TechBrief

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STRATEGIES FOR IMPROVING SUSTAINABILITY OF ASPHALT PAVEMENTS

ABSTRACT

This Tech Brief summarizes guidance to the pavement community on sustainability considerations for asphalt pavement systems, as presented in greater detail in the recently published *Towards Sustainable Pavement Systems: A Reference Document* (FHWA 2015b). 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 is emphasized.

This Tech Brief focuses exclusively on sustainability considerations associated with asphalt-surfaced pavement structures and the materials used in their construction. For the purposes of this document, all permanent surfaces constructed with asphalt concrete are generically referred to as "asphalt" pavements.

The primary audience for this document is practitioners doing work within and for government transportation agencies, 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.

INTRODUCTION

An increasing number of agencies, companies, organizations, institutes, and governing bodies are embracing principles of sustainability in managing their activities and conducting business. A sustainable approach focuses on the overarching goal of considering key environmental, social, and economic factors in the decision-making process. Sustainability considerations are not new and, in fact, have often been considered indirectly or informally. In recent years, significant efforts have been made to quantify sustainability effects and to incorporate more sustainable practices in a systematic and organized manner.

A companion Tech Brief (FHWA 2014) presents a summary of the application of sustainability concepts to pavements. It provides an introduction to these concepts and how they are applied as best practices in the industry, focusing on current and emerging technologies and trends.

A sustainable pavement is one that achieves its specific engineering goals, while, on a broader scale, (1) meets basic human needs, (2) uses resources effectively, and (3) preserves/restores surrounding ecosystems. Sustainability is context sensitive and thus the approach taken is not universal, but rather unique for each pavement application. Furthermore, a "sustainable pavement" as defined here is not yet fully achievable. Today it is an aspirational goal to be worked towards, and ultimately achieved at some point in the future as sustainability best practices continue to evolve.

This Tech Brief highlights "sustainability best practices" for asphalt pavements, which are considered to be processes, actions, and features that advance the state of the practice towards more sustainable pavements. Specifically, "sustainability best practices" are those that either (1) go above and beyond required regulatory minimums or current standard practice, or (2) show innovation in meeting those minimums and standards. As described here, these sustainability best practices do not achieve sustainability, but they are improvements on current common practice and represent progress towards sustainability.

As a system characteristic that encompasses economic, environmental, and social dimensions, sustainability is necessarily the highest level consideration for an infrastructure system and not just an added feature. Simply put, sustainability means "consider everything." Other considerations (e.g., safety, conservation, ecosystem health, education, open space) are an expression of (1) various sustainability components, (2) an order of precedence for those components, and (3) a plan to operationalize those components.

In order to better understand the many facets of pavement sustainability, it is essential to consider the entire pavement life cycle (shown in figure 1), which can be divided into the following phases: production of materials, pavement design, construction, use, maintenance and preservation, and end of life. This Tech Brief introduces each of these phases, describes their interrelationships, and discusses the processes that may take place in each, as well as their impacts on sustainability. Many of these processes are interrelated and can conceivably be included in several different phases; however, each process will be addressed primarily within the discussion pertaining to the phase with which it is most closely associated.

- *Material Production.* Material production includes all processes in the acquisition (e.g., mining and crude oil extraction) and processing (e.g., refining, manufacturing and mixing) of pavement materials.
- *Design.* The design stage refers to the process of identifying the structural and functional requirements of a pavement for given site conditions (i.e., subgrade, climate, traffic, existing pavement structure, etc.), as well as the determination of the pavement structural composition and accompanying materials. It includes new pavement, rehabilitation and reconstruction.
- *Construction.* The construction stage includes all processes and equipment associated with the construction of the initial pavement.

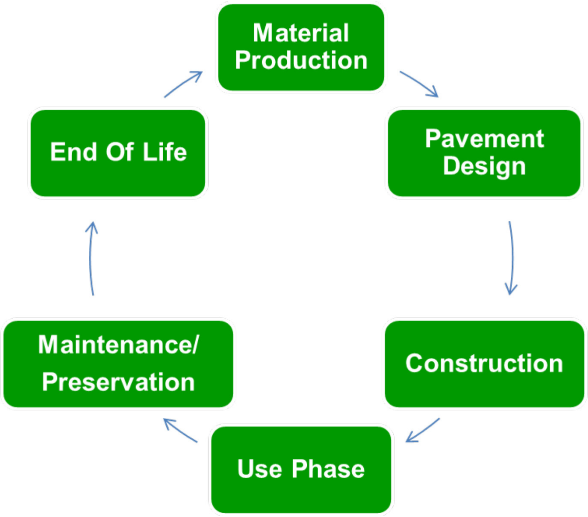


Figure 1. Pavement life-cycle phases.

- *Use Phase.* The use phase refers to the operation of the pavement and its interaction with vehicles, people and the environment.
- *Maintenance/Preservation.* These are activities applied at various times throughout the life of the pavement that maintain its overall serviceability.
- *End of Life.* The end of life refers to the final disposition and subsequent reuse, processing, or recycling of the pavement after it has reached the end of its useful life.

SUSTAINABILITY STRATEGIES FOR THE SELECTION, DESIGN, AND PRODUCTION OF ASPHALT MATERIALS

The asphalt material phase encompasses the extraction and processing of the raw materials, transportation to the plant, the asphalt mixture design and proportioning, as well as the plant operations to the point where the material is placed in trucks for transportation to the project site. Some typical sustainability questions that arise with regards to pavement material decisions include:

- Does the improved pavement system performance associated with the use of longer lasting materials offset the impacts of higher costs and possible higher production- and transportation-related impacts?
- Does the use of a particular material increase the variability of pavement performance, thereby increasing the frequency of required repairs?
- Do specifications that limit the use of lower impact materials effectively reduce the risk of poor performance, or do they prevent the opportunity to improve overall project sustainability?

- 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 considered for use in a pavement construction project, will the inclusion of the RCWM make the resulting material more difficult to recycle in the future?

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.

Asphalt Materials and Mixtures

Asphalt binder or cement comes from the heavier and more polar molecules that are present in many crude petroleum sources (AI 2007). Asphalt binder may be found in natural deposits where geological conditions have left primarily asphalt-type binder mixed with fine dust material. However, the vast majority of asphalt binder used for pavement comes from petroleum refineries that also make other products. Petroleum residues from the distillation of crude oils are the starting materials for asphalt binder production. Of the multitude of crude oils commercially available, only a limited number are considered suitable for producing asphalt binder of the required quality in commercial quantities. The source of crude oil can have a significant effect on the energy and environmental impact of a specific asphalt binder as the processes needed to extract, process, transport, and refine it to produce asphalt binder and other products will vary with the source.

Mixtures of asphalt and aggregate are used for a wide range of pavement applications, from sprayed maintenance treatments that seal the surface, to asphalt concrete (asphalt) used for thick structural sections. 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 also used to produce *asphalt emulsion, polymer-modified asphalt, rubberized asphalt*, and *asphalt cutback*.

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.*
- *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, such as air-cooled iron blast furnace slag aggregate.*
- *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. In some regional markets recycled asphalt shingles can be categorized as waste, whereas in other markets it is clearly a recycled material because it has economic value beyond the cost of transport and disposal*

- *Asphalt emulsion* is made by shearing asphalt cement 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* (HMA) 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 to 329 °F (135 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* (WMA) represents a broad range of technologies used with asphalt concrete that allow the mixture to stay workable and compactable at lower temperatures than typical HMA. 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 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 properties needed for different applications, most typically with enhanced high temperature performance characteristics. 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 recycled asphalt pavement (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.

The entire life cycle must be considered when considering the sustainability of asphalt materials and mixtures, not only from an economic perspective but also from an environmental perspective. The ideal solution will be a function of the materials, traffic, climate, construction processes, and the overall goals and agency priorities.

The asphalt binder in asphalt materials carries much of the total environmental impact of the mixture because of the impact of petroleum acquisition and refining. The use of RAP in asphalt replaces not only virgin aggregate, but the RAP binder is also reused as binder (at least in part), thereby reducing the amount of virgin binder needed in the new asphalt. Thus, the use of RAP in new asphalt reduces the need for virgin asphalt cement and aggregate, both non-renewable and finite materials.

Some strategies for reducing the environmental impact of asphalt mixtures include the following:

- Reduce the virgin binder content in asphalt mixture through the increased use of RAP; however, impacts on performance for different applications must be considered.
- Extend the service lives of asphalt materials through increased standards for greater compaction (no tradeoffs), use of WMA to improve compaction, better mixture designs, and appropriate use of polymers and/or recycled tire rubber.
- Improve efficiency of plant processes to allow producing asphalt mixtures at desired quality (to achieve required volumetrics) but with reduced energy consumption.
- Reduce transportation distances of all raw materials through the use of more local materials while maintaining target specifications, quality requirements, and expected performance.
- Reduce the need for transportation by using in-place recycling such as full-depth recycling (FDR) and cold in-place recycling (CIR), plant recycling using RAP, and greater use of local materials (considering tradeoffs with performance).

Aggregate Materials

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 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.

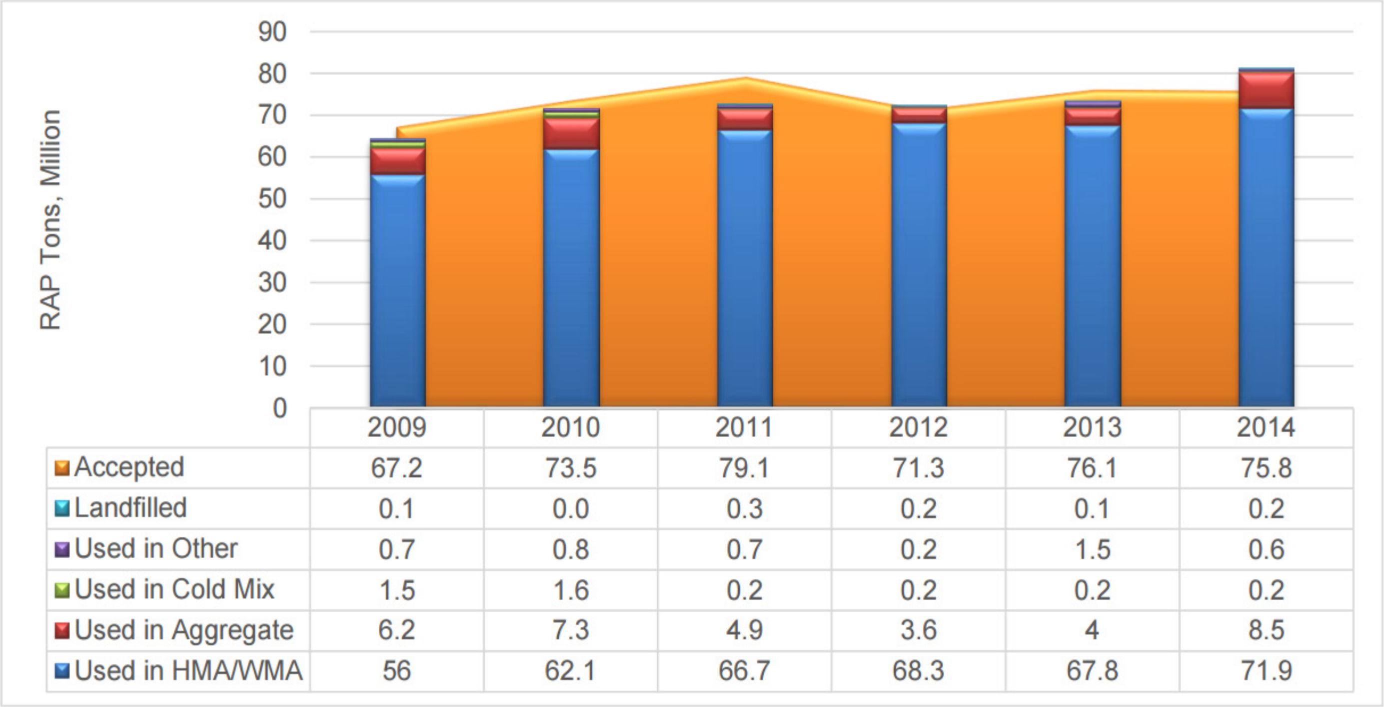
Aggregate used in unbound bases and subbases may be derived from natural sources or may be manufactured or derived from recycled pavement materials or other suitable demolition materials. For HMA, aggregate may be used from natural sources or RAP or manufactured sources. From a sustainability perspective, it is convenient to combine manufactured aggregates with recycled materials into a recycled, co-product, or waste material (RCWM) category, that includes the following:

- Reclaimed asphalt pavement (RAP): RAP is most often produced when existing asphalt 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 can be used in aggregate bases. Figure 2 shows data on RAP use in the U.S. from 2009 through 2014.
- 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.
- Other materials used in asphalt and in unbound base and subbases include air-cooled blast furnace slag (ACBFS), steel furnace slag (SFS), and foundry sand, depending on local availability.

Major sustainability issues related to use of virgin aggregate in pavements include:

- Environmental damage caused by quarries, and sand and gravel pits from which virgin natural aggregate are extracted, much of which can be mitigated through restoration when aggregate extraction has been completed;
- Transportation-related energy consumption and emissions from transportation, which are highly dependent on the mode of transport (marine, train or truck) and distance aggregate are moved; and
- Energy consumption and emissions from processing aggregates to improve them for use in pavement materials.

A major source of environmental burden associated with aggregate production is transportation. Aggregate must be transported from the source to the job site for unbound bases and subbases, and transported to the concrete or asphalt mixing plant and then to the project site. Transport-related impacts primarily involve the burning of fossil fuel-based fuels in trucks or other



	2009	2010	2011	2012	2013	2014
🟧 Accepted	67.2	73.5	79.1	71.3	76.1	75.8
🟦 Landfilled	0.1	0.0	0.3	0.2	0.1	0.2
🟪 Used in Other	0.7	0.8	0.7	0.2	1.5	0.6
🟩 Used in Cold Mix	1.5	1.6	0.2	0.2	0.2	0.2
🟥 Used in Aggregate	6.2	7.3	4.9	3.6	4	8.5
🟦 Used in HMA/WMA	56	62.1	66.7	68.3	67.8	71.9

Figure 2. RAP use in the U.S., 2009 through 2014 in millions of tons (Hansen and Copeland 2015).

transport vehicles. The energy use and greenhouse gas (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.

Aggregates in Asphalt Mixtures

In addition to the general aggregate sustainability considerations described previously, it is important to consider the impacts of aggregate properties (e.g., aggregate grading, interaction with asphalt and other performance related properties affecting durability and functionality) and the use of RCWMs on the sustainability of asphalt mixtures. These properties include shape, texture, and mechanical durability. One distress that substantially shortens asphalt pavement life 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.

Strategies for Improving the Sustainability of Aggregate Use in Asphalt Pavements

Strategies for reducing environmental impact from aggregates used in asphalt pavement structures include:

- Reduce the use of virgin aggregate through increased use of RCWMs, increased aggregate and pavement durability, and increased pavement design life.
- Reduce the impact of virgin aggregate acquisition and processing through improved mining practices.
- Reduce the impact of aggregate transportation through mode choice, greater use of local materials (without compromising performance requirements), and optimally located construction staging and processing areas.

Asphalt Mixture Design and Production

Asphalt mixture design and production needs 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. Several key considerations are:

- Selection of the final binder content based on relationships between the binder content and other mixture volumetric proportions. These include the risks of using too much binder, that results in rutting and shoving. Also considered are the risks of too little binder, which results in early cracking, raveling, water damage, and inadequate compaction, all of which have additional negative impacts that affect the long-term performance of the asphalt 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.
- Consideration of the use of polymers or rubberized asphalt to produce a binder with the properties needed for different applications, most typically with enhanced high and/or temperature performance characteristics.

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 (ME) pavement design methods.

Use of RCWMs

The use of RCWMs continues to increase for economic and environmental reasons. A proper engineering evaluation must be done when using RAP in asphalt paving mixtures to ensure that its properties benefit the performance of the mixture.

In general, recycled materials should be used for the "highest use." Because the asphalt binder in RAP can replace the environmental burden of virgin asphalt production, the highest use 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.

Warm Mix Asphalt

Almost without exception, increasing the density and decreasing the variability of asphalt materials will improve performance. Warm Mix Asphalt (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.

WMA technologies are used with asphalt 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).

Strategies for Improving Sustainability in Asphalt Mixture Design

The major sustainability-related challenge facing materials for asphalt pavements is that the production of asphalt is energy and GHG emission intensive. Reductions in those energy and emission levels are best achieved by expanding efforts to reduce the amount of asphalt needed over time. This can be achieved primarily by reducing the virgin binder content of asphalt mixtures, and extending the lives of asphalt mixtures. Other approaches for improving the sustainability of materials for asphalt pavements include use of less virgin aggregate, and reducing the environmental impacts of mixing, transporting and placing asphalt mixtures as summarized in table 1.

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.

Table 1. Approaches to improving pavement sustainability with 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 is 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 is available.	Reduce impact from otherwise using virgin binder.	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 Consumed Energy 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 produce 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	Improved 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.
	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, binder production impact 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.

SUSTAINABLE STRATEGIES IN ASPHALT PAVEMENT DESIGN

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

1. Identifying the functional and structural requirements of the pavement including its design life and potential constraints and considering the sustainability goals.
2. Gathering key design inputs such as material properties, traffic loadings, and climatic factors.
3. Selecting pavement type and associated materials, layer thicknesses, and construction specifications to achieve the desired performance.
4. Using design alternatives that consider the above processes 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 in figure 3. Although sustainability and life-cycle assessment are gaining recognition, 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). However, pavement designs that improve environmental sustainability often also reduce life-cycle costs, largely as the result of reductions in natural resource requirements and energy consumption over the life cycle.

The following items may be included in project-specific requirements for the design of a particular asphalt pavement: expected design life; smoothness; speed of construction; surface texture for friction, noise and splash/spray; storm water 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 (i.e., pavement will need to be replaced or removed before its design life is reached); urban heat island impact; and 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 (e.g., passenger mobility and safety) and freight (i.e., ability to facilitate the transport of goods without damage or delay), the surrounding community, and the environment (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.

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

- Surface and structural performance.
  - Smoothness, texture and structural response affect vehicle fuel consumption. Smoothness also affects vehicle life and freight damage costs. These characteristics of the surface and structure vary with time and should be considered over the entire life cycle.
  - It is important to consider the impacts of future maintenance and rehabilitation activities on pavement sustainability, especially in terms of their effects on structural performance and pavement smoothness.
  - Surface performance is context sensitive in that it is very critical to pavements exposed to higher traffic volumes and less important from a fuel use standpoint 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 associated with intervening maintenance or rehabilitation.
- 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 because of the need for additional maintenance and rehabilitation activities.
  - The selection of the design life should include consideration of end-of-life alternatives or use of extremely long-lived pavement which will not be expected to need reconstruction.
- Asphalt pavement type selection.
  - The asphalt 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 (if not designing extremely long-lived pavement).

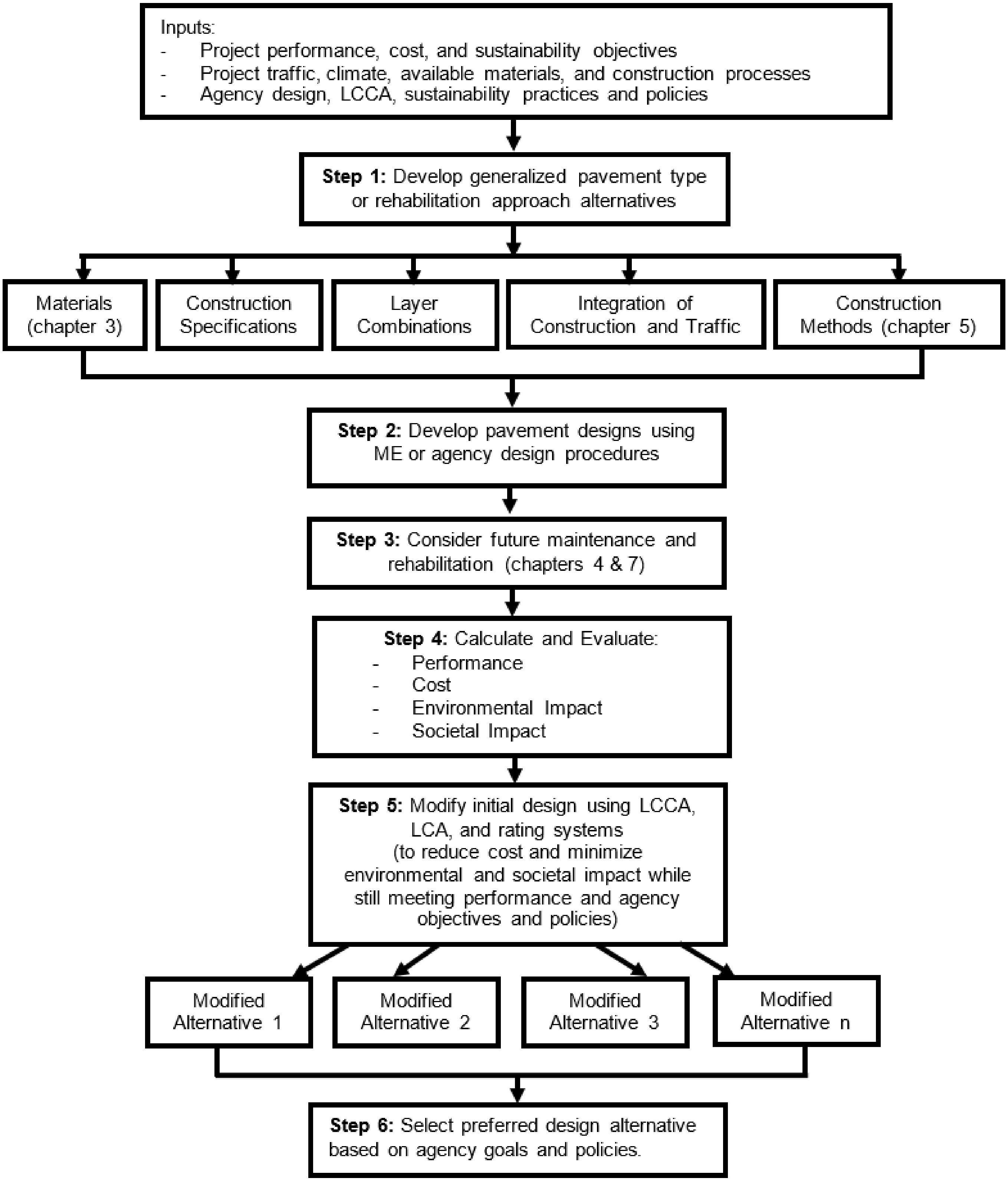


Figure 3. Overall process for considering sustainability in pavement design.
(Note: Chapter numbers refer to the chapters in FHWA-HIF-15-002 [FHWA 2015b]).

  - The relative sustainability impacts of different asphalt 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.
  - The ability to achieve quality construction with available materials and construction equipment and expertise impacts the sustainability of the pavement.
  - Traffic delays in construction work zones may result in negative sustainability impacts where traffic volumes are high and traffic management plans (TMP) cannot mitigate delays. Safety is also affected by the type and duration of construction work zones.
- Construction quality requirements.
- Recycling strategies.

The impact on pavement environmental impacts of these types of decisions can be assessed through use of life-cycle assessment (LCA) and overall sustainability can be assessed through use of sustainability ratings systems as part of an overall assessment process.

Mechanistic-Empirical Design

Mechanistic-empirical (ME) pavement design methods offer much greater opportunity than empirical design methods to consider alternative materials, pavement structures, and construction procedures, including comparisons of alternatives offering improved cost and environmental sustainability. Empirical pavement design methods, which are based on observations of the performance of in-service pavements without consideration of the mechanics of pavement behavior, can only consider how pavements perform within the range of conditions (e.g., material types, pavement types and design features, environmental conditions and traffic loadings) upon which the design model was calibrated. ME design directly considers key material properties and geometric conditions (e.g., stiffness, fatigue resistance, low-temperature cracking properties, permanent deformation resistance, and thermal expansion) and how the pavement reacts to applied vehicle and environmental loads and is able to relate those parameters directly to pavement performance through available response and performance models. Thus, ME design allows the development of designs using new materials, geometries, and other conditions that have not been used or encountered before based on the results of analyses conducted using pavement structural models. ME design can estimate critical asphalt pavement distresses (e.g., fatigue cracking, rutting, reflective cracking) and roughness (i.e., International Roughness Index [IRI]) versus time, which allows the designer to consider alternative trigger levels for maintenance and rehabilitation. In addition to changes in materials and pavement types, ME design permits the evaluation of changing construction specifications through consideration of their effect on materials properties.

The AASHTOWare Pavement ME Design Software is currently the most commonly used ME tool for pavement design (both for new pavements and overlays) with some state DOTs (e.g., California, Texas, and Illinois), industry organizations, and countries utilizing other asphalt pavement ME design procedures and software tools. ME design methods are available for both new asphalt pavements and for rehabilitation design. Structural rehabilitation strategies for asphalt-surfaced pavements include asphalt and bonded concrete overlays, in-place recycling with and without stabilization and long-life rehabilitation and reconstruction.

Design Life Improvement

Longer life design options may afford the opportunity to reduce life-cycle costs, user delays, and environmental impacts as compared to a standard 20-year pavement design. Longer life pavements with design lives of 30 to 60 years (or more) can be achieved as a policy objective in new, rehabilitated, and reconstructed pavements and are generally justified for higher volume facilities.

Longer life pavements use more durable materials and/or provide greater structural capacity. Higher structural capacity can be achieved by increasing pavement thickness, by increasing the stiffness and/or strength of critical layers, or both. Because of the increased thicknesses or increased material stiffnesses/strengths, or the use of more durable materials, longer life designs may have higher initial costs and/or greater initial environmental impacts, but the overall life-cycle costs and environmental impacts are often expected to be less.

Innovative longer life asphalt pavement designs may be developed to provide a number of sustainability benefits both at the beginning (material production phase) and through the overall life cycle, including:

- Use of ME design method and advanced characterization of materials, along with more stringent construction specifications, optimized material selection can be made to increase service life with the same thickness or potentially reduce cross-sectional area to achieve same service life. An example is shown in figure 4, where two long-life pavements have been designed for the same high level of traffic (about 200 million equivalent singleaxle load [ESAL] applications), but one has been optimized to reduce its thickness through changes in materials and construction specifications. The pavement on the left is designed with a standard asphalt mix and typical compaction specifications, while the pavement structure on the right makes use of stiffer asphalt and increased compaction in the middle and bottom layers. This reduces strains at the bottom of the asphalt layers that cause cracking, and the tighter compaction specifications also increase the cracking resistance of the materials.

- Incorporation of higher quantities of RAP in the middle layer while maintaining similar service life. This reduces the amount of new asphalt binder used (and its commensurate environmental burden), while increasing the pavement structural capacity and reducing its viscoelastic energy dissipation.
- Use of modified or rubberized (containing recycled tire rubber) open-graded surfaces to reduce noise, slow storm water runoff, trap pollutants, and provide a sacrificial layer for top-down cracking.
- Use of recycled concrete pavement or building waste as the granular base layer.

Traditional Materials and ME Design

- 535 mm thick (21 in.)
- 8% air voids
- Same mix design throughout and standard asphalt

ME Design using: improved compaction, stiffer binder, and rich bottom

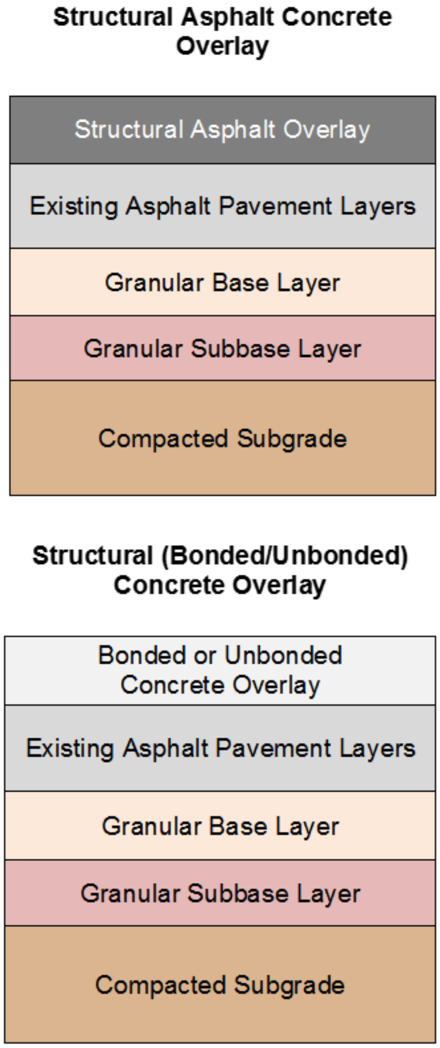
- 300 mm thick (12 in.)
- 75 mm (3 in.) polymer modified with 5% air voids
- 150 mm (6 in.) stiffer asphalt with 5% air voids
- 75 mm (3 in.) stiffer asphalt with 2% airvoids + 0.5% asphalt

Figure 4. Example of use of materials selection and construction specifications to reduce pavement thickness and environmental impact (adapted from Harvey 2012).

It is noted that 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.

Asphalt Pavement Rehabilitation Using Overlays

Structural rehabilitation strategies for asphalt-surfaced pavements include asphalt and concrete (bonded and unbonded) overlays. Schematic cross sections of these various overlay types are provided in figure 5. Thin overlays, either asphalt or concrete overlays of thickness less than about 2 inches (51 mm), add minimum structural load-carrying capacity and are used to address functional pavement issues. Those thin overlays are discussed in more detail in the preservation and maintenance part of this tech brief.


Structural Asphalt Concrete Overlay

Structural (Bonded/Unbonded) Concrete Overlay

Figure 5. Cross sections of asphalt pavement structures rehabilitated with overlays (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. 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 remove 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. However, full-depth reclamation, 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, 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]).

Design with Local and Recycled Materials

Traditional asphalt pavements sections include opportunities for the use of recycled materials such as concrete demolition in the base and subbase layers, as well as various recycled materials in the asphalt layer such as recycled tires in rubberized asphalt. These options are often particularly attractive and decrease environmental impacts when the original pavement structure is the source of the recycled materials such as when RAP is used in the asphalt layers.

Use of local materials reduces transportation cost and environmental impacts. Opportunities for using more local materials, and particularly local recycled materials should be sought. However, properties affecting the service life of the pavement must be considered though proper mix design and structural design.

Additional Design Strategies and Features that Impact Sustainability

Use of Porous Asphalt Materials for Surface Layers and in Structures for Storm Water Management

Asphalt pavement surface layers may be selected to achieve certain functional and structural objectives including durability, high friction, noise reduction, and desired friction. In addition to tire/pavement noise benefits, thin open-graded friction course (OGFC) asphalt surfaces transmit storm water 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 storm water discharge and also results in pollutants being captured in the open-graded layer (Grant et al. 2003). Use of rubberized (using recycled tires) or polymer-modified binders in OGFC overlays will often provide improved resistance to raveling and cracking.

Pavements can also be constructed using porous materials to capture and store storm water runoff, allowing it to percolate into the ground and thereby recharge groundwater supplies and/or control discharge outflow. Fully porous pavements are defined as those in which all pavement layers are intended to be porous and the underlying pavement structure serves as a reservoir to store water during precipitation events in order to minimize the adverse effects of storm water runoff. An example of a fully porous pavement structure is shown in figure 6. An FHWA tech brief on fully porous pavements outlines an overview of the benefits, limitations and applications of porous asphalt pavements with stone reservoirs (FHWA 2015a).

The U.S. EPA (2010) cites the use of fully porous pavements as a Best Management Practice (BMP) for handling storm water runoff on a local and regional basis. Most applications of fully porous pavements in North America have not been subjected to high-speed traffic or heavy trucks, which reflects concerns about durability.

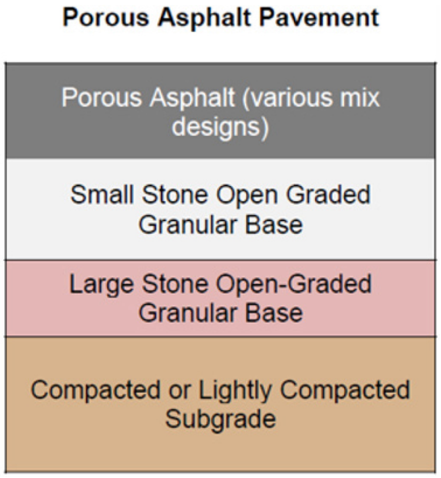


Figure 6. Cross section of a porous asphalt pavement.

Structural design methods are empirical in nature and are available from the National Asphalt Pavement Association (Hansen 2008) for design of porous asphalt pavements. For state highway agencies, fully permeable pavements are being considered as a shoulder retrofit adjacent to conventional impermeable pavement with geosynthetics used to prevent water from affecting the layers in the impermeable pavement, and for some low-speed applications carrying trucks. An ME design approach and a preliminary life-cycle cost analysis (LCCA) have been produced for fully porous asphalt pavements to potentially 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).

Issues and Trade-offs in Asphalt Pavement Design

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 decisions should include consideration of maintaining the overall structural capacity of the pavement, its overall functional capabilities (e.g., smoothness, friction), and future roadway recycling and reuse.

Consideration of Use Phase in Design

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

- Smoothness over the design life of the pavement (increased pavement roughness increases vehicle fuel consumption and may reduce time between maintenance and rehabilitation activities).
- Overall pavement longevity (increased longevity decreases life-cycle costs and reduces the environmental and social impacts associated with materials production, construction, and periodic maintenance and rehabilitation).

The relative importance of each of these factors depends, in large part, on the traffic volumes using the facility. Where traffic volumes are heavy, 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 over the life cycle.

Consideration of Early versus Later Impacts

One approach to assess the risk of whether life-cycle cost, user delay and environmental impact goals are met in design is the concept of "payback time." Payback time is defined as the period between the initial impact of an alternative with higher initial impact due to use of premium materials and/or thicker layers and the time to achieve a zero difference compared to the standard approach, after which there is a net reduction in impact. Simply put, it is the time required to recoup the benefits (e.g., cost, environmental, or social) associated with a pavement design investment. For pavement, this involves increasing the time (years) before the first rehabilitation or reconstruction, reducing the level and frequency of maintenance during the life, and keeping a pavement smoother over its life.

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 having greater uncertainty regarding the ability of the assessment to accurately quantify them and whether they will actually occur. Using appropriate tools and methods like LCCA and LCA, payback time can be calculated to evaluate when the initial investment made for longer life pavements can be regained from economic and environmental perspective.

An example of the payback time for a specific case study is provided in figure 7, 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.

The example shown in figure 7 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 2012).

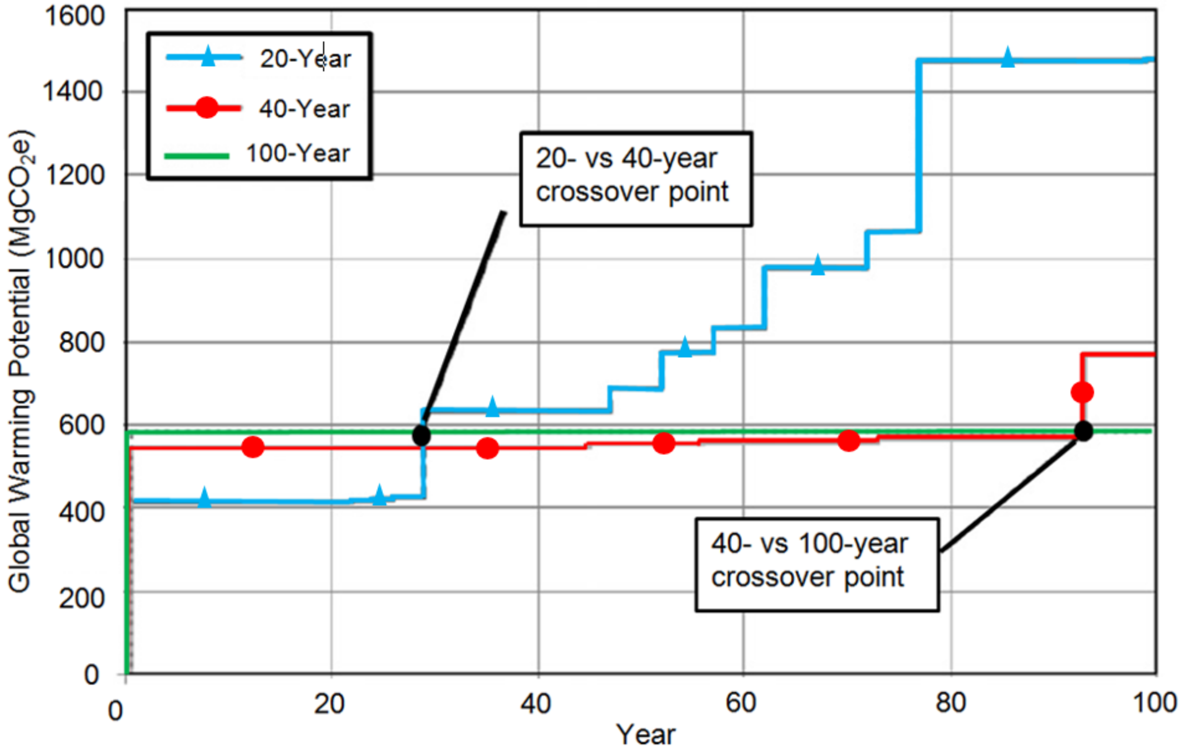


Figure 7. Example of payback time analysis considering only the material production and construction phases of three different pavement design lives (modified from Santero 2009).

SUSTAINABLE STRATEGIES IN ASPHALT PAVEMENT CONSTRUCTION

Critical areas of pavement construction that can have a significant effect on the overall sustainability of a paving project include: (1) fuel consumption during material transport and construction operations; (2) exhaust and particulate emissions; (3) traffic delays, congestion, and noise emissions generated during construction; (4) construction quality, as it impacts pavement performance and overall life; and (5) constructed characteristics of the pavement surface, which impact surface friction (safety), noise, and possibly fuel efficiency during the use phase. These areas can be categorized as being related to construction operations (areas 1, 2 and 3) or constructed characteristics, including quality (e.g., areas 4 and 5). Some of these critical construction items that can positively affect pavement sustainability are discussed in the next sections.

Sustainability of Pavement Construction Operations

Pavement construction factors that impact pavement system sustainability over the life cycle include: (1) construction-related energy consumption; (2) effects of construction operations on the surrounding area (including particulate and gas emissions, noise, effects on residents and businesses, and effects on wetlands and streams); and (3) the economics of construction practices, including user costs resulting from construction-related traffic delays.

Construction-Related Energy Consumption

In general, pavement construction is an energy-intensive process that involves excavation, earthwork movement, material processing, production and placement, and compaction/consolidation of the paving layers. 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. Other factors that can affect energy consumption include fuel types used (e.g., diesel fuel, gasoline, biodiesel and compressed natural gas) and the type of power source for stationary construction equipment (i.e., generator driven vs. grid powered). External factors that influence construction fuel consumption (independent of equipment efficiency) 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).

Effects on the Surrounding Area

The use of heavy equipment for earth moving and construction operations generates engine combustion emissions that may significantly impact local air quality in surrounding areas. Heavy-duty construction equipment is usually diesel powered, which produces NO_x, GHG, and diesel particulate matter (PM) as significant emissions. Diesel exhaust PM emissions are reported as a toxic air contaminant, posing chronic and carcinogenic public health risks (AEP 2012). The EPA has established stringent standards for carbon monoxide, volatile organic carbon, nitrogen oxides, and PM that a vehicle and engine may emit, and manufacturers, refineries, and mixing plants are responsible for meeting those standards.

Construction processes can also indirectly impact the surrounding area through resulting congestion, traffic delays, noise and other adverse effects. Construction analysis programs for pavements, such as CA4PRS (Lee, Harvey, and Samadian 2005), can be used to analyze the effects of pavement design, construction logistics, and traffic operation options on construction-related traffic delays and construction window policies. The impact of traffic delays on vehicle energy consumption and GHG emissions 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.

Economics of Construction Practices

The construction practices used have direct bearing on both the initial construction costs and the long-term, life-cycle costs of the pavement project. Changes in construction practices to enhance the sustainability of the project (such as noise and pollution reduction procedures, controlling erosion and storm water 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 their effective impacts. 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 because of 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).

Techniques for Improving the Sustainability of Construction Operations

The following sections describe strategies for improving the sustainability of construction operations. A national effort is currently underway to develop a guidebook for selecting and implementing sustainable highway construction practices under NCHRP Project 10-91).

Reducing Construction-Related Energy Consumption and Emissions

Some practices for reducing fuel consumption and emissions from construction equipment include minimizing haul distances with the use of on-site recycling and optimally located staging areas (Ferrebee 2014; Smith et al. 2014), selecting appropriate equipment types and sizes for the job, implementing limitations on idling, using alternative fuels, retrofitting construction equipment with improved emissions control equipment, and using hybrid equipment.

Reducing Construction Impacts on Surrounding Environment

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 asphalt and concrete plants, and consideration of the proximity of residential and light commercial areas in the selection of plant and materials storage locations.

Approaches to reducing noise and noise impacts include equipment modifications and proper equipment maintenance, and time-of-day restrictions on some (or all) construction activities. Practices for minimizing pollution from runoff and erosion include the use of perimeter control barriers (fences, straw bales, etc.), minimization of the extent of disturbed areas, application of erosion control matting or blankets, and site planning to store/stockpile materials away from waterways.

Traffic delays and disruption of residents and businesses can be reduced by the use of effective traffic control and lane closure strategies, the establishment of performance goals and measures for work zones, the optimize construction sequencing, and the use of intelligent transportation systems to dynamically manage traffic.

Accelerated construction techniques can also be employed to minimize the duration of construction and associated lane closure times. Examples of materials and construction processes that may accelerate construction include selection of asphalt materials to reduce required pavement thickness (as shown in figure 4) since paving time is generally linearly proportional to asphalt thickness, and optimization of trucking logistics and cooling of multi-lift asphalt paving. Each of these options may expedite the construction process, thus reducing user delays, reducing emissions, and improving safety (by reducing the risk of crashes).

Impacts of Constructed Characteristics on Pavement Sustainability

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, etc.), as described herein.

Construction Quality

Long service life is one of the primary drivers of pavement sustainability and 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.

In many cases, increases in performance can be achieved with small increases in construction quality and concomitant reductions in overall variability. A careful review of construction specifications may show where increased levels of quality could be achieved that would positively impact performance. The implementation of effective quality assurance (QA) plans will promote higher levels of quality.

There are many aspects of asphalt pavement construction for which QA is essential in order to achieve the full potential for longevity (and, therefore, sustainability) of asphalt pavements. These include (but are not limited to): placement and laydown in accordance with prevailing standards and specifications, monitoring and preventing segregation at the plant during the production and loading stages and during the paving operations, proper construction of longitudinal joints, achieving target in-place density requirements, and achieving smoothness through proper placement and compaction techniques.

Achieving Target Density Requirements to Increase Pavement Life

Almost without exception, meeting the density requirements and decreasing the variability of HMA materials improves pavement performance with minimal additional environmental impact during construction. In addition, this decreases the number of times maintenance and rehabilitation are needed in the life cycle which reduces the amount of material used in the life cycle.

Meeting desired asphalt density is a result of implementing proper specifications and the application of effective quality control (QC) practices regarding compaction that are well known in the industry. With most current mixes achieving good densities only requires a few additional roller passes while the mix is in the range of optimal compaction temperatures. 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 mix or using a softer binder to improve reflection cracking resistance), achieving the density requirements through compaction improves both rutting and cracking resistance. WMA is a relatively new set of technologies being used to better control mix compaction, and may also offer the possibility of lower production temperatures and energy use.

Achieving target density requirements plays a critical role in the construction of any type of asphalt layers. A strong correlation exists between service life and in-place density of asphalt layers (Puangchit et al. 1983; Christensen 2006; Buncher 2012). Increased density of granular base and subbase layers used in asphalt pavements also results in increased performance and reduced the impact on the environmental. Direct sustainability benefits of meeting in-place density requirements can easily be quantified by LCA and LCCA as the service life of pavement is improved.

Target density requirements can generally be achieved by improving the quality control of construction activities. Several strategies that can be used to meet density requirements are:

- Proper use of compaction equipment and procedures and incorporation of automated compaction systems to better control the in-place density of compacted layers. Since 2008, the FHWA has been leading a national effort to advance the implementation of intelligent compaction technology to improve compaction of materials that include granular and cohesive soils, stabilized bases, and asphalt layers. Intelligent compaction technology is defined as a process that includes vibratory rollers equipped with a measurement and control system that can automatically control compaction parameters (e.g., density, stiffness) during the compaction process (Xu et al. 2012, Horan et al. 2012, FHWA 2013).
- Stringent control on laydown temperatures and requirements depending on lift thickness, mixture type, and base temperature.
- Determination of proper lift thickness based on nominal maximum aggregate size (NMAS) of the mix. The general practice is to use a ratio of lift thickness to NMAS of at least 3:1 for fine grade mixtures and 4:1 for coarse graded mixtures (Brown et al. 2004). However, it is important to note that lift thickness may have consequences on the overall sustainability calculations as it will influence construction sequence and productivity. An overall analysis of the effects of improved compaction levels with varying lift thicknesses should be determined by LCA.
- Utilization of WMA technologies can also help achieving density requirements, even at lower temperatures.
- Proper construction of longitudinal joints and/or installation of joint sealing materials to prevent premature and excessive joint deterioration and reduce water infiltration to the underlying layers (Buncher 2012).
- Use of innovative and emerging technologies to improve construction quality and meet target density requirements uniformly through the entire project. These techniques include the use of infrared thermographic scanning to monitor surface layer temperatures during construction and to detect potential zones for segregation due to thermal segregation. In addition, application of nondestructive techniques such as ground penetrating radar (GPR) has been gaining acceptance for pavement layer thickness measurement and preliminary work on density of quality control (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).

Smoothness

Smoothness is an important pavement construction quality indicator. Achieving a high level of smoothness during initial construction as well as maintaining it throughout the service life of pavements is considered to be a key factor in improving overall fuel economy and reducing vehicle related emissions, especially for heavily trafficked sections. For pavements carrying high traffic volumes, the effects of pavement smoothness on fuel economy and resulting impacts on energy use and GHG emissions can be greater than any differences caused by different materials or construction techniques. An example of this can be seen in figure 8 (Wang et al. 2012), which shows the time it takes to pay back the initial energy and emissions caused by construction of a thin asphalt overlay (construction and materials shown as negative value at beginning of life) through vehicle fuel savings after construction, compared with leaving the pavement with a rough surface. While this is only one example, the figure illustrates the effects of two values of constructed smoothness, with lower levels of constructed smoothness resulting in lower net savings in energy and emissions compared to high levels of construction smoothness.

Studies have also shown that, when structural or material durability problems are not present, improvements in initial ride quality translate directly into longer pavement service life (Smith et al. 1997). Obtaining good initial smoothness levels during the construction of new or rehabilitated high traffic volume roadways, and maintaining those levels of smoothness throughout their service lives, can result in large reductions of use-phase energy consumption and emissions compared to the impacts associated with the use of different materials or construction techniques. Smoothness acceptance levels should be part of the construction specifications.

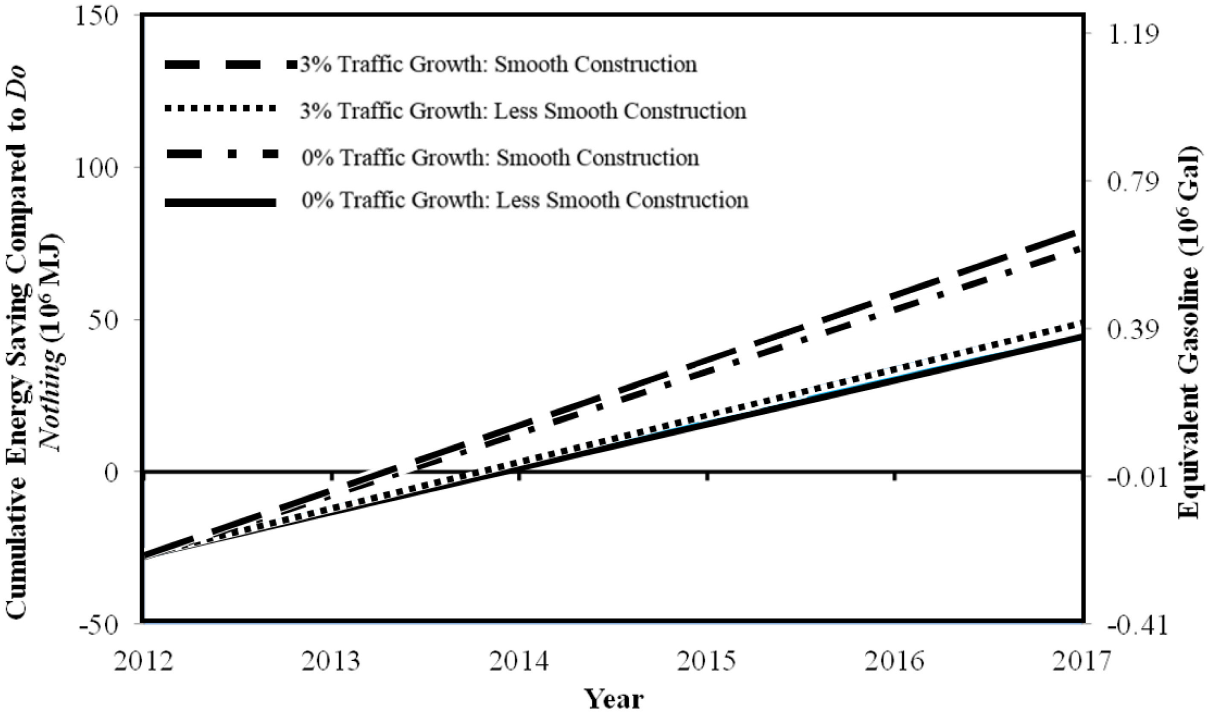


Figure 8. Payback time in MJ and equivalent gallons of gasoline for a high volume interstate route over 5-year analysis period for thin asphalt overlay vs. leaving the pavement rough, considering two levels of constructed smoothness (Wang et al. 2012). (Initial IRI values: less smooth construction = 63 inches/mile [1 m/km], smooth construction = 106 inches/mile [1.67 m/km]).

Sustainable Asphalt Pavement Construction Summary

Asphalt pavement construction activities offer many opportunities to adopt practices that improve the sustainability of the pavement system. Highly visible examples include the use of on-site recycling to produce durable pavements while minimizing hauling impacts through the use of locally available materials. Less obvious examples are the impacts that good construction practices can have on fuel consumption, user vehicle expenses, and agency repair costs during the use phase.

The potential impacts of the pavement 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 2009; Ferrebee 2014). 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.

SUSTAINABLE STRATEGIES FOR THE PRESERVATION/MAINTENANCE OF ASPHALT PAVEMENTS

Diminishing budgets and 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. Pavement preservation inherently improves pavement sustainability. It often employs low-cost, low-environmental-impact treatments to prolong 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, 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.

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. 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. 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.

Overview of Asphalt Pavement Preservation Treatments HOIAQ

Asphalt-surfaced pavements include any pavement surfaced with an asphalt material, whether asphalt concrete (i.e., HMA, WMA) or an asphalt surface treatment. The following maintenance and preservation treatments are most commonly considered for asphalt pavements: joint/crack sealing; patching; chip seals; slurry seals; microsurfacing; cold in-place recycling; hot in-place recycling; and non-structural or overlays (both asphalt and concrete) designed to enhance functionality (e.g., thin wearing courses for friction and/or noise). 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.

Assuming that preservation treatments all generally use combinations of aggregate, water, 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 asphalt 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.

Key parameters affecting sustainability of asphalt pavements in selection of a preservation or maintenance technique are timing of treatment, service life of the individual treatment, smoothness performance after treatment is applied, duration of lane closures, and life extension added to the existing pavement. Table 2 provides a qualitative summary of the impacts of several asphalt pavement preservation and maintenance treatments on pavement sustainability. The sustainability impact of any one treatment is very difficult to assess, and ultimately the economic, environmental, and social impacts of the entire strategy should be assessed in its entirety.

Construction quality plays a role in the sustainability impacts of pavement preservation and maintenance that is similar to the role played in new construction. Increased construction quality extends pavement and treatment life and reduces environmental burden, and treatments that are constructed with higher levels of initial smoothness and that are maintained in a smooth condition over their lives will result in reduced energy use and GHG emissions. The additional effort required to achieve additional quality is generally very low.

For a high volume route, the timing and performance of the selected treatment can play a significant role in determining sustainability impact. More frequent maintenance and rehabilitation will result in preservation of existing pavement in good condition, and generally will result in a smoother and safer surface for road users. The improved smoothness can help reduce vehicle fuel use, provided users don't drive faster, and vehicle damage and associated road user costs. On the other hand, more frequent maintenance and rehabilitation result in more frequent environmental impacts from materials production and construction, and also result in greater cost for the agency (compared with leaving the pavement in bad condition without restoring it; the cost of keeping a pavement in good condition goes down over the life cycle). In general, the results change considerably depending on the expected treatment performance, traffic levels, and emissions from materials, construction, and end-of-life scenarios. The application of 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 for both the agency and road users.

Although there is ample 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 practices impact sustainability. This is partly due to variability and uncertainty in a host of factors (including the existing pavement condition, climatic factors, traffic loading, and

Table 2. Summary of relative sustainability impacts of selected asphalt-surfaced pavement preservation and maintenance techniques.

Treatment	Relative Treatment Life (✓to✓✓✓✓)	Relative Initial Cost ($ to $$$$)	Relative Environmental Impact	Societal Impact
Crack Filling and Sealing	✓	$	Low	Reduced traffic delays; less pleasing aesthetics and potential roughness.
Asphalt Patching	✓✓	$	Variable; Depends on patching amount and improvement gained	Reduced traffic delays compared to other treatments; negative impact on ride quality and noise.
Chip Seal	✓✓	$$	Medium to high, Depends on thickness and binder type	Increases safety by improving friction, reduced traffic delays; reduced ride quality due to rough surface, increases noise
Slurry Seal	✓✓	$$	Medium	Increases safety by improving friction; reduced traffic delays, improves aesthetics
Microsurfacing	✓✓✓	$$	Variable; Highly dependent on system and materials used, treatment life and improvements gained in ride quality	Increases safety by improving friction, reduced traffic delays; improves aesthetics
Ultra-thin and Thin HMA Overlay	✓✓✓✓	$$$	High; Use of WMA, RAP, RAS, and local materials may reduce construction impact	Improved ride quality, fuel savings, improved safety through improved friction; reduces splash and spray, noise; improved aesthetics; some improved structural value. (impacts depend on whether overlay is open or gap graded)
Hot In-Place Recycling	✓✓✓	$$$	Medium to high; Reuse of existing materials reduces impact.	Improved ride quality, improved safety through improved friction; reduces splash and spray, noise; improved aesthetics
Cold In-Place Recycling	✓✓✓	$$$	Variable; depends on additives use and type of surface applied, reuse of materials reduces impact	Improved ride quality, improved safety through improved friction; reduces splash and spray, noise; improved aesthetics
Bonded Concrete Overlay	✓✓✓✓	$$$$	Medium; Virgin materials and concrete materials increase impact, thinner cross section reduces impact.	Increases safety through improved friction and drainage; improved ride quality and aesthetics

treatment performance). However, it is expected that use of thinner maintenance/preservation treatments in a timely manner to preserve existing pavement structure and extend the time between rehabilitation treatments will result in lower life-cycle environmental impacts and cost than allowing pavement to deteriorate to the point and more frequent use of rehabilitation treatments to restore condition.

Strategies for Improving Sustainability of Pavement Preservation and Maintenance Activities

The general strategies for improving sustainability of preservation and maintenance treatments for asphalt-surfaced pavements include limiting the use of new material, use of thinner cross sections, maintaining high levels of smoothness, and increased construction quality. These approaches all reduce environmental burden and contribute to more sustainable treatments. Significant differences may exist in the results of approaches that are used to reduce environmental impacts, depending on project-specific characteristics. For example, as traffic volume increases, maintaining smooth surfaces becomes 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.

Integration of Preservation into Pavement Management Systems

The benefits of pavement management are well documented, and include: support for enhanced planning at the strategic, network and project levels; decision making based on observed and forecasted conditions rather than opinions; and the ability to generate alternate scenarios for future pavement conditions based on different budget scenarios or management approaches.

The integration of pavement preservation into pavement management requires a deliberate effort on the part of transportation agencies to re-evaluate their existing data collection activities, to revise and update performance modeling approaches, and to improve overall program development activities. The desired outcome 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.

SUSTAINABLE STRATEGIES FOR ASPHALT PAVEMENT END OF LIFE

When the pavement reaches its end of life, it may remain in place and reused as part of the supporting structure for a new pavement, recycled in place, or removed and recycled or landfilled. Each of these activities has an economic cost and an environmental impact (consumption of raw materials, energy input, emissions) that should be considered in the end-of-life (EOL) phase.

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.

The economic, environmental, and societal benefits of appropriately *reusing* the existing pavement structure are generally the highest of all end-of-life options for asphalt 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.

Asphalt pavements are recycled and reused at a higher rate than any other construction materials (EPA 2009). Commonly used EOL strategies for asphalt pavements include techniques to recycle materials in a central plant or in place, as described below. According to industry data, in 2012 less than one 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 distribution of the uses of RAP is shown in figure 9.

A Strategy for Optimizing the Use of Recycled Materials

Optimizing the use of recycled materials often implies its use in the highest possible value application (e.g., surface course aggregate as opposed to base or fill applications). However, 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.

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, even when subprime materials are locally available). LCCA and LCA provide the means for determining the critical distance for transporting recycled materials compared to using local virgin materials to ensure efficiency and sustainability.

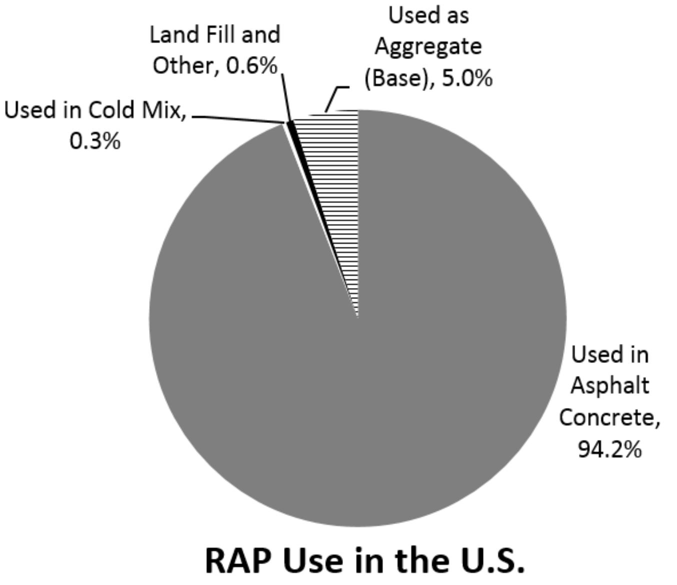


Figure 9. Recycling and reuse statistics of RAP (data compiled from Hansen and Copeland (2013).

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 from different sources may be kept in different stockpiles, or may be blended. It is usually screened into two, or sometimes three, different sizes at asphalt plants (called fractionation). The two techniques of central plant recycling include hot central plant recycling (HCPR) and cold central plant recycling (CCPR).

Blending and fractionating RAP at the central plant increases product uniformity and, consequently, produces more consistent asphalt concrete containing RAP. Issues associated with increased use of RAP in some urban plant locations include the need for more land area and dust control.

The sustainability impact of RAP contents should be quantified over the pavement life cycle using appropriate tools. Horvath (2004), Ventura, Monéron, and Jullien (2008), and, more recently, Aurangzeb et al. (2013) and Aurangzeb and Al-Qadi (2014) discuss environmental benefits and trade-offs of using RAP in pavements from a pavement life-cycle perspective. Figure 10 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 For example, when asphalt mixtures with 30 percent, 40 percent, and 50 percent RAP are used in a 12-inch (300-mm) thick, 12-ft (3.7-m) lane, and 6-ft (1.8-m) shoulder, LCCA showed a net savings of $56,000 to $94,000/mi ($35,000 to $58,000/km), whereas LCA showed energy savings of 800 to 1400 MBTU/mi and GHG reductions of 70 to 117 tons/mi (64 to 106 MT/mi) when 30 percent to 50 percent RAP was added to the asphalt mixtures (Aurangzeb and Al-Qadi 2014).

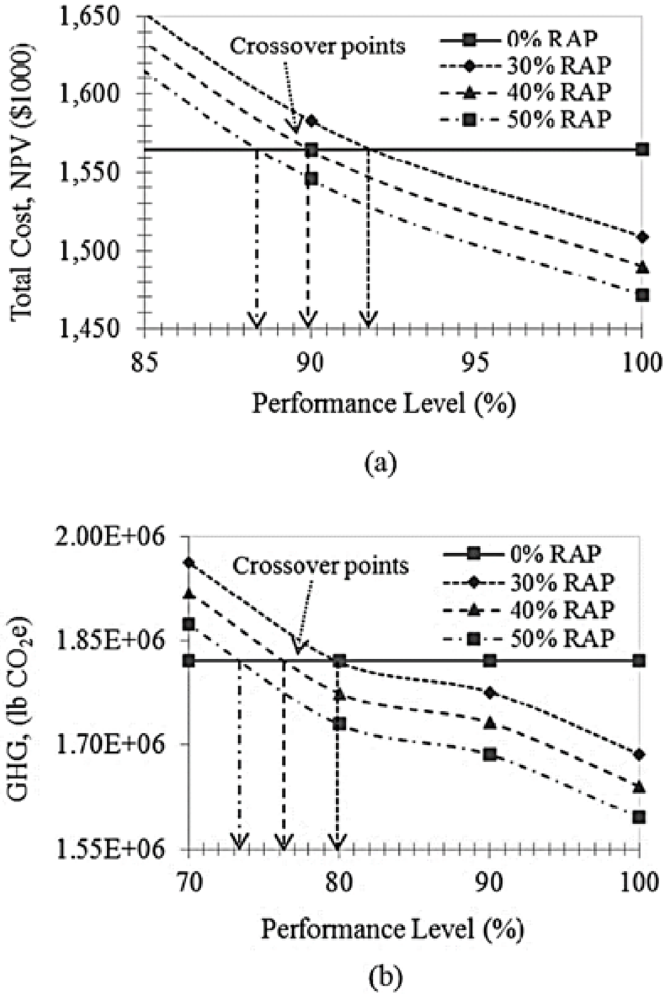


Figure 10. Optimal performance levels of an asphalt layer with varying levels of RAP based on (a) total cost and (b) GHG emissions (Aurangzeb and Al-Qadi 2014).

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 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 including reclaimer, milling machine, stabilizer, pugmill mixer/paver, or a portable crushing and screening unit (Thompson, Garcia, and Carpenter 2009).

There are several comprehensive references that document best practices for FDR construction (e.g., Stroup-Gardiner 2011; Wirtgen 2004; ARRA 2001). At the same time, the successful installation and performance of FDR projects has been well documented in the literature, including in Nevada (Bemanian, Polish, and Maurer 2006); Canada (Berthelot et al. 2007); Minnesota (Dai et al. 2008); Georgia (Smith, Lewis, and Jared 2008); California (Jones et al. 2010); Indiana (Nantung, Ji, and Shields 2011) and Virginia (Diefendorfer and Apeagyei 2011).

Project selection, mixture design, the selection of appropriate additives for the project, and effective compaction are all critical to the effective construction of FDR. 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. 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 asphalt content). The most commonly used additives are portland cement, lime, quicklime, fly ash, asphalt emulsion, foamed asphalt, fly ash and lime, emulsion and lime slurry, cement and emulsion combinations and cement and foamed asphalt combinations. Selection of the additives can vary based on the on-site characteristics and design requirements. The importance of compaction and achieving target density is as critical as selecting the right amount and type of additive (ARRA 2014).

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. It is often true that, as noted previously, the economic, environmental, and societal benefits of appropriately *reusing* the existing pavement structure are generally the highest of all end-of-life options for asphalt pavements, and that the economic and environmental costs of *disposal* are generally quite high. 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. In order to realistically assess the benefits of the various EOL options, all options and their associated costs should be evaluated, including all of the factors that may potentially contribute to the costs and environmental implications of each. These important factors include technology (e.g., on-site or off-site processing), disposal costs (if any materials are to be landfilled), transportation, and the quality of the recycled material.

The reuse and recycling of asphalt pavements results in economic and environmental impacts for both the old and new pavement structures. It is important, therefore, to properly *allocate* costs and benefits related to pavement reuse and recycling between the old and new pavement systems, taking care to avoid double counting in both systems.

Strategies for Improving End-of-Life Sustainability

Some general approaches to improving sustainability with regard to pavement recycling at the end of its life along with associated environmental benefits are summarized below.

- *Use in-place and plant recycling of asphalt pavement materials* following best practices for candidate locations, mix and structural design, and construction quality.
- *Manage RAP stockpiles following best practices*, including fractionation and moisture control.

SUMMARY

This Tech Brief summarizes guidance concerning sustainability considerations for asphalt pavement systems, as presented in detail in FHWA's recently published *Towards Sustainable Pavement Systems: A Reference Document* (FHWA 2015b). 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, recognizing the importance of context sensitivity and assessing trade-offs in developing sustainable solutions.

Several of the strategies, technologies and innovations that have been presented are contributing to asphalt pavement sustainability initiatives, including: reductions in energy and emission levels associated with the production and use of asphalt mixes through increased use of RCWMs, particularly RAP, use of mechanistic-empirical design procedures for more effective pavement structural design, improved use of local and marginal aggregates, adoption of construction practices that improve construction quality, particularly those that improve compaction such as improved quality assurance and use of WMA, use of construction practices that reduce fuel use and GHG emissions, proper application of low-environmental-impact pavement preservation and preventive maintenance activities to prolong pavement life and defer major rehabilitation and reconstruction activities, and increased utilization of RAP materials in the highest feasible applications.

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