tool for striking off the concrete surface, sometimes referred to as a Strikeoff.

Separation. The tendency, as concrete is caused to pass from the unconfined ends of chutes or conveyor belts, for coarse aggregate to separate from the concrete and accumulate at one side; the tendency, as processed aggregate leaves the ends of conveyor belts, chutes, or similar devices with confining sides, for the larger aggregate to separate from the mass and accumulate at one side; the tendency for solids to separate from the water by gravitational settlement.

Set. The condition reached by a cement paste, mortar, or concrete when it has lost plasticity to an arbitrary degree, usually measured in terms of resistance to penetration or deformation. Initial set refers to first stiffening. Final set refers to attainment of significant rigidity.

Skid Number (SN). A standard test measure of the friction between a braking tire and the pavement surface.

Slipform Paving. A type of concrete paving process that involves extruding the concrete through a machine to provide a uniform dimension of concrete paving.

Slurry Seal. A mixture of quick- or slow-setting emulsified asphalt, well-graded fine aggregate, mineral filler, and water. It is used to fill cracks and seal areas of bituminous pavements, to restore a uniform surface texture, to seal the surface to prevent moisture and air intrusion into the pavement, and to provide skid resistance.

Soundness. In the case of a cement, freedom from large expansion after setting. In the case of aggregate, the ability to withstand aggressive conditions to which concrete containing it might be exposed, particularly those due to weather.

Spalling. The breakdown of the slab edges within 0.6 m (2 ft.) of the side of the joint caused by excessive stresses at the joint or crack or poor joint forming/sawing practices.

Specification Limit(s). The limiting value(s) placed on a quality characteristic, established preferably by statistical analysis, for evaluating material or construction within the specification requirements. The term can refer to either an individual USL or an LSL, called a single specification limit, or to USL and LSL together, called double specification limits.

Stakeholders. A person, group, or organization that affects or can be affected by an agencies actions.

Steel-Wheel Vibratory Rollers. A compaction device used to compress underlying asphalt layers. The amount of compactive force is adjusted by changing the frequency and amplitude of vibration.

Stone Matrix Asphalt (SMA). A hot-mix asphalt consisting of a mix of asphalt cement, stabilizer material, mineral filler, and gap-graded aggregate. A gap-graded aggregate is similar to an open-graded material, but is not quite as open.

Subbase. Layer of material immediately beneath the base course.

Subgrade Soil. The native soil prepared and compacted to support a pavement structure.

Superpave™. Short for "Superior Performing Asphalt Pavement" a performance-based system for selecting and specifying asphalt binders and for designing asphalt mixtures.

Supplementary Cementitious Material. Mineral admixtures consisting of powdered or pulverized materials, which are added to concrete before or during mixing to improve or change some of the plastic or hardened properties of Portland cement concrete. Materials are generally natural or by-products of other manufacturing processes.

Surface Friction. The retarding force developed at the tire-pavement interface that resists sliding when braking forces are applied to the vehicle tires.

Surface Texture. The characteristics of the pavement surface that contribute to both surface fiction and noise. Surface texture is comprised of microtexture and macrotexture.

Tamping. The operation of compacting freshly placed concrete by repeated blows or penetrations with a tamping device.

Thin Asphalt Overlays. Plant-mixed combinations of asphalt cement and aggregate that are commonly placed in thicknesses between about 0.75 and 1.50 inches (19 and 38 mm).

Tradeoff Analysis. Comparisons of alternative solutions, particularly involving consequences of reallocating funds between programs.

Transverse Crack. A crack in the pavement surface that is perpendicular to the direction of travel.

Transverse Tining. Surface texture achieved by a hand held or mechanical device equipped with a rake-like tining head that moves laterally across the width of the paving surface.

Ultra-Thin Whitetopping (UTW). Thin concrete overlays of existing asphalt pavements that consist of very thin (2 to 4 inches [51 to 102 mm]) layers of concrete bonded to an existing asphalt pavement.

Unbonded Concrete Overlay. Overlay of new concrete placed onto distressed existing concrete pavement with a layer of asphalt or other medium between the new and old concrete surface to separate them.

User Costs. Costs incurred by highway users traveling on the facility and the excess costs incurred by those who cannot use the facility because of either agency or self-imposed detour requirements. User costs typically are comprised of vehicle operating costs (VOC), crash costs, and user delay costs.

Utilization. Process of applying labor, funds, information, and other resources to implement projects and services for the transportation system.

Validation. (1) The process of confirming the soundness or effectiveness of a product (such as a model, a program, or specifications) thereby indicating official sanction; (2) The mathematical comparison of two independently obtained sets of data (e.g., agency acceptance data versus contractor data) to determine whether it can be assumed they came from the same population [The *validation* of a product often includes the *verification* of test results.]

Verification. The process of determining the accuracy of test results, by examining the data or providing objective evidence, or both. [Verification sampling and testing may be part of an acceptance program (to verify contractor testing used in the agency's acceptance decision).]

Vibration. Energetic agitation of concrete produced by a mechanical oscillating device at moderately high frequency to assist consolidation and compaction.

Void. Gaps beneath pavements (usually concrete slabs) that lead to poor support conditions and high deflections.

Warm Mix Asphalt (WMA). A general term for technologies that reduce the temperature needed to produce and compact asphalt mixtures for the construction of pavements. Utilization of WMA technology can reduce compaction temperatures by approximately 25 to 80 °F (14 to 25 °C).

Weathering. The hardening and aging of the asphalt binder.

Well-Graded Aggregate. Aggregate having a particle size distribution that will produce maximum density; i.e., minimum void space.

Whitetopping. Concrete overlay pavement placed on an existing asphalt pavement.