APPENDIX 1

June 1993

ENGINEERING AND ENVIRONMENTAL ASPECTS OF RECYCLED MATERIALS FOR HIGHWAY CONSTRUCTION

Final Report

Environmental Protection Agency

Office of Health and Environmental Assessment
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Federal Highway Administration

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Foreword

The information provided in this report constitutes a condensation of a literature search and a survey of highway agencies. The report gives a basic overview and assessment of different technologies, processes, and methods for the recycling of different types of materials into various highway components and for highway construction.

Byron Lord, Acting Director
Office of Engineering and Highway
Operations Research and Development

Notice

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16. Abstract

This report presents an assessment of environmental aspects and engineering factors related to the utilization of recycled materials in highway construction. A basic overview and assessment of different technologies, processes, and methods for recycling of various material into highway appurtenances and for highway construction are presented with consideration of environmental/health risks.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³

NOTE: Volumes greater than 1000 l shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	ac
ha	hectares	2.47	acres	mi²
km²	square kilometers	0.386	square miles	
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

(Revised August 1992)

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

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ACRONYMS

AI	Asphalt Institute
ARAM	Asphalt-rubber and aggregate membrane
ARHM	Asphalt-rubber hot mix
ARPG	Asphalt Rubber Producers Group
ATSDR	Agency for Toxic Substances and Disease Registry
CRAVE	Carcinogen Risk Assessment Verification Endeavor
CRM	Crumb rubber modifier
DNA	Deoxyribonucleic acid
DGHMA	Dense Graded Hot-Mix Asphalt
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
HMA	Hot-mix asphalt
IARC	International Agency for Research on Cancer
IRIS	Integrated Risk Information System
MIBK	Methyl isobutyl ketone (4-methyl-2-pentanone)
NAPA	National Asphalt Paving Association
NAS	National Academy of Sciences
NCAT	National Center for Asphalt Technology
NIOSH	National Institute for Occupational Safety and Health
NMR	Nuclear magnetic resonance
OGFC	Open Graded Friction Course
OSHA	Occupational Safety and Health Administration
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzo-p-dioxins
PCDF	Polychlorinated dibenzofurans
PEL	Permissible exposure level
RAP	Recycled asphalt pavement
RfD	Reference dose
RUMAC	Rubber modified hot-mix asphalt concrete
TACB	Texas Air Control Board
VOST	Volatile Organics Sampling Train
WRI	Western Research Institute

CHAPTER 1. INTRODUCTION

ENVIRONMENTAL CONSIDERATIONS

Environmental health issues related to the production, use, recycling, and disposal of asphalt paving mixtures modified with waste materials, such as scrap tire rubber, plastic, and glass, can be viewed as having two major dimensions:

- The production of new complex mixtures of hazardous materials.
- The redistribution of hazardous components of the modifying agents in the environment.

Both derive from the fact that asphalt cement, rubber, plastic, and glass are complex mixtures that contain hazardous constituent chemicals.

New mixtures will be produced when the components of rubber, plastic, or glass are added to asphalt paving mixtures. The toxicological properties of these modified asphalt pavements may be different from conventional asphalt pavements. Components of the modifying agent and asphalt cement may interact physically or chemically to produce synergistic or antagonistic effects on biological systems. In addition, the fate of the components in the environment may be altered, resulting in changes in exposure profiles. The significance of these potential interactions is that characterization of risks associated with modified asphalt paving mixtures may not be accurately predicted from assessments of conventional asphalt paving mixtures or the modifying agents as separate entities.

Rubber tires, plastic, and glass are currently being disposed of, stored, and recycled to varying degrees. These processes result in the destruction, dilution, or concentration of the hazardous components of these materials in various environmental media and give rise to a continuum of exposure profiles and related risks. Production, application, recycling, and disposal of asphalt pavements modified with rubber, plastic, or glass will result in the removal of some quantity of these materials from the current waste stream and will alter the distribution of the constituent materials in the environment. Exposure patterns will change as a result.

Predicting the change in human and environmental exposures resulting from incorporating modifying agents into asphalt paving mixtures is an enormous challenge. The complexity of the problem can be understood by considering the pathways of human exposure to rubber-derived chemicals during the production, application, and use of asphalt paving mixtures containing crumb rubber modifier (CRM). Similar pathways will be associated with other types of modified asphalt pavements. During storage and processing of scrap tires for the production of CRM for use in asphalt paving mixtures, constituents of rubber will enter and exit intermediate pools that have varying mobilities in certain environmental media. For example, 40-mesh CRM can more easily become airborne than rubber in a stored tire. Some rubber constituents may volatilize during heating of the asphalt-rubber paving mixture. Although stored tires are generally considered to represent a relatively immobile waste pool for rubber, occasionally a tire storage facility ignites and large amounts of hazardous material are rapidly transported into the air. As a result of use of CRM in asphalt pavements, rubber constituents will be transferred from a highly concentrated and relatively immobile waste pool at a tire storage facility to a highly diluted matrix of paved road surfaces. If certain components of rubber are more mobile and more readily transported to water from the asphalt pavement matrix, environmental exposures to these chemicals may be greater near a road surface made of asphalt pavement modified with CRM than near a tire storage facility. On the other hand, release of rubber-derived chemicals from asphalt pavement made with CRM may be no greater than releases that result from tire wear.

The challenge for risk characterization is to analyze both the "new mixtures" and the "redistribution" dimensions to the problem and arrive at quantitative estimates of the net change in risk that will result from production, application, recycling, and disposal of modified asphalt pavements. A complete risk characterization should also consider the relative risk of <u>not</u> producing modified asphalt pavements. For example, the risks associated with altering the existing waste stream via production, use, disposal, and recycling of asphalt pavements modified with CRM should be compared to the risks associated with other tire waste options such as storage or combustion. The overall strategy for developing a risk characterization of this scope is contained in the National Academy of Sciences (NAS) paradigm (described in chapter 2).(1) The major limitation is the availability of high quality data to support dose-response and exposure assessment. In chapter 2 of this report, the available data relevant to risk characterization of modified asphalt pavements are profiled, and select data are analyzed in an attempt to estimate the upper bounds on relative risk of asphalt paving mixtures modified with CRM vs. conventional asphalt paving mixtures.

ENGINEERING CONSIDERATIONS

Background

Over the years, the population growth, changing life styles, new technologies, and the resultant flood of low-cost disposable products have greatly increased domestic waste generation to the point that sanitary landfill sites can no longer accommodate demand. Landfills are quickly reaching capacity and it is becoming more difficult to find new landfill sites due to societal concerns and environmental criteria. Consequently, many areas of the country have developed or attempted to develop recycling programs for the purpose of resource recovery and to reduce the demand for landfill space.

There is, at this time, considerable emphasis on the use of recycled materials for highway construction. Many States have initiated legislation to direct their highway agencies to investigate the possibility of recycling different waste byproducts into highway pavements and/or appurtenances. Section 1038 of public law 102-240, the "Intermodal Surface Transportation Efficiency Act" enacted by Congress on December 18, 1991, directs the U.S. Environmental Protection Agency and the U.S. Department of Transportation, in cooperation with the States, to conduct studies on the use of recycled materials in highway construction. It is hoped that this effort will provide sufficiently detailed information to establish the benefits, disadvantages, and overall feasibility of recycling materials into highway applications.

Technical Problems Associated with Disposal and Recycling of Materials for Highway Applications

The recent status of recycled material utilization in transportation construction has been summarized by Emery and MacKay as shown in table 1.(2) The ranking, number of users, and number of agencies with specifications covering the material's use provide an indication of the material's availability, cost, and feasibility for use in construction. The first four ranked materials (asphalt pavement, concrete, blast furnace slag, and fly ash) are materials that have been commonly recycled or reused in highway construction. Steel slag (ranked fifth) must be carefully evaluated and controlled because of potential problems with expansion due to chemical composition and age. Silica fume is an example of a low quantity material that is being used frequently to produce high strength concrete. Similarly, waste foundry sand and glass are generated in relatively low quantities, which relegates their use to applications near the supply source.

The belief that hot-mix asphalt (HMA) modified by plastics, crumb rubber, or other material will automatically improve pavement properties such as resistance to rutting or durability neglects many other factors involved in long-term performance. Major factors contributing to pavement performance are: (1) subsurface moisture and drainage conditions relative to subgrade soil and granular base characteristics, (2) thickness and quality of granular base materials, (3) asphalt mixture quality and rate of aging of asphalt binders, (4) climatic exposure conditions (freeze-thaw, rapid cooling, high temperature), and (5) characteristics of heavy trucks with different wheel and load configurations.

The concept of using recycled materials as an additive to conventional pavements is more difficult than if the recycled materials were used to fabricate specific appurtenances (e.g., plastic fencepost) on highways due to the complex and variable nature of HMA. Basically, all highways utilize gravels, sands, crushed stone, or synthetic aggregates for the construction of pavements (both asphalt and concrete). The availability, engineering properties, and costs for these aggregates vary from one locality to the next. The specifications, especially for the particle size distribution for asphalt mixtures, concrete mixtures, or base and subbase courses, vary between States. Consequently, the addition of any particulate type recycled material (crushed glass, crumb rubber, fly ash, etc.) often requires modification of aggregate gradation specifications to accommodate the recycled material without adversely affecting quality.

Current HMA specifications, among other criteria, specify the selection of crushed aggregate that has a desired gradation (particle size distribution). Although two or more different aggregates may be blended to meet specifications (e.g., for asphalt paving mixture), the addition of recycled materials may necessitate changing the aggregate producer's operations and/or State specifications. It is not always possible to add other materials (e.g., recycled materials) to conventional asphalt paving mixtures, portland cement concrete, or

Table 1. Provincial and State use of wastes and byproducts in transportation construction.[1]

Rank[2]	Material	Users		Specifications	
		P[3]	S[4]	P	S
1	Old Asphalt	10	42	3	19
2	Old Concrete	4	29	1	8
3	Blast Furnace Slag				
	Air-Cooled	2	18	1	12
	Pelletized	1	1	1	
	Granulated	1	15	1	2
4	Fly Ash	4	46	1	12
5	Steel Slag	4	18	1	4
6	Silica Fume	4	15	1	2
7	Nickel and Copper Slags	2	2	1	1
8	Bottom Ash	2	6		1
9	Mine Waste Rock	4	10		
10	Waste Tires	2	19		5
11	Kiln Dusts				
	Lime	1	6		
	Cement		3		
12	Waste Foundry Sand	1	2		
13	Waste Glass	1	2	1	2
14	Waste Shingles	1	1		

[1] Summarized from a survey of transportation departments completed during the first quarter of 1991. Also includes specific city and demonstration uses. Survey response achieved was 100 percent.

[2] Rank is based on an overall evaluation of current and potential uses in terms of material availability, technical suitability, favorable economics and positive environmental impact.

[3] P - Provinces. Number out of 10 Provinces, plus the Yukon and Northwest Territories.

[4] S - States. Number out of 50 States, plus the District of Columbia.

granular base courses without reducing strength, durability, overall performance, and/or cost-effectiveness.

Another important aspect of using recycled materials such as crumb rubber from discarded tires is the recyclability of asphalt pavements containing crumb rubber. Currently, there is very little experience with recycling asphalt pavements containing crumb rubber. A significant consideration in the use of recycled materials in asphalt or concrete pavement is whether or not it has subsequent or cascading effects upon recycling of pavement or reuse of the pavement materials. If the capability of recycling pavements is lost, then the magnitude of the disposal problem has been escalated with the end result being that the recycling of waste byproducts has been greatly diminished.

FORMULATION AND RESPONSE TO SURVEYS OF HIGHWAY AGENCIES

The initial research effort was concentrated on the documentation of literature pertaining to the use of recycled materials in highway construction and the formulation of detailed spreadsheets for each major topic area (material type) as given in the following list:

- A1A Hot-Mix Asphalt Containing Crumb Rubber Modifier (15 pages).
- A1B Asphalt Rubber Spray Applications (11 pages).
- A1C Recycling of Hot-Mix Asphalt Pavements Containing Crumb Rubber (18 pages).
- B1A Recycling of Pavements Using Over 80 Percent RAP (14 pages).
- B1B Plastics in Highway Construction (11 pages).
- B1C Crushed Glass in Highway Construction (7 pages).
- B1D Reuse, Recycling, and Disposal of Other Recycled Materials Used in Highway Construction (13 pages).

The first survey forms (SUR-1) titled "Disposal/Utilization of Materials Removed from Highways" were mailed to highway agencies' construction engineers (appendix A). The second mailing included the second and third one-page survey forms (SUR-2 and SUR-3), entitled "Information Urgently Needed and Critical to Our Survey of Hot-Mix Asphalt Containing Crumb Rubber Modifier (CRM)," and "Information That is Needed and Critical to Our Survey on Recycling of Hot-Mix Asphalt Pavements Containing Crumb Rubber Modifier," respectively. These two survey forms, cover letter, and a shortened version of the detailed spreadsheets may be found in appendix B.

The response to these questionnaires are summarized by State, Province, or municipality in table 2. Those agencies that responded may have indicated some form of activity in the recycling of a given material or they may have excluded the material from use. In some

Table 2. Summary of responses to surveys.

STATE	Sur1	Sur2	Sur3	A1A	A1B	A1C	B1A	B1B	B1C	B1D
Alabama	+									
Alaska	+	+								
Arizona	+	+	+	+	+	+	+	+	+	+
Arkansas	+									
California	+	+								
Colorado	+	+	+	+	+	+	+	+	+	+
Connecticut	+	+	+	+	+	+	+	+	+	+
Delaware										
Florida	+	+	+	+	+		+		+	
Georgia	+	+		+	+	+	+	+	+	
Hawaii		+	+						+	
Idaho	+	+	+	+	+	+	+	+	+	+
Illinois	+	+	+	+	+	+	+	+	+	+
Indiana	+	+		+						
Iowa	+	+		+						
Kansas	+	+	+							
Kentucky	+	+	+	+	+	+	+	+	+	+
Louisiana	+	+	+							
Maine	+	+	+	+	+	+	+	+	+	+
Maryland	+	+	+	+	+	+	+	+	+	+
Massachusetts	+									
Michigan	+	+	+	+	+	+	+	+	+	+
Minnesota	+	+			+				+	
Missouri	+	+		+	+				+	+
Mississippi	+	+		+			+			
Montana										
Nebraska	+	+		+			+			
New Hampshire	+	+	+			+	+	+	+	
New Jersey		+	+	+					+	
New Mexico		+		+	+	+	+			
New York	+	+	+	+	+	+	+	+	+	+
Nevada										
North Carolina		+					+			
North Dakota	+	+	+	+	+	+	+	+	+	+
Ohio	+	+		+			+			
Oklahoma	+	+		+			+			
Oregon	+	+		+	+		+	+		+
Pennsylvania	+	+		+	+	+	+	+	+	+
Rhode Island	+	+	+				+			
South Carolina	+	+	+	+	+	+	+	+	+	+
South Dakota	+						+			
Tennessee	+									
Texas	+	+	+	+	+	+	+	+	+	+
Utah	+	+	+	+	+	+	+	+	+	+
Vermont	+	+	+	+	+	+	+	+	+	+
Virginia	+									
Washington	+						+			
W. Virginia							+			
Wisconsin	+	+								
Wyoming	+	+	+	+						
No. States Responding	42	39	23	29	22	19	30	19	23	18

CANADA
Province

Alberta	+		+	+	+	+	+	+	+	+
Manitoba	+									
N. Brunswick	+									
Nova Scotia	+						+			
Ontario	+	+	+	+		+	+		+	
Saskatchewan	+									

cases, the highway agency submitted detailed research reports that have been reviewed and suitable information documented on the survey forms and/or the spreadsheet questionnaires.

TECHNICAL APPROACH FOR SEARCH AND EVALUATION OF LITERATURE ON HUMAN HEALTH AND ENVIRONMENTAL RISKS

The initial focus was to identify existing scientific literature and data that might be relevant to characterizing relative human health and environmental risks associated with the manufacture, application, and recycling of conventional vs. modified asphalt pavements. A literature search was conducted with the objective of profiling the types of information that are currently available to support an assessment of relative risk and to identify information gaps. The results of this search were captured in an annotated bibliography.

As it became apparent that existing data were inadequate to support a complete characterization of relative risk, effort was redirected towards evaluating the few available studies in which hazardous emissions from conventional and modified asphalt paving mixtures were compared. The rationale was that it might be possible to use the results of these studies to project exposures to humans and the environment, and thereby establish upper and lower bounds on the magnitude of relative risk.

Production of Annotated Bibliography[3]

The annotated bibliography includes studies related to the following topics:

- Composition, environmental chemistry, environmental effects, and health effects of conventional asphalt paving mixtures and asphalt paving mixtures modified by the addition of crumb rubber, plastic, or glass.
- Chemicals released to the environment from rubber, plastic, and glass.
- Chemical hazards associated with alternative means of tire disposal and recycling.
- Environmental chemistry, environmental effects, and health effects of chemicals released into the environment from asphalt paving mixtures.

The bibliography was assembled by identifying relevant studies; indexing these studies with keywords that characterize the content of each study and provide a mechanism for sorting the bibliography by subject; and entering brief comments regarding the methods, results, or content of each study.

Identification of Relevant Studies

Relevant studies were identified by computer literature searches, tree-searches of review articles, discussions with scientists and engineers at the Federal Highway Administration (FHWA), Environmental Protection Agency (EPA), Western Research Institute (WRI), and the University of Florida, and phone queries to selected manufacturing and regulatory organizations involved in highway construction or materials manufacture, including the National Asphalt Paving Association (NAPA), Asphalt Institute (AI), National Center for Asphalt Technology (NCAT), and Asphalt Rubber Producers Group (ARPG).

Computer searches of on-line bibliographic data bases were initially conducted to identify reports on "asphalt"; separate search strategies were used to capture information on composition and environmental chemistry, environmental effects, or health effects. Each strategy was applied to several electronic data bases, including:

- CAS on-line (primarily chemistry information).
- TOXLINE (primarily toxicity information).
- NTIS (government publications).
- APILIT (petroleum industry data base).
- COMPENDEX (engineering and technology data base).
- CIN (chemical industry information).

Searches by CAS number were also conducted, including searches of the following data bases:

- EFDB (environmental fate information).
- TSCATS (unpublished environmental fate, exposure, environmental effects, and health effects information).

Literature searches were screened by environmental chemists and toxicologists to identify pertinent studies. Reports that contained information on environmental emissions were retrieved and the data were reviewed to identify the chemicals that had been shown to be released into the environment. Available emissions studies are limited to asphalt and asphalt modified with CRM, and generally limited to measurements of priority toxics (e.g., air and water toxics). The latter limitation reflects the focus of these studies on detecting potential noncompliance with State and Federal pollution laws. As a result, many chemicals in crumb rubber and other asphalt modifiers have not been monitored. In order to identify chemicals that have the potential for release into the environment, computer searches were conducted for sources of information on leaching and volatilization from tires, rubber, plastic, and glass, and information regarding composition, disposal, and recycling of tires. These reports were reviewed to identify potential emissions.

Searches were conducted to identify authoritative reviews, including those prepared by the EPA, Agency for Toxic Substances and Disease Registry (ATSDR), National Institute for Occupational Safety and Health (NIOSH), and Occupational Safety and Health Administration (OSHA), on the environmental chemistry and health and environmental effects of chemicals reported to be emitted from conventional or modified asphalt pavements. For some emitted chemicals, reviews were not located and it was necessary to conduct additional computer literature searches to identify primary sources of information on the environmental fate and toxicity of the chemical.

Assignment of Index Keywords and Comments

Reports were indexed using a standardized scheme. The keywords allow the user to quickly determine the subject of any study in the bibliography, including for example, such details as the test material, the endpoints examined, the species tested, and the route of exposure for a toxicity study. The keywords also allow sorting of the bibliography for selected review of entries on a specific subject (e.g., all human epidemiology studies on asphalt). Comments were recorded as needed to summarize important study details that could not be accommodated in the keyword index, as well as results.

Literature Survey and Review

The identified literature was surveyed for information pertinent to performing an assessment of the relative health risks of conventional asphalt pavements vs. asphalt pavements modified by the addition of CRM, plastic, or glass. Health effects data were available only for conventional asphalt paving mixtures. Therefore, it was not possible to do a comparative risk assessment using traditional methods. However, several studies were located that compared air emissions from conventional asphalt paving mixtures to asphalt paving mixtures modified by the addition of CRM. These studies were reviewed in detail in the hope that it might be possible to use the results of these studies to project exposures to humans and the environment, and thereby establish upper and lower bounds on the magnitude of relative risk.

The studies that were reviewed fall into three groups: studies of environmental emissions from asphalt hot-mix plants during virgin operation, studies of environmental emissions from asphalt hot-mix plants using recycled asphalt pavement (RAP), and studies of worker exposure from asphalt mixing plant operations and road-paving operations. For each pertinent study, emissions profiles for conventional and rubber-modified asphalt paving mixtures were compared. Studies within each of the three groups were also compared to each other and to additional, similarly-designed studies of conventional asphalt pavement emissions in an attempt to identify patterns that could point to differences in relative risk between conventional and rubber-modified asphalt paving mixtures.

None of the available studies that contained comparisons of emissions from conventional and modified asphalt pavements included a sampling regimen adequate to support statistical testing for differences in emissions between conventional and modified asphalt pavements.

Therefore, comparisons were based on mean values and offer only rough indications of trends in the data. Comparisons of results between different studies were based on means, or even ranges, and were useful only for indicating broad patterns in the data.

REPORT ORGANIZATION

This report has been formulated to provide a synthesis of available information relating to environmental/health aspects, physical characteristics, and the engineering considerations involved in the use of recycled materials in highway construction. Considerable emphasis has been placed upon recycled material utilization in pavements since this has considerably more impact on the quality and longevity of our highway system than the use of recycled materials for highway appurtenances (e.g., signs, guardrail posts, fence posts, etc.).

Information on the use of recycled materials and their environmental/health consideration has been derived from an extensive literature search. The intent of the report is to provide a fairly concise, but comprehensive, overview of the most important aspects regarding use of recycled materials in highway construction. The references and bibliography are documented to allow the reader to investigate any subject area in more detail. It is not intended that the report be all-inclusive and reiterate all aspects and detail provided in the literature. Rather, it is the intent that the reader gain a good perspective or overview of the status of current technology, potential or actual benefits, problems or disadvantages, and the need for further research.

Another source of key information was obtained from survey forms and questionnaires sent to the different State (Provincial) highway agencies. A one-page questionnaire on each of the following topics and a letter of transmittal was sent to different highway agencies:

- Hot-Mix Asphalt Containing Crumb Rubber Modifier.
- Recycling of Hot-Mix Asphalt Containing Crumb Rubber Modifier.
- Disposal/Utilization of Materials Removed from Highways.

Additional detailed spreadsheet questionnaires were included in the mailing. The requested information pertained to the following subjects:

- Hot-Mix Asphalt Containing Crumb Rubber Modifier.
- Asphalt-Rubber Spray Applications.
- Recycling of Pavements Using Over 80 Percent RAP.
- Plastics in Highway Construction.
- Crushed Glass in Highway Construction.

- Reuse, Recycling, and Disposal of Other Recycled Materials Used in Highway Construction.

The data derived from these survey forms were analyzed to evaluate the current level of activity of the different agencies in their utilization of recycled materials in highway construction. Also, information regarding performance or problems with pavements and appurtenances containing or made from recycled materials was evaluated and summarized according to each type of recycled material.

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1. National Academy of Sciences, *Risk Assessment in the Federal Government: Managing the Process*, Washington, DC: National Academy Press (1983).

2. John Emery and Michael MacKay, *Use of Waste and By-Products as Pavement Construction Materials*, presented at the 1991 TAC Annual Conference, Winnipeg, Manitoba, Canada (paper available from John Emery Geotechnical Engineering Limited, Downsview, Ontario).

3. Unpublished Report, *Annotated Bibliography: Human Health and Ecological Risks Associated with the Manufacture, Application, and Recycling of Asphalt Paving Materials Containing Crumb Rubber, and Other Materials Reclaimed from Commercial and Municipal Waste Streams*, U.S. Federal Highway Administration, Washington, DC (1993).

CHAPTER 2. ENVIRONMENTAL ASSESSMENT

RISK ASSESSMENT OF ASPHALT PAVING MATERIALS AND MODIFIED ASPHALT PAVING MATERIALS

Risk Assessment—Definitions and Basic Concepts

Risk assessment is defined for the purpose of this study as the qualitative or quantitative characterization of the potential adverse effects of a chemical on human health or the environment. Risk assessment can be thought of as an integration of four processes (figure 1):(1)

- Hazard identification.
- Dose-response assessment.
- Exposure assessment.
- Risk characterization.

Hazard Identification	Does the chemical produce adverse effects?
Dose-Response Assessment	What is the relationship between dose and adverse effect?
Exposure Assessment	What exposures occur or are anticipated?
Risk Characterization	What is the estimated incidence of adverse effect at a given exposure?

Figure 1. Elements of risk assessment.

Hazard Identification

The objective of the hazard identification is to identify chemical properties or characteristics that may initiate or contribute to adverse ecological or human health effects. Hazard identification is usually the initial step in a risk assessment. Hazard identification results in information used for dose-response and exposure assessments, which are integrated in risk characterization to estimate the incidence of adverse effects associated with a given exposure scenario.

Hazard identification consists of data collection and analysis, with a focus on the following issues:

- The validity and meaning of experimental and monitoring data.
- The weight-of-evidence that a substance causes a given toxic effect or will persist in the environment.
- The likelihood that the effect observed in a given population (e.g., experimental animals) will occur in other populations (e.g., humans).

Hazard identification is not limited to specific exposure scenarios; this is deferred to the exposure assessment and risk characterization phases of risk assessment. The risk characterization phase determines if the conclusions of hazard identification are relevant to a specific exposure scenario. For example, hazard identification considers whether or not a chemical can potentially cause cancer in humans, not whether cancer is likely to occur within a given population living near an emission source.

Hazard identification encompasses a review of all data relevant to evaluating or predicting the environmental fate and toxicity potential of a chemical. This includes the analysis of structure-activity relationships that provide additional insight regarding the fate or toxicity potential of the chemical.

Dose-Response Assessment

The objective of dose-response assessment is to characterize the relationship between the dose of the chemical and incidence or severity of adverse effect. Dose-response functions are usually established in experimental studies in which the dose can be rigorously controlled and the response rigorously evaluated. It is usually feasible to examine only the high dose region of the dose-response relationship in experimental studies; therefore, dose-response assessment often involves extrapolating response rates from high to low doses. This is usually accomplished through the use of probabilistic models. Epidemiological studies can provide information about response rates at doses associated with environmental or occupational exposure levels, although causal relationships between exposure and response are often obscured by exposures to other hazards. Experimentally derived dose-response functions can sometimes be validated with epidemiological studies. Dose-response assessment considers and attempts to quantify uncertainties related to extrapolating dose-response functions across species, age, sex, and subpopulations.

Exposure Assessment

The objective of exposure assessment is to quantify the magnitude, frequency, and duration of exposure to humans or other organisms that might be adversely affected by exposure to a chemical. Exposure can occur through various environmental media such as air, food, water, and soil. The exposure medium determines the physiological routes through which exposure is translated into dose, for example, inhalation; ingestion; or absorption across skin, gills, or roots. Exposure assessment also considers indirect routes of exposure, for example, bioconcentration in food or prey organisms.

Exposure assessment considers the fate of chemicals released from the source and estimates the levels that would be expected to occur in relevant environmental media as a function of time, direction, and distance from the source. This information can be used to estimate dose to an organism at a specific location over a specific length of time. Numerous variables can affect transport and persistence of a chemical in the environment. These include rates of abiotic and biodegradation, water solubility, adsorption to soil, volatility, and dispersion and diffusion in air and water. These variables are, in turn, dependent on the physical and chemical properties of the chemical, characteristics and location of the source, and numerous environmental variables such as wind velocity, precipitation, soil characteristics, topography, and ground and surface water characteristics. Exposure assessment often relies on a combination of environmental monitoring and theoretical models of fate processes to simulate exposure gradients.

Risk Characterization

The objective of risk characterization is to predict the incidence of adverse effects that will result from a given exposure scenario. Risk characterization integrates dose-response assessment with exposure assessment. Risk characterization may assign quantitative contributions to sources of risk that are relevant to managing risk, for example, the contribution of various exposure pathways to total risk (e.g., inhalation of air vs. ingestion of food vs. dermal contact with water). Other dimensions of risk may also be considered in a risk characterization, such as risk gradients across species, age, sex, geographic location, or socioeconomic status. Assigning values to various dimensions of risk allows the risk manager to weigh mitigation or remediation options relative to the magnitude each will have on total risk.

Risk characterization considers uncertainties in the hazard identification, dose-response assessment, and exposure assessment. Sources of uncertainties are identified and quantified, if possible, in absolute or relative terms in order to assess the confidence in the risk estimates. Examples of sources of uncertainty include: interspecies extrapolations, extrapolations of risks from less-than-chronic exposure to lifetime exposure, extrapolations across routes of exposure, extrapolation from one subpopulation to another (e.g., adults to children), and inadequate information about exposure or dose-response relationships.

Risk Assessment of Complex Mixtures

Risk characterizations of complex mixtures such as asphalt present a unique set of problems and uncertainties.(2) The U.S. Environmental Protection Agency (EPA) recommends three approaches to risk assessment of complex mixtures that should be selected based on the availability and quality of data on the:[(2)]

- Mixture of concern.
- Similar mixtures.
- Components of the mixture.

The ideal risk characterization would be based primarily on data on the incidence of adverse effects in populations or organisms exposed to the exact "mixture of concern"; however, such data are difficult to obtain and are usually not available. It is important to emphasize that the "mixture of concern" is a dynamic concept. A plant producing asphalt-rubber hot mix (ARHM) will produce a continuum of mixtures of varying composition in the environment as a result of environmental fate processes acting on each chemical in the emissions mixture. Thus, the "mixture of concern" will change across time and space; for example, it will be different for a worker at an asphalt production facility than for a person residing several miles upwind from the plant or several miles downwind from the plant. It will also be different for different target populations at a given location or time; for example, the "mixture of concern" for a human will be different from that for soil invertebrates or aquatic species.

Experimental and epidemiological approaches can be used to assess risks associated with a given mixture of concern. For example, an array of soil samples can be collected from specific locations in the vicinity of an asphalt plant and subjected to toxicity bioassays. Such studies may identify hazards and establish dose-response relationships for the mixtures at those locations; however, greater uncertainty will be associated with extrapolation to other locations. Epidemiologic studies can capture more realistic profiles of environmental exposures (at least as it applies to the target population studied). However, subjects are usually exposed to other hazards in addition to the mixture of concern, making it more difficult to establish causal relationships and dose-response relationships that can be extrapolated to different exposure scenarios.

Studies of "similar" or "surrogate" mixtures can be used to support a risk characterization of the mixture of concern. For example, if the objective is to characterize the health risks in a population residing several miles upwind from an asphalt plant producing ARHM, the mixture of concern would be the exposure mixture at that location. A laboratory study in which mice are exposed to the ARHM, or an epidemiology study of workers at the asphalt plant producing ARHM, are studies of "similar mixtures" because the study mixture may not have the same composition as the "mixture of concern"; the change in the composition of the emissions across time, distance, and direction from the source is not simulated in these studies. Studies of "similar mixtures" can provide information about hazard identification or dose-response functions. However, greater uncertainty is associated with applying this information to assessments of risk associated with the "mixture of concern."

Risk assessments of complex mixtures can also be based on a "component" approach. In this approach, exposure and dose-response assessments of the hazardous components of the mixture are integrated into an estimate of combined risk. This approach relies on the availability of high quality data on the composition of the mixture, dose-response relationships and environmental fate of the various components, environmental monitoring of the mixture components, and certain critical assumptions about the interactions, or lack of interactions, between components. If it is assumed that the components do not interact toxicologically, then combined risk may be estimated as the sum of risks associated with the individual mixture components. This approach may underestimate or overestimate combined risk if synergistic or antagonist interactions occur.

Risk Assessment—Major Issues Related to Modified Asphalts

In the context of the National Academy Sciences (NAS) paradigm, the major issues that must be addressed in order to assess the relative risks of manufacture, application, recycling, and disposal of asphalt paving mixtures modified with rubber, plastic, or glass can be summarized as follows:(1)

- Are the chemical compositions of conventional and modified asphalt paving mixtures, and emissions from production, application, and recycling of these mixtures, adequately characterized to support hazard identification?
- Are environmental monitoring data adequate to support assessments of exposure to humans or other organisms in the environment?
- Is the information on the environmental fate and toxicity of the major hazardous constituents of asphalt pavements and modifying agents adequate to support exposure models?
- Is there adequate information on dose-response relationships for components of conventional and modified asphalt paving mixtures, and/or for the "mixtures of concern" or "similar mixtures"?
- Are the toxicologic interactions that occur between the chemical constituents of modified asphalt pavements adequately characterized?

HAZARD IDENTIFICATION/DOSE-RESPONSE ASSESSMENT

In this section, information on the composition and health effects of conventional asphalt paving mixtures are summarized. A brief discussion is presented on the possible components of asphalt pavements modified by the addition of CRM. No information on the human health effects or environmental effects of asphalt pavements modified with CRM was located. Furthermore, no information on the composition or human health and environmental effects of asphalt pavements modified with other types of waste materials or on recycled asphalt paving material modified with CRM was located.

Conventional Asphalt Pavement

Composition

Asphalt cement is a complex mixture of aromatic and paraffinic compounds with a molecular weight range of 500 to at least 2,500.(3,4) The components present in a particular asphalt cement are dependant on the source of the crude oil from which the asphalt cement was obtained, as well as the exact processing conditions used to manufacture and process the asphalt cement. Thus, a complete chemical analysis of an asphalt cement would necessarily apply only to that specific asphalt cement and could not reasonably be applied to other asphalt cements with different origins and processing methods. Asphalt cements are not manufactured to a specific composition, rather they are manufactured and sold to comply with performance-based specifications. Nonetheless, polycyclic aromatic hydrocarbons (PAH) such as naphthalene, fluorene, anthracene, fluoranthene, and benzopyrenes, and long chained hydrocarbons (e.g., nonane, decane, and dodecane) have been consistently detected in asphalt cements from diverse sources and manufacturing conditions. (See references 5 through 9.) table 3 shows some of the chemicals commonly found in asphalt cement.

Aged or weathered asphalt pavement is chemically different than new asphalt pavement. No data were found in the available literature concerning the chemical composition of aged asphalt pavement. Some information, however, is available concerning the types of chemical changes that accompany the aging process.(10) In general, aging is accompanied by an increase in the asphaltene content of the asphalt cement (asphaltenes are large, complex nonpolar molecules) by condensation of oils and resins (polar materials) to asphaltenes. Asphaltenes, however, undergo oxidation to produce lower molecular weight materials with increased oxygen content.

Health Effects of Asphalt

The discussion herein is restricted to an overview of potential health effects of asphalt and PAH, a class of compounds that are thought to be responsible, at least in part, for the carcinogenicity of certain fossil fuels and their products. The PAH are an example of hazardous components of asphalt. Other hazardous chemicals are present in asphalt and may contribute to the toxicity of asphalt (e.g., benzene). The association between certain fossil fuel products and their constituents (e.g., mineral oils and certain monocyclic aromatic hydrocarbons and PAH, such as benzene and benzo[a]pyrene) and skin cancer in humans and laboratory animals has focused research on the ability of petroleum products, including asphalts, to produce cancer. The EPA currently has no guidelines regarding the carcinogenic or noncarcinogenic health hazards presented by asphalt, and ATSDR has not prepared a toxicological profile on asphalt.(11,12)

Some of the studies available on the health effects of asphalt involved exposure specifically to paving asphalt, but others were based on exposure to roofing asphalt or mastic asphalt. Although there may be some differences in composition between the various types

Table 3. Some commonly found chemicals in asphalt.(6,7,28)

CAS Number	Chemical Name
50-32-8	Benzo[a]pyrene
53-70-3	Dibenz[a,h]anthracene
53-70-3	1,2,5,6-Dibenzanthracene
56-49-5	3-Methylcholanthrene
56-55-3	Benz[a]anthracene
71-43-2	Benzene
83-32-9	1,2-Dihydroacenaphthylene
85-01-8	Phenanthrene
86-73-7	Fluorene
86-74-8	9H-Carbazole
91-20-3	Naphthalene
92-24-0	Tetracene
98-86-2	Acetophenone
100-52-7	Benzaldehyde
108-88-3	Toluene
111-65-9	Octane
111-84-2	Nonane
112-40-3	Dodecane
112-95-8	Eicosane
120-12-7	Anthracene
124-18-5	Decane
129-00-0	Pyrene
142-82-5	Heptane
191-07-1	Coronene
191-97-2	Benzo[g,h,i]perylene
192-97-2	Benzo[e]pyrene
193-39-5	Indeno[1,2,3-cd]pyrene
198-55-0	Perylene
206-44-0	Fluoranthene
207-08-9	Benzo[k]fluoranthene
208-96-8	Acenaphthylene
217-59-4	Triphenylene
218-01-9	Chrysene
544-76-3	n-Hexadecane
593-45-3	Octadecane
629-50-5	Tridecane
629-59-4	Tetradecane
629-62-9	Pentadecane
629-78-7	Heptadecane
629-92-5	Nonadecane
629-94-7	Heneicosane
629-97-0	Docosane

Table 3. Some commonly found chemicals in asphalt (Continued).(6,7,28)

CAS Number	Chemical Name
629-99-2	Pentacosane
630-01-3	Hexacosane
630-02-4	Octacosane
630-03-5	Nonacosane
632-51-9	1,1',1'',1'''-(1,2-Ethenediylidene)tetrakisbenzene
638-67-5	Tricosane
638-68-6	Triacontane
646-31-1	Tetracosane
1120-21-4	Undecane
1330-20-7	Xylene
25551-13-7	Trimethylbenzene
26140-60-3	Terphenyl
28804-88-8	Dimethylnaphthalene

of asphalts, there are also many similarities. Because the data base on paving asphalt itself is not complete, studies of the toxicity of all types of asphalts were included in the discussion, so as not to exclude potentially relevant information.

Several epidemiology studies have investigated the relationship between exposure to asphalt and health effects in humans. Hammond et al. demonstrated a statistically significant association between long-term occupation in the roofing industry (> 20 years) and elevated mortality from cancer of the lung.(13) A significantly increased risk of lung cancer among roofers was also reported by Menck and Henderson.(14) Additional supporting data were obtained by Milham, who reported elevated proportional mortality ratios for lung and laryngeal cancer among roofers.(15) Interpretation of these studies with respect to the ability of asphalt to cause cancer is complicated because roofers in these studies may have been exposed to fumes of petroleum-based asphalt and/or fumes of coal-tar pitch, a material that is more enriched in benzo[a]pyrene and other PAH than is asphalt, and adjustments for confounding exposure to other carcinogens (e.g., tobacco smoke) were not made.(16)

A series of studies were recently conducted by Hansen.(17-19) Hansen found that mortality due to cancer was significantly higher among older, unskilled workers in the Danish asphalt industry than among older, unskilled workers from other Danish industries.(17) Nonsignificant increases in mortality were seen for respiratory, digestive, and bladder cancers, while a significant increase was found for brain cancer. However, this study was compromised by classification of exposure category based only on employment on the date of the census. In another study, Hansen studied a historical cohort of heavily exposed mastic asphalt workers and found that cancer mortality was significantly increased compared to the total Danish male population.(18,19) Tumor sites with significantly increased mortality were the lung, mouth, esophagus, and rectum. Confounding variables, such as smoking, urbanization, and potential exposure to coal-tar pitch were controlled. Mortality due to liver cirrhosis and respiratory diseases (bronchitis, emphysema, and asthma) were also elevated in the mastic asphalt workers. The Occupational Safety and Health Administration (OSHA) has proposed a permissible exposure level (PEL) derived from the study by Hansen showing significantly increased risk of lung cancer in Danish mastic asphalt workers.(20)

Studies of the health effects of asphalt in animals consist mostly of skin painting and injection studies. The results of these studies were mixed. Hueper and Payne found that four paving asphalt cements of differing manufacture produced mild-to-moderate carcinogenic responses in mice, rabbits, and rats exposed for up to 2 years by dermal application or intramuscular injection.(21) Simmers et al. reported that a pooled sample of six petroleum asphalts (including some that were air-blown) produced a high incidence of malignant tumors at the site of treatment in mice tested by skin painting and subcutaneous injection.(22) Bingham and Barkely found malignant skin tumors in 9 of 17 mice treated with twice weekly dermal applications of a "raw petroleum pitch" dissolved in toluene.(23) On the other hand, negative results were obtained in studies of eight paving grade asphalt cements, a penetration grade 150-200 asphalt cement, and a roofing asphalt.(9,24,25)

The International Agency for Research on Cancer (IARC) concluded that there was sufficient evidence for the carcinogenicity of extracts of steam-refined bitumens and air-refined bitumens in experimental animals, limited evidence for the carcinogenicity of undiluted steam-refined bitumens and cracking residue bitumens, and inadequate evidence that undiluted air-refined bitumens are carcinogenic to animals or that bitumens are carcinogenic to humans.(26,27) Bingham et al. concluded from their review of the animal experiments that the "potential for inducing cancer by petroleum-derived asphalts, which in certain instances is clearly less than that of coal tar products, is dependent in a complex way upon their source and is influenced by refining history and the processing of the final mixtures."(16)

In a study completed after IARC's review, Niemeier et al. observed statistically significant elevations of skin tumor incidence in two different strains of mice treated with cyclohexane/acetone solutions of fume condensates from heated type I or type III roofing asphalts; the fumes were generated at approximately 200 °C or 300 °C.(28) This study also examined the carcinogenicity of fume condensates from type I or type III coal-tar pitch and found carcinogenic responses to these materials as well. PAH, including naphthalene, benzo[a]pyrene, and benzofluoranthenes, were detected in condensed fumes from asphalt and coal-tar pitch, but the PAH concentrations were approximately 10-fold to 100-fold higher in coal-tar pitch fume condensates than in fume condensates from roofing asphalts. The investigators noted that the magnitude of the differences in PAH concentrations (particularly benzo[a]pyrene) between asphalt and coal-tar pitch fume condensates was not in scale with the carcinogenic response to the two types of materials and speculated that compounds other than PAH (e.g., aliphatic hydrocarbons) may have enhanced the carcinogenic activity of the low amounts of PAH in the asphalt materials. Nuclear magnetic resonance (NMR) analysis of the fume indicated that less than 1 percent of the asphalt fume material used in this experiment was aromatic, and greater than 99 percent was aliphatic, whereas the coal-tar pitch fume contained more than 90 percent aromatic compounds.

Studies have shown that extracts of bitumen and bitumen fumes were not mutagenic in *Salmonella* and did not produce deoxyribonucleic acid (DNA) unwinding in rat liver *in vivo*.(8,29,30) Application of a "black bitumen paint" to human skin (*in vitro*) or mouse skin (*in vivo*) produced damage to skin DNA (i.e., DNA adducts detected by ^{32}P-postlabeling).(31,32) The test material was not chemically characterized by the investigators, but was described as a commercial preparation containing 57 percent (v/v) bitumen; it is not clear whether the material was derived from coal-tar or petroleum distillation residue.

Health Effects of Polycyclic Aromatic Hydrocarbons (PAH)

U.S. EPA reviewed the available research literature on 15 PAH found in the environment.(33) PAH are, in general, well-studied as mutagenic agents in short-term tests and as carcinogens in animals. U.S. EPA presented evidence for cancer weight-of-evidence classifications of group B2, probable human carcinogens, for seven PAH's (benzo[a]anthracene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, chrysene, dibenzo[a,h]-anthracene, and indeno[1,2,3-cd]pyrene) based on inadequate evidence of carcinogenicity in humans and adequate evidence in animals.(33) These classifications were verified by the Carcinogen Risk Assessment Verification Endeavor (CRAVE) Work Group and are listed on the U.S. EPA Integrated Risk Information System (IRIS).(11) Data were considered sufficient to derive a quantitative risk estimate for oral exposure for only one of the seven PAH — benzo[a]pyrene. Evidence for classifications of group D, not classifiable as to human carcinogenicity, were presented for eight PAH (acenaphthylene, anthracene, benzo[g,h,i]-perylene, fluoranthene, fluorene, naphthalene, phenanthrene, and pyrene) based on inadequate evidence for carcinogenicity in humans or animals.

Little information is available concerning noncarcinogenic health effects produced by PAH. Nevertheless, data from animal studies are suitable for the derivation of reference doses (RfD's) for several PAH including naphthalene, acenaphthene, anthracene, fluoranthene, fluorene, and pyrene.(33)

Asphalt Pavement Modified with CRM

Composition

The addition of modifying agents to asphalt paving mixtures will change the chemical composition of the mixtures and, potentially, the composition of manufacturing and application emissions. As with conventional asphalt pavements, the composition of modified asphalt pavements will vary with feed materials and manufacturing processes, but for modified asphalt pavements this includes variation in the composition or availability of components of the CRM, which may vary depending on such factors as the type of rubber, production methods, and particle size. Studies of the composition of asphalt pavements modified with CRM were not located. However, the potential complexity of the composition of modified asphalt pavements is apparent from a survey of the types of chemicals in rubber. Figure 2 shows a partial listing of the types of chemicals used in the manufacture of rubber. A list of high production volume constituents of rubber that might be anticipated to occur in asphalt pavements modified with CRM is presented in table 4. It is not known which of these chemicals may be present in aged waste tires, asphalt pavements modified with CRM, or tire dust generated from tire wear.

EXPOSURE ASSESSMENT

This section summarizes the available data on environmental emissions and worker exposure due to production, application, and recycling of asphalt paving mixtures modified with CRM. For studies that included monitoring of emissions from conventional asphalt paving mixtures, the results regarding conventional asphalt pavement are discussed as well. In addition, the results of studies that investigated only emissions from conventional asphalt pavements are presented, where possible, for comparative purposes, although it was beyond the scope of this document to discuss the results of these studies in detail. No information was located on emissions from the production, application, recycling, or disposal of paving asphalts modified with materials other than CRM.

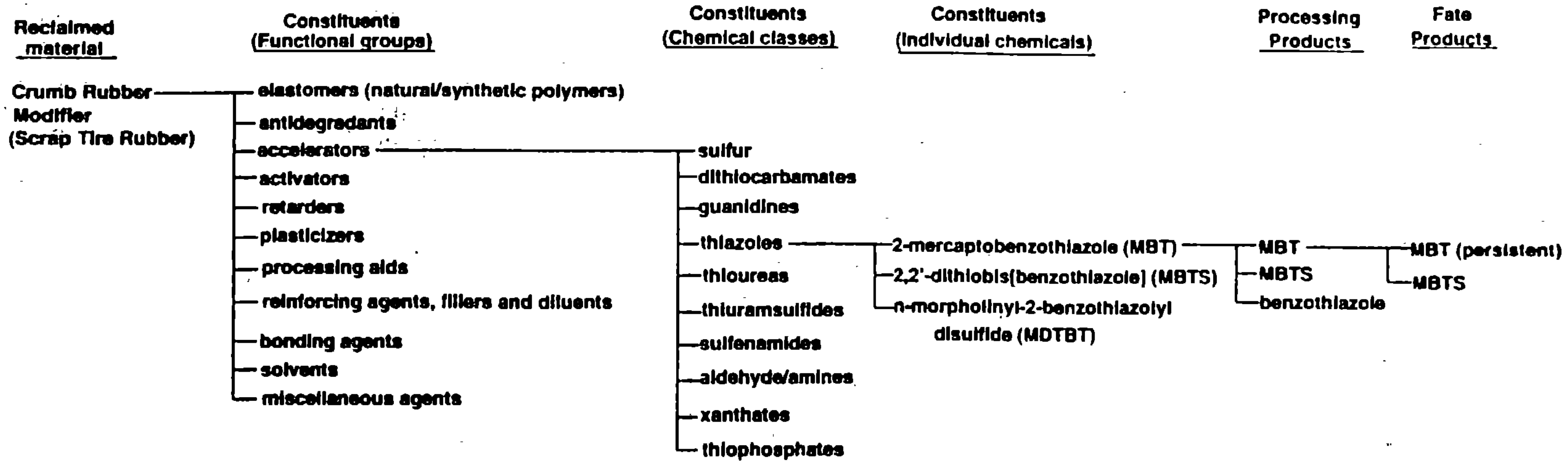

Figure 2. Some of the types of chemicals used in rubber manufacture.

Table 4. Rubber chemicals with significant production volumes.

Rubber Accelerators

— Thiazoles

N-tert-Butyl-2-benzothiazolesulfenamide
2,2'-Dithiobis[benzothiazole]

Antioxidants

— *para*-Phenylenediamines

000101-54-2 4-Aminodiphenylamine
000101-72-4 N-Isopropyl-N'-phenyl-p-phenylenediamine
000793-24-8 N(1,3-Dimethylbutyl)-N'-phenyl-1,4-benzenediamine
001047-16-1 Cinquasia Red
015233-47-3 N-(1-Methylheptyl)-N'-phenyl-1,4-benzenediamine

— Phosphites

000140-08-9 Tris(2-chloroethyl)phosphite
026523-78-4 Nonylphenol phosphite
031570-04-4 2,4-Di-tert-Butylphenol, phosphite (3:1)

— Phenolics

000088-60-8 Phenol, 2-(1,1-dimethylethyl)-5-methyl-
000090-00-6 Phenol, 2-ethyl-
000095-48-7 Phenol, 2-methyl-
000095-65-8 Phenol, 3,4-dimethyl-
000095-87-4 Phenol, 2,5-dimethyl-
000096-69-5 Phenol, 4,4'-thiobis 2-(1,1-dimethylethyl)-5-methyl-
000104-43-8 Phenol, 4-dodecyl-
000105-67-9 Phenol, 2,4-dimethyl-
000106-44-5 Phenol, 4-methyl-
000108-39-4 Phenol, 3-methyl-
000108-68-9 Phenol, 3,5-dimethyl-
000118-82-1 Phenol, 4,4'-methylenebis 2,6-bis(1,1-dimethylethyl)-
000119-47-1 Phenol, 2,2'-methylenebis 6-(1,1-dimethylethyl)-4-methyl-
000123-07-9 Phenol, 4-ethyl-
000128-37-0 Phenol, 2,6-bis(1,1-dimethylethyl)-4-methyl-
000526-75-0 Phenol, 2,3-dimethyl-
000527-60-6 Phenol, 2,4,6-trimethyl-
000576-26-1 Phenol, 2,6-dimethyl-methyl-

Table 4. Rubber chemicals with significant production volumes (Continued).

000620-17-7	Phenol, 3-ethyl-
001300-71-6	Phenol, dimethyl-
001319-77-3	Phenol, methyl-
001323-65-5	Phenol, dinonyl-
001806-26-4	Phenol, 4-octyl-
002409-55-4	Phenol, 2-(1,1-dimethylethyl)-4-methyl-
002416-94-6	Phenol, 2,3,6-trimethyl-
007786-17-6	Phenol, 2,2'-methylenebis 4-methyl-6-nonyl-
025154-52-3	Phenol, nonyl-
027193-86-8	Phenol, dodecyl-
068815-67-8	Phenol, thiobis\tetrapropylene-
084852-15-3	Branched Nonylphenol
Acyclic Compounds	
Accelerators	
— Dithiocarbamic acid derivatives	
000128-04-1	Carbamodithioic acid, dimethyl-, sodium salt
000136-23-2	Zinc, bis(dibutylcarbamodithioato-S,S')-, (T-4)-
000513-74-6	Carbamodithioic acid, monoammonium salt
013927-77-0	Nickel, bis(dibutylcarbamodithioato-S,S')-, (SP-4-1)-
015890-25-2	Antimony, tris(dipentylcarbamodithioato-S,S')-, (OC-6-11)-
— Mercaptans	
000111-88-6	n-Octyl mercaptan
— Miscellaneous	
000097-77-8	Disulfiram
000090-30-2	N-Phenylnaphthalamine
000091-53-2	Quinoline, 6-ethoxy-1,2-dihydro-2,2,4-trimethyl-
000103-34-4	Morpholine, 4,4'-dithiobis-
000793-24-8	1,4-Benzenediamine, N-(1,3-dimethylbutyl)-N'-phenyl-
000836-30-6	Benzenamine, 4-nitro-N-phenyl-

Sampling strategies in all of the comparative studies discussed below involved a total of three or four short sampling periods for determination of emissions. In some cases, the three or four sampling periods for a given type of asphalt pavement were all performed consecutively on a single day. Hot-mix asphalt production is, by nature, a highly variable process, dependent on parameters such as fueling rate of the dryer, mix temperature, asphalt throughput rate, and asphalt binder content, which are all themselves subject to variation.(34) Extensive sampling would be required to determine emission rates with the degree of precision necessary to differentiate between emissions from conventional and modified asphalt pavements. The limited sampling performed in the available studies was inadequate to assess emissions from mixing of asphalt pavements with satisfactory precision, as demonstrated by the erratic nature of the sampling results for many chemicals and the resultant large standard errors. The data base was insufficient to support statistical testing of differences in emission rates between conventional and modified asphalt pavements. Therefore, comparisons of emissions from conventional and modified asphalt paving mixtures were, of necessity, based only on mean emission rates for the various constituents. However, standard errors are shown with their associated means in the tables of emission rates so that the reader may judge the variability of the specific comparisons made in the text. Due to the highly variable nature of the available emissions data, comparisons based only on mean values, as made in the text below, can offer only rough indications of trends in the data and do not necessarily imply the existence of meaningful differences. Variation within a set of samples for a particular contaminant from a particular type of asphalt pavement frequently spanned several orders of magnitude. Therefore, in the following discussion, emission rate differences between conventional and modified asphalt pavements of less than one order of magnitude (tenfold increase or 90 percent decrease) were not generally considered to indicate meaningful differences.

Studies of Environmental Emissions From Asphalt Mixing Plants (Virgin Operation)

Thamesville (Ontario) Study

This study was conducted jointly by the Ministries of Transportation and the Environment of the Province of Ontario. Results are available only in preliminary form.(35,36) The study consisted of field trials conducted at a drum-mix plant in Thamesville, Ontario. Stack emissions were monitored during mixing of conventional hot-mix asphalt pavement (HMA) and rubber-modified hot-mix asphalt concrete (RUMAC).

The drum-mix plant was a Boeing Model 200 equipped with a Venturi scrubber. The Genco burner on the plant was fueled by No. 2 stove oil during the trials. Coarse and fine aggregates entered the drum at the burner end. CRM, constituting 2 percent by weight of the aggregate, was added directly to the drum (dry process) 3.5 m from the nonburner end. Asphalt cement (Petro-Canada 85-100 penetration grade), making up 5.3 percent of the HMA formula and 6.1 percent of the RUMAC formula, was added to the drum 4.1 m from the nonburner end. These discharge points were roughly two-thirds of the way up the drum towards the burner end; mixing time in the drum was approximately 1 min. The burner flame was encased in a pyrocone to prevent pyrolysis of the asphalt binder and CRM. A dense-graded mix (HL 4) was used as the base for both the HMA and RUMAC. CRM added to the RUMAC was #4 mesh size. The mixing plant operated at a production rate of 140 to 162 Mg/h during the emissions testing. Mix temperature averaged 154 °C at discharge from the drum.

Emissions were monitored in the main exhaust stack of the plant using the Metals Sampling Train, Trace Organics Sampling Train, Volatile Organics Sampling Train (VOST), Fluorides Sampling Train, and Continuous Emissions Monitoring for combustion gases. Four trials were conducted for the standard mix and three trials were conducted for the asphalt-rubber mix (except that there were four trials for VOST testing of the asphalt-rubber mix). Emission rates (mg/Mg asphalt concrete produced) were calculated from measured stack concentrations by taking into account stack conditions, such as percent moisture in stack gas, stack pressure, and stack velocity, at the time of monitoring.

The results of the emissions tests at the Thamesville plant are shown in table 5. Emission rates for elements during mixing of conventional asphalt ranged from < 0.01 mg/Mg for silver to > 2,000 mg/Mg for calcium. For most elements, emission rates were lower during mixing of RUMAC than during mixing of HMA. The largest difference was a 70-percent lower emission rate for boron from RUMAC than from HMA. Silver and tellurium were the only elements that were detected only during mixing of HMA and not during mixing of RUMAC. However, both of these elements were found in minute concentrations close to apparent detection limits; thus, only a slightly lower emission concentration from RUMAC would have resulted in nondetection of the two elements. Emission rates were slightly (less than twofold) higher for a few elements (antimony, selenium, and vanadium) emitted at relatively low concentrations during mixing of RUMAC (< 5 mg/Mg). Bismuth was the only element released during mixing of RUMAC, but not HMA; however, only small amounts of bismuth were emitted during mixing of RUMAC (< 0.5 mg/Mg). Although emission rates of most elements (including those with the highest emission rates such as calcium, magnesium, and iron) were lower during mixing of RUMAC than mixing of HMA, total particulate emissions were higher (34 g/Mg, HMA; 62 g/Mg, RUMAC). The difference in the mean particulate emissions was less than twofold, but noteworthy because of the relatively large amounts involved. Among gaseous inorganic compounds, there were slightly (less than 30 percent) lower emission rates for hydrogen chloride and fluorides and slightly (less than twofold) higher emissions for nitric acid and sulfuric acid during mixing of RUMAC than during mixing of HMA.

For PAH, which constitute the bulk of the semivolatile compounds monitored, emission rates during mixing of HMA ranged from < 0.01 mg/Mg for acenaphthene and *m*-terphenyl to 271 mg/Mg for 9,10-dimethylanthracene. Emission rates of PAH were higher during mixing of RUMAC than during mixing of HMA. Total semivolatile emission rates were 3.5-fold higher (555 mg/Mg, HMA; 1,932 mg/Mg, RUMAC) and there was a remarkably consistent pattern of threefold to ninefold higher emission rates for most individual PAH. The most notable exception to this pattern was 7,12-dimethylbenzo[a]anthracene, which was emitted in relatively small quantities (1 mg/Mg) during mixing of HMA, but was not

Table 5. Emission factors (mg/Mg) from the Thamesville (Ontario) study.

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Modified: Conventional HMA
Inorganics					
Aluminum	442	(79)	331	(64.5)	0.75
Antimony	0.0802	(0.0136)	0.143	(0.012)	1.78
Arsenic	0.632	(0.228)	0.401	(0.204)	0.63
Barium	5.56	(0.2)	4.68	(1.16)	0.84
Beryllium	0.0365	(0.0069)	0.0155	(0.007)	0.42
Bismuth	BDL	—	0.418	(0.418)	—
Boron	12.5	(5.4)	3.47	(2.08)	0.28
Cadmium	0.0537	(0.0137)	0.0316	(0.0069)	0.59
Calcium	2347	(516)	2193	(494)	0.93
Chromium	2.43	(0.57)	1.21	(0.08)	0.50
Cobalt	1.07	(0.19)	0.512	(0.030)	0.48
Copper	3.1	(0.5)	1.73	(0.24)	0.56
Iron	903	(181)	607	(105)	0.67
Lead	1.77	(0.11)	1.44	(0.27)	0.81
Lithium	0.68	(0.12)	0.552	(0.099)	0.81
Magnesium	1806	(1,201)	585	(111)	0.32
Manganese	36.7	(5.9)	21.5	(3.2)	0.59
Mercury	0.682	(0.201)	0.46	(0.11)	0.67
Molybdenum	0.842	(0.130)	0.51	(0.13)	0.61
Nickel	65.7	(5.3)	37.4	(12.7)	0.57
Phosphorus	13	(3)	8.4	(1.7)	0.65
Potassium	242	(38)	181	(43)	0.75
Selenium	0.0537	(0.0212)	0.0916	(0.0561)	1.71
Silicon	162	(36)	117	(14)	0.72
Silver	0.00575	(0.00575)	BDL	—	0.00
Sodium	97.5	(28.8)	53.2	(4.3)	0.55
Strontium	3.57	(0.75)	3.07	(0.74)	0.86
Tellurium	0.0115	(0.0115)	BDL	—	0.00
Tin	2.85	(1.01)	3.33	(1.85)	1.17
Titanium	5.35	(0.96)	5.46	(0.57)	1.02
Vanadium	2.03	(0.26)	2.93	(0.12)	1.44
Zinc	8.91	(1.47)	6.2	(1.4)	0.70
Total cations+anions	10,482	—	10,999	—	1.05
Total particulates	33,735	(3,880)	62,038	(29,012)	1.84
Hydrogen chloride	109	(26)	94.1	(15.2)	0.86
Nitric acid	233	(23)	409	(52)	1.76
Sulfuric acid	3930	(236)	6314	(182)	1.61
Fluorides	42.3	(8.2)	30.4	(5.6)	0.72

Table 5. Emission factors (mg/Mg) from the Thamesville (Ontario) study (Continued).

Contaminant	Conventional HMA		Modified HMA		Modified: Conventional HMA
	Mean	(Standard Error)	Mean	(Standard Error)	
Semivolatiles					
Acenaphthene	0.00731	(0.00731)	3.996	(3.991)	546.65
Acenaphthylene	1.797	(0.791)	6.3	(2.6)	3.51
Anthracene	3.475	(0.973)	11.143	(4.825)	3.21
Benzo[a]anthracene	0.473	(0.128)	1.718	(0.694)	3.63
Benzo[b]fluoranthene	0.576	(0.121)	1.827	(0.707)	3.17
Benzo[k]fluoranthene	0.861	(0.577)	0.931	(0.387)	1.08
Benzo[a]fluorene	2.158	(0.291)	5.972	(2.689)	2.77
Benzo[b]fluorene	0.829	(0.162)	2.22	(0.95)	2.68
Benzo[ghi]perylene	0.119	(0.050)	0.566	(0.186)	4.76
Benzo[a]pyrene	0.117	(0.038)	0.462	(0.120)	3.95
Benzo[e]pyrene	0.101	(0.038)	0.489	(0.223)	4.84
Biphenyl	7.628	(2.746)	32.653	(16.024)	4.28
9,10-Dimethylanthracene	270.973	(96.195)	858.744	(421.427)	3.17
7,12-Dimethylbenzo[a]anthracene	0.969	(0.969)	BDL	—	0.00
Fluoranthene	0.59	(0.19)	4.074	(1.741)	6.91
Fluorene	8.748	(3.193)	30.335	(13.135)	3.47
Indeno[123cd]pyrene	BDL	—	0.0257	(0.0257)	—
2-Methylanthracene	3.795	(1.385)	13.436	(6.516)	3.54
1-Methylnaphthalene	24.797	(17.606)	110.267	(55.386)	4.45
2-Methylnaphthalene	35.093	(25.618)	138.79	(68.91)	3.95
1-Methylphenanthrene	16.124	(4.676)	53.72	(24.19)	3.33
9-Methylphenanthrene	5.245	(1.705)	17.618	(8.137)	3.36
Naphthalene	153.846	(62.308)	568.269	(252.630)	3.69
Perylene	0.736	(0.217)	2.822	(1.140)	3.83
Phenanthrene	12.043	(4.336)	45.845	(21.969)	3.81
Pyrene	1.575	(0.433)	9.156	(4.229)	5.81
m-Terphenyl	0.00859	(0.00515)	0.0797	(0.0796)	9.28
o-Terphenyl	0.151	(0.082)	0.68	(0.42)	4.50
Triphenylene/chrysene	2.208	(0.607)	8.004	(3.512)	3.63
Chlorinated dibenzodioxins	0.000195	(0.000122)	0.000273	(0.000273)	1.40
Chlorinated dibenzofurans	0.0026	(0.0022)	0.000092	(0.000060)	0.04
Chlorobenzenes	0.00349	(0.00033)	0.755	(0.296)	216.33
Chlorophenols	0.0142	(0.0048)	0.659	(0.365)	46.41
Polychlorinated biphenyls	0.0597	(0.0224)	0.095	(0.056)	1.59
Total semivolatile organics	555.121	—	1931.66	—	3.48

Table 5. Emission factors (mg/Mg) from the Thamesville (Ontario) study (Continued).

Contaminant	Conventional HMA Mean	Conventional HMA (Standard Error)	Modified HMA Mean	Modified HMA (Standard Error)	Modified: Conventional HMA
Volatiles					
Acetone	1.54	(0.32)	4.2	(2.2)	2.73
Benzene	234	(52)	206	(42)	0.88
Bromomethane	0.0534	(0.0315)	0.0142	(0.0142)	0.27
2-Butanone	16.8	(10.8)	8.97	(1.62)	0.53
Carbon disulfide	40.4	(5.7)	84.2	(5.0)	2.08
Chlorobenzene	0.0259	(0.0259)	BDL	—	0.00
Chloroethane	0.111	(0.067)	0.0183	(0.0183)	0.16
Chloromethane	617	(528)	175	(11)	0.28
Ethylbenzene	172	(80)	48.8	(6.8)	0.28
Methylene Chloride	1.72	(1.46)	2.74	(2.68)	1.59
4-Methyl-2-pentanone	BDL	—	130	(51)	—
Styrene	127	(46)	89	(32)	0.70
Tetrachloroethene	BDL	—	0.0201	(0.0201)	—
Toluene	312	(122)	252	(49)	0.81
1,1,1-Trichloroethane	0.0693	(0.0398)	0.947	(0.554)	13.67
Trichloroethene	BDL	—	0.957	(0.933)	—
Trichlorofluoromethane	0.115	(0.092)	0.0136	(0.0136)	0.12
Vinyl chloride	1.13	(0.66)	0.193	(0.193)	0.17
Xylenes (total)	895	(510)	319	(83)	0.36
Total volatile organics	2419	—	1,322	—	0.55

BDL = below detection limit

detected during mixing of RUMAC. Indeno[1,2,3-cd]pyrene was detected only during mixing of RUMAC, but at very low levels (0.03 mg/Mg) close to the apparent detection limit.

Emission rates among chlorinated semivolatiles during mixing of HMA were very low, ranging roughly from 0.0002 mg/Mg for polychlorinated dibenzodioxins to 0.06 mg/Mg for polychlorinated biphenyls. Emissions of most of these compounds were higher during mixing of RUMAC. For chlorobenzenes and chlorophenols, the differences were large (46-fold to 216-fold), while for polychlorinated dibenzo-*p*-dioxins (PCDD), and polychlorinated biphenyls (PCB) the differences were small (less than twofold). In contrast to these results, emission rates for polychlorinated dibenzofurans (PCDF) were 96 percent lower during mixing of RUMAC than during mixing of HMA.

Emission rates for volatile organic chemicals during mixing of HMA ranged from 0.03 mg/Mg for chlorobenzene to 895 mg/Mg for mixed xylenes. Emission rates of most volatile organic compounds were lower during mixing of RUMAC than during mixing of HMA. The difference was close to 70 percent for those chemicals having the greatest emission rates (xylenes, chloromethane). Emissions of total volatile organics were lower by roughly 45 percent during mixing of RUMAC (2,400 mg/Mg, HMA; 1,300 mg/Mg, RUMAC). Although most volatile organic compounds were emitted at lower rates during mixing of RUMAC than during mixing of HMA, there were several exceptions. Acetone and methylene chloride were emitted at higher rates from RUMAC, but the results for these chemicals are suspect because both of them are potential laboratory-introduced contaminants. Carbon disulfide was also emitted at a higher rate from RUMAC, although the difference was only twofold. 1,1,1-Trichloroethane was emitted at a tenfold higher rate from RUMAC than HMA; however, the emission rate from RUMAC was still relatively low (1 mg/Mg). The most striking finding among volatile organics was the emission of relatively large quantities (130 mg/Mg) of 4-methyl-2-pentanone (methyl isobutyl ketone) during mixing of RUMAC. This compound was not detected during mixing of HMA. The emission rate of 130 mg/Mg for 4-methyl-2-pentanone means that during mixing of RUMAC this compound had the fourth highest emission rate among volatile organics, after xylenes (319 mg/Mg), toluene (252 mg/Mg), and benzene (206 mg/Mg), and accounted for 10 percent of all volatile emissions. Two other chemicals, trichloroethene and tetrachloroethene, were also detected only during mixing of RUMAC, but emission rates for these chemicals were relatively low (1 and 0.02 mg/Mg, respectively).

Haldimand-Norfolk (Ontario) Study

Contained in one of the reports on the Thamesville, Ontario study were the results of a study of emissions from a batch plant during mixing of conventional HMA and HMA modified with CRM.(36) This study was conducted by the Regional Municipality of Haldimand-Norfolk within the Province of Ontario. Details regarding the mixing process and the addition of CRM at this plant were not located. Sampling methods appear to have been similar to those used in the Thamesville study; except for the absence of the fluorides sampling train, the lists of chemicals monitored in the two studies are almost identical.(34,36) In the Haldimand-Norfolk study, three trials were conducted for the CRM asphalt mix and for VOST testing of the standard mix. Emission rates (mg/Mg asphalt concrete produced) were calculated from measured stack concentrations by taking into account stack conditions at the time of monitoring.

The results of the emissions tests are shown in table 6. Emission rates for inorganic elements during batch mixing of conventional HMA ranged from 0.07 mg/Mg for tellurium to 155 g/Mg for calcium. For most inorganics, emission rates were lower during batch mixing of modified HMA than during mixing of conventional HMA. Differences came close to 90 percent for a few elements (chromium, selenium). Tin was detected only during mixing of conventional HMA. The emission rate for tin from conventional HMA was relatively low (11 mg/Mg), but still larger than those of several other elements. The emission rate of copper was sixfold higher during mixing of modified HMA, but was still relatively low (less than 10 mg/Mg). Slightly (less than twofold) higher emission rates from modified HMA occurred for several elements (i.e., barium, lithium, magnesium, mercury, silicon, sodium, strontium). Bismuth was emitted at a rate of 13 mg/Mg during mixing of modified HMA, but was not detected during mixing of conventional HMA. Total particulate emissions from the batch plant were very high (approaching 1 kg/Mg) for both conventional and modified HMA; emissions were slightly higher during mixing of modified HMA (910 g/Mg) than during mixing of conventional HMA (710 g/Mg).

Emission rates for PAH ranged from 0.001 mg/Mg for *p*-terphenyl to 65 mg/Mg for naphthalene during mixing of conventional HMA. Emissions of most PAH were higher during mixing of modified HMA. The differences were mostly between twofold and fourfold, although emission rates of *m*- and *p*-terphenyls from modified HMA were more than tenfold higher than from conventional HMA. The most notable finding among semivolatile chemicals was the emission of 7.4 mg/Mg of tetralin during mixing of modified HMA. This was the fourth highest emission rate among semivolatiles emitted from the batch plant during mixing of modified HMA, after naphthalene (22 mg/Mg), 2-methylnaphthalene (8.5 mg/Mg), and 9,10-dimethylanthracene (7.5 mg/Mg), and it accounted for 12 percent of total semivolatile emissions. Tetralin was not detected during mixing of conventional HMA. Although emissions were higher for most PAH during mixing of modified HMA, total semivolatile emissions were lower (95 mg/Mg, conventional HMA; 59 mg/Mg, modified HMA). This reflects the fact that the emission rate of naphthalene, the PAH with the highest rate of emission, was lower by 65 percent. Lower emission rates were also seen for 1-methylnaphthalene and 2-methylnaphthalene, two of the other PAH emitted at high rates. Acenaphthene and 7,12-dimethylbenzo[a]anthracene were detected only during mixing of conventional HMA. Although emission rates for these chemicals were relatively low (0.6 and 0.2 mg/Mg, respectively), they were higher than emission rates for many other PAH.

Emission rates of chlorinated semivolatiles ranged from 0.0001 mg/Mg for PCDD to 0.02 mg/Mg for PCB during mixing of conventional HMA. Mixing of modified HMA produced small amounts of PCDF (0.0003 mg/Mg) and chlorophenols (0.02 mg/Mg), which were not emitted during mixing of conventional HMA. Emission rates of chlorobenzenes and PCB were slightly (less than twofold) higher during mixing of modified HMA, while emissions of PCDD were 80 percent lower.

Table 6. Emission factors (mg/Mg) from the Haldimand-Norfolk (Ontario) study.

	Conventional HMA		Modified HMA		
Contaminant HMA	Mean	Standard Error	Mean	Standard Error	Modified: Conventional
Inorganics					
Aluminum	2,531	—	1,899	(603)	0.75
Antimony	1.15	—	0.492	(0.335)	0.43
Arsenic	2.92	—	2.09	(0.95)	0.72
Barium	122	—	160	(391)	1.31
Beryllium	0.432	—	0.228	(0.043)	0.53
Bismuth	BDL	—	13.4	(8.9)	—
Boron	36.7	—	17.1	(2.0)	0.47
Cadmium	0.252	—	0.156	(0.012)	0.62
Calcium	15,5351	—	145,722	(22,714)	0.94
Chromium	36.1	—	4.63	(2.06)	0.13
Cobalt	3.74	—	2.71	(0.60)	0.72
Copper	1.19	—	6.67	(2.234)	5.61
Iron	5,660	—	3,776	(1,657)	0.67
Lead	5.29	—	5.11	(1.39)	0.97
Lithium	2.3	—	2.75	(0.27)	1.20
Magnesium	80,758	—	88,526	(4089)	1.10
Manganese	237	—	210	(18)	0.89
Mercury	1.26	—	1.57	(0.06)	1.25
Molybdenum	12.7	—	2.36	(0.42)	0.19
Nickel	21	—	8.32	(2.02)	0.40
Phosphorus	128	—	86.6	(33.5)	0.68
Potassium	1,265	—	1,136	(164)	0.90
Selenium	0.864	—	0.12	(0.09)	0.14
Silicon	638	—	857	(317)	1.34
Sodium	222	—	445	(54)	2.00
Strontium	4,074	—	6,022	(1,286)	1.48
Tellurium	0.072	—	0.036	(0.036)	0.50
Tin	10.7	—	BDL	—	0.00
Titanium	69.4	—	61.8	(26.0)	0.89
Vanadium	8.14	—	5.11	(1.95)	0.63
Zinc	32.8	—	21.1	(7.1)	0.64
Total cations+anions	251,371	—	249,096	—	0.99
Total particulates	714,481	—	908,445	(62,939)	1.27
Hydrogen chloride	139	—	102	(25)	0.73

Table 6. Emission factors (mg/Mg) from the Haldimand-Norfolk (Ontario) study (Continued).

	Conventional HMA		Modified HMA		
Contaminant HMA	Mean	(Standard Error)	Mean	(Standard Error)	Modified: Conventional
Semivolatiles					
Acenaphthene	0.638	—	BDL	—	0.00
Acenaphthylene	1.007	—	0.499	(0.124)	0.50
Anthracene	0.0159	—	0.0245	(0.0190)	1.54
Benzo[a]anthracene	0.007990	—	0.0246	(0.0124)	3.08
Benzo[b]fluoranthene	0.0489	—	0.124	(0.067)	2.54
Benzo[k]fluoranthene	0.0218	—	0.099	(0.055)	4.54
Benzo[a]fluorene	0.0282	—	0.122	(0.013)	4.33
Benzo[b]fluorene	0.0224	—	0.0486	(0.0306)	2.17
Benzo[ghi]perylene	0.0969	—	0.111	(0.047)	1.15
Benzo[a]pyrene	0.004930	—	0.0418	(0.0389)	8.48
Benzo[e]pyrene	0.0172	—	0.0757	(0.0586)	4.40
Biphenyl	1.277	—	1.9	(0.1)	1.49
Coronene	0.0351	—	0.0364	(0.0090)	1.04
9,10-Dimethylanthracene	4.681	—	7.538	(2.829)	1.61
7,12-Dimethylbenzo[a]-anthracene	0.223	—	BDL	—	0.00
Fluoranthene	0.279	—	0.218	(0.059)	0.78
Fluorene	0.502	—	0.612	(0.057)	1.22
Indeno[123cd]pyrene	0.007270	—	0.0281	(0.0201)	3.87
2-Methylanthracene	0.0245	—	0.0239	(0.0239)	0.98
1-MNethylnaphthalene	7.58	—	5.942	(0.103)	0.78
2-Methylnaphthalene	11.106	—	8.477	(0.294)	0.76
1-Methylphenanthrene	0.431	—	0.876	(0.142)	2.03
9-Methylphenanthrene	0.141	—	0.276	(0.033)	1.96
Naphthalene	65	—	22.343	(3.354)	0.34
Perylene	0.003670	—	0.004	(0.005)	1.09
Phenanthrene	0.894	—	1.181	(0.416)	1.32
Pyrene	0.367	—	0.295	(0.003)	0.80
m-Terphenyl	0.0036	—	0.162	(0.004)	45.00
o-Terphenyl	0.0312	—	0.124	(0.009)	3.97
p-Terphenyl	0.001010	—	0.0823	(0.0043)	81.49
Tetralin	BDL	—	7.365	(0.723)	—
Triphenylene/Chrysene	0.0888	—	0.238	(0.036)	2.68
Chlorinated dibenzodioxins	0.000122	—	0.000025	(0.000025)	0.21
Chlorinated dibenzofurans	BDL	—	0.000342	(0.000130)	—
Chlorobenzenes	0.007690	—	0.009140	(0.001003)	1.19

Table 6. Emission factors (mg/Mg) from the Haldimand-Norfolk (Ontario) study (Continued).

	Conventional HMA		Modified HMA		
Contaminant HMA	Mean	(Standard Error)	Mean	(Standard Error)	Modified: Conventional
Semivolatiles (continued)					
Chlorophenols	BDL	—	0.0203	(0.0056)	—
Polychlorinated biphenyls	0.0243	—	0.0406	(0.0159)	1.67
Total semivolatile organics	94.619	—	58.964	—	0.62
Volatiles					
Acetone	BDL	—	27.2	(15.1)	—
Benzene	42.2	—	29	(3)	0.69
Bromodichloromethane	0.0409	—	BDL	—	0.00
Bromomethane	BDL	—	0.0229	(0.0229)	—
2-Butanone	0.243	—	5.33	(2.95)	21.93
Carbon Disulfide	49.7	—	36.7	(5.3)	0.74
Chloroethane	0.121	—	0.316	(0.073)	2.61
Chloromethane	4.05	—	15.1	(1.8)	3.73
1,1-Dichloroethane	16.7	—	17.7	(3.1)	1.06
1,2-Dichloroethane	2.34	—	0.558	(0.303)	0.24
1,1-Dichloroethene	0.255	—	0.683	(0.682)	2.68
Ethylbenzene	10.9	—	16	(4)	1.47
2-hexanone	BDL	—	2.18	(2.18)	—
Methylene chloride	21.3	—	28.7	(6.0)	1.35
4-methyl-2-pentanone	BDL	—	15.8	(4.4)	—
Styrene	5.87	—	7.5	(2.6)	1.28
Tetrachloroethene	BDL	—	0.526	(0.209)	—
Toluene	30.6	—	36.1	(7.1)	1.18
1,1,1-Trichloroethane	7.51	—	16.9	(7.4)	2.25
Trichloroethene	BDL	—	0.42	(0.15)	—
Trichlorofluoromethane	0.212	—	0.415	(0.057)	1.96
Vinyl acetate	BDL	—	3.7	(2.0)	—
Vinyl chloride	0.0459	—	0.0571	(0.0570)	1.24
Xylenes (total)	57.4	—	65.9	(15.2)	1.15
Total volatile organics	249	—	327	—	1.31

BDL = below detection limit

During mixing of conventional HMA, emission rates for volatile organic chemicals ranged from 0.04 mg/Mg for bromodichloromethane to 57 mg/Mg for mixed xylenes; the rate for total volatile organics was 250 mg/Mg. During mixing of modified HMA, emissions of total volatile organic compounds were slightly higher (330 mg/Mg). Emissions of most individual volatiles were higher as well during mixing of modified HMA, although most of the observed differences were less than twofold. The most notable exception was 2-butanone, which had an emission rate from modified HMA that was more than tenfold higher than that from conventional HMA (0.24 mg/Mg, conventional HMA; 5.3 mg/Mg, modified HMA). Several volatile organic compounds were detected only during mixing of modified HMA. These included chemicals emitted in small amounts (< 1 mg/Mg: bromomethane, trichloroethene, and tetrachloroethene), moderate amounts (2 to 4 mg/Mg: 2-hexanone and vinyl acetate), and relatively large amounts (> 15 mg/Mg: 4-methyl-2-pentanone and acetone). The emission rate of 16 mg/Mg for 4-methyl-2-pentanone made up 5 percent of total volatile emissions during mixing of modified HMA. The results regarding acetone are suspect because acetone is a potential laboratory contaminant during VOST analysis. Bromodichloromethane was the only volatile organic compound that was emitted during the mixing of conventional HMA, but not during mixing of modified HMA. However, it was emitted in very small quantities (0.04 mg/Mg).

Parmer County (Texas) Study

A joint study by the Texas Department of Transportation and Texas Air Control Board included monitoring of stack emissions during mixing of HMA and ARHM at a drum-mix plant in Parmer County, Texas.(37) The drum-mix plant was a Barber-Greene plant equipped with a Venturi scrubber. CRM was added to the mix by the wet process (i.e., it was added to the asphalt binder before the binder was mixed with the aggregates in the drum). CRM was added to the mix at 18 percent by weight of the binder. The percent of binder used in the mix was not reported. The mixing plant operated at a production rate of 287 to 302 mg/h during the emissions testing. Mix temperature was 171 °C (340 °F) during mixing of HMA. ARHM was mixed at 171 °C (340 °F) and 150 °C (302 °F) in separate trials. Other production details were not available.

Emissions were monitored in the exhaust stack of the plant for total particulates (EPA method 5 and TACB method 23), total hydrocarbons (EPA method 25A), formaldehyde (EPA method 0011), semivolatile organic chemicals (EPA modified method 5), and selected volatile organic chemicals (VOST). Three trials were conducted for each test condition [HMA, ARHM at 171 °C (340 °F), and ARHM at 150 °C (302 °F)]. The duration of the trials for total particulate, formaldehyde, and semivolatile was 62.5 min, while that for VOST chemicals was 20 min. All testing was conducted over a 3-d period. Emission rates were calculated as pounds per hour from measured stack concentrations by taking into account stack conditions at the time of monitoring. For this report, emission rates were converted to units of mg/Mg asphalt pavement produced by dividing the emission rate (lb/h) by the plant production rate (ton/h) and converting to metric units. This adjustment was made so that the data could be directly compared with the data from the Thamesville (Ontario) and Haldimand-Norfolk (Ontario) studies.

Emission rates at the Parmer County drum-mix plant are shown in table 7. Emissions of total particulates were approximately 27 g/Mg for HMA. Particulate emissions were slightly higher (less than a twofold difference) during mixing of ARHM at 171 °C (340 °F). Particulate emissions during mixing of ARHM at 150 °C (302 °F) were 50 percent lower compared to ARHM at 171 °C (340 °F).

Emission rates for semivolatile organic compounds during mixing of HMA ranged from approximately 3 mg/Mg for 2-methylphenol and n-nitrosodiphenylamine to approximately 800 mg/Mg for formaldehyde. Differences between HMA and ARHM at 171 °C (340 °F) were not substantial. The largest difference was a fourfold higher emission rate for acenaphthene from ARHM. Emission rates of other chemicals were either less than twofold higher (e.g., 2-methylnaphthalene, anthracene, n-nitrosodiphenylamine, and butyl benzyl phthalate) or less than 50 percent lower (e.g., formaldehyde, fluorene, naphthalene, phenanthrene, and phenol). Emissions during mixing of ARHM at 150 °C (302 °F) were generally lower compared to ARHM at 171 °C (340 °F). Although the differences were small (< 50 percent) in most cases, they approached 90 percent lower for a few chemicals (phenanthrene and butyl benzyl phthalate). Formaldehyde and naphthalene both had slightly higher emissions from 150 °C (302 °F) ARHM compared to 171 °C (340 °F) ARHM. Several semivolatile chemicals were emitted only during mixing of ARHM. Pyrene (6 mg/Mg) and 4-methylphenol (25 mg/Mg) were detected only during mixing of ARHM at 171 °C (340 °F). Dibenzofurans (30 mg/Mg) and bis(2-ethylhexyl)phthalate (5 mg/Mg) were detected during mixing of ARHM at both temperatures, with emission rates at 150 °C (302 °F) lower by more than 50 percent compared to 171 °C (340 °F). Isophorone was detected only during mixing of ARHM at 150 °C (302 °F). 2-Methylphenol was the only semivolatile chemical that was detected only during the mixing of HMA. However, the emission rate for this chemical (3 mg/Mg) was the lowest among the semivolatile chemicals monitored.

Monitoring of volatile organic chemicals at the Parmer County drum-mix plant was limited to benzene, styrene, and 1,3-butadiene. During mixing of HMA, styrene emissions were roughly 80 mg/Mg and benzene emissions were roughly 1,100 mg/Mg. During mixing of ARHM at 171 °C (340 °F), emissions of each of these chemicals were slightly (< 10 percent) lower. Compared to emissions from CRM mixing at 171 °C (340 °F), emissions of these chemicals during CRM mixing at 150 °C (302 °F) were higher, although only slightly (less than twofold). 1,3-Butadiene (224 mg/Mg) was detected only during mixing of ARHM at 150 °C (302 °F). Emission rates for total nonmethane hydrocarbons showed a pattern similar to benzene and styrene; the rate was slightly lower during the mixing of ARHM at 171 °C (340 °F) and slightly higher during the mixing of ARHM at 150 °C (302 °F) [94 g/Mg, conventional; 85 g/Mg, ARHM at 171 °C (340 °F); 113 g/Mg, ARHM at 150 °C (302 °F)].

San Antonio (Texas) Study

A second study, jointly sponsored by the Texas Department of Transportation and Texas Air Control Board, was conducted at a drum-mix plant in San Antonio, Texas.(38) CRM was added to the asphalt using the wet process. CRM made up 18 percent by weight of the

Table 7. Emission factors (mg/Mg) from the Parmer County (Texas) study.

	Conventional HMA		Modified HMA		Reduced Temperature Modified HMA			
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Mean	(Standard Error)	Modified: Conventional HMA	Reduced Temperature Modified: Conventional HMA
Inorganics								
Total particulate (EPA)	26,779.2	(2,219.6)	44791.2	(18926)	26349.2	(1532.7)	1.67	0.98
Total particulate (TACB)	38,068.3	(4,220.0)	71916	(20402)	44370.8	(630.3)	1.89	1.17
Semivolatiles								
Formaldehyde	790.361	(69.413)	403.244	(160.363)	551.887	(210.609)	0.51	0.70
Acenaphthene	7.88784	(7.88784)	29.5816	(29.5816)	15.3729	(7.6864)	3.75	1.95
Anthracene	20.5084	(20.5084)	31.1385	(15.5693)	52.2679	(4.6119)	1.52	2.55
Fluorene	55.2148	(17.3532)	26.4677	(26.4677)	19.9848	(10.7610)	0.48	0.36
2-Methylnaphthalene	697.285	(94.654)	751.995	(151.022)	559.574	(33.820)	1.08	0.80
Naphthalene	421.21	(48.90)	266.234	(45.151)	333.592	(76.865)	0.63	0.79
Phenanthrene	39.4392	(9.4654)	24.9108	(24.9108)	3.07458	(3.07458)	0.63	0.08
Pyrene	BDL	—	6.2277	(3.1138)	BDL	—	—	—
Bis(2-ethylhexyl)phthalate	BDL	—	4.67078	(3.11385)	1.53729	(1.53729)	—	—
Butyl benzyl phthalate	6.31027	(0.03155)	14.0123	(0.4671)	1.53729	(1.53729)	2.22	0.24
Dibenzofurans	BDL	—	29.5816	(29.5816)	12.2983	(12.2983)	—	—
Isophorone	BDL	—	BDL	—	7.68645	(7.68645)	—	—
2-Methylphenol	3.15513	(3.15513)	BDL	—	BDL	—	0.00	0.00
4-Methylphenol	BDL	—	24.9108	(24.9108)	BDL	—	—	—
n-Nitrosodiphenylamine	3.15513	(3.15513)	6.2277	(6.2277)	BDL	—	1.97	0.00

Table 7. Emission factors (mg/Mg) from the Parmer County (Texas) study (Continued).

Contaminant	Conventional HMA		Modified HMA		Reduced Temperature Modified HMA		Modified: Conventional HMA	Reduced Temperature Modified: Conventional HMA
	Mean	(Standard Error)	Mean	(Standard Error)	Mean	(Standard Error)		
Volatiles								
Phenol	44.1719	(22.0859)	20.24	(15.57)	16.9102	(16.9102)	0.46	0.38
Benzene	1075.9	(208.2)	949.725	(457.736)	1680.26	(132.21)	0.88	1.56
Styrene	82.0335	(41.0167)	77.8463	(29.5816)	155.266	(59.954)	0.95	1.89
1,3-Butadiene	BDL	—	BDL	—	224.444	(224.444)	—	—
Total hydrocarbons	93638.1	(7583.4)	84657.9	(18488.5)	11318	(778)	0.9	1.21

BDL = below detection limit

binder, and the binder made up 7.5 to 9.0 percent of the asphalt pavement produced. The plant was equipped with a baghouse rather than a scrubber and operated at a production rate of 340 to 363 mg/h during the emissions testing. Mix temperature was 163 °C (325 °F) for HMA. ARHM was mixed at 163 °C (325 °F) and 149 °C (300 °F) in separate trials. Other production details were not reported.

Emissions were monitored in the baghouse exhaust stack of the plant for total particulates (EPA method 5 and TACB method 23), total hydrocarbons (EPA method 25A), semivolatile organic chemicals (EPA modified method 5), volatile organic chemicals (VOST), and 1,3-butadiene (EPA method 18). Three trials were conducted for each test condition [HMA, ARHM at 163 °C (325 °F), and ARHM at 149 °C (300 °F)]. Trials for total particulate, semivolatile organics, and 1,3-butadiene lasted 60 min, while trials for VOST chemicals lasted 20 min. All testing was conducted over a 6-d period. Emission rates were calculated as pounds per hour from measured stack concentrations by taking into account stack conditions at the time of monitoring. For this report, emission rates were converted to units of mg/Mg asphalt pavement produced.

Emission rates at the San Antonio drum-mix plant are shown in table 8. Total particulate emissions were 51 g/Mg for HMA and 10 g/Mg for ARHM at 163 °C (325 °F). Particulate emissions for ARHM at 149 °C (300 °F) were similar to ARHM at 163 °C (325 °F). All trials for emissions from HMA were conducted on the same day, and it was suggested in the study report that baghouse failure may have inflated the numbers for particulate emissions from HMA in this study.

The only semivolatile organic chemicals detected during mixing of HMA were 2-methylnaphthalene (1,600 mg/Mg), naphthalene (350 mg/Mg), and phenanthrene (120 mg/Mg). The emission rate for total PAH during mixing of HMA was 2,100 mg/Mg. The phenanthrene emission rate was roughly twofold higher during mixing of ARHM at 163 °C (325 °F), but there was very little difference between emission rates of the other PAH during HMA and ARHM mixing. Phenanthrene was not detected during mixing of ARHM at 149 °C (300 °F). For naphthalene, 2-methylnaphthalene, and total PAH, lower ARHM temperature resulted in only slightly lower emission rates.

Emissions of VOST compounds during mixing of HMA ranged from 1 mg/Mg for methylene chloride to 400 mg/Mg for acrolein. Emissions of VOST compounds generally were higher during mixing of ARHM at 163 °C (325 °F). Total VOST emissions were threefold higher during mixing of ARHM than during mixing of HMA (1,300 mg/Mg, HMA; 3,700 mg/Mg, ARHM at 163 °C (325 °F)). Emission rates of xylenes, ethylbenzene, and toluene were similarly higher during mixing of ARHM at 163 °C (325 °F); these were among the individual VOST compounds emitted at the highest rates. Emission rates for styrene, carbon disulfide, and methylene chloride (considered to be a possible laboratory contaminant) were 10-fold to 100-fold higher during mixing of ARHM at 163 °C (325 °F); all were emitted at relatively low rates (< 10 mg/Mg) from HMA. Acrolein and acrylonitrile, which were emitted at relatively high rates from HMA, were emitted at substantially (approximately 90 percent) lower rates from ARHM at 163 °C (325 °F). Emission rates of volatile compounds during mixing of ARHM generally were lower under reduced tempera-

Table 8. Emission factors (mg/Mg) from the San Antonio (Texas) study.

	Conventional HMA		Modified HMA		Reduced Temperature Modified HMA			Reduced Temperature
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Mean	(Standard Error)	Modified: Conventional HMA	Modified: Conventional HMA
Inorganics								
Total particulate (EPA)	51060.7	(11465.8)	9737.52	(1134.97)	10343.7	(2979.3)	0.19	0.20
Total particulate (TACB)	53085.6	(11633.4)	12845.8	(515.9)	12936.1	(2656.9)	0.24	0.24
Semivolatiles								
2-Methylnaphthalene	1617.33	(201.20)	1840.46	(130.26)	1577.35	(88.99)	1.14	0.98
Naphthalene	350.809	(54.169)	381.762	(42.561)	305.668	(21.925)	1.09	0.87
Phenanthrene	119.946	(59.328)	211.517	(10.318)	BDL	—	1.76	0.00
Total PAH (MM5)	2088.08	(314.61)	2432.44	(180.56)	1883.02	(110.921)	1.16	0.90
Volatiles								
Acetone	116.076	(18.443)	99.5677	(31.4696)	31.2116	—	0.86	0.27
Acrolein	406.525	(19.088)	52.7503	(52.7503)	93.506	—	0.13	0.23
Acrylonitrile	111.82	(8.38)	17.0245	(8.5123)	29.0191	—	0.15	0.26
Benzene	96.9883	(9.6730)	63.842	(7.351)	81.7694	—	0.66	0.84
2-Butanone	23.8601	(0.5159)	25.2789	(10.4469)	17.1535	—	1.06	0.72
Carbon disulfide	7.48048	(3.99819)	106.79	(44.37)	BDL	—	14.28	0.00
Chlorobenzene	BDL	—	1.54768	(1.54768)	BDL	—	—	—
Ethylbenzene	198.233	(10.447)	560.391	(420.712)	49.3969	—	2.83	0.25
Methylene chloride	1.03179	(1.03179)	96.0854	(34.6939)	10.5758	—	93.12	10.25
4-Methyl-2-pentanone	BDL	—	1189.52	(1189.52)	BDL	—	—	—

Table 8. Emission factors (mg/Mg) from the San Antonio (Texas) study (Continued).

	Conventional HMA		Modified HMA		Reduced Temperature Modified HMA			
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Mean	(Standard Error)	Modified: Conventional HMA	Reduced Temperature Modified: Conventional HMA
Styrene	5.67484	(2.83742)	109.757	(85.381)	2.57947	—	19.34	0.45
Toluene	93.6349	(5.2879)	376.474	(300.380)	54.8138	—	4.02	0.59
Xylenes (total)	264.396	(9.415)	989.229	(694.911)	63.4551	—	3.74	0.24
Total VOC (VOST)	1325.72	—	3688.26	—	433.481	—	2.78	0.33
1,3-Butadiene	488.81	(488.81)	BDL	—	BDL	—	0.00	0.00
Total speciated organics	3902.62	—	6122	—	2316.5	—	1.57	0.59
Total hydrocarbons	34745.5	(2321.5)	107925	(53756)	56671.1	(35106.6)	3.11	1.63

BDL = below detection limit

ture conditions. These differences exceeded 90 percent for some chemicals (e.g., styrene, ethylbenzene, and xylenes) and brought emission levels for ARHM at 149 °C (300 °F) lower than emission levels for HMA for most chemicals. Exceptions were acrolein and acrylonitrile, which were emitted at twofold higher rates from ARHM at 149 °C (300 °F) compared to ARHM at 163 °C (325 °F). A striking result was the emission of large amounts of 4-methyl-2-pentanone (1,190 mg/Mg) during mixing of ARHM at 163 °C (325 °F). This was the highest emission rate for any volatile organic during mixing of ARHM at 163 °C (325 °F) and made up 32 percent of total VOST emissions under these conditions. This chemical was not detected during mixing of HMA or ARHM at 149 °C (300 °F). The same pattern was seen for chlorobenzene, but this chemical was emitted only in small amounts (1.5 mg/Mg) during mixing of ARHM. The opposite pattern was found for 1,3-butadiene, which was emitted at a rate of 500 mg/Mg during mixing of HMA, but was not detected during mixing of ARHM at either temperature. Total nonmethane hydrocarbon emissions were 35 g/Mg during mixing of HMA, 108 g/Mg during mixing of ARHM at 163 °C (325 °F), and 57 g/Mg during mixing of ARHM at 149 °C (300 °F).

Discussion, Including Studies of Environmental Emissions From Conventional HMA

Emission rates of chemicals released during mixing of conventional and modified HMA in the Thamesville (Ontario), Haldimand-Norfolk (Ontario), Parmer County (Texas), and San Antonio (Texas) studies are presented in table 9, along with the results of other studies that monitored stack emissions during mixing of conventional HMA without RAP.(39-44) Examination of table 9 shows that interstudy variance is large. For most chemicals, the interstudy range of emission rates is similar to, or exceeds, the intrastudy differences between conventional and modified HMA paving mixtures. The interstudy ranges exceed a factor of 10 for many chemicals and a factor of 1,000 for some chemicals. Potential sources of this variation are numerous and include type of plant, type of burner fuel, type of emission control, source of asphalt, mix specifications, mix temperature, process by which rubber is added to the mix, and CRM particulate size and gradation, among other factors.

For most chemicals, the interstudy range of emission rates for conventional and modified HMA overlap and exceed the differences between conventional and modified HMA emissions observed within each study. For example, the magnitude of the higher emission rate of PAH from RUMAC in the Thamesville (Ontario) study is relatively small compared to the interstudy range of emission rates for PAH. This does not preclude the possibility that for a given plant, there may be a pattern of higher PAH emissions from mixing modified as compared to conventional HMA. However, the magnitude of the difference that derives from the addition of CRM to the mix may be insignificant compared to differences in PAH emissions that result from other variables (e.g., type of mixing plant). In light of the high interstudy variability of emissions for both conventional and modified HMA, it can be argued that for most chemicals, the effect of CRM on emissions may be relatively small compared to the effects of other variables.

Of all the potentially meaningful differences between conventional and modified HMA emissions identified in the individual study descriptions above, only one consistent finding

Table 9. Emission factors (mg/Mg) for conventional and modified HMA.

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Inorganics					
Aluminum	442	(80)	331	(65)	1
	2,531	—	1,899	(603)	2
	40.93	—	BDL	—	3
Antimony	0.0802	(0.0136)	0.143	(0.012)	1
	1.15	—	0.492	(0.335)	2
Arsenic	0.632	(0.227)	0.401	(0.204)	1
	2.92	—	2.09	(0.953)	2
Barium	5.56	(0.92)	4.68	(1.16)	1
	122	—	160	(40)	2
Beryllium	0.0365	(0.0069)	0.0155	(0.0078)	1
	0.432	—	0.228	(0.043)	2
	0.20	—	BDL	—	3
Bismuth	BDL	—	0.418	(0.417)	1
	BDL	—	13.40	(8.90)	2
Boron	12.50	(5.37)	3.47	(2.08)	1
	36.70	—	17.10	(1.97)	2
Cadmium	0.0537	(0.0137)	0.0316	(0.0069)	1
	0.252	—	0.156	(0.012)	2
	3.04	—	BDL	—	3
Calcium	2,347	(516)	2193	(494)	1
	15,5351	—	145,722	(22,716)	2
	3,140.66	—	BDL	—	3
Chromium	2.43	(0.57)	1.21	(0.08)	1
	36.10	—	4.63	(2.06)	2
	1.42	—	BDL	—	3
Cobalt	1.07	(0.19)	0.512	(0.030)	1
	3.74	—	2.71	(0.59)	2
Copper	3.10	(0.46)	1.73	(0.24)	1
	1.19	—	6.67	(2.23)	2
Iron	903	(181)	607	(105)	1
	5,660	—	3,776	(1,657)	2
	52.78	—	BDL	—	3

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Lead	1.77	(0.11)	1.44	(0.27)	1
	5.29	—	5.11	(1.39)	2
	0.34	—	BDL	—	3
Lithium	0.68	(0.12)	0.552	(0.099)	1
	2.30	—	2.75	(0.27)	2
Magnesium	1,806	(1201)	585	(111)	1
	80,758	—	88,526	(4,089)	2
	108.40	—	BDL	—	3
Manganese	36.70	(5.87)	21.50	(3.23)	1
	237	—	210	(18)	2
	3.55	—	BDL	—	3
Mercury	0.682	(0.201)	0.46	(0.11)	1
	1.26	—	1.57	(0.06)	2
	10.84	—	BDL	—	3
Molybdenum	0.842	(0.130)	0.51	(0.13)	1
	12.70	—	2.36	(0.42)	2
Nickel	65.70	(5.26)	37.40	(12.74)	1
	21	—	8.32	(2.02)	2
	1.22	—	BDL	—	3
Phosphorus	13	(3)	8.40	(1.70)	1
	128	—	86.60	(33.50)	2
Potassium	242	(36)	181	(43)	1
	1,265	—	1,136	(164)	2
Selenium	0.0537	(0.0212)	0.0916	(0.0561)	1
	0.864	—	0.12	(0.09)	2
Silicon	162	(37)	117	(13)	1
	638	—	857	(317)	2
Silver	0.005750	(0.005750)	BDL	—	1
		—	BDL	—	2
Sodium	97.50	(28.76)	53.20	(4.30)	1
	222	BDL	445	(54)	2
Strontium	3.57	(0.75)	3.07	(0.74)	1
	4,074	—	6,022	(1,286)	2

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Tellurium	0.0115	(0.0115)	BDL	—	1
	0.072	—	0.036	(0.036)	2
Tin	2.85	(1.01)	3.33	(1.85)	1
	10.70	—	BDL	—	2
Titanium	5.35	(0.96)	5.46	(0.57)	1
	69.40	—	61.80	(26.05)	2
Vanadium	2.03	(0.26)	2.93	(0.12)	1
	8.14	—	5.11	(1.95)	2
	16.92	—	BDL	—	3
Zinc	8.91	(1.47)	6.20	(1.36)	1
	32.80	—	21.10	(7.07)	2
	3.85	—	BDL	—	3
Total cations+anions	10,482	—	10,999	—	1
	251,371	—	249,096	(104,985)	2
Total particulate	33,735	(3,879)	62,038	(29,012)	1
	714,481	—	908,445	(62,938)	2
	51,060.70	(11,465.80)	9,737.52	(1,134.97)	4
	BDL	—	10,343.70	(2,979.29)	4*
	26,779.20	(2,219.64)	44,791.20	(18,926)	5
	BDL	—	26,349.20	1,532.68	5*
	137,000	—	BDL	—	6
	BDL	—	6,934.40	—	7
	3,384.15	—	BDL	—	3
Semivolatiles					
Formaldehyde	790.361	(69.413)	403.244	(160.363)	5
	BDL	—	551.887	(210.609)	5*
	77	—	BDL	—	6
Acenaphthene	0.007310	(0.007310)	3.996	(3.991)	1
	0.638	—	BDL	—	2
	7.887840	(7.887840)	29.5816	(29.5816)	5
	BDL	—	15.3729	(7.6864)	5*
Acenaphthylene	1.797	(0.791)	6.30	(2.58)	1
	1.007	—	0.499	(0.124)	2

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Anthracene	3.475	(0.973)	11.143	(4.825)	1
	0.0159	—	0.0245	(0.0189)	2
	20.5084	(20.5084)	31.1385	(15.5693)	5
	BDL	—	52.2679	(4.6118)	5*
	0.71	—	BDL	—	3
Benzo[a]anthracene	0.473	(0.127710)	1.718	(0.694)	1
	0.007990	—	0.0246	(0.0123)	2
	0.02	—	BDL	—	3
Benzo[a]fluorene	2.158	(0.291)	5.972	(2.689)	1
	0.0282	—	0.122	(0.013)	2
Benzo[a]pyrene	0.117	(0.038)	0.462	(0.120)	1
	0.004930	—	0.0418	(0.0388)	2
	BDL	—	BDL	—	5
	BDL	—	BDL	—	5*
	BDL	—	BDL	—	3
Benzo[b]fluoranthene	0.576	(0.120)	1.827	(0.707)	1
	0.0489	—	0.124	(0.067)	2
	0.40	—	BDL	—	6
	0.05	—	BDL	—	3
Benzo[b]fluorene	0.829	(0.162)	2.22	(0.95)	1
	0.0224	—	0.0486	(0.0306)	2
Benzo[e]pyrene	0.101	(0.038)	0.489	(0.223)	1
	0.0172	—	0.0757	(0.0586)	2
	0.02	—	BDL	—	3
Benzo[ghi]perylene	0.119	(0.050)	0.566	(0.186)	1
	0.0969	—	0.111	(0.047)	2
Benzo[k]fluoranthene	0.861	(0.577)	0.931	(0.387)	1
	0.0218	—	0.099	(0.055)	2
	0.05	—	BDL	—	3
Biphenyl	7.628	(2.746)	32.653	(16.024)	1
	1.277	—	1.90	(0.12)	2
Bis(2-ethylhexyl)phthalate	BDL	—	4.670780	(3.113850)	5
	BDL	—	1.537290	(1.537290)	5*
Butyl benzyl phthalate	6.310270	(0.031551)	14.0123	(0.4671)	5
	BDL	—	1.537290	(1.537290)	5*

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Chlorobenzenes	0.003490	(0.000332)	0.755	(0.296)	1
	0.007690	—	0.009140	(0.001003)	2
Chlorophenols	0.0142	(0.0048)	0.659	(0.365)	1
	BDL	—	0.0203	(0.0056)	2
Coronene	BDL	—	BDL	—	1
	0.0351	—	0.0364	(0.0090)	2
Dibenzodioxins (chlorinated)	0.000195	(0.000122)	0.000273	(0.000273)	1
	0.000122	—	0.000025	(0.000025)	2
Dibenzofurans (chlorinated)	0.0026	(0.002171)	0.000092	(0.000060)	1
	BDL	—	0.000342	(0.000130)	2
Dibenzofurans	BDL	—	29.5816	(29.5816)	5
	BDL	—	12.2983	(12.2983)	5*
9,10-Dimethylanthracene	270.973	(96.195)	858.744	(421.427)	1
	4.681	—	7.538	(2.829)	2
7,12-Dimethylbenzo[a]-anthracene	0.969	(0.969)	BDL	—	1
	0.223	—	BDL	—	2
	0.30	—	BDL	—	6
Fluoranthene	0.59	(0.19)	4.074	(1.741)	1
	0.279	—	0.218	(0.059)	2
	0.70	—	BDL	—	6
	0.29	—	BDL	—	3
Fluorene	8.748	(3.193)	30.335	(13.1354)	1
	0.502	—	0.612	(0.056)	2
	55.2148	(17.3532)	26.4677	(26.4677)	5
	BDL	—	19.9848	(10.7610)	5*
Indeno[123cd]pyrene	BDL	—	0.0257	(0.0257)	1
	0.007270	—	0.0281	(0.0201)	2
	0.30	—	BDL	—	6
	0.01	—	BDL	—	3
Isophorone	BDL	—	BDL	—	5
	BDL	—	7.686450	(7.686450)	5*
2-Methylanthracene	3.795	(1.385)	13.436	(6.516)	1
	0.0245	—	0.0239	(0.0239)	2
1-Methylnaphthalene	24.797	(17.606)	110.267	(55.386)	1
	7.58	—	5.942	(0.103)	2

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
2-Methylnaphthalene	1,617.33	(201.20)	1,840.46	(130.26)	4
	BDL	—	1.577.35	(88.99)	4*
	35.093	(25.618)	138.79	(68.91)	1
	11.106	—	8.477	(0.294)	2
	697.285	(94.654)	751.995	(151.022)	5
	BDL	—	559.574	(33.820)	5*
1-Methylphenanthrene	16.124	(4.68)	53.72	(24.19)	1
	0.431	—	0.876	(0.142)	2
9-Methylphenanthrene	5.245	(1.705)	17.618	(8.137)	1
	0.141	—	0.276	(0.033)	2
2-Methylphenol	3.155130	(3.155130)	BDL	—	5
	BDL	—	BDL	—	5*
4-Methylphenol	BDL	—	24.9108	(24.9108)	5
	BDL	—	BDL	—	5*
Naphthalene	350.809	(54.169)	381.762	(42.561)	4
	BDL	—	305.668	(21.925)	4*
	153.846	(62.308)	568.269	(252.630)	1
	65	—	22.343	(3.354)	2
	421.21	(48.90)	266.234	(45.151)	5
	BDL	—	333.592	(76.864)	5*
N-Nitrosodiphenylamine	3.155130	(3.155130)	6.2277	(6.2277)	5
	BDL	—	BDL	—	5*
Perylene	0.736	(0.217)	2.822	(1.140)	1
	0.003670	—	0.004	(0.005)	2
	0.02	—	BDL	—	3
Phenanthrene	119.946	(59.33)	211.517	(10.318)	4
	BDL	—	BDL	—	4*
	12.043	(4.335)	45.845	(21.969)	1
	0.894	—	1.181	(0.416)	2
	39.4392	(9.4654)	24.9108	(24.9108)	5
	BDL	—	3.074580	(3.074580)	5*
	10.20	—	BDL	—	3
Phenol	44.1719	(22.0859)	20.24	(15.57)	5
	BDL	—	16.9102	(16.9102)	5*
Polychlorinated Biphenyls	0.0597	(0.0223)	0.095	(0.056)	1
	0.0243	—	0.0406	(0.0159)	2

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

Contaminant	Conventional HMA Mean	Conventional HMA (Standard Error)	Modified HMA Mean	Modified HMA (Standard Error)	Reference
Pyrene	1.575	(0.433)	9.156	(4.229)	1
	0.367	—	0.295	(0.003)	2
	BDL	—	6.2277	(3.1138)	5
	BDL	—	BDL	—	5*
	0.80	—	BDL	—	6
	0.77	—	BDL	—	3
m-Terphenyl	0.008590	(0.005154)	0.0797	(0.0796)	1
	0.0036	—	0.162	(0.004)	2
o-Terphenyl	0.151	(0.081)	0.68	(0.42)	1
	0.0312	—	0.124	(0.009)	2
p-Terphenyl	BDL	—	BDL	—	1
	0.001010	—	0.0823	(0.0043)	2
Tetralin	BDL	—	BDL	—	1
	BDL	—	7.365	(0.723)	2
Triphenylene/Chrysene	2.208	(0.607)	8.004	(3.512)	1
	0.0888	—	0.238	(0.036)	2
Chrysene	0.12	—	BDL	—	3
Total PAH	2088.08	(314.70)	2,432.44	(180.563)	4
	BDL	—	1,883.02	(110.917)	4*
	19.70	—	BDL	—	6
	12.26	—	BDL	—	3
Total VOC (MM5)	6816.30	—	BDL	—	8
Total Semivolatile Organ	555.121	—	1931.66	—	1
	94.619	—	58.964	—	2
Volatiles					
Acetone	116.076	(18.443)	99.5677	(31.4696)	4
	BDL	—	31.2116	—	4*
	1.54	(0.32)	4.20	(2.20)	1
	BDL	—	27.20	(15.08)	2
Acrolein	406.525	(19.088)	52.7503	(52.7503)	4
	BDL	—	93.506	—	4*
Acrylonitrile	111.82	(8.38)	17.0245	(8.5123)	4
	BDL	—	29.0191	—	4*

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Benzene	96.9883	(9.6730)	63.842	(7.3515)	4
	BDL	—	81.7694	—	4*
	234	(51)	206	(42)	1
	42.20	—	29	(3)	2
	1075.90	(208.24)	949.725	(457.736)	5
	BDL	—	1,680.26	(132.207)	5*
Bromodichloromethane	BDL	—	BDL	—	1
	0.0409	—	BDL	—	2
Bromomethane	0.0534	(0.0315)	0.0142	(0.0142)	1
	BDL	—	0.0229	(0.0229)	2
1,3-Butadiene	488.81	(488.81)	BDL	—	4
	BDL	—	BDL	—	4*
	BDL	—	BDL	—	5
	BDL	—	224.444	(224.444)	5*
2-Butanone	23.8601	(0.5159)	25.2789	(10.4469)	4
	BDL	—	17.1535	—	4*
	16.80	(10.84)	8.97	(1.60)	1
	0.243	—	5.33	(2.95)	2
Carbon Disulfide	7.480480	(3.998190)	106.79	(44.37)	4
	BDL	—	BDL	—	4*
	40.40	(5.66)	84.20	(5.05)	1
	49.70	—	36.70	(5.30)	2
Chlorobenzene	BDL	—	1.547680	(1.547680)	4
	BDL	—	BDL	—	4*
	0.0259	(0.0259)	BDL	—	1
	BDL	—	BDL	—	2
	0.111	(0.067)	0.0183	(0.0183)	1
Chloroethane	0.121	—	0.316	(0.073)	2
Chloromethane	617	(527)	175	(11)	1
	4.05	—	15.10	(1.83)	2
1,1-Dichloroethane	BDL	—	BDL	—	1
	16.70	—	17.70	(3.07)	2
1,2-Dichloroethane	BDL	—	BDL	—	1
	2.34	—	0.558	(0.303)	2
1,1-Dichloroethene	BDL	—	BDL	—	1
	0.255	—	0.683	(0.682)	2

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Ethylbenzene	198.233	(10.447)	560.391	(420.712)	4
	BDL	—	49.3969	—	4*
	172	(80)	48.80	(6.83)	1
	10.90	—	16	(4.06)	2
2-Hexanone	BDL	—	BDL	—	1
	BDL	—	2.18	(2.18)	2
4-Methyl-2-pentanone	BDL	—	1,189.52	(1,189.52)	4
	BDL	—	BDL	—	4*
	BDL	—	130	(51)	1
	BDL	—	15.80	(4.38)	2
Methylene Chloride	1.031790	(1.031790)	96.0854	(34.6939)	4
	BDL	—	10.5758	—	4*
	1.72	(1.46)	2.74	(2.68)	1
	21.30	—	28.70	(5.96)	2
Styrene	5.674840	(2.837420)	109.757	(85.381)	4
	BDL	—	2.579470	—	4*
	127	(46)	89	(32)	1
	5.87	—	7.50	(2.64)	2
	82.0335	(41.0167)	77.8463	(29.5816)	5
	BDL	—	155.266	(59.954)	5*
Tetrachloroethene	BDL	—	0.0201	(0.0200)	1
	BDL	—	0.526	(0.209)	2
Toluene	93.6349	(5.2879)	376.474	(300.380)	4
	BDL	—	54.8138	—	4*
	312	(122)	252	(49)	1
	30.60	—	36.10	(7.09)	2
1,1,1-Trichloroethane	0.0693	(0.0398)	0.947	(0.554)	1
	7.51	—	16.90	(7.41)	2
Trichloroethene	BDL	—	0.957	(0.933)	1
	BDL	—	0.42	(0.15)	2
Trichlorofluoromethane	0.115	(0.092)	0.0136	(0.0136)	1
	0.212	—	0.415	(0.057)	2
Vinyl Acetate	BDL	—	BDL	—	1
	BDL	—	3.70	(2.01)	2
Vinyl Chloride	1.13	(0.65)	0.193	(0.193)	1
	0.0459	—	0.0571	(0.0570)	2

Table 9. Emission factors (mg/Mg) for conventional and modified HMA (Continued).

	Conventional HMA		Modified HMA		
Contaminant	Mean	(Standard Error)	Mean	(Standard Error)	Reference
Xylenes (Total)	895	(510)	319	(83)	1
	57.40	—	65.90	(15.22)	2
	264.396	(9.415)	989.229	(694.911)	4
	BDL	—	63.4551	—	4*
Total VOC (VOST)	1,325.72	—	3,688.26	—	4
	BDL	—	433.481	—	4*
	2,419	—	1,322	—	1
	249	—	327	—	2
	11,635.50	—	BDL	—	8
Total Hydrocarbons	149,932	—	BDL	—	9
	93,638.10	(7,583.36)	84,657.90	(18,488.50)	5
	BDL	—	113,180	(778)	5*
	34,745.50	(2,321.53)	107,925	(53,756)	4
	BDL	—	56,671.10	(35106.60)	4*
	14,000	—	BDL	—	6

[1] Thamesville, Ontario study (U.S. FHWA, 1992)(36)
[2] Haldimand-Norfolk, Ontario study (U.S. FHWA, 1992)(36)
[3] U.S. EPA, 1985(44)
[4] San Antonio, Texas study (Southwestern Laboratories, 1992)(38)
[5] Parmer County, Texas study (WEST, 1992)(37)
[6] Khan et al., 1977;(43) Khan and Hughes, 1977(42)
[7] AirNova, 1992(39)
[8] Gunkel and Bowles, 1985(41)
[9] Beggs, 1981(40)

* = reduced temperature; BDL = below detection limit

emerged from comparison of all the studies together. 4-Methyl-2-pentanone (methyl isobutyl ketone or MIBK) was detected only during mixing of modified HMA in three out of the four comparative studies: Thamesville (Ontario), Haldimand-Norfolk (Ontario), and San Antonio (Texas).(35-38) It was not monitored in the Parmer County (Texas) study.(37) Furthermore, although the levels detected during mixing of modified HMA varied over a factor of 100 between the three studies, these levels were among the highest for volatiles in each of the three studies, constituting 5 to 32 percent of the total volatile emissions.

The source of the MIBK emitted during mixing of modified HMA is not known for certain. MIBK itself is not expected to be present in high concentrations in tire rubber. However, it is plausible that MIBK is a thermal degradation product of isoprene (2-methyl-1,3-butadiene), which is an important chemical used in the manufacture of butyl rubber. This is consistent with the observation that the rate of emission of MIBK was higher during mixing of ARHM at high temperatures than during mixing of ARHM at lower temperatures in the San Antonio (Texas) study.(38)

In view of the results of monitoring studies that suggest that MIBK (108-10-1) is emitted during mixing of HMA modified by the addition of CRM, a brief review of the environmental fate and toxicity of MIBK is presented here, based on more detailed reviews by U.S. EPA and Krasavage et al.(45,46)

MIBK in the atmosphere reacts with photochemically generated hydroxyl radicals so that the half-life in air is estimated to be < 1 day. This chemical has relatively high water solubility and a low soil adsorption coefficient, suggesting that it should be highly mobile in soil. MIBK has been identified in leachates from landfills and is a potential groundwater contaminant.

MIBK is absorbed from the respiratory tract following inhalation exposure, and from the digestive tract following oral exposure. The compound is metabolized by ω-1 oxidation to the corresponding hydroxy ketone, and carbonyl reduction to the secondary alcohol, in guinea pigs. Excretion is predominantly in the urine.

MIBK vapor is an irritant. Acute inhalation exposure to MIBK (> 100 ppm) may produce weakness, loss of appetite, headache, eye and throat irritation, nausea, vomiting, and diarrhea. MIBK is also a central nervous system depressant. Acute inhalation of high concentrations (> 1,000 ppm) can produce ataxia, unconsciousness, and death in animals, and possibly humans as well. Following longer-term exposure by either the oral or inhalation route, target organs are the kidney (increased organ weight and general nephropathy in rats of both sexes, hyaline droplet nephropathy in male rats) and liver (increased organ weight and hepatomegaly, without accompanying histopathological changes, in rats and mice of both sexes). Several studies looked for, but failed to find, convincing evidence for physical damage to the nervous system in animals exposed to MIBK for prolonged periods. Inhalation exposure to MIBK produced fetotoxic effects (developmental delay) at an exposure concentration (3,000 ppm) that also produced overt maternal toxicity (hypoactivity, ataxia, partial paralysis). Studies regarding carcinogenicity of MIBK were not located, but genotoxicity studies were mostly negative.

Studies of Environmental Emissions From Asphalt Mixing Plants (RAP Operation)

New Jersey Study

Only one study was located that investigated emissions from recycling of RAP already containing crumb rubber. In this study, sponsored by the New Jersey Department of Transportation, asphalt pavement containing 3 percent crumb rubber was milled and added as RAP to an I-5 surface course being mixed in a drum plant using a 20 percent RAP addition rate.(47-49) The milled pavement had been applied 1 year earlier as RUMAC containing 3 percent crumb rubber added by the dry process (PlusRide® mixture #12), but had failed prematurely due to excessive raveling. Emissions testing was limited to monitoring of carbon monoxide, total hydrocarbon, and total particulate emissions from the stack of the drum plant during mixing of I-5 with 20 percent rubber-modified and conventional RAP. Two monitoring tests, each 1 hour in duration, were conducted for both types of RAP. Both testing sessions for rubber-modified RAP were conducted on the same day; one of the tests for conventional RAP was also conducted on this day, while the other was conducted several days earlier. The particulate emission rates were very similar for both types of RAP—0.59 kg/h (1.30 lb/h) during mixing of HMA containing conventional RAP and 0.60 kg/h (1.32 lb/h) during mixing of HMA containing rubber RAP. The stack concentrations of total hydrocarbons (dry volume of methane equivalents corrected to 7 percent O_2) were also very similar—33 ppm for conventional RAP and 29 ppm for rubber RAP. However, there were higher stack concentrations of carbon monoxide (dry volume corrected to 7 percent O_2) during mixing of HMA containing rubber RAP (448 ppm) than during mixing of HMA containing conventional RAP (306 ppm). Carbon monoxide emissions may be affected by any number of variables, including humidity and temperature, and erratic variations in carbon monoxide emissions were noted throughout this study.(48) Therefore, the apparent finding of slightly higher carbon monoxide emissions during use of rubber-modified RAP may not have been due to the presence of rubber in the RAP. This study, although far from conclusive, found no clear evidence to suggest that emissions from the mixing of HMA containing rubber RAP differed meaningfully from emissions from the mixing of HMA containing conventional RAP.

Studies of Worker Exposure From Asphalt Mixing Plant Operations and Road-Paving Operations

NAPA Study

A pilot study of occupational exposure to asphalt rubber fumes was recently released by NAPA.(50) Personal and area air samples were collected during road-paving operations on 2 consecutive days in August 1992. During this study, ARHM that was prepared using the wet process at a batch-mixing plant in Canyon County, California, was used to repave over existing asphalt roadbase at two paving sites (one each day) in Valencia, California. The ground rubber, a mixture of three parts tire rubber (20 to 30 mesh) to one part natural rubber (50 mesh), was fed continuously into a mixing chamber [204 to 218 °C (400 to 425 °F)] where it was blended with AR 4,000 standard paving-grade asphalt cement containing extender oil to produce an asphalt-rubber binder consisting of 20 percent ground rubber. The binder was then transported to the asphalt-rubber reaction tank, where it was circulated continuously for 30 to 45 min at 204 °C (400 °F). In the mixing plant, the asphalt-rubber binder was added to aggregate to produce an open-graded ARHM surface course consisting of asphalt-rubber binder (10 percent), crushed stone (74 percent), sand (15 percent), and mineral filler (1 percent). At the paving sites, the ARHM material was applied to the road surface using conventional paving equipment and techniques at temperatures ranging from 132 to 177 °C (270 to 350 °F).

Two sampling schemes were used to collect personal air samples from workers at the paving sites. According to the primary scheme, a worker had to carry four independent sampling trains: one to evaluate exposure to total particulate (Modified NIOSH 0500), benzene-soluble fraction of total particulate (NIOSH 5023), PAH (NIOSH 5506), and sulfur heterocyclics (Heritage Research Group method), and others to evaluate exposure to volatile aromatic compounds (NIOSH 1500), 1,3-butadiene (OSHA 56), and nitrosamines (OSHA 27). Because carrying this apparatus was a burden to workers, a secondary sampling scheme that included only the first sampling train was also used. Only a limited number of personal air samples were actually collected. The primary sampling scheme was carried out on a single worker, who was employed as a screedman (observes and adjusts thickness and width of asphalt layer). The secondary sampling scheme was carried out on two additional workers, one laborer (dumps asphalt load from trucks, observes advancement of paver, directs trucks delivering asphalt) and one paver operator (operates/drives the paver). In addition to personal air samples, some area air samples were also collected. Area air samples were collected, using the primary sampling scheme, from the rear of the paving machine and from the headspace of the liquid asphalt storage tank and the asphalt-rubber reaction tank at the hot-mix plant. All samples were collected on both days of the study, although two personal air samples (laborer and paver operator on day 1) were damaged in such a way that total particulate and benzene-soluble fraction could not be determined for these samples. Analysis of field blanks showed that background contamination with 1,3-butadiene was unacceptably high, indicating that no meaningful interpretation of the 1,3-butadiene data was possible. Therefore, results regarding 1,3-butadiene are not discussed further below.

Levels of total particulate in the personal air samples ranged from 0.71 to 2.16 mg/m^3, with the benzene-soluble fractions ranging from 0.29 to 1.54 mg/m^3. The percent of total particulate that was soluble in benzene ranged from 41 to 87 percent in the different samples. Eight of the seventeen PAH that were sampled for (fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo[b]fluoranthene, and benzo[e]pyrene), were detected in at least one personal air sample and four of these (phenanthrene, anthracene, fluoranthene, and pyrene) were detected in all six personal air samples collected. Detected concentrations ranged from 0.67 to 9.48 μg/m^3 for fluorene, 0.80 to 9.48 μg/m^3 for phenanthrene, 0.23 to 3.79 μg/m^3 for anthracene, 0.45 to 5.97 μg/m^3 for fluoranthene, 0.11 to 2.18 μg/m^3 for pyrene, 0.11 to 0.95 μg/m^3 for chrysene, 0.08 to 0.10 μg/m^3 for benzo[b]fluoranthene, and 0.06 to 0.57 μg/m^3 for benzo[e]pyrene. None of the three sulfur heterocyclics that were sampled for (thianthrene, dibenzothiophene, thianaphthene), were detected in any of the personal air samples, but low molecular weight sulfur heterocyclics were detected at concentrations ranging from 45 to 455 μg/m^3 in all six samples. Two peaks were seen in the low-molecular weight region of five of the six samples. However, it was noted that quantification of low molecular weight sulfur heterocyclics by the Heritage Research Group method is crude and subject to error. None of the seven nitrosamines (n-nitrosodibutylamine, n-nitrosodiethylamine, n-nitrosodimethylamine, n-nitrosodipropylamine, n-nitrosomorpholine, n-nitrosopiperidine, and n-nitrosopyrrolidine) or five volatile aromatic compounds (benzene, toluene, ethylbenzene, xylenes, and styrene) sampled for, were detected in the personal air samples from the screedman who participated in the primary sampling scheme. Comparison of the results among the different members of the paving crew suggests that the laborer received lower exposure than the paving operator or screedman. Total particulate, benzene-soluble fraction of total particulate and percent of total particulate soluble in benzene were all lowest in the laborer. The laborer also had the lowest PAH exposure and the lowest exposure to low molecular weight sulfur heterocyclics. The screedman generally had the highest levels of exposure.

Results from area air samples collected at the rear of the paver suggest that paving crew workers could be exposed to higher contaminant levels than revealed by personal air samples in this study. Total particulate levels in these area samples averaged 5.54 mg/m^3; the benzene soluble fraction averaged 4.86 mg/m^3 and accounted for approximately 88 percent of the total particulate. The eight PAH detected in the personal air samples were detected in the area air samples at concentrations similar to the highest of the personal air samples. An additional three PAH, not found in any of the personal air samples, were detected as well: naphthalene (10.21 μg/m^3), benzo[k]fluoranthene (0.37 μg/m^3), and dibenz[a,h]anthracene (0.10 μg/m^3). In contrast to the results of the personal air samples, one of the sulfur heterocyclics (dibenzothiophene) was detected in the area air samples (12.11 μg/m^3). Low molecular weight sulfur heterocyclics were detected at concentrations of 127 to 720 μg/m^3, and two peaks were observed. Benzene was present at the detection limit (0.07 mg/m^3) in one of the area air samples; the other volatile aromatics were not detected. Nitrosamines were not detected, although results were available only for 1 day.

Both paving sites were located on relatively busy highways. Workers were exposed to gasoline and diesel exhaust in addition to asphalt fumes, but this was not thought to have significantly influenced the results. Worker smoking was limited to an occasional cigarette by the laborer; tobacco smoke was not thought to have biased the results. Winds were light to moderate the first day and higher on the second day, but wind direction and speed were not thought to have influenced the sampling results; no windblown dust was observed.

At the mixing plant, area samples were collected from the headspace of the liquid asphalt storage tank and the asphalt-rubber reaction tank. Noteworthy differences between the tanks, other than rubber content, were higher temperature of the liquid asphalt tank [210 to 218 °C (410 to 425 °F)] compared to the asphalt-rubber reaction tank [195 to 198 °C (383 to 386 °F)] and more stable product levels in the liquid asphalt storage tank. The same 10 PAH's were detected in the headspace of the liquid asphalt storage tank and the asphalt-rubber reaction tank; however levels of individual PAH were higher in the former tank by as much as fivefold (see table 10). The PAH detected were the same as those found in the area

Table 10. PAH in tank headspace samples ($\mu g/m^3$).(53)

Polyaromatic Hydrocarbon	Liquid Asphalt Storage Tank	Asphalt/Rubber Reaction Tank
Naphthalene	795	333
Acenaphthylene	6,515	5,066
Fluorene	1,366	512
Phenanthrene	2,706	1,229
Anthracene	398	282
Fluoranthene	1,102	488
Pyrene	261	227
Chrysene	1,025	209
Benzo[b]fluoranthene	471	92
Benzo[e]pyrene	949	188

sample at the paving site, with the exception of the absence of benzo[k]fluoranthene and dibenz[a,h]anthracene and the addition of acenaphthylene. The absence of benzo[k]-fluoranthene and dibenz[a,h]anthracene is understandable because these PAH were detected at very low limits in the paving site area sample and detection limits were thirtyfold higher in the tank area samples due to the complex nature of the headspace fume matrix. Among the sulfur heterocyclic compounds, both dibenzothiophene and thianaphthene were detected in both tanks. Levels of dibenzothiophene were higher in the liquid asphalt storage tank (5,698 $\mu g/m^3$) than the asphalt-rubber reaction tank (1,261 $\mu g/m^3$ in one sample; undetected in the other). Levels of thianaphthene were slightly higher in the reaction tank (1,612 $\mu g/m^3$ vs. 1,226 $\mu g/m^3$). Very high concentrations of low- and high-molecular weight sulfur heterocyclics were detected in both tanks, with the higher levels occurring in the liquid asphalt storage tank. Concentrations were 323,257 $\mu g/m^3$ (88 to 94 peaks) and 151,292 $\mu g/m^3$ (28 to 30 peaks) for low- and high-molecular weight sulfur heterocyclics, respectively, in the liquid asphalt tank, compared to 161,092 $\mu g/m^3$ (77 to 78 peaks) and 73,104 $\mu g/m^3$ (23 to 27 peaks), respectively, in the asphalt-rubber reaction tank. All of the volatile aromatic compounds sampled for, were detected in area samples from both tanks. Levels of benzene, toluene, xylenes, and styrene were several-fold higher in the rubber-asphalt reaction tank (24.84, 32.89, 158.24, and 9.91 mg/m^3, respectively) than the liquid asphalt storage tank (4.96, 11.4, 39.92, and 2.6 mg/m^3, respectively). However, levels of ethylbenzene were similar in both tanks (11.10 vs. 10.15 mg/m^3). Four of the seven nitrosamines sampled for, were detected in headspace samples from the asphalt-rubber reaction tank (n-nitrosodiethylamine at 1.12 $\mu g/m^3$, n-nitrosodimethylamine at 11.66 $\mu g/m^3$, n-nitrosodipropylamine at 10.09 $\mu g/m^3$, and n-nitrosomorpholine at 9.43 $\mu g/m^3$). Two of these were also detected at lower concentrations in the headspace samples from the liquid asphalt storage tank (n-nitrosodimethylamine at 1.25 $\mu g/m^3$ and n-nitrosomorpholine at 6.20 $\mu g/m^3$).

Comparison of the headspace results for the liquid asphalt storage tank and the asphalt-rubber reaction tank might suggest that the addition of rubber leads to higher levels of volatile aromatic compounds and nitrosamines, and lower levels of PAH and sulfur heterocyclics. However, this is not really a valid comparison to make, due to the presence of several confounding factors. For example, reduced levels of PAH and sulfur heterocyclics could be due to a lower temperature in the reaction tank or depletion of these substances from the liquid asphalt in the storage tank prior to mixing with rubber in the reaction tank.

ARPG Study

A previous study of worker exposure to asphalt emissions when using rubber-asphalt mixes was published by ARPG.(51) In this study, workers from various mixing plants and paving sites in southern California were monitored for exposure to total particulates (OSHA method), total aromatic hydrocarbons (NIOSH 1500), benzene (NIOSH 1501), coal-tar pitch volatiles (NIOSH 5023), and PAH (NIOSH 5506) using personal air sampling. The specific PAH monitored for, were phenanthrene, anthracene, pyrene, chrysene, and benzo[a]pyrene. A total of nine separate tests were conducted over a 2.5-year period. Four of the tests involved the mixing or laying of ARHM, four involved the spraying of asphalt-rubber and aggregate membrane (ARAM), and one involved the monitoring of exposure during non-asphalt-rubber applications. The asphalt-rubber binder used in this study was a mixture of paving-grade liquid asphalt, 15 to 17 percent automotive tire rubber, 5 percent natural rubber, and 2 percent extender oil (added to enhance the reaction process). Temperature during mixing was 204 to 218 °C (400 to 425 °F). For ARHM application, the asphalt-rubber binder was added to aggregate in the mixing chamber of the hot-mix plant, transported to the job site, and laid down using conventional paving equipment and procedures at temperatures of 196 to 204 °C (385 to 400 °F). For ARAM application, the asphalt-rubber binder was sprayed on the road [2.49 to 3.17 L/m^2 (0.55 to 0.70 gal/yd^2)] and then covered with heated aggregate [127 to 162 °C (260 to 325 °F)] precoated with paving-grade liquid asphalt (0.70 to 1.0 percent by weight of aggregate).

The initial test was conducted during an ARAM application in Costa Mesa on September 8, 1988. Total aromatic hydrocarbons were monitored in an aggregate control operator (0.62 mg/m^3) and blender operator (0.95 mg/m^3) at the mixing plant and a bootman (1.63 mg/m^3) at the paving site. Total particulates were monitored in a laborer/rubber feeder (26.4 mg/m^3) at the mixing plant and a raker (23.0 mg/m^3) at the paving site. The second test, conducted during an ARAM application in Whittier on December 28, 1989, involved monitoring of two workers at the mixing plant and two workers at the paving site for exposure to benzene. Detectable levels of benzene were not found in the personal air samples of any of these workers. In the third test, six mixing plant workers were monitored for exposure to benzene (n=3) or coal-tar pitch volatiles (n=3) during mixing of ARHM in Irwindale on January 8, 1990. Neither contaminant was detected in any of the samples collected.

Subsequent tests involved monitoring for coal-tar pitch volatiles and PAH. In test number 4, an ARAM application in Palm Springs on March 22 and 23, 1990, monitoring was conducted on three workers at the mixing plant (1 day only) and five workers at the paving site (three on both days). PAH were not detected in personal air samples from any of these workers. Coal-tar pitch volatiles ranged from undetected up to 3.0 mg/m^3 in the mixing plant workers and undetected to 0.96 mg/m^3 in the paving site workers. Test number 5 was an ARHM application in the Rosemead/Whittier area on May 23 through 31, 1990. Two workers at the mixing plant were monitored on 2 days and three or four workers at the paving site were monitored on 3 days. PAH were not above detectable limits in any of the samples collected. In contrast, coal-tar pitch volatiles were found in almost all samples. Concentrations ranged from 1.0 to 4.6 mg/m^3 in samples from mixing plant workers and undetected to 7.8 mg/m^3 in samples from paving site workers. Because test number 5 was conducted in a heavily congested area, additional tests (numbers 6 and 7) of ARHM application were conducted in low-traffic areas. Test number 6 involved monitoring of four workers at the paving site in the residential area of Rosemead on September 17, 1990. PAH were detected in samples from the paver operator (0.002 mg/m^3), raker (0.003 mg/m^3), and one of the screedmen (0.005 mg/m^3). The specific PAH identified was pyrene. Coal-tar pitch volatiles were detected only in the sample collected from the other screedman (0.69 mg/m^3). Test number 7, conducted in residential Monterey Park on February 14 and 15, 1991, involved monitoring two workers at the mix plant on 1 day and two or three workers at the paving site on both days. PAH were not detected in personal air samples from mixing plant workers, but four paving worker air samples contained phenanthrene (0.002 to 0.02 mg/m^3), one contained pyrene (0.006 mg/m^3), and one contained benzo[a]pyrene (0.004 mg/m^3). Coal-tar pitch volatiles were not found in samples from mixing plant workers, but ranged from undetected up to 3.5 mg/m^3 in paving-site workers.

Test number 8 involved monitoring three paving-site workers during ARAM application in Pasadena on September 26 and 27, 1990. Pyrene (0.003 to 0.01 mg/m^3) was detected in four personal air samples and phenanthrene (0.002 mg/m^3) was detected in one. Coal-tar pitch volatiles were detected in samples from the bootman (1.8 to 2.9 mg/m^3) and the spreader operator (0.44 to 0.90 mg/m^3), but not the beltman. The final test, number 9, involved monitoring for coal-tar pitch volatiles during manhole adjusting activities that did not involve asphalt-rubber application. Coal-tar pitch volatiles were detected at 1.5 mg/m^3 in one sample and were undetected in the other three samples collected.

Discussion, Including Studies of Worker Exposure to Conventional Asphalt

Several studies have been conducted to monitor worker exposure to conventional asphalt fumes. The results of these studies are summarized in tables 11 and 12. Because of differences between the studies, only general comparisons can be made between the studies of worker exposure to asphalt pavements modified with CRM and studies of worker exposure to conventional asphalt pavements. The range of particulate exposure in the NAPA study (0.71 to 2.16 mg/m^3) was within the range of values reported in studies of worker exposure to conventional asphalt pavement (0.02 to 15.1 mg/m^3). Particulate levels in the ARPG study (23 to 26 mg/m^3) were somewhat higher, however. Worker exposure to PAH appeared to be somewhat higher in the NAPA and ARPG studies than in studies of worker exposure to conventional asphalt. Specific PAH found at higher concentrations in workers exposed to modified asphalt pavement included anthracene, benzo[a]pyrene, fluoranthene, fluorene, phenanthrene, and pyrene. These results are suggestive of relationships that may exist between occupational exposure to modified asphalt pavements and breathing air concentrations of particulates and PAH, but do not provide any real evidence for the existence of such relationships.

RISK CHARACTERIZATION

The available data are inadequate to develop a quantitative characterization of absolute or relative risk associated with the production, application, recycling, or disposal of asphalt paving mixtures modified with CRM, plastic, or glass. Numerous gaps exist in the data needed to support hazard identification, dose-response assessment, and exposure assessment of these mixtures. The most critical data that are lacking are environmental monitoring data that can be used to define the "mixtures of concern" or "similar mixtures" for the purpose of dose-response and exposure assessment. The monitoring data on modified asphalts are limited to a few studies on air emissions during mixing of HMA modified with CRM and two preliminary studies of worker exposure. These data are not adequate to estimate exposure levels to humans or other organisms near or distant from these mixing facilities. Nevertheless, the stack emission studies provide some information regarding the relative magnitude of differences in exposure levels that might be anticipated to result from mixing of

Table 11. Worker exposure to conventional asphalt fumes—particulates.

Worker Location	Total Particulate (mg/m^3)	Benzene-Soluble Fraction of Total Particulate (mg/m^3)	Reference
Mixing plant	0.1-15	0.011-1.7	AI, 1991(52)
Paving crew	0.11-0.86	0.03-4.4	AI, 1991(52)
Paving crew	0.143-1.079	BDL-0.756	NAPA, 1989(53)
Paving crew	0.15-5.61	ND	Puzinauskas, 1980(54)
Paving crew	0.4-15.1	0.1-0.3	Brandt et al., 1985(5)
Paving crew	0.58-0.83	0.16-0.17[1]	Monarca et al., 1987(8)
Paving crew	0.02-1.29	ND	Norseth et al., 1991(55)
Mixing plant	0.069-4.06	0.017-0.152	Braszczynska et al., 1987(56)
Paving crew	0.16-0.80	0.14-0.71	Braszczynska et al., 1987(56)

[1] Cyclohexane-soluble fraction of total particulate

BDL = below detection limit; ND = not determined

Table 12. Worker exposure to conventional asphalt fumes—PAH.

	Worker exposure ($\mu g/m^3$)				
Contaminant	Mixing Plant[1] (51)	Paving Crew[1] (52)	Paving Crew[1] (53)	Paving Crew[1] (7)	Paving Crew[2] (8)
Acenaphthene	BDL-4	BDL-6.9	BDL	ND	1.26
Acenaphthylene	BDL	BDL-8.1	BDL-8.52	ND	BDL
Anthracene	BDL	BDL-0.11	BDL-0.65	ND	0.13
Benzo[a]anthracene	BDL	BDL	BDL-0.19	2.25-8.78	3.50
Benzo[b]fluoranthene	BDL	BDL	BDL-0.09	ND	1.03
Benzo[k]fluoranthene	BDL	BDL	BDL	0.01-0.05	0.67
Benzo[g,h,i]perylene	BDL	BDL	BDL	0.03-0.10	0.19
Benzo[a]pyrene	BDL	BDL	BDL-0.07	BDL-0.02	0.61
Benzo[e]pyrene	BDL	BDL-0.27	BDL	ND	ND
Chrysene	BDL	BDL-0.2	BDL	0.19-2.49	0.20
Dibenzo[a,h]anthracene	BDL-0.38	BDL	BDL-0.19	BDL-0.01	0.98
7,12-Dimethylbenzo[a]anthracene	ND	ND	ND	0.02-0.14	ND
Fluoranthene	BDL-0.61	BDL-0.37	BDL-1.52	0.78-0.92	1.13
Fluorene	BDL-1.7	BDL-0.98	BDL-2.36	ND	0.08
Indeno[1,2,3-cd]pyrene	BDL-0.5	BDL	BDL-10.42	0.01-0.04	0.05
Naphthalene	BDL-6.3	1.3-15	BDL-9.48	ND	0.24
Perylene	ND	ND	ND	BDL-0.06	ND
Phenanthrene	BDL-0.76	BDL-1.3	BDL-6.29	ND	0.22
Pyrene	BDL	BDL-0.31	BDL-1.55	0.33-2.14	0.54
Total PAH	ND	ND	3.10-28.41	4.32-12.99	9.70

[1] Range

[2] Mean values (range not provided)

BDL = below detection limit; ND = not determined conventional vs. modified HMA. If certain very simplistic assumptions are accepted, some conclusions can be made regarding the upper bounds on relative risk associated with production of conventional and modified HMA. These assumptions are as follows:

- The processing methods used in the Thamesville (Ontario), Haldimand-Norfolk (Ontario), Parmer County (Texas), and San Antonio (Texas) studies are representative of methods that would be used in other plants.

- Emission rates of the chemicals monitored in these studies are good indices of exposure levels in the immediate vicinity of the plant.

- Exposures that might result from these emissions, in the near vicinity of the plant, represent the major determinants of the upper bound on risk that would apply to populations of all species at all locations.

The first assumption regarding processing methods is probably not valid, given that the technology for production of asphalt pavements modified with CRM is currently evolving and is likely to continue to evolve based on the results of performance studies. The second assumption regarding indexing of exposure to emission rates is probably reasonable at locations very near the asphalt plant and during the mixing process, however, it becomes progressively less valid at other times and as the distance from the plant increases. Over this distance, fate process will become an increasingly more important factor in defining the exposure "mixture of concern."

The third assumption, that exposure (indexed to emission rate) is the major determinant of risk, is extremely tenuous for the following reasons. Small differences in the level of exposure to highly toxic chemicals, or small differences in exposure levels that persist for long durations, can substantially impact risk. Furthermore, all of the hazardous chemicals that are emitted from asphalt paving mixtures (conventional and modified) may not have been monitored in the Texas and Ontario studies; some chemicals may have escaped observation because they were not in the monitoring protocol.

If the above caveats are set aside for the sake of speculation, and the three assumptions are accepted, it is possible to draw some limited conclusions regarding relative risk of conventional asphalt paving mixtures vs. asphalt paving mixtures modified by the addition of CRM. Although some differences in the emission patterns between conventional and modified asphalt pavements were detected in studies that compared mixing of both pavements at the same facility, for most chemicals, the magnitude of these differences were small compared to differences between studies. This suggests that for most chemicals, differences in emission rates resulting from the addition of CRM to the mix are smaller (or at least no larger than) the differences produced by other factors. If the above three assumptions hold, then it can be concluded that the risks associated with release of these chemicals from asphalt paving mixtures modified with CRM may be no greater than the risks associated with conventional asphalt paving mixtures (i.e., the relative risk due to release of these chemicals may not be different from the relative risk of 1). This conclusion may not apply to 4-methyl-2-pentanone (methyl isobutyl ketone or MIBK), which was consistently observed to be emitted from modified asphalt paving mixtures, but not conventional asphalt paving mixtures. Here again, with of the exception of the previous three assumptions, this would suggest the possibility that the relative risk associated with release of MIBK is greater than the relative risk of 1 (i.e., the risk associated with the release of MIBK from modified asphalt pavement is greater than that from conventional asphalt pavement). The magnitude of the relative risk cannot be quantified with the existing data.

SUMMARY

Although there are considerable amounts of data on individual components of asphalt paving mixtures, rubber, plastic, and glass that are relevant to risk assessment, high quality data on the composition, emissions, exposures, and dose-response relationships for asphalt pavements modified with these materials are lacking. This precludes deriving estimates of absolute or relative risk associated with production, application, recycling, or disposal of modified vs. conventional asphalt pavements.

Studies of emissions during production of conventional and modified asphalt pavements were analyzed to determine if the results would lead to any insight regarding relative risk. Intrastudy differences in emission rates between conventional and modified asphalt paving mixtures were generally smaller than interstudy differences by factors of 10 to 100. This suggests that variables other than CRM may be more important determinants of emission rates for most chemicals. Risks associated with the release of most chemicals from conventional and modified asphalt pavements may not be significantly different. The one exception is methyl isobutyl ketone, which was consistently observed to be emitted during mixing of asphalt pavement modified with CRM, but not during mixing of conventional asphalt. These conclusions must be highly caveated with assumptions regarding the relationship between the emission rates observed in these studies, and human health and environmental risks.

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CHAPTER 3. ENGINEERING ASSESSMENT

CRUMB RUBBER MODIFIER

Overview

Approximately 242 million tires that are comprised of over 1.8 million megagrams (Mg) (2 million tons) of rubber are discarded annually.(1,2) Currently, about 11 percent of these scrap tires are used as a tire-derived fuel (TDF) source for heat or power generation. About 5 percent are exported and less than 7 percent are recycled or processed for other products. Of this 7 percent, about 2 percent is used in tire manufacturing, 3 percent is turned into rubber products (e.g., floor mats, mudguards, carpet padding, etc.), and 2 percent is used as crumb rubber in asphalt pavements. This leaves 77 percent to be placed into stockpiles, landfills, or to be illegally dumped. However, about 49 States have enacted legislation regulating the disposal of scrap tires. At least 18 States have developed market incentive programs for recycling or use as TDF.(1)

The disposal of scrap tires into landfills is an expensive process since tires occupy a large space and present both a fire hazard and a health hazard.(3) Landfilling fees in the U.S. range between $31.80 and $98.00/Mg ($35 and $108/ton) for whole scrap tires.(1) Often whole tires are not allowed in the landfill and shredding is necessary prior to disposal. With shredding costs of about $22.70/Mg ($25/ton), the landfill fees range between $11.80 and $40.90/Mg ($13 and $45/ton). This results in approximate savings of $0 to $34.50/Mg ($0 to $38/ton) when shredded tire rubber is used in place of whole scrap tires.

An alternative is to use shredded tires as a TDF source in power plants, tire manufacturing plants, cement kilns, and pulp and paper production.(1,4) The high heat value of scrap tire rubber 37.9 MJ/kg (16,000 Btu/lb) vs. 27.5 MJ/kg (12,000 Btu/lb) for most coal) makes it a viable fuel although it is often used in combination with other fuels (composite fuel) and burned in a fluidized bed to facilitate efficient combustion and minimize handling problems.

Alternative uses for whole tires, including erosion control, retaining walls, highway crash barriers, reefs, and breakwaters, playground equipment, etc., do not have much potential for significant scrap tire utilization and in some cases may be considered as aesthetically undesirable.(1)

Another major approach is to process the scrap tires for use in the manufacturing of rubber products, pavements, sludge composting, split tire products, playground gravel substitute, pyrolosis, etc.(3) The generation of used tires has been drastically reduced by new tires having greater life and the used tires being upgraded by retreading. The National Tire Dealers and Retreaders Association claims that properly inspected retreaded tires have lifetimes and failure rates comparable to new tires.(1) Currently, it is estimated that about 50 percent of the usable tires are being scrapped.(1) This is due to the user frequently replacing all tires on the vehicle when only one or two are worn out.

The following segments of this chapter of the report contain an overview of crumb rubber modifier (CRM), processes for blending or mixing, and available methods and applications that range from a stress-absorbing membrane (SAM) to hot-mix asphalt (HMA) paving mixtures. Also, since there are numerous terms used in CRM technology, a list of more commonly used words and their definitions are presented in the following section.

Definitions of Terminology[1]

This document uses the terminology as defined below.

- Ambient Ground CRM — Crumb rubber that is produced by processing scrap tire rubber at ordinary room temperature.

- ARM-R-SHIELD™ — A trade name of the Arizona Refining Company for an asphalt rubber produced by a wet process using about 20 percent crumb rubber (20 to 40 percent devulcanized and 60 to 80 percent ambient ground vulcanized, all passing through the no. 40 sieve), 2 to 4 percent extender oil, and 76 to 78 percent asphalt cement. Blending is usually performed for about 15 s at 190 to 220 °C (originally patented by the Union Oil Company).

- Asphalt Rubber (AR) — Asphalt cement modified by the addition of a crumb rubber modifier. (Also a general term used as an adjective and referring to a specific use or application of asphalt rubber, e.g., asphalt rubber binder, asphalt rubber hot-mix, asphalt rubber pavement, etc.)

- Beugnet Method — A wet processing method developed in France that is marketed under the trade name Flexochape™ using crumb rubber, an extender oil, and a catalyst that is mixed directly with asphalt cement at elevated temperature (180 °C). The formulation for this storable asphalt rubber binder is:

	Typical
Asphalt 80/100	81.5 percent
CRM (100 percent passing through the no. 20 sieve)	10.0 percent
Oil extender	6.0 percent
Catalyst (synthetic elastomer, storage at 160 °C)	2.5 percent

- Bitumar Method — A wet process method originating in Montreal, Canada that is claimed to completely dissolve 10 percent of the crumb rubber modifier (passing through the no. 5 sieve) into the asphalt cement. (Trade name: EcoFlex™.)

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[1] Definitions based upon those provided in *State of the Practice—Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier*, Publication No. FHWA-SA-92-022, Federal Highway Administration, May 1992. Modifications, additions, and deletions of portions or entire definitions as listed in this publication were done to enhance clarity.

- Buffing Waste — A high quality scrap tire rubber that is a byproduct from the conditioning of tire carcasses in preparation for retreading.

- Continuous Blending Method — A wet processing method using a continuous production mode to produce various asphalt rubber paving materials.

- Crackermill — A CRM production process that tears apart tire rubber by passing the material between rotating corrugated steel drums, reducing the size of the rubber to a crumb particle (generally 4.75 mm to 425 μm (no. 4 to no. 40) sieve).

- Crumb Rubber — Scrap tire rubber that has been processed to particle sizes usually less than 9.5 mm (sometimes referred to as ground tire rubber GTR or CRM).

- Crumb Rubber Modifier (CRM) — A general term for scrap tire rubber that is reduced in size and is used as a modifier in asphalt paving materials.

- Cryogenic — A CRM production process that freezes the scrap tire rubber and crushes the rubber to the desired particle size.

- Devulcanized Rubber — Tire rubber treated by heat, pressure, and the addition of softening agents to alter the properties of the rubber.

- Diluent — A light petroleum product (typically kerosene) added to an asphalt rubber binder just before the binder is spray-applied to the pavement surface.

- Dry Process — Any method that mixes the crumb rubber modifier with the aggregate either before or after the mixture is charged with asphalt binder. This process only applies to hot-mix asphalt production.

- Extender Oil — An aromatic oil used to supplement the asphalt/crumb rubber modifier reaction (often provides oil to reduce viscosity and to replace oils adsorbed by the crumb rubber modifier).

- Generic Dry Method — A dry processing method using a crumb rubber modifier with particle sizes generally less than 2 mm that is mixed with either dense-graded, open-graded, or gap-graded aggregates to modify the asphalt binder and/or provide rubber aggregate.

- Granulated CRM — Cubical, uniformly shaped, cut crumb rubber particles that are generally produced by a granulator.

- Granulator — An ambient CRM production process that shears the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance, reducing the size of the rubber to a crumb rubber particle (generally 9.5 mm to 2.00 mm (3/8 in to no. 10 sieve)).

- Ground CRM — Irregularly shaped torn crumb rubber particles with a large surface area that are generally produced by a crackermill.

- McDonald Method — A wet batch processing method used in the production of various asphalt rubber paving materials generally formulated using the following:

Temperature	190 °C to 205 °C
CRM particle size	2.00 mm (No. 10 sieve) and finer
Amount of CRM (by weight of total binder)	15 to 25 percent
Process time	45 minutes

  This method incorporates the developments of ARCO and Suhuaro.

- Micro-Mill — A CRM production process that further reduces the particle size of the crumb rubber below a 425 μm (no. 40) sieve.

- Overflex™ — A trade name of the Sahuaro Petroleum and Asphalt Company for an asphalt rubber produced by the wet process using about 20 percent crumb rubber by weight, generally without extender oil or other additives.

- PlusRide® Method — A patented dry processing method using about 2 to 3 percent (by weight of mix) coarse rubber particles (e.g., 1 to 7 mm) that are added to a gap-graded aggregate.

- Pressure Reaction Method — A wet processing method that involves a preblending of CRM in the hot-asphalt cement followed by a pressure reaction system to achieve reaction times considerably less than 15 min. The processing equipment will be available through Modified Asphalt Systems, Inc. (MASI).

- Reaction — The interaction between asphalt cement and crumb rubber modifier when blended together. The reaction, more appropriately defined as polymer swell, is due to the absorption of aromatic oils from the asphalt cement into the polymer chains of the crumb rubber. It is not considered to be a "chemical reaction."

- Rubber Aggregate — Crumb rubber modifier added to hot-mix asphalt mixture using the dry process that retains its physical shape and rigidity.

- Rubber-Modified Hot Mix Asphalt (RUMAC) — Hot-mix asphalt mixtures that incorporate crumb rubber modifier primarily as rubber aggregate.

- Shredding — Scrap tire recycling process that reduces scrap tires to pieces 0.15 m^2 (6 in^2) and smaller.

- Stress-Absorbing Membrane (SAM) — A surface treatment (chip seal) using an asphalt rubber spray application and cover aggregate.

- Stress-Absorbing Membrane Interlayer (SAMI) — A membrane beneath an overlay designed to resist the stress/strain of reflective cracks and delay the propagation of the crack through the new overlay. The membrane is a spray application of asphalt rubber binder and cover aggregate.

- Wet Process — Any method that blends a crumb rubber modifier with the asphalt cement prior to incorporating the binder in the asphalt mixture.

Crumb Rubber Modifier Production and CRM Paving Processes/Products

The use of crumb rubber in highway pavement construction may be considered as experimental or operational depending upon the type of application and the past experience within a given State. Crumb rubber may be blended with an asphalt cement (wet process) prior to mixing with aggregates or it may be added (dry process) directly to the aggregates prior to mixing with asphalt or directly to the asphalt mixture during the mixing process. The characteristics of the crumb rubber and the equipment systems used to produce CRM are often dependent upon the applications that are to be used on the paving project.

Generally, scrap tires are converted to crumb rubber by first shredding and then processing in a granulator, crackermill, cryogenic system, or micro-mill to produce the desired particle size and surface texture. In the process, steel and fiber, which constitute about 30 percent by weight of the tire, are removed. Generally, whole tires contain 20 to 26 percent synthetic rubber and 21 to 33 percent natural rubber.(5) The granulator produces particle sizes in the range of 2.00 to 9.5 mm, which are often used in RUMAC.(6)

Crumb rubber from a crackermill or micro-mill (particles < 2.0 mm (< 0.08 in)) may be used in the dry or wet process to produce dense-graded, open-graded, or gap-graded mixtures. The smaller the crumb rubber particles, the greater the flexibility in its use for hot-mix applications. Florida has followed this approach by using micro-mill CRM that minimizes the influence of CRM particle size on the VMA and improves binder homogeneity, which facilitates the testing of the CRM binder. Gap-graded mixtures should be deficient in aggregate sizes to accommodate the rubber particles that swell due to their absorption of malthenes (oils) from the asphalt cement (a size/time/temperature-dependent reaction). Consequently, the properties of dense-graded asphalt rubber mixtures may be affected depending upon particle size and amount of CRM. The dense-graded aggregate blend must be able to accommodate the rubber particle sizes without excess expansion or dilation of the compacted mixtures. Similarly, the amount of rubber used in the mix, if excessive, will produce swelling or prevent adequate compaction due to the high viscosity of the asphalt-rubber binder regardless of whether the dry or wet process is used.

Overview of CRM Construction Methods

PlusRide®

The PlusRide® method is a patented RUMAC mixture marketed under the trade name of PlusRide®. This method is a dry process using a blend of ground and granulated rubber added to a gap-graded aggregate with the addition of an asphalt cement binder. The coarse rubber particles act as compressible elastic aggregate that flex under traffic.(7) This flexing has the advantage of breaking up ice and providing better skid resistance during pavement icing conditions than conventional HMA mixtures.(8) The experience of different States ranges from poor mix design and construction, to no difference between PlusRide® and conventional pavement, to improved skid resistance with slightly more rutting than the control section.

Chunk Rubber

The Cold Regions Research and Engineering Laboratory (CRREL) experimented with the use of chunk rubber in hot mix asphalt to improve ice debonding.(5) This laboratory evaluation involved the use of RUMAC mixture, including PlusRide®, where chunk rubber is added as part of the aggregate component.(2) The CRREL concept was to produce a gap-graded CRM/aggregate asphalt mix using various amounts of rubber (3 to 100 percent) to replace aggregate while maintaining the desired CRM/aggregate gradation. The CRM gradation was modified to provide a particle size range from 4.75 mm (no. 4 sieve) up to a 12.5-mm (1/2-in) sieve.

Generic Dry

The Generic Dry method differs from the other dry processing methods because the CRM can be added to conventional open-graded, gap-graded, or dense-graded asphalt concrete mixtures with only slight modification of the aggregate gradation. Consequently, variations in aggregate blend gradations between various localities does not require significant adjustments in gradation to accommodate the CRM. The amount and particle size of CRM used in an asphalt mix is dependent upon whether or not the aggregate gradation has sufficient void space for the CRM without creating excessive expansion or dilation of the mix. Therefore, certain gap-graded aggregate blends are much more adaptable to this process than dense-graded mixtures.

McDonald

The most widely used wet processing method is probably the McDonald method that has been used throughout the Southwestern U.S. to produce asphalt-rubber membranes (SAM), asphalt-rubber membrane interlayers (SAMI), and asphalt-rubber hot-mix.(5,9) This is a wet batch process where the CRM is added to hot asphalt cement (~ 185 °C to 200 °C) in a low agitation mixer and is then pumped into a holding tank where the CRM/asphalt is circulated for 45 min at about 190 °C to complete the reaction prior to metering into the mix at the asphalt hot-mix plant.(5,10) The time required to achieve satisfactory reaction is usually determined using a rotational viscometer by evaluating when a uniform viscosity has been attained.

Continuous Blending

The Continuous Blending wet processing method relies on using finely ground rubber, e.g., 425 or 180 μm (no. 40 and 80 sieve, respectively), to facilitate short blending times (< 15 min) at temperatures ranging between 150 °C and 177 °C.(11,12) The underlying concept is to provide continuous production of AR binder without "batch" blending and reacting the asphalt cement and CRM. This concept may be extended to the asphalt terminal where blending immediately prior to transport to the construction project could be achieved. Although storage time is extended up to 4 days or more using a finely ground CRM, there are questions relating to storage and the potential for separation over long time periods.(11) Some form of continuous agitation may be necessary.

Beugnet

Development work on the Beugnet method began in 1981. In 1985 it was found that a catalyst added to the process produced an improved AR binder.(13) Experimentation with this wet process indicated that 10 percent CRM produced the greatest viscosity without separation or the need for agitation. Subsequently, the formulation given below, which goes under the trade name Flexochape™, was selected as generally being the most desirable for AR paving applications.(13) The key advantage of this method is that viscosity and ring and ball (R&B) softening point remained fairly constant over 6-day storage in a hermetically sealed vessel without agitation with the exception that R&B softening increased within the first 2 days.

Bitumar

Bitumar, Inc., has developed a patented wet process method that is marketed under the trade name Ecoflex™. According to their promotional literature, Ecoflex™ contains 10 percent CRM of 4- to 10-mesh size that can be blended at refineries or at liquid bulk asphalt terminals, transported, and used at asphalt hot-mix plants without any modifications to existing plants or construction equipment. The unique aspect is that Bitumar claims that their method produces complete dissolution of the CRM to ensure permanent and irreversible homogeneity. They state "it guarantees extended storage stability and allows for the eventual recycling of the pavement itself."

Applications/Performance

Arizona started evaluating CRM materials in the mid-1960's and California has been evaluating CRM on State highways since the mid 1970's. In most States, experimentation with CRM in HMA has occurred within the last 5 years. The ensuing discussion on applications and performance is based upon research reports and survey data.

Spray Applications

- **Stress-Absorbing Membrane (SAM)**

The SAM or asphalt-rubber chip seals have been used commonly in the Southwest and even in South Africa.(14,15) Some improvements noted on well-designed and constructed SAM's are improved adhesion to chips, which reduce chip loss under traffic, increased resistance to reflection cracking due to improved flexibility, and increased durability and weatherability.(15) In California, CALTRAN's experience with SAM construction has been generally very good.(16) Damage claims for broken windshields were minimal or nonexistent except in a few cases that were attributed to poor traffic control during construction. CALTRAN's overall appraisal of SAM constructibility and performance was excellent and the service record history showed good life-cycle costs and maintenance-free performance.

Similarly, in Arizona the application of SAM's on U.S. Routes and State Routes extended the service life of the pavements about 8 and 10 years, respectively.(17) In the case of the U.S. Routes, about 40 percent of the pavements were older than 23 years at the time of the SAM treatment. Interstate pavements averaged about 11 years when a SAM was applied that extended the life on the average of 5 years (50 percent).

In colder climates, the SAM's appear to give more variable performance. Two SAM test sections were constructed in Minnesota that gave diverse performance.(18) The section that gave good performance had high quality aggregate that was precoated with 0.5 percent of a 120/150 pen AC. The SAM project that failed included similar AR application rates, but excessive rock dust on the chips and high moisture content, due to rain, were attributed to the extensive loss of aggregate. In their opinion, there was a place for SAM's somewhere between a hot-mix overlay and an emulsion chip seal.

Two SAM experimental sections were constructed with the addition of an emulsion sand seal in Connecticut.(19) After 9 years, cracks were almost nonexistent, but the control section was so extensively cracked that it was not meaningful to make crack length measurements. Several other SAM sections were placed and after 4 or 5 years, one was chip sealed and the other overlaid with 50 mm of asphalt concrete, which is essentially a SAMI. The amount of cracking in the control sections was two to three times that on the SAM sections. SAM's are more effective in reducing chip loss when properly constructed under favorable weather conditions.

- **Stress-Absorbing Membrane Interlayers (SAMI)**

Arizona placed approximately 528 km (330 mi) of SAMI's between 1975 and 1980. The age of pavements prior to application of a SAMI ranged from 8 to 44 years. The mean life of the SAMI's on Interstate, State Routes, and U.S. Routes was 9, 9.5, and 7.8 years, respectively, although individual projects extended up to 15 years.(17) Slightly better performance was achieved on Interstate pavement even though they received 10 times the load repetitions than the State or U.S. Routes. This was attributed to either the better condition of the Interstate pavements or the greater thickness of overlay [1,000 mm vs. 500 mm (39.4 in vs. 19.7 in)] used on the Interstate. Comparisons of SAMI to control sections indicated very little difference in distress, however, one project had an overlay thickness of 110 mm (4.5 in) on the control vs. 60 mm (2.4 in) for the SAMI. Typically, other forms of distress, such as roughness and bleeding, had a greater effect on service life than cracking.

The primary findings from eight SAMI test sections on three construction projects in Minnesota indicated a reduction in cracking on two projects, but reflective cracking was not totally eliminated.(18) The third SAMI project provided little or no reduction in reflective cracking over the conventional overlays. Some aggregate loss and pickup of the AR was experienced from construction traffic. Also, a short segment of a SAMI had an excessively heavy spray application of AR, resulting in instability requiring replacement. Construction of the SAMI's were performed without much difficulty, but their ability to extend an overlay's life span was not established.

Similarly, in Connecticut, the SAMI's did not perform better than conventional overlays and in several cases, even worse.(19) However, this poor performance may have been attributable to the use of crushed stone hot-mix overlay resulting in the stone being forced into the SAMI during overlay compaction.

FHWA demonstration projects in 8 States indicated that 7 of the 10 SAMI projects provided the same relative performance as conventional overlay.(20) Only two projects were considered to be better than the control sections. Similarly, New Mexico concluded SAMI's do retard the rate of reflective cracking or necessarily prevent reflective cracking.(21) Florida found that open-graded mixtures should not be placed over SAMI's and that SAMI's performed better over old pavement than freshly placed leveling courses because aggregate embedment and flushing of AR was prevented.(22) The evaluation of two SAMI projects in Pennsylvania indicated an insignificant increase in service life, but the use of SAMI was not economically justified.(23) Vermont found that a 50-mm-thick overlay was more effective in preventing reflection cracking than the SAMI.(24)

The cost of a SAM or SAMI is somewhere in the range of \$1.55 to \$2.15 /m^2 (\$1.30 to \$1.80/yd^2) or approximately twice the cost of a conventional chip seal.(16-18) However, if the cost for the SAMI is combined with the cost of a 30- to 50-mm (1.2-in to 2.0-in) thick overlay, the total rehabilitation cost is only 30 to 40 percent greater than using only the overlay.

Dense-Graded Mixtures

The performance of dense-graded AR mixtures is highly dependent upon the gradation of the CRM, aggregate gradation, volume of voids in the mineral aggregate, characteristics of the asphalt cement or asphalt rubber, climatic and traffic conditions, and the type and degree of pavement distress (e.g., amount of cracking) existing prior to placement of the overlay. Eighteen test sections constructed with 38 mm (1.5 in) of dense-graded RUMAC mixtures containing 1 and 2 percent (by weight of mix) CRM (30 mesh) in Connecticut using the generic dry process were compared to the control section after 9 years of service.(19) One percent CRM reduced the amount and rate of longitudinal cracking as compared to the control except in those sections that were originally highly distressed. The use of 2 percent CRM apparently affected the hardness of the binder resulting in twice the amount of longitudinal cracking that was produced on control sections.

Section 403, Hot-Mix Asphalt Concrete Pavement Specifications for New York that were adopted in 1992, provides the option for the use of 18 percent by weight of binder of a 3.2-mm (0.125-in) maximum size CRM in the generic dry process for asphalt concrete mixtures.(25)

Recently (1992), test road sections in Iowa with CRM contents ranging between 5 and 20 percent (by weight of asphalt) were constructed using the Continuous Blending and McDonald wet process methods to pave AR test sections on five different projects. (See references 26 through 30.) Although it is too soon to evaluate performance, these AR pavement sections appear to be in the same condition as the conventional (control) sections. It was concluded that dense-graded AR mixtures can be constructed with little or no difference from that of a conventional mix. On the first two projects a problem with shoving and cracking occurred during rolling and sticking (pick up) of the AR mix to the drum of the roller.(26,28) Segregation was a problem on the third project and it was alleviated by using flowboy trucks instead of dump trucks.(27) The conventional control mix also had the same segregation problem as the AR mixture.

Maryland designed a dense-graded AR mixture using a 12.5-mm (0.5-in) nominal maximum size aggregate and an asphalt rubber binder containing 18 percent CRM (4.8-mm (0.19-in) maximum particle size) with extender oil as necessary (7 percent maximum) to meet the AR binder specifications.(31) The aggregate gradation was altered from the conventional mix to increase the voids in the mineral aggregate (VMA) from 16.8 to 20.3, which changed the binder content from 5.5 percent to 7.2 percent for the AR mixture. A 1.61-km (1-mi) long AR test section was constructed with only minimal problems. Initial performance of the pavement up to 7 months after construction indicates minimal rutting and visually no difference between conventional and AR test sections. However, average friction numbers for the AR section are about 10 units lower than for the conventional pavement immediately after construction.

The McDonald process was used in Missouri to blend an AR binder.(32) An AC-5 with 15 percent (by weight of binder) CRM was used in a dense-graded aggregate blend and placed as a 1.61-km (1.0-mi) long test section on I-70 during August 1990. The overall performance of the AR concrete mixture was satisfactory over the first 4 months except friction numbers were 10 to 15 units less than the control section.

In general, the costs for dense-graded AR concrete mixtures using the wet process is two to three times the cost of conventional mixtures. It appears that costs using the dry process may be as low as 1.3 to as high as 2.0 times the cost for conventional dense-graded mixtures.(33,34) A survey by the State of Maryland of State Highway Agencies indicated that about 75 percent of those using CRM were paying between $48.50 to $97.00/Mg ($40 to $80/ton) of hot-mix.

Gap-Graded Mixtures

A gap-graded aggregate HMA has a gradation that is deficient in or has no material in one or more of the intermediate sieve sizes. In other words, one or more of the sieves in a series of sieves used for gradation analysis would not have any retained aggregate. The purpose of using a gap-graded aggregate blend is to provide space for the rubber aggregate and to maintain course aggregate contact without dilation when the voids are filled with fine aggregate and asphalt cement.(5)

Probably the most well-known method for gap-graded rubber aggregate mixtures is that called PlusRide®. It is a very resilient material that makes it a difficult material to evaluate using conventional tests in the laboratory.(35) However, its potential attributes are improved skid resistance because of its deicing characteristics resulting from its high resiliency (deformation under load). Braking tests conducted in Alaska showed a 19 to 25 percent reduction in stopping distance during icy road conditions.(8,34)

The variable performance history of PlusRide® in Colorado indicated either a problem with proper formulation and construction, or using it to correct extensively distressed pavements. The major problem encountered in Colorado was raveling, which appears to be caused by cohesive failure and is most prevalent in traffic and turn lanes on facilities with higher volumes of vehicles.(35) Apparently, it is necessary to place these RUMAC mixtures at air-void contents near 4.6 percent to achieve good performance.(36) This necessitates laboratory design voids somewhere in the range of 3 to 4 percent. The desired air-void content is usually achieved by increasing both mineral filler and asphalt cement contents. The cost per ton of PlusRide® in the Anchorage area exceeds the cost of conventional hot-mix by 43 percent.(37)

Open-Graded Mixtures

High permeability and high skid resistance are two characteristics of open-graded friction course (OGFC) mixtures. These mixtures are specially designed with a high void content to minimize hydroplaning and splash/spray by increasing the ability of the water to drain through the mix and away from the pavement surface. The use of asphalt rubber binder increases the binder's viscosity and allows for an increase in binder content without the problem of binder migration (drain-down). The resulting increase in asphalt film thickness is essential for OGFC mixture durability.

OGFC projects in Florida were constructed using both McDonald and Continuous Blending methods.(10,12) Test sections in both projects appear to be performing well after 2 to 3 years of service. A generic dry method with 10 percent CRM (by weight to binder) was included in one project without any noticeable difference in constructibility or performance to date. One project on I-95 involved 57.6 lane-kilometers (36 lane-miles) of conventional OGFC and 6.4 lane-kilometers (4 lane-miles) of OGFC containing 12 percent CRM in the asphalt rubber binder. The cost of the AR friction course was 30 percent over the cost per square yard of conventional OGFC. More recently, a project near Tampa resulted in only a 10 percent increase in cost using terminal blending of the AR binder.

Since 1988, Arizona has constructed seven projects using an asphaltic concrete friction course (ACFC) to control reflective cracking in severely cracked concrete pavement. Since the earliest sections were placed in 1988, no cracks have reflected through. Despite the higher cost of asphalt rubber compounds, the material is more cost effective because a 50-mm (2-in) or less ACFC provides better reflective cracking control than a significantly larger and more costly layer of HMA.(38)

Recycling Pavements Containing Crumb Rubber Modifier

The literature search did not reveal any documented projects or experience relating to the recycling of asphalt pavements containing CRM. Furthermore, the responses from State highway agencies as requested in the letter and survey form no. 3 in appendix B indicate that only three projects have been recycled. These projects were located in New Jersey, the District of Columbia, and Ontario, Canada.

The Ontario Ministry of Transportation used a drum mixer and batch plant in the production of a dense-graded hot-mix for pavement rehabilitation in October 1991. After being in service for 1.5 years, the pavement was cracked and raveling. Overall performance was rated poor compared to the control.

The New Jersey Department of Transportation used 20 percent RAP containing CRM (PlusRide®) in a dense-graded hot-mix for pavement construction during August 1992. No difference was observed between the construction of the recycled and control pavement sections. It is too early to quantify its performance.

An open-graded recycled mix with CRM RAP was used in the construction of a pavement in the District of Columbia. However, this pavement was overlaid shortly after being constructed in September 1992.

The lack of information and the concern over the ability to effectively recycle CRM pavements without technical and environmental difficulties suggest that further research is essential. If certain types (particle size) and concentrations (amount) of CRM prevented effective recycling of pavements, then it would severely impact those State and other highway agencies that currently have viable asphalt pavement recycling programs.

Results From Survey of State Highway Agencies

Appendix B provides examples of the letter of transmittal, one-page questionnaires that were sent to State highway agencies in the U.S. and to Ministries of Transportation in Canada. Thirty-two States and the NY/NJ Port Authority responded to the CRM pavement survey, including two States that have not used CRM technology. Table 13 presents a summary of the most important variables of CRM technology, i.e., type of process, type of application, age of test section, and relative performance rating.

The summary presented at the bottom of table 13 indicates that 70.2 percent of all reported CRM projects used a wet process and almost 61 percent of the total involved the McDonald method. The Continuous Blending method, which was developed in the late 1980's, accounted for 7.7 percent of the projects. Methods such as the generic dry (14.2 percent) and PlusRide® (10.3 percent) processes comprised most of the projects that used the dry process.

The applications portion of the table indicates that almost 40 percent of the projects were dense-graded HMA mixtures and about 29 percent gap-graded HMA mixtures. Surprisingly, the number of SAMI projects (27) greatly exceeded the SAM projects (2). This occurred primarily because numerous SAM projects were not reported. Most of the SAMI projects were constructed with asphalt rubber using the McDonald method. The performance of the SAMI's were rated as being about the same as the control sections. Projects that were 8 to 14 years old will be overlayed in the near future, which assumes that they have approached the end of their service life.

The majority of dense-graded CRM projects have been in service for less than 5 years, except for numerous older projects in California that have, in general, a performance rating better than the control sections. These older projects were primarily constructed using the McDonald method, whereas the younger projects across the country utilized the generic dry, Continuous Blending, and McDonald methods. Performance rating on projects less than 5 or 6 years old generally were equivalent to the performance of the control sections.

Performance of the gap-graded CRM mixtures with the PlusRide® method varied from better to worse than conventional mixtures in the control sections. The other wet and dry methods used with the gap-graded CRM mixtures on the projects performed essentially the same as the control. The open-graded friction course projects using McDonald and generic methods are too young to assess performance differences.

The majority of dense-graded CRM projects have been in service for less than 5 years, except for numerous older projects in California that have, in general, a performance rating better than the control sections. These older projects were primarily constructed using the McDonald method, whereas the younger projects across the country utilized the generic dry,

Table 13. Summary of responses to the surveys on CRM pavements.

STATE/ DISTRICT	WET PROCESS			DRY PROCESS				APPLICATION					PERFORMANCE						Overlay in Near Future	FORMULATION			
	Method (Trade Name)			Method (Trade Name)				Spray		Asphalt Concrete			Age (Mo)	Performance Compared to Control						Compare: Test to Control Sect.			CR (%)
	McDon	Continuous	Overflex	Generic	PlusRide	Ram Flex	Flomix	SAM	SAMI	Dense	GAP	OGFC		Rutting	Crack	Ravel	Strip	Overall		Same W/O	Conv. Mix	Same Grd	
Alaska					1						1		163						N		x		
Alaska					1						1		89	4	3	3	3	4	N		x	n	
Alaska					1						1		137	3	3	2	3	3	N		x	n	
Alaska					1						1		89	4	3	3	3	4	N		x	n	
Arizona	1968 - 1988 ARIZONA HAS CONSTRUCTED OVER 10 PROJECTS THAT WERE EVALUATED IN THE DEVELOPMENT OF ASPHALT-RUBBER SYSTEMS.																						
Arizona	1985-1992 OVER 50 PROJECTS PLACED. REPORTS AND TABULATED INFORMATION ARE BEING EVALUATED.																						
California							1			1			170	3	4	4		4	N	x	x	y	
California	1									1			144	3	5	6		5	Y	x	x	y	
California	1									1			144	3	5	6		5	N				
California	1									1			132	4	4	4		4	91				
California	1											1	120	3	4	4		4	Y	x	x	y	
California	1												120		5	6		5	N				
California	1									1			120	3	5	6		5	Y	x	x	y	
					1						1		108	3	5	6		6	Y		x	n	
California	1									1			84						Y				
California						1				1			108	2	2	2		2	Y	x	x	y	
California						1				1			96	3	2	2		2	Y	x	x	y	
California	1									1			96						Y				
California	1												89					3	92		x	y	
California					1						1		72	3	4	4		4	Y		x	n	
California	1											1	84						N				
California	1									1			68						Y				
California	1									1			48	4	4	3		4	Y	x	x	y	
					1						1		48	4	4	3		4	Y		x	n	
California	1									1			52	3	2	2		4		x	x	y	
					1						1		52	3	5	6		5			x	n	
California	1											1	48						N				
California	1									1			41						N				
California	1									1			36						N				
California	1										1		30					4	N		x	n	
California	1									1			16					3	N	x	x	y	
California	1									1			15					3	N	x	x	y	
	1										1		15					3	N	x	x	y	
California	1								1				16					3	N		x	n	
California	1									1			5					3	N	x	x	y	
	1										1		5					3	N			n	
	1								1				5					3	N				
California	1									1			3						N	x	x	y	
	1								1				3						N				
California	1										1		3						N				
California	1										1		18						N				
	1								1				18						N				
California	1										1		4						N				
California	1										1		8					3	N	x	x	y	
California	1									1			8					3	N			n	

Table 13. Summary of responses to the surveys on CRM pavements (Continued).

STATE/ DISTRICT	WET PROCESS			DRY PROCESS				APPLICATION					PERFORMANCE						Overlay in Near Future	FORMULATION			
	Method (Trade Name)			Method (Trade Name)				Spray		Asphalt Concrete			Age (Mo)	Performance Compared to Control						Compare: Test to Control Sect.			CR (%)
	McDon	Continuous	Overflex	Generic	PlusRide	Ram Flex	Flomix	SAM	SAMI	Dense	GAP	OGFC		Rutting	Crack	Ravel	Strip	Overall		Same W/O	Conv. Mix	Same Grd	
California	1								1				8					3	N				
California	1								1				18						N			n	
					1						1		18						N			n	
California	1										1		7						N				
Caltrans	1										1		300		5				Y				
Caltrans	1								1				188						Y			n	
Caltrans	1								1				15						N		x	n	
Caltrans									1				8						N			n	
Caltrans	1												96		3				Y		x	n	
Caltrans	1								1				39		3				N			n	
Caltrans	1								1				132					5	Y			n	
Caltrans	1								1				144						Y		x	n	
Caltrans	1								1				132		3				11/89		x	n	
Caltrans	1								1				108					4	4/92		x	n	
Caltrans	1								1						3				88			n	
Colorado	* * * *	* * * * * * *	* * * * *	* N/A *	* * * * *	* * * * *	* * * *	* * *	* * *	* * * *	* * *	* * *	* * * *	* * *	* * *	* * *	* * *	* * *	* * * *	* * * * * *	* * * * *	* * * * *	* * *
Connecticut	1									1			146		4	3	3	4	N		x	y	
Florida	1									1			45	3	3	3	3	3	N	x	x	y	
Florida	1											1	42		3	3	3	3	N	x	x	y	
Florida	1								1				162	3	5	3	3	4	6/92				
Florida		1										1	27						N	x	x	y	
Georgia (*)		1										1	2						N	x	x	n	
Georgia (*)		1								1			2						Y	x	x	y	
Hawaii	* * * *	* * * * * * *	* * * * *	* N/A *	* * * * *	* * * * *	* * * *	* * *	* * *	* * * *	* * *	* * *	* * * *	* * *	* * *	* * *	* * *	* * *	* * * *	* * * * * *	* * * * *	* * * * *	* * *
Idaho	1										1			**					N				
Illinois				1						1			14	3	3	3	3	3	N		x	n***	
Illinois	1										1		5	3	3	3	3	3	N		x	n	
Indiana	1									1			29	3	3	3	3	3	N		x	y	1
Indiana				1						1			18	3	3	3	3	3	N		x	y	2
Indiana				1						1			18	3	3	3	3	3	N		x	y	3
Indiana				1						1			18	3	3	2	3	3	N		x		
Iowa	1									1			6	3	3			3	N		x	n	
Iowa		1								1			14	3	3			3	N		x	n	
Iowa		1								1			14	3	3			3	N		x	n	
Iowa		1								1			16	3	3			3	N		x	n	
Iowa		1								1			4	3	3			3	N		x	n	
Iowa		1								1			18	3	3			3	N		x	n	
Kansas ($)				1						1			5	3	3	3	3	3	N	x	x	y	
($)				1							1		6	3	3	3	3	3	N	x	x	y	
Kansas									1				172	3	1	3	3	1	Y			n	
Kansas	1									1			16	3	4	3	3	4	N			y	
	1										1		16	3	4	3	3	4	N				
Kansas ($)				1						1			17	3	2	2	3	3	N	x	x	y	
Kansas	1									1			27	4	2	1	3	2	N	x	x		
Kansas	1									1			28	3	1	3	3	2	N	x	x	y	
Kentucky	* * * *	* * * * * * *	* * * * *	* N/A *	* * * * *	* * * * *	* * * *	* * *	* * *	* * * *	* * *	* * *	* * * *	* * *	* * *	* * *	* * *	* * *	* * * *	* * * * * *	* * * * *	* * * * *	* * *

Table 13. Summary of responses to the surveys on CRM pavements (Continued).

STATE/ DISTRICT	WET PROCESS			DRY PROCESS				APPLICATION					PERFORMANCE						Overlay in Near Future	FORMULATION			
	Method (Trade Name)			Method (Trade Name)				Spray		Asphalt Concrete			Age (Mo)	Performance Compared to Control						Compare: Test to Control Sect.			CR (%)
	McDon	Continuous	Overflex	Generic	PlusRide	Ram Flex	Flomix	SAM	SAMI	Dense	GAP	OGFC		Rutting	Crack	Ravel	Strip	Overall		Same W/O	Conv. Mix	Same Grd	
Louisiana	1										1		0						N		x	n	
Maine	1									1			17	3	3	3	3	3	N	x	x	y	
Maryland	1									1			17	3	3	3	3	3	N	x	x	y	
Michigan											1		17	3	2	3	3	3	N	x	x	y	
Michigan										1			27	4	2	3	3	2	N	x	x	y	
Michigan				1						1			156	4	3	1	1	2	93	x	x	y	
Minnesota										1			5	3	3	1	3	1	Y	x	x	y	
Minnesota											1		5	3	3	1	3	1	Y	x	x	y	
Minnesota					1						1		101	4	4	3	3	4	N		x	y	
Minnesota					1						1		101	3	3	1	3		N		x	y	
Minnesota	1									1			100	3	4	3	3	3	N	x	x	y	
Minnesota				1							1		29	3	2	1	1		Y	x	x	y	
Missouri	1									1			28	3	3	4	3	3	N		x	n	
Missouri	1									1			15	3	3	3	3	3	N		x	n	
Missouri	1										1		15						N				
Mississippi		1								1			14	5	5	6	5	5	N	x		y	
Nebraska	1										1		2					3	N		x	n	
Nebraska	1										1		24	3	4	3	3	4	N		x	n	
New Hampshire	1								1				168	3	4	3	3	3	Y		x	y	
New Jersey		1										1	5	3	3	3	3	3	N		x	n	
New Jersey		1								1			27	3	3	3	3	3	N	x	x	y	
New Jersey					1						1		101	3	3	3	3	3	N		x	n	
New Mexico					1						1		24	1	1	1	1	1	10/86			n	
New Mexico															2								
New Mexico	1								1				156	3	3			3	N		x	y	
New Mexico	1								1				173						Y		x	y	
New York 1				1						1			40	3	2	3	3	3	N		x	y	1
B-Project 1				1						1			40	3	2	2	3	2	N		x	y	2
(NY) 1				1						1			40	3	3	1	1	1	Y		x	y	3
(NY) 1					1						1		40	3	3	1	3	1	Y		x	y	
New York 2				1						1			40	3	3	3	3	3	N		x	y	1
D-Project 2				1						1			40	3	3	3	3	3	N		x	y	2
(NY) 2				1						1			40	3	3	1	1	1	Y		x	y	3
(NY) 2					1						1		40	3	3	3	3	3	N		x	y	
NY/NJ Pt Auth.					1								116	1	3	1	2	2	Y		x	n	
North Carolina				1						1			16	3	5	1	3	1	Y		x	y	
North Carolina				1						1			19	3	4	2	3	3	N		x	y	
North Carolina										1			1	3	3	3	3	3	N		x	y	
North Carolina	1								1				1						N				
North Carolina	1										1		1						N			y	
North Carolina	1									1			1						N			y	
North Dakota	• • • •	• • • • • •	• • • • •	• N/A •	• • • • •	• • • • •	• • • •	• • •	• • •	• • • •	• • •	• • •	• • • •	• • •	• • •	• • •	• • •	• • •	• • • •	• • • • • •	• • • • •	• • • • •	• • •
Ohio	1										1		24					4	N		x	n	
Ohio	1										1		24					3	N				
Ohio	1										1		6						N				
Ohio	1										1		6						N				

Table 13. Summary of responses to the surveys on CRM pavements (Continued).

STATE/ DISTRICT	WET PROCESS			DRY PROCESS				APPLICATION					PERFORMANCE						Overlay in Near Future	FORMULATION			
	Method (Trade Name)			Method (Trade Name)				Spray		Asphalt Concrete			Age (Mo)	Performance Compared to Control						Compare: Test to Control Sect.			CR (%)
	McDon	Continuous	Overflex	Generic	PlusRide	Ram Flex	Flomix	SAM	SAMI	Dense	GAP	OGFC		Rutting	Crack	Ravel	Strip	Overall		Same W/O	Conv. Mix	Same Grd	
Ohio	1										1		6						N				
Ohio	1										1		6						N				
Ohio	1										1		6						N				
Oklahoma				1							1		127		1	1	1	1	Y		x	y	
Oklahoma	1									1			127		2				Y		x	n	
Oklahoma	1									1			128		2				Y	x	x	y	
Oklahoma	1											1	15	1					Y				
Oregon	1											1	16	3	3	3	3	3	Y		x	n	
Oregon			1							1			16	3	3	1	1	2	Y		x	n	
Oregon			1							1			8	3	3	3	3	3	N		x	n	
Oregon	1											1	4	3	3	3	3	3	N		x	n	
Oregon	1											1	4	3	3	3	3	3	N		x	n	
Oregon	1										1		5	3	3	3	3	3	N		x	n	
Oregon			1							1			27	3	3	3	3	3	N		x	n	
Oregon			1							1			27	3	3	3	3	3	N		x	n	
Oregon			1							1			4	3	3	3	3	3	N		x	n	
Oregon				1							1		88	3	2	1	3	2	N		x	n	
Oregon	1										1		88	3	4	3	3	4	N		x	n	
Pennsylvania		1											14	3	4	3	3	4	N	x	x	y	
Rhode Island				1							1		65	3	3	3	3	3	N		x	n	
South Carolina				1							1		8	3	3	2	3	3	N		x		
Utah											1		6						N		x	n	
Vermont		1							1				161	3	1	1	3	3	N		x	n	
Vermont		1						1					161	3	1	1	3	3	N		x	n	
Vermont		1						1					164	3	1	1	3	2	10/80		x	n	
Wisconsin	1									1			60	2	1	2	3	1	1993	x			RAP
Wisconsin	1									1			60	3	1	1	1	1	Y	x		y	RAP
Wisconsin	1								1				60	3	1	1	1	1	Y	x		y	
Wisconsin	1								1				32	3	1	3	3	1	Y	x			
Wisconsin	1									1			32	3	1	3	3	1	Y	x	x	y	
Wisconsin	1								1				32	3	1	3	3	1	Y				
Wisconsin	1									1			32	3	1	3	3	1	Y	x	x	y	
Wyoming	1										1		17	3	3	3	3	3	N	x	x	y	
TOTAL SECTIONS	94	12	3	22	16	2	1	2	27	68	46	12	55.2 AVERAGE AGE (Mo)										
PERCENT OF TOTAL	60.6	7.7	1.9	14.2	10.3	1.3	0.6	1.3	16.9	42.5	28.8	7.5											

CRM PERFORMANCE SUMMARY TABLE

Rating	Rutting	Crack	Rave	Strip	Overall
1	3	14	20	9	16
2	2	9	10	1	11
3	83	55	52	68	60
4	9	16	5	0	20
5	1	10	7	1	8
Total	98	104	94	79	115
Weighted Average	3.0	3.0	2.7	2.8	3.0

RATING SCALE
(1) POOR
(2) SLIGHTLY SUBSTANDARD
(3) AVERAGE
(4) GOOD
(5) EXCEPTIONALLY GOOD

NOTES:
* = Novophalt® (Modified asphalt using CRM)
$ = 80-Mesh CRM Used
** = No Test Section Set Up, Not Considered Experimental
*** = Mix Contains 15% RAP
@ = Bitumar EcoFlex®

Table 13. Summary of responses to the survey on CRM pavements (Continued).

SUMMARY OF PERFORMANCE RATINGS ACCORDING TO APPLICATION AND METHOD

WET PROCESS				PERFORMANCE (Average Rating)				
Application	Method	No. Projects	Avg. Age	Rutting	Cracking	Raveling	Stripping	Overall
SAM	Overflex	2	162.5	3.0	1.0	1.0	3.0	2.5
SAMI	Overflex	1	161.0	3.0	1.0	1.0	3.0	3.0
SAMI	McDonald	25	86.8	3.1	3.0	3.0	2.6	3.1
Dense	McDonald	32	56.9	3.0	2.9	3.1	2.9	3.0
Dense	Continuous	7	12.4	3.3	3.3	4.0	4.0	3.3
GAP	McDonald	13	42.1	3.3	3.6	3.0	3.0	3.4
OGFC	McDonald	7	31.4	2.4	3.2	3.2	3.2	3.2
OGFC	Continuous	1	5.0	3.0	3.0	3.0	3.0	3.0

DRY PROCESS				PERFORMANCE (Average Rating)				
Application	Method	No. Projects	Avg. Age	Rutting	Cracking	Raveling	Stripping	Overall
Dense	Generic	20	29.2	3.1	3.0	2.3	2.6	2.6
Dense	RamFlex	2	102.0	2.5	2.0	2.0	—	2.0
Dense	Flomix	1	170.0	3.0	4.0	4.0	—	4.0
GAP	Generic	2	17.0	3.0	2.5	2.0	2.0	3.0
GAP	PlusRide	18	78.1	3.0	3.1	2.5	2.6	3.1

Continuous Blending, and McDonald methods. Performance rating on projects less than 5 or 6 years old generally were equivalent to the performance of the control sections.

Performance of the gap-graded CRM mixtures with the PlusRide® method varied from better to worse than conventional mixtures in the control sections. The other wet and dry methods used with the gap-graded CRM mixtures on the projects performed essentially the same as the control. The open-graded friction course projects using McDonald and generic methods are too young to assess performance differences.

Assessment

Is CRM technology viable and cost-effective in applications relating to construction and rehabilitation of asphalt pavements? The answer to this question is not readily apparent in the literature or from State highway agency responses to the survey on CRM utilization. States located in the hot, dry, southwestern U.S. (e.g., California and Arizona) have extensive experience with AR membranes and mixtures. In general, they have had only a few failures and are generally satisfied with the constructability and performance of pavements containing CRM. However, highway agencies in the northern States, where wet and cold weather is more prevalent, have not observed any major improvement in performance over their conventional HMA pavements. In fact, numerous CRM pavements and CRM test sections performed worse than the conventional pavement or control sections. The exact causes of early failures were not identified, but they may be a result of weather-affected construction problems.

Costs are high during initial development and experimentation. This is quite apparent in CRM applications for asphalt pavement construction. At this time, many experimental CRM projects have been recently constructed. Costs are high because projects are short in length and experimental. There are indications that newer processes or adaptations to conventional production methods may reduce costs and provide reasonably good economic advantage from a life-cycle cost standpoint.

The information derived from the literature and surveys of State highway agencies indicates that SAM and SAMI's often give variable performance. This is attributed to adverse climate conditions, poor mixture design and construction, or trying to correct severe pavement distress problems (e.g., extensive cracking), which probably could not be corrected without major reconstruction. The successful use of SAM and SAMI's in the Southwest may be due to the dry, hot climate, and long construction season, which can be beneficial from the construction standpoint, but extensive experience also undoubtedly contributes measurably to their success. The main deterrent to the new user of SAM's and SAMI's is the initial cost — about twice the cost of a conventional chip seal. Even though problems have occurred, there are other projects where it has been demonstrated that SMA and SAMI membranes are cost-effective.

Based on the survey data returned, the recent experimental applications of CRM throughout the U.S. appear to be predominately in dense-graded hot-mix asphalt (HMA) using the generic dry, McDonald, and Continuous Blending methods. These projects are of insufficient age to properly evaluate their performance. The use of CRM in dense-graded mixtures can pose a problem because of insufficient VMA unless the CRM particle size quantity is small enough or the aggregate gradation is altered.

The major unknown in using these materials is the potential for their influence on the recycling process. Experience with the recycling of RAP containing CRM is limited.

RUMAC HMA design is based on the premise that the aggregates are properly gap-graded to accommodate the rubber aggregate particles. The variation in performance of pavements constructed in this manner suggests that mix formulation, the degree of resiliency, and effectiveness of construction are affecting the behavior of the material. Since Alaska has found the PlusRide® method to work well in their climatic conditions, why in some cases has it performed poorly in other climates and States?

Other recent projects involving gap-graded CRM mixtures using other methods have not been in service for a long enough time to evaluate their performance. If rubber aggregate and gap-graded aggregate blends are to be used effectively for surface mixtures, the effects of CRM particle size, amount of CRM and aggregate gradation on the properties of the mix, and the performance of the pavement need to be established.

The various applications/methods for utilization of CRM in asphalt pavements are for the most part reasonably effective. The greatest deterrents from the use of CRM is the high initial cost and the variable performance that seems to be associated with climate and selection of proper application, mix design, and construction. The assessment of information from the literature and the surveys of highway agencies has provided some insight into the problems of CRM technology. Specific recommendations are as follows:

- There is a need to evaluate the recyclability of hot mix asphalt pavements containing CRM. The investigation should encompass the use of RAP that contains AR and RUMAC paving mixtures. Potential problems that need to be addressed are: (1) the effect of asphalt-rubber mixtures and membranes on the aggregate gradation and the degree of fines generation, and other associated problems encountered in the cold milling process and (2) the degree to which malthenes (light ends) from recycling agents or new asphalt cements are absorbed by the CRM in the RAP during the hot mixing and in-service life of the recycled mixture.

- Layer equivalencies and/or test properties associated with mechanistic design for AR mixtures and membranes should be developed. In either case, the equivalency or structural design parameters must be related to the degree of distress and the structural response of the pavement before the application of AR membrane or AR mixtures to achieve desirable performance and pavement life.

- CRM/asphalt cement interaction should be evaluated to establish absorption of malthenes, degree of rubber particle swell or solubility, and influence on binder properties in relation to size and amount of CRM. Processing methods, both wet and dry, should be evaluated to determine the effects of time, temperature, pressure, mechanical mixing, etc., on the CRM/asphalt interaction. Process (reaction) time, storage time, or equilibrium conditions must be established for wet processing methods. It should be determined whether or not the product of the dry process can be made equivalent to the product of the wet process based on the fineness and quantity of CRM used in the mixture.

- Mixture design method(s) should be developed to accommodate the use of CRM using either dry or wet processing methods. The combined influence of CRM particle size and aggregate gradation needs to be evaluated and suitable criteria established for selection of amount and size of CRM and total binder contents for each application.
- Test methods and specification guidelines need to be established for effective construction control. These methods and specifications should be readily adopted or incorporated into existing quality control and quality assurance procedures.

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RECYCLING OF ASPHALT PAVEMENTS USING AT LEAST 80 PERCENT RECYCLED ASPHALT PAVEMENT (RAP)

Overview

Recycling of asphalt pavements has been shown to be both technically and economically viable, and has been among the standard practices of many State and local highway agencies in the United States in recent years. The benefits of asphalt recycling include cost savings, conservation of asphalt and aggregate resources, conservation of energy, preservation of existing highway geometrics, and preservation of the environment.

From the standpoint of conservation of natural resources, it is desirable to use as much RAP (Recycled Asphalt Pavement) as possible in the recycled asphalt paving mixtures. However, the maximum percentage of RAP that could be incorporated in a recycled mixture might be limited by the properties of the RAP used. Old asphalt pavement usually contains a binder that is hard and brittle, and an aggregate that has been degraded to some extent. The general principle in asphalt recycling is to blend the RAP with a soft asphalt or rejuvenating agent, and a coarse aggregate in the proper proportions such that the resulting recycled mixture would have a binder of suitable rheological properties and an aggregate blend of desirable gradation. A very high percentage (over 80 percent) of RAP could only be used under the following circumstances:

- The RAP is lean in asphalt, and additional soft asphalt could be incorporated without addition of virgin aggregate.

- The RAP contains a soft binder that need not be rejuvenated and could allow for some further hardening from the recycling process.

If the aggregate in the RAP contains an excessive amount of fines, an adequate proportion of virgin coarse aggregate would need to be added to upgrade the aggregate gradation. This would require a lower percentage of RAP to be used in the recycled asphalt mixture.

Currently, there are only three asphalt recycling processes that can successfully utilize at least 80 percent RAP. They are: (1) cold in-place recycling, (2) hot in-place recycling, and (3) hot-central plant recycling by means of the proprietary CYCLEAN® process.

Cold in-place recycled materials are usually used as a stabilized base course to be covered with a chip seal in low-volume roads, or overlaid with a hot or cold surface mix. Pavements with excessive patching, weak subgrade due to water damage, or stripping problems are not recommended for cold in-place recycling.

Hot surface recycling is usually used to correct surface defects such as roughness and weathering of pavements that are structurally adequate. Currently, this recycling process is also limited to a depth of 50 mm (2 in).

Among these three recycling processes, the hot central plant recycling can produce mixes of the highest quality. The hot recycled mixes are usually used as surface structural mixes. However, due to the problem with smoke emission, utilization of greater than 80 percent RAP in the recycled mix has been limited to the CYCLEAN® process that uses the microwave technology. For conventional hot mix asphalt plants, the typical maximum RAP is limited to 30 to 50 percent of the mix. Conventional plants producing hot mix asphalt with RAP contents exceeding those limits usually fail to meet local air quality requirements.

Definitions of Recycling Categories

The Federal Highway Administration classifies asphalt pavement recycling into surface, cold-mix, and hot-mix recycling.(1) The definitions for these three categories are as follows:

- <u>Surface Recycling</u> — Reworking in-place of the surface of an asphalt pavement to a depth of less than about 50 mm (2 in) by any of the suitable machinery available (such as heater-planer, heater-scarifier, hot-milling, cold-planing, or cold-milling devices). This operation is a continuous, single-pass, or multistep process that may involve the use of added materials, including aggregate, modifiers, or asphalt mixtures (virgin or recycled).

- <u>Cold-Mix Recycling</u> — Reuse of untreated base materials and/or asphalt pavement that is either processed in-place or at a central plant with the addition of asphalt emulsions, cutbacks, portland cement, lime, and/or other materials as required to achieve desired mix quality, followed by placement and compaction.

- <u>Hot-Mix Recycling</u> — Removal of more than the top 25 mm (1 in) of an asphalt pavement with or without removal of underlying pavement layers (e.g., untreated base materials) that is processed by sizing, heating, and mixing in a central plant with additional components such as aggregate, bitumen, or recycling agents and then relaid and compacted according to standard specifications for conventional hot mixtures (e.g., hot mix asphalt base, binder, and leveling or surface course).

Results from Survey of Highway Agencies

Currently, 31 State transportation or highway departments in the U.S. and 3 transportation departments from Canada have responded to the survey on the use of at least 80 percent RAP in asphalt pavements. A condensed summary of the survey results is displayed in table 14. Of these 34 responses, 8 States in the U.S. and 1 Province in Canada have indicated experience with the use of at least 80 percent RAP.

Of these seven positive responses, three States have indicated experience with using at least 80 percent RAP in hot-in-plant mixes. The mixers used were a CYCLEAN® (microwave heater) mixer and a drum mixer with a special heat shield. The reported projects that used the CYCLEAN® method had ages ranging from 2 to 25 months. The overall condition of these pavements was good, and no rutting, cracking, raveling, or stripping problems were reported. However, due to the young age of these pavements, the long-term performance of these mixtures could not be assessed. The project that used the drum mixer was reported to have performed well and carried loads in excess of design. Light raveling and moderate-to-high cracking were reported after 8 years of service.

Serious smoke emission problems have been reported when high percentages of RAP were used in conventional asphalt mixers. When more than 70 percent RAP was used in demonstration projects in Oregon, smoke emissions with opacities above 20 percent were encountered.(2,3)

Only one State has responded as having had experience with using over 80 percent RAP in hot surface recycling. The process used a Pyrotech hot in-place recycling train. Problems with excessive numbers of starts and stops, which caused excessive roughness requiring pavement grinding, were reported. This problem might be due to the inexperience of the contractor. The reported projects were only 3 to 5 months old, and thus their long-term performance could not be assessed.

Five States and one Canadian Province have indicated experience with using over 80 percent RAP in cold in-place recycling. The typical equipment used in the recycle train include a milling machine and a continuous pug mill with emulsion feed. Of the old pavement, 25 to 127 mm (1 to 5 in) could be milled off and mixed in place with an added asphalt emulsion and coarse aggregate. The compacted cold-recycled mixtures were usually covered with a chip-seal or sand-seal for low-volume roads, and overlaid with a hot-mix surface course for medium- or high-volume roads. The cold-recycled mixtures generally performed well. Problems reported included slight raveling, cracking, and bleeding.

Table 14. Summary of the survey on pavements using more than 80 percent RAP.

STATE	METHOD USED (Plant Type)				Recovery Process & Depth	MIX FORMULATION				HOT MIX BINDER AND TEMP (F)					AGE (mo)	PERFORMANCE					SEE NOTE
	In situ Traveling		Conven	Microwave		% RAP Used	Additives Used	% Virg. Agg.	% Total Aph Cont	% From RAP	% New Aphlt	%Total Binder	Temp @ Pit	Temp @ Site		Performance Compared to Control					
	Cold Pit	Hot Pit	Hot Pit	Cyclean® Pit												Rutting	Crack	Ravel	Strip	Overall	
Colorado	••••	••••	••••	•••••	•••••••	••••	•• N/A ••	••••	•••••	••••	•••••	••••	•••••	•••••	••••	•••	•••	••	••	••••	11
Florida	••••	••••	••••	•••••	•••••••	••••	•• N/A ••	••••	•••••	••••	•••••	••••	•••••	•••••	••••	•••	•••	••	••	••••	1
Georgia				1	Stockpile	100			5.42	5.45	0	5.45	300	290	17	4	4	4	4	4	
Georgia				1	Stockpile	100	4% Rejuvenator		5.42	5.45	0	5.45	300	290	17	4	4	4	4	4	
Georgia				1	Stockpile	90	4% Rejuvenator	10	5.42	5.45	0	5.45	300	290	17	4	4	4	4	4	2
Georgia				1	Stockpile	80	4% Rejuvenator	10	5.42	5.45	0	5.45	300	290	17	4	4	4	4	4	3
Georgia				1	Stockpile	90		10	5.21	5.21	0	5.21	300	290	15	4	4	4	4	4	4
Georgia				1	Stockpile	90		10	5.21	5.21	0	5.21	300	290	24	4	4	4	4	4	
Georgia					Stockpile	90		10	5.21	5.21	0	5.21	300	290	17	4	4	4	4	4	4
Georgia				1	Stockpile	90		10	5.21	5.21	0	5.21	300	290	20	4	4	4	4	4	4
Georgia				1	Stockpile	90		10	5.21	5.21	0	5.21	300	290	23	4	4	4	4	4	4
Georgia				1	Stockpile	90		10	5.21	5.21	0	5.21	300	290	20	4	4	4	4	4	4
Idaho		1			2" Milled	80	AC-5	20	5.5$	6.5$	2$				3						12,$
Idaho		1			2" Milled	80	AC-10	20	5.8$	6.5$	1.5$				3						12,$
Idaho		1			2" Milled	80	AC-5	20	5.0$	5.8$	1.5$				5						12.$
Idaho		1			2" Milled	100		0	5-6$						5						12.$
Kentucky	••••	••••	••••	•••••	•••••••	••••	•• N/A ••	••••	•••••	••••	•••••	••••	•••••	•••••	••••	•••	•••	••	••	••••	
Maryland	••••	••••	••••	•••••	•••••••	••••	•• N/A ••	••••	•••••	••••	•••••	••••	•••••	•••••	••••	•••	•••	••	••	••••	1
Mississippi	1				3.5" Milled	88		unk	unk						10	1	1	1	1	1	
Nebraska	1				4" Milled	100		0	unk						1						
New Hampshire	1				4" Sc & Crs	100	MS Binder		6.8	5.8	1	6.8			2						14
New Mexico	1				3 - 5" Milled										0 - 108	3	5	3	3	4	13

(°F - 32)/1.8 = °C

NOTES:

ALL RESPONSES INDICATED NO SAFETY OR ENVIRONMENTAL PROBLEMS WERE ENCOUNTERED.
ALL PAVEMENT SECTIONS ARE TRAFFIC LANES EXCEPT WHERE NOTED.
ALL PERCENTAGES ARE BY WEIGHT OF MIX UNLESS NOTED OTHERWISE.

PERFORMANCE RATING SCALE:

(1) POOR
(2) SLIGHTLY SUBSTANDARD
(3) AVERAGE
(4) GOOD
(5) EXCEPTIONALLY GOOD

Table 14. Summary of the survey on pavements using more than 80 percent RAP (Continued).

1 - NO EXPERIENCE WITH OVER 80% RAP.
2 - VIRGIN AGG. IS 10% LOCAL SAND.
3 - VIRGIN AGG. IS 10% #89 STONE.
4 - TEST SECTION IS SHOULDER WIDENING.
5 - DRUM MIXER USED. PAVEMENT PERFORMED WELL.
6 - PROJECT DID NOT GO WELL RATING.
7 - PROJECT WAS A SUCCESS RATING.
9 - MARGINAL SUCCESS RATING.
10 - VERY SUCCESSFUL RATING.
11 - ONE-HALF PROJECT PLACED WITH LIME ADDITIVE.
12 - PYROTECH HOT-IN-PLACE RECYCLING TRAIN USED.
13 - THESE ARE GENERAL CONDITIONS ONLY, NEW MEXICO HAS 120 PROJECTS.
14 - SC & CRSH = SCARIFY, REMOVE, CRUSH RAP MATERIAL.
$ - PERCENT BY WEIGHT OF RAP AGG. & VIRGIN AGG.

Table 14. Summary of the survey on pavements using more than 80 percent RAP (Continued).

STATE	METHOD USED (Plant Type)				Recovery Process & Depth	MIX FORMULATION				HOT MIX BINDER AND TEMP (F)					AGE (mo)	PERFORMANCE					SEE NOTE
	In situ Traveling		Conven	Microwave		% RAP Used	Additives Used	% Virg. Agg.	% Total Aph Cont	% From RAP	% New Aphlt	%Total Binder	Temp @ Pit	Temp @ Site		Performance Compared to Control					
	Cold Pit	Hot Pit	Hot Pit	Cyclean* Pit												Rutting	Crack	Ravel	Strip	Overall	
North Carolina	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1
North Dakota	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	
Ohio	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1
Oklahoma	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1
Oregon			1		Stockpile	60	AR-2000	20	5.2	3.7	1.5	5.2	250		186						5
Oregon	1				2" Milled	100	1.1% HFE-150								54					Note 6	
Oregon	1				2" Milled	100	.5% CMS-2S								54					Note 7	
Oregon	1				2" Milled	100	1.1% HFE-150								54						
Oregon	1				2" Milled	100	1% CMS-2S								78					Note 7	8
Oregon	1				2" Milled	100	1.4 - 1.5% CMS								79					Note 7	8
Oregon	1				2 - 4" Milled	100	1% CMS-2S								78					Note 6	8
Oregon	1				2.5 - 4" Milled	100	1.4% CMS-2S								78					Note 7	8
Oregon	1				1.5 - 2" Milled	100	1 - 2% CMS-2S								84					Note 7	8
Oregon	1				2" Milled	100	1 - 2% CMS-2S								90					Note 9	
Oregon	1				1.5" Milled	100	2% CMS-2S								102					Note 10	
Oregon	1				2" Milled	100	.4% CMS-2S								30						11
Pennsylvania				1	1.5" Milled	90	RenOil-1735	10	4.1 - 4.6						3						
Rhode Island	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1
South Dakota	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1
Vermont	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	
Washington	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1
West Virginia	• • • •	• • • •	• • • •	• • • • •	• • • • • • • •	• • • •	• • N/A • •	• • • •	• • • • •	• • • •	• • • • •	• • • •	• • • • •	• • • • •	• • • •	• • •	• • •	• •	• •	• • • •	1

(°F - 32)/1.8 = °C; 1 in = 25.4 mm

NOTES:

ALL RESPONSES INDICATED NO SAFETY OR ENVIRONMENTAL PROBLEMS WERE ENCOUNTERED.
ALL PAVEMENT SECTIONS ARE TRAFFIC LANES EXCEPT WHERE NOTED.
ALL PERCENTAGES ARE BY WEIGHT OF MIX UNLESS NOTED OTHERWISE.

PERFORMANCE RATING SCALE:

(1) POOR
(2) SLIGHTLY SUBSTANDARD
(3) AVERAGE
(4) GOOD
(5) EXCEPTIONALLY GOOD

Table 14. Summary of the survey on pavements using more than 80 percent RAP (Continued).

1 - NO EXPERIENCE WITH OVER 80% RAP.
2 - VIRGIN AGG. IS 10% LOCAL SAND.
3 - VIRGIN AGG. IS 10% #89 STONE.
4 - TEST SECTION IS SHOULDER WIDENING.
5 - DRUM MIXER USED. PAVEMENT PERFORMED WELL.
6 - PROJECT DID NOT GO WELL RATING.
7 - PROJECT WAS A SUCCESS RATING.
9 - MARGINAL SUCCESS RATING.
10 - VERY SUCCESSFUL RATING.
11 - ONE-HALF PROJECT PLACED WITH LIME ADDITIVE.
12 - PYROTECH HOT-IN-PLACE RECYCLING TRAIN USED.
13 - THESE ARE GENERAL CONDITIONS ONLY, NEW MEXICO HAS 120 PROJECTS.
14 - SC & CRSH = SCARIFY, REMOVE, CRUSH RAP MATERIAL.
$ - PERCENT BY WEIGHT OF RAP AGG. & VIRGIN AGG.

was generally attributed to the addition of an excessive amount of asphalt emulsion in the recycled mix. In most cases, the observed distress, such as cracking or rutting, was attributed to the problem in the hot-mix surface course or the open-grade friction course that was placed on top of the cold-recycled mixture, rather than to the cold-recycled mixture itself.

Performance of Recycled Asphalt Pavements Using At Least 80 Percent RAP

Due to the limited usage of hot central-plant recycled asphalt mixtures using over 80 percent RAP, long-term performance data on these materials are not available. In the Oregon demonstration project, satisfactory recycled asphalt mixtures incorporating from 80 to 100 percent RAP were able to be designed in the laboratory to meet all the Hveem mix design criteria.(2) However, in actual construction, due to problems with emission, only 70 percent RAP was incorporated in the hot recycled mix. Though the new recycled pavement surface was reported to be rougher than an average new hot mix asphalt pavement, the recycled pavement was reported to perform well and to have carried traffic well in excess of the design loadings after 10 years of service.

When properly executed, hot surface recycling is an effective rehabilitation method to correct surface defects of pavements that are structurally sound. The Ontario Ministry of Transportation reported that the hot-surface recycled mix surface looked older and drier.(4) It was thought to be due to the asphalt cement not being rejuvenated sufficiently. The performance of these pavements was reported to be comparable to conventionally rehabilitated pavements. Since all the longitudinal joints were formed hot in the hot surface recycling process, centerline cracks were reported to be less likely to arise. The typical reported distresses are coarse aggregate loss from the surface and reflective cracking after 1 year of service. Reflective cracking is usually expected when a thin overlay (conventional or recycled) is placed over a cracked pavement.

The overall performance of cold in-place recycled pavements has been very good on a large percentage of the projects.(5) Of the 13 recycled projects reported by California DOT, 9 were reported as having good performance after 5 years of service. Poor performance in the California projects was attributed to moisture damage, nonuniform distribution of binder, or excessive binder contents in the different projects. The cold in-place recycling project in Indiana was reported to be performing better than the conventional pavement. Kansas and Maine DOT's reported less reflective cracking in the cold-recycled pavements as compared with conventional and hot-recycled pavements. Of the 54 projects constructed from 1984 to 1986 in New Mexico, only one project showed signs of distress (rutting) as of 1987. Of the 52 cold-recycled pavements evaluated in Oregon, 47 had good or very good performance. Pavements that had poor performance were attributed to: (1) using too high a recycling agent content, (2) placing a tight seal or dense wearing course too soon, (3) placing the cold-recycled mixture on a delaminated layer of old pavement, and (4) failing to provide some type of seal before freeze/thaw conditions. Oregon DOT reported service lives for low volume roads of 6 to 8 years for cold in-place recycled pavements with chip seal when projects are properly selected.(6)

First Cost Comparison of Recycled Asphalt Pavements Using At Least 80 Percent RAP

Substantial cost-savings from hot-mix asphalt recycling have been reported and well documented in the literature. However, the available information deals mainly with recycled pavements using less than 80 percent RAP. In Florida, where up to 50 percent RAP could be incorporated in the recycled hot mix, the cost savings from the utilization of hot asphalt recycling is 15 to 30 percent as compared with the conventional paving approach.(7) In demonstration project no. 39 in Oregon, where 74 percent RAP was used in the hot recycled mixture, a cost savings due to the saving of asphalt cement and aggregate was indicated.(3) A savings of 2,452 Mg (2,756 tons) of asphalt cement was equated to a cost savings of $220,472. The unit cost in providing the virgin aggregate was $5.65/Mg ($5.03/ton), while the crushing cost for the RAP was $1.63/Mg ($1.45/ton). Cost savings were also reported in the demonstration project in Utah for the utilization of 70 percent RAP.(8)

Substantial cost savings have also been reported in hot in-place and cold in-place recycling. The Ontario Ministry of Transportation reported an average cost savings of 10 percent to 20 percent when a 40-mm (1.6-in) hot in-place recycled asphalt layer was compared with a 40-mm (1.6-in) conventional hot-mix overlay.(4) The Oregon Department of Transportation reported that, with the exception of two failures, the life-cycle costs for cold in-place recycled projects ranged from 37 percent to 82 percent of the hot-mix overlay alternative, when no credit is given to the hot-mix overlay for increased structural section.(6) Indiana Department of Transportation reported that the cold recycling process was significantly less expensive that the hot-mixed material.(9) The cost of a plant-mixed base was three times that of the cold in-place recycled material.

Assessment

Currently, there are three asphalt recycling processes that can successfully utilize at least 80 percent RAP. They are: (1) cold in-place recycling, (2) hot in-place recycling, and (3) hot central-plant recycling by means of the proprietary CYCLEAN® process.

Cold in-place recycled materials are usually used as a stabilized base course to be covered with a chip seal in low-volume roads, or overlaid with a hot or cold surface mix. When properly executed, cold in-place recycling can produce roads of excellent rideability with minimal rutting and cracking.(10-12) Careful selection of projects for cold in-place recycling is needed to ensure success. Pavements with excessive patching, weak subgrade due to water damage, or stripping problems are not recommended for cold in-place recycling.(10,11)

Hot-surface recycling is usually used to correct surface defects such as roughness and weathering of pavements that are structurally adequate.(4,13) The recycling process is also limited to a depth of 50 mm (2 in). Smoke formation can be a problem in hot-surface recycling when the pavement surface is overheated.(4) If properly executed, hot in-place recycling has been shown to be a cost-effective technique for pavement rehabilitation.

Among these three recycling processes, the hot central-plant recycling can produce mixes of the highest quality. The properly designed and evaluated hot-recycled mixes are equally good or better than conventional hot mixes, and are usually used as surface structural mixes. However, due to the problem with smoke emission, utilization of greater than 80 percent RAP in the recycled mix has been limited in conventional hot-mix plants. The CYCLEAN® process, which uses the microwave technology, has been used successfully to produce mixes containing as much as 100 percent RAP without smoke emission problems. Recent development in drum mixer technology, such as the counter flow dryer-drum mix coater and the double-barrel drum mixer, has minimized the smoke emission problem in hot-mix recycling.(14) However, these pollution-free drum mixers are set up to recycle only up to 50 percent RAP, due to the small demand to produce mixes containing more than 50 percent RAP. For a RAP material that has been substantially aged and deteriorated, adequate amounts of virgin aggregate and recycling agent are required to be added to the RAP to produce a high-quality hot mix. This will limit the percentage of RAP that could be incorporated in the recycled mix.

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CRUSHED GLASS APPLICATIONS

Overview

As with most solid wastes, the exact amount currently being generated is not known, but it was estimated that in 1988 approximately 10.9 million Mg (12 million tons) of glass were discarded and about 1.46 million Mg (1.5 million tons) were used primarily as cullet for glass manufacturing.

In the late 1960's only 3.4 million Mg/yr (3.5 million tons/yr) were being generated, which included about 26 to 30 billion glass bottles and jars.(1-3) This constitutes an average increase of almost 0.49 Mg/yr (0.5 million tons/yr) since 1968.

Glass recovered from the solid waste stream for recycling into glass products must be sorted by color and be free from contaminants that tend to be cost prohibitive. (See references 1, 4, 5, and 6.) In general, few sources of recycled glass exist, although cullets from bottling plants, dairies, breweries, etc., or glass cleaned and separated at the source (e.g., household separation) has proven to be economically feasible.(6) However in 1990, glass that had been separated and crushed for recycling into glass containers sold for about \$62/Mg (\$60/ton).(5) Even crushed, sorted glass selling for \$31 to \$62/Mg (\$30 to \$60/ton) and unsorted glass costing as much as \$34/Mg (\$33/ton) for disposal in landfills is expensive relative to conventional fine aggregate at \$1.1 to \$4.1/Mg (\$1 to \$4/ton) and high quality coarse aggregate usually at less than \$15.5/Mg (\$15/ton).(5,6) Obviously, the availability, cost, and proximity to the source of utilization will influence the economics.

Glass has been used primarily on an experimental basis in the construction of highways, therefore no established specifications for its use exist. Approximately nine States have set specifications covering the incorporation of crushed glass into conventional highway materials.(7) Applications include its use or disposal for:

- Partial replacement of fine aggregate in asphalt paving mixtures.
- Substitution of fine aggregate in unbound base courses.
- Mixing with embankment soils.
- Glass beads in line striping.
- Pipe bedding and filter materials in pavement edge drains.

Its direct use in portland cement concrete (PCC) is not feasible because of poor bonding (adhesion), adverse chemical reaction, and reduction in concrete strength.(8) However, the introduction of zirconosilicate glass and manufacturing of glass fibers or foamed glass for use in PCC may provide benefits, but at a substantial increase in cost.

Specific applications of disposed, crushed glass in highway construction are presented and discussed in the following sections.

Asphalt Paving Mixtures

The results of research on the use of recovered glass in bituminous concrete by Malisch et al. is among the first reported attempts to utilize glass in highway pavements.(1-3) Their findings indicated that mixtures composed entirely of glass aggregate could be designed by the Marshall test, but degradation of elongated glass particles occurred during compaction, and when exposed to water, loss of asphalt films (stripping) from the glass aggregate occurred. The use of antistripping compounds or slow-setting cationic emulsions tended to improve the resistance to stripping. Inspection of the test results for two different mixtures indicated that the Marshall stability was low, being generally comparable to a sand asphalt hot mix, and the flow was excessively high, except when the gradation was altered to increase the voids in the mineral aggregate.

Opinions of researchers on the suitability of glass aggregate are quite different. In Israel, 10 to 30 percent ground glass was used successfully as an admixture to increase skid resistance of their limestone and dolomitic aggregates.(9) The key advantage was that the crushed glass admixture was economically viable as compared to the prohibitive costs for basaltic and granitic aggregates. However, Heinrich and Lindemann did not recommend the use of glass because of poor adhesion between bitumen and glass, and also, because the price of used glass was high, thereby offering no benefits for highway use.(10) The Vermont Agency for Transportation constructed, without any apparent problems, 0.29 lane-kilometers (0.48 lane-miles) of pavement containing 10 percent crushed glass crushed to 92 percent, passing the 9.5-mm (3/8-in) sieve.(11) Glasphalt has been successfully mixed and placed on low-volume or low-speed roads in at least 45 locations in the U.S. and Canada between 1969 and 1988, but no high-speed highway application currently exist.[2] (12)

Most Glasphalt has been placed on city streets, driveways, and parking lots. One advantage for major parking areas is the increased reflectivity during nighttime conditions. A commercial establishment's parking lot in Wisconsin was paved using 10 percent crushed glass at additional cost to improve reflectivity.(3) However, visibility of painted line striping may be impaired by the reflectivity of asphalt mixtures containing glass.(12)

Hughes concluded from laboratory tests that it was feasible to use glass providing:(5)

- It is crushed to < 9.5-mm (3/8-in) size with no more than 6 percent minus no. 200 sieve.
- The amount of glass does not exceed 15 percent of the total mix.
- The tensile strength ratio (TSR) is 0.9 or greater because of the propensity to suffer moisture damage.

These findings were based upon partial replacement of sand and greenstone aggregates in the conventional mix with crushed glass that did not change the gradation significantly. However, the use of crushed glass as an admixture could have a substantial influence on the gradation and mixture's properties.

A similar laboratory study was conducted by Murphy et al. using a control mix, a mix with 15 percent replacement with coarse crushed glass, and a third mix with 15 percent fine crushed glass.(6) The crushed glass produced a 15 to 20 percent reduction in Marshall stability and a 20 percent lower dry tensile strength. When the tensile strengths of the three mixtures were evaluated after moisture conditioning, the control, coarse glass, and fine glass mixtures had reductions of 25 to 30, 15, and 50 percent, respectively. However, the coarse glass mixture had a 1.0 percent lower air-void content than the control mix, and moisture-conditioned coarse glass mixtures with and without the antistripping additive had the same tensile strength. Probably, the increased surface area of the fine crushed glass mixture combined with its propensity for stripping caused the 50 percent reduction in tensile strength. The tensile test results indicated that the moisture-conditioned specimens for the three mixtures were not affected by the antistripping additive. The authors' recommendations allowed the use of crushed glass in asphalt mixtures with the following restrictions:

- Maximum of 15 percent crushed glass (by weight of total aggregates).
- Requirement of 100 percent passing the 9.5-mm (3/8-in) sieve with no more than 8 percent passing the no. 200 sieve.
- Asphalt mixtures containing crushed glass shall contain an antistripping additive that can be demonstrated to satisfactorily improve the moisture damage resistance of the mixture.

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[2] Glasphalt is a term adopted for asphalt paving mixtures that contain crushed glass.

- Crushed glass shall not be used in dense-graded or open-graded friction course mixtures.

Also, they recommended that these special provisions could be included in specific contracts involving asphalt paving where a source of glass is available. However, the use of glass should be optional to the contractor to allow the most economical materials to be used.

Several reports that were written on the use of waste materials in highway construction have emphasized different aspects of glass in asphalt paving mixtures.(8,14) The loss of adhesion between asphalt and glass as well as the fracture of glass under traffic and the fact that it crushes more easily than quality aggregate is noted in both reports. A maximum of 15 percent glass in HMA is considered as acceptable, except that it should be used only in the base course to minimize potential skid resistance and surface raveling problems. Because of the various problems with glass, it is preferred that glass in wearing courses be limited to use on low-speed and low-volume streets and highways.(14)

Embankment and Base Materials

The use of glass in unbound aggregate base layers and in embankment construction has been considered by several States.(8,14) The Washington State DOT has prepared a proposed general special provision that allows aggregate base with reclaimed glass to be processed and used as crushed surfacing base course, gravel backfill, pipe bedding material, etc.(14) However, the blended material (aggregate and crushed glass) must conform to all specifications in section 9-03 of the standard specifications, except that the Los Angeles abrasion requirement is waived in certain applications. Furthermore, the blended material cannot have more than 15 percent reclaimed glass and no more than 10 percent larger than 6.4 mm (1/4 in) shall be glass. In essence, they have accommodated the use of glass providing the aggregate-glass blend conforms to the conventional aggregate specifications.

Maine's special provisions, section 203, allow the disposal of crushed glass in place of common borrow in subgrades or embankments. They require the crushed glass to be placed and compacted in a maximum thickness of 200 mm, loose measure. The top of the layer must be a minimum of 600 mm below the finished surface of the subgrade and 600 mm above the natural original ground elevation. It is paid for on the basis of common borrow. This approach allows for disposal of glass, but it does not really provide for use as a substitute material as is done by the Washington State DOT.

The literature pertaining to glass in highway construction was evaluated by Halstead who concluded that the preferred use of waste glass is in the construction of embankments and fills.(7) More research and field experimental projects are needed before crushed glass can be used as a partial replacement for aggregates.

Other Applications

Crushed glass has been used directly as an aggregate replacement for highway subdrain (french drain) construction.(15) In most cases, even when using conventional aggregates, a geotextile must be used to act as a filter to prevent clogging by fine-grained soil particles.

Many other applications require the processing of glass into specialized products such as mineral wool insulation, tiles, and glass beads. The U.S. Bureau of Mines Ceramic Research Laboratory in Tuscaloosa, Alabama, has made glass beads in the 100- to 200-mesh range using the glass fraction from incinerator residue.(15) These types of products are generally experimental or of limited production and cannot be considered accepted as commercially operational systems. However, glass beads made from 100 percent recycled soda lime window glass for use in highway striping paints are manufactured in Oregon by Potters Industries (documented on page I-68, appendix I of reference 13).

Results From Survey of State Highway Agencies

Five of the twenty-three States responding to the survey on crushed glass in highway construction reported no experience with the use or recycling of glass. Of the remaining States, 12 test pavements were constructed with crushed glass being used as a soil additive or as an admixture to hot-mix asphalt. All test sections were less than 28 months old, so long-term performance information was not available. Florida is evaluating glass in a hot-mix asphalt surface course, structural mix, and as an aggregate for soil stabilization. No difference between test sections was observed after 4 months of service.

Similarly, Pennsylvania constructed an asphalt pavement and a stabilized subgrade using 100 mm (4 in) of glass covered by 200 mm (8 in) of soil. The section proved to be unstable, but showed that blending of soil and glass appears to have provided satisfactory results. Raveling of small glass pieces occurred and after 27 months they reported that this asphalt pavement section exhibited poor performance. They reported that glass should be limited to base and binder courses if it is used in asphalt pavements. Furthermore, they believe the only benefit of using glass in pavements was the avoidance of landfill costs that range from \$52 to \$72/Mg (\$50 to \$70/ton) of glass. The cost of processing glass prior to use was \$15 to \$21/Mg (\$15 to \$20/ton), which does not include transportation, handling, and additional construction costs.

New Jersey has constructed five projects using glass in the binder course and one in the friction course. To date, no difference has been observed between glass sections and conventional sections. No benefits are expected from the use of glass other than removal of this material from the waste stream. However, New York allows glass as a replacement for up to 5 percent of aggregate weight as an option in all contracts other than for wearing course asphalt mixtures. Conversely, Connecticut does not use glass as an additive to hot mix asphalt due to potential safety and/or performance problems of inadequate skid resistance, raveling, broken glass, or glare. They do allow glass to be used as a fill material for embankments.

Hawaii and Maryland permit glass in hot-mix asphalt base courses, but they have not used glass as yet. The city and county of Honolulu has two experimental Glasphalt parking lots in current use.

New Hampshire uses glass for soil stabilization in base and subbase construction. Minnesota's test section used glass to successfully stabilize a sandy soil for use as a base course. In Missouri, the availability of good aggregates makes the costs associated with using glass prohibitive.

Assessment

The quantity of crushed glass is relatively small with respect to potential uses in the highway network. Also, the availability of crushed glass for highway construction is limited to areas near cities that are major generators of glass. Because of its value, glass that has been sorted is best suited for recycling back into glass products.

Crushed glass has been used successfully as an aggregate replacement in base course materials, as a drainage media, and in asphalt pavements subjected to light traffic volumes. Some States already allow its use as a partial replacement of granular materials providing the materials containing glass meet the test requirements as specified for the application (e.g., base course, subgrade, etc.) This approach can be utilized in States that do not currently allow the use of crushed glass as a partial replacement of granular material.

In summary, glass has been incorporated into the base and subbase layers of highway pavements. However, at this time it should be considered experimental as an aggregate replacement in surface coarse mixtures. The use of glass typically increases the cost of the pavement without imparting any beneficial attributes to a pavement other than reflectivity. It can generally be considered as being non-beneficial to the properties of conventional construction materials and to the performance of highway pavements.

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RECYCLED PLASTIC APPLICATIONS

Overview

Plastics constitute over 7 percent by weight of the municipal solid waste (MSW) stream or approximately 12 to 20 percent of the volume.(1,2) Estimates of the total amount of plastics generated yearly range from 12.7 to 22.7 million Mg/yr (14 to 25 million tons/yr). Most plastic materials are derived from petroleum. Therefore, the value of plastics are strongly related to petroleum prices. For instance, a 2-liter soft drink bottle, which consists of a polyethylene terephthalate (PET) bottle and a polyethylene (PE) basecup, may sell for up to $1.76/kg ($0.80/lb) for the PET plastic.(2) This is about twice the price of aluminum. One organization recycles approximately 45,400 Mg (50,000 tons) of soda bottles returned by consumers in those States with bottle deposit laws.(1)

Other types of resins and plastic products in the MSW stream include:(2,3)

- Low-density polyethylene (LDPE): film and trash bags.
- High-density polyethylene (HDPE): 1-gal milk jugs.
- Polystyrene (PS): egg cartons, plates, and cups.
- Polyvinyl chloride (PVC): siding, flooring, and pipes.
- Polypropylene (PP): luggage and battery casings.

As with any high-cost material, the key to recycling appears to be the availability of sorted and reasonably clean material that is acquired prior to co-mingling with other materials in the MSW stream. Therefore, emphasis should be placed on the collection of sorted material to maximize utilization rather than attempting to sort from co-mingled materials.

The use of plastics in highway construction includes products or uses for the following products or applications and their approximate recycled plastic content:(3-7)

Geotextiles	60 percent to 100 percent PET, PP
Traffic control barricades	100 percent
Fence posts	100 percent
Guard rail posts	(experimental)
Flexible delineator posts	50 percent to 100 percent
Posts (sign and supports)	100 percent
Speed bumps	100 percent
Concrete grade stakes	100 percent
Curb edging	100 percent HDPE, LDPE, or PP
Concrete cylinder molds	97 percent PP
Drainpipe	20 to 60 percent
Lumber (plastic)	100 percent HDPE, LDPE, or PP
Parking bollards	97 percent, HDPE, LDPE, PE, PET

Parking stops	100 percent
Fencing (plastic)	100 percent
Park benches	100 percent
Signs (roadway)	100 percent
Temporary curbing	100 percent
Modifier for hot-mix asphalt pavements	0 to 100 percent

The use of plastics in highway construction is being examined by seven States.(3) Most post-consumer and co-mingled plastics that are recycled go into the manufacturing of products. Some of these products find application to highway construction, e.g., traffic cones, rebar spacers, and those previously listed.(8) The literature research has shown that the primary use of plastics in highway construction is in the fabrication of construction and traffic safety products.

Asphalt and Mixture Modifier Applications

There are numerous processes that blend virgin plastics (polymers) with asphalt cements to produce polymer-modified asphalt cements and mixtures. Considerable technical information is available in the literature on this subject. Numerous highway rehabilitation projects in Europe, the U.S., and other countries have been successfully paved with asphalt mixtures containing these polymers.(5) The only two known products that include recycled plastic polymer-modified asphalt cement are Novophalt® and Polyphalt™, both of which meet new SHRP asphalt pavement specifications.[3,4](5)

The properties of conventional paving grade asphalt cements compared with those processed into Novophalt® indicate that the viscosity and stiffness of the binder are increased substantially by polymer modification. Laboratory rutting/wheel-tracking tests performed by Nievelt Laboratories in Austria and the Transport and Road Research Laboratory (TRRL) in Crowthorne, England resulted in much lower rutting of the polymer-modified asphalt mixtures than the original asphalt mixtures.(6) Although it is a different process, Polyphalt™ uses polyethylene in similar concentrations so the properties of the asphalt and mixtures should be similar to that achieved using Novophalt®.

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[3] A trade name for a polymer-modified asphalt that is produced by the high-shear blending of 4 to 6 percent polyolefins (by weight of asphalt cement), primarily LDPE (virgin with 85 to 95 percent recycled), with asphalt cement. Marketed by Novophalt® America, Inc.

[4] A trade name for a polymer-modified asphalt cement using an emulsifying agent that keeps the PE in suspension for storage. It was developed under the auspices of the University of Toronto Innovations Foundation. This process uses 100 percent recycled polyethylene that is blended with the asphalt cement in concentrations ranging from 3 to 10 percent (by weight of asphalt cement).

Highway pavements constructed in Georgia with Novophalt® are performing well after one year of service. On I-75, polymer- (plastic) modified test sections had considerably less rut depth than the control.(6) Also, Novophalt® was used in the construction of SMA test sections, but their age is insufficient to assess differences in performance. A project in Canada had 6- to 7-mm-deep ruts in both conventional and polymer-modified sections. No difference was observed in crack resistance or overall performance of the pavement test section.(5) In general, beneficial properties and improved performance can be achieved using polymers. However, polymers are not a cure-all. Proper selection and proportioning of asphalt cements and aggregates is still an essential element in achieving good performing pavements.

A Novophalt®-modified hot mix asphalt pavement costs about $6.35 to $7.26/Mg ($7.00 to $8.00/ton) of hot-mix over that for the conventional mix, or about a 30 percent increase in cost. If increased service life and lower maintenance costs can be realized, the life-cycle cost of polymer-modified binders will be lower than that of conventional mixtures.(5)

Other Uses of Plastics

The list of products given in the overview represent those produced by manufacturers that are useable directly in highway structures (geotextiles, drainpipe, etc.), for construction (traffic control barricades, cones, concrete cylinder molds, etc.) and for appurtenances to the highway system (fence, fence posts, delineator posts, signs). Some States have specifications for plastic fence posts and delineator posts (Florida, New York, Nevada, Tennessee).(3) Maine specification 652.02 was amended to include "All barricades, cones, drums, and construction signs may be constructed from new or recycled plastic."

Collection of post-consumer plastics by resin type rather than co-mingled plastics would enhance manufacturers' product quality and provide greater incentive for utilization of recyclable plastics assuming demand from the consumer (highway agencies) also expanded.

Results from Survey of State Highway Agencies

Nineteen States responded to the survey on recycled plastics for highway construction. Of those responding, six States have not utilized recycled plastics. In 1991, Georgia used approximately 2.7 Mg (3 tons) of recycled LDPE in the construction of Stone Matrix Asphalt (SMA) and Porous European Mixtures (PEM) test sections on I-85 in Jackson County. Also, 45.4 Mg (50 tons) of recycled LDPE was used in 15,300 Mg (18,000 tons) of open-graded friction course (OGFC) mix that was placed on I-75 in Bartow County in 1992. Both projects used the Novophalt® process to produce the polymer-modified asphalt cement. No "drain down" problems occurred even though a higher binder content was used on the polymer-modified section. There has been insufficient time to assess the performance of these test sections.

Connecticut is conducting studies to evaluate, under field conditions, delineator posts containing 46 percent recycled plastic. Also, traffic barricades made of 100 percent recycled HDPE were tried on an Interstate construction project. Their light weight and inability to be anchored caused excessive blowdown of the barricades. However, traffic cones made from PLV or LDPE are being purchased for maintenance and construction detours. The supplier does not specify recycled content even though the State has a standard specification on recycled plastic content of traffic cones.

Michigan uses delineator posts, landscape timbers, and picnic table boards containing recycled plastic. Research into plastic guardrail posts, including dynamic load tests and ultraviolet warping behavior tests, are currently underway. Guardrail post pendulum tests will be performed at -3 °C, 20 °C, and 49 °C to determine if posts conform to a minimum fracture energy of 7510 N•M (5,500 ft-lb). If successful, crash tests will be performed. The current cost disparity between wood and recycled plastic guardrail posts is substantial, $16.00 for wood vs. $62.00 for plastic (approximately four times greater). Another major problem with recycled plastic posts is the variability in strength parameters due to impurities.

Oregon has used about 5.5 Mg (5 tons) of recycled plastic sign and fence posts, snow poles, and sound barrier walls on an experimental basis to evaluate their performance throughout various locations in Oregon. When these products were installed, the increased weight of the recycled plastic necessitated increased personnel and machinery.

Assessment

In summary, recycled plastic guardrail posts and other experimental posts that are not currently a manufactured product, have insufficient performance data to evaluate their suitability for use in highway construction. Impurities, which affect strength properties and densities that are greater than those found in wood products, suggest that it may be impractical to use recycled plastics in certain applications. Increased costs, as much as four times greater than wood, may result in life-cycle costs that are excessively high if service life is not dramatically increased.

However, it seems reasonable to assume that State highway agencies can utilize currently manufactured recycled plastic products providing they meet standard requirements/ specifications. Although many manufacturers label their products with the recycled content, all producers should have similar labeling to facilitate purchasing of products according to specifications.

The use of virgin plastic polymers for modification of asphalt cements is not a new technology. However, the chemical variability in recycled plastics has been a deterrent to the use of waste plastics in pavements. Other than differences in processing and type of polymer, those processes using recycled plastics (Novophalt® and Polyphalt™) are similar. Test sections are not yet old enough to determine if lower life-cycle costs will offset increased initial expense.

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OTHER MATERIALS

Coal Ash

Overview

There are three basic forms of ash produced in the combustion of coal for power generation: fly ash (FA), dry bottom ash, and wet-bottom boiler slag.(1) In 1991, 65 Mg (72 million tons) of ash were produced, with a breakdown of 74 percent fly, 20 percent bottom, and 6 percent boiler slag.(2,3,5) Fly ash consists mostly of the noncombustible mineral material that is removed from the combustion chamber with the hot combustion gases. Electrostatic precipitators or baghouses collect the ash. FA is a very fine, light dust—primarily rock detritus that has collected in the fissures of coal seams, and constitutes from 8 to 14 percent of the coal's weight. Bottom ash can be either dry or wet, depending on the type of boiler in which the coal is burned. Bottom ash is the heavier, noncombustible particles that collect in the bottom of a dry-bottom boiler. If a wet-bottom boiler is employed, the molten ash is tapped from the boiler and cooled using water that produces a slag material.

The primary constituents of coal fly ash are silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3). In bituminous coal, the relative percentages are 55 percent and 26 percent, respectively. For lignite and subbituminous coals, the ratios are 40 percent, 17 percent with an additional 24 percent of calcium oxide (CaO). Other ingredients common to all coals include ferric oxide (Fe_2O_3) and magnesium oxide (MgO). Trace elements of arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver also occur, but in extremely small amounts.(2,3)

Applications

Fly ash has been incorporated into a number of highway-related construction activities. In general, the six areas most often cited include:

- Lime (or cement)/fly ash/aggregate base course.
- Stabilized fly ash pavement.
- Lime/fly ash/soil subbase material.
- Fly ash embankments.
- Fly ash structural fill.
- Fly ash in grouts.

The amount of ash used in the U.S. varies. In 1986 for example, approximately 18 percent of the fly ash, 27 percent of the bottom ash, and 52 percent of the boiler slag was used in all applications.(3) Of this amount, 26 percent was used by the electric utilities themselves.(3) However, due to the much greater amounts of fly ash being produced, it is the primary material used today in highway construction activities. Fly and bottom ashes are used primarily as additives in cement and concrete products, road bases, and in structural fills. Boiler slag is used as blasting grit, roofing granules, or for snow and ice control.

Approximately 9 percent of the annual generation is incorporated into cement and concrete products.(3) Furthermore, the adoption of other uses in highway construction will further reduce the amount of ash for disposal. Several southern States (Alabama in particular) have used the ash as a base material. In a demonstration, 36,300 Mg (40,000 tons) of ash were placed as a 152- to 203-mm (6- to 8-in) layer under an asphalt paving course. Georgia used it by combining it with cement and placing it as subgrade, base, and with the blacktop.(6)

Table 15 illustrates the wide variety of uses of coal ash, while several States have specifications or guidelines that deal specifically with the use of ash as shown in table 16.

While incorporating ash into the above areas can improve the particular characteristics, there is also an economic benefit as well. In 1987, the average price of coal ash was \$22/Mg (\$20/ton).(7) [This figure varies by region—lower in the Southwest, \$13/Mg (\$12/ton) and higher in the Northwest, \$77/Mg (\$70/ton).](3) If used as a replacement, substantial costs-savings may be incurred since the typical cost of cement averages \$143/Mg (\$130/ton).(3)

While FA is nonuniform in composition as outlined above, its major constituents are present in relatively standard proportions. Thus, it can be said that in general, all fly ashes, in the presence of lime and moisture, exhibit pozzolanic properties. Some FA contain sufficient free lime to self-harden without the addition of lime or cement. Generally, lime is added to a lime-fly ash-aggregate mixture from a low of 2 percent to a high of 8 percent.(2) FA values range from 8 to 36 percent. Typical proportions are 2.5 to 4 percent lime and 10 to 15 percent FA. Aggregate sizes range from fine to coarse. In general, a fine-grained aggregate will produce better durable mixes, but coarser-grained aggregate exhibits higher strength and is more mechanically stable.

Curing conditions can greatly affect the final properties. The two primary variables are time and temperature. For example, at temperatures below 4 °C (40 °F), the reaction process ceases. Thus, as the temperature rises, the pozzolanic reaction rate increases. It has been found that the chemical reactions will continue as long as there is sufficient lime and FA available to react. Cores taken over a 10-year period have shown continued strength gain.

Admixtures have been added to lime/fly ash (LFA) mixtures in order to accelerate strength development as well as to improve the short-term durability. As is the case of most of these types of materials, the compressive strength is substantially greater than the tensile strength. Since tension is difficult to measure, it is common to combine tension and compression into the flexural strength. In general, flexural strength is approximately 20 percent of the compressive strength. Other factors that are considered in the evaluation of LFA mixtures include durability, bending resistance (stiffness), fatigue, and the coefficient of thermal expansion. Another very interesting characteristic of LFA is its autogenous healing or the ability to repair itself across internal cracks that may form.

Lime and fly ash added to aggregates (LFAA mixtures) have been used to produce a high-quality base course in flexible pavement systems, and a high-quality subbase in rigid pavement systems. Lime-fly ash-aggregate (LFAA) mixtures are used as base or subbase courses. Compressive strength up to 2.1 kg^f/mm^2 (3,000 lbf/in^2) have been found from a number of sites, however, 0.35- to 0.70-kg^f/mm^2 (500- to 1000-lbf/in^2) values are more common. A wearing surface must be applied in order to protect the material from abrasive effects of traffic from weather and water infiltration.

The LFA and LCFA mixtures lend themselves to conventional construction techniques. The primary requirements needed to produce a good base or subbase include: thorough

Table 15. Uses of coal ash (from reference 3).

FLY ASH

1. Raw material in portland cement.
2. Replacement for cement in concrete.
3. Cement replacement in precast concrete products.
4. Ingredient in aerated concrete.
5. Mineral filler in asphaltic concrete.
6. Aggregate for the stabilization of highway subgrades.
7. Aggregate for road base material.
8. Raw material in the manufacture of lightweight aggregates.
9. Material for structural fill.
10. Material for flowable fill or backfill.
11. Raw material for metal reclamation.
12. Filler material in plastics.
13. Sanitary landfill cover or liner.
14. Backfill for controlling subsidence in abandoned mines.
15. Backfill for fighting mine fires.
16. Amelioration of soils.
17. Raw material in brick manufacture.
18. Ingredient in the manufacture of roofing felt.
19. Raw material for making mineral wool insulation.
20. Source of cenospheres.
21. Ingredient in grouts.
22. Material for absorbing oil spills.
23. Medium for filtering insulating oils used by utilities.
24. Absorbent for dewatering sewage sludge.
25. Fixation ingredient for sulfate sludge.
26. Flowability agent in molding sand.

USES OF BOTTOM ASH

1. Aggregate in cold-mix asphalt.
2. Ingredient in bituminous stabilized bases for highways.
3. Aggregate in portland cement stabilized bases for highways.
4. Grit for ice-covered roads.
5. Filter material.
6. Structural fill.

USES OF BOILER ASH (Slag)

1. Sand-blasting grit.
2. Filter material for water treatment.
3. Raw material for mineral wool insulation.
4. Roofing granules in asphalt shingles.
5. Grit for ice-covered roads.
6. Structural fill and road bases.
7. Aggregate in highway construction.

Table 16. States with guidelines for use of ash (from reference 3).

STATE	USE OF ASH
Arkansas	Soil stabilization - lime/fly ash pressure injection Pressure-grouting concrete pavement
Georgia	Lime-fly ash-soil construction Soil cement construction Mineral filler
Illinois	Pozzolanic aggregate mixture Mineral Filler Pozzolan Fine aggregate for trench backfill and bedding and French drains Pozzolanic base course - type A Pozzolanic-aggregate mixture (PAM)
Kansas	Aggregate for bituminous mixtures Aggregate for ice control Aggregate for bituminous maintenance and repair
Mississippi	Lime-fly ash-treated courses
Montana	Mineral filler
New Jersey	Aggregate-lime-pozzolan stabilized base course
New York	Subsealing concrete pavement Mineral filler
North Carolina	Aggregates for bituminous plant mixes (mineral filler)
North Dakota	Portland cement concrete Lime-fly ash-treated subbase Econocrete Aggregate base
Ohio	Ash embankment Aggregate base Supplemental specification for aggregate-lime fly ash base
Oklahoma	Fly ash modified subgrade
Pennsylvania	Aggregate-lime-fly ash stabilized base course Anti-skid materials
Tennessee	Aggregate-lime-fly ash stabilized base course
Texas	Test method for sampling fly ash Departmental materials specification for fly ash
Wyoming	Portland cement-fly ash-treated base

mixing, uniform spreading with a minimum of segregation, and compaction to a high relative density.

Assessment

Based on the literature and the results of the spreadsheet surveys, the following general statements may be made regarding coal ash utilization.

- Fly ash has been used as an additive/partial replacement in PCC for over 50 years.(6) Over 5.5 million Mg (6 million tons) annually are used in transportation-related concrete materials.(6)

- The quantity of ash in a particular application is limited by either a percentage of absolute volume (e.g., 20 to 30 percent) or weight (e.g., maximum 15 percent) of cementitious material. In HMA, typical percentages of ash to asphalt cement is 0.6 to 1.2 by weight.

- Primary usage involves one of the following areas:(2)

  - In PCC, both as an additive and/or cement replacement.
  - Mineral filler in HMA pavements.
  - As a fine aggregate.
  - Embankment/fill material.
  - Stabilized base course component.
  - Flowable backfill component.

As a general rule, the low cost and enhancing properties of coal ash make it an excellent material for highway construction.

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Incinerator Ash

Overview

The disposal of domestic (household and commercial) garbage results in the generation of approximately 181 million Mg (200 million tons) per year of solid waste.(1) Of this, 14.5 million Mg (16 million tons) is incinerated producing 7.3 million Mg (8 million tons) of waste ash. Approximately 90 percent of this is bottom ash.(4)

The waste ash generated in the incineration of municipal solid wastes (MSW) is similar to that generated in coal-fired power plants. However, the properties of the MSW ash tend to vary significantly depending on the source.(2)

Raw samples of MSW ash contain cans, wire, organics, and other materials not fully reduced in the initial incineration. Multiple screening is necessary to remove unreduced particles.

Applications

MSW bottom ash stabilized with lime or portland cement concrete has been used in highway construction. It is also felt that the bottom ash could be used to replace sand or gravel completely in mix designs.(2) The use of ash in this application would be favorable due to the fact that it has a lower unit weight than conventional sands.

MSW fly ash is more suitable for incorporation into pavements at a rate of approximately 25 to 50 percent by weight due to its finer gradations and fewer contaminates (unburned particles). Concrete produced using MSW fly ash has been shown to meet ASTM compressive strength standards.(2)

Assessment

The use of MSW incinerator ash is made attractive by the low material cost, savings in landfill requirements, and potential availability. Early estimates placed economic savings of MSW ashes at $5/Mg ($4.50/ton) of in-place material.(3) Although ash contains high levels of leachable contaminants such as heavy metals, testing has shown that MSW ash concretes are below established toxicity limits.(2)

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Slags

Overview

The predominant form of slag is blast furnace-produced during the process of separating iron from the rock ore. It is formed when the iron ore, coke, and a flux (dolomite and/or limestone) are melted together in a blast furnace. Once smelting is complete, the aluminates and silicates of the ore and coke ash have been chemically bonded to the lime. The other types of slags include steel, nickel, and copper. Annually, approximately 21 million Mg (23 million tons) of slag is produced. Of this, 67 percent [14 million Mg (15.4 million tons)] is iron slag and the remainder [7 million Mg (7.6 million tons)] is steel slag.(1) Nickel and copper slags are usually combined into a single category since they are both iron silicate nonferrous material. Their use is not widespread—however, there is interest in using it in blended cement, base stabilization, and as fine aggregate in HMA.(2)

Applications

There are five types of slag produced from blast furnace operations:(3)

- Air-cooled — Produced by simply pouring the molten blast-furnace slag into pits and permitting it to cool under ambient conditions. It is usually then crushed and screened and used as an all-purpose construction aggregate. Its primary uses include:

  - Concrete (plain and reinforced).
  - Bituminous pavements (skid-resistance).
  - High stability base course (macadam surfaces and bases, dense-graded aggregate, bituminous stabilized base, or soil-aggregate base).

  Unscreened slag is also used for construction of bases and fills. Air-cooled slag is the predominant form of processed slag accounting for 89 percent of slag sales in 1989.(1)

- Expanded — By applying water, steam, or compressed air to the molten slag, a lightweight, expanded aggregate is produced. It is not commonly used in highway construction, except for producing light-weight concrete products.

- Granulated — Suddenly quenching the molten material in water results in a non-crystalline, granular material. It will gain strength with time, and it exhibits good compaction characteristics. This is used frequently for embankment fill or highway bases. When used as a base material, it exhibits excellent insulative properties and can be used effectively in frost-heavy situations. Due to its strength-gaining characteristics, it can be used in slag cement manufacturing. The three primary types of cementitious materials include:

  - Combining portland cement and slag to produce portland blast furnace slag cement.

  - Mixing slag, anhydrite, and portland cement to produce a super-sulfated cement.

  - Ground slag alone used as a partial replacement for portland cement.

- Pelletized — The molten slag is solidified in a spinning drum while subjected to water and air quenching. It is a lightweight material used as an aggregate for concrete. It can be vitrified to assume strength-gain properties as in granulated slag.

Steel furnace slag is produced in the making of steel. It typically exhibits high bulk density, and is frequently used as base course and for highway shoulders. The additional unit weight of steel mill slag produces higher skid resistance when used in asphalt mixes for wearing surfaces. Other benefits derived from its use in both dense- and open-graded HMA's, include high stability and good striping resistance.

Assessment

The use of blast furnace slag is generally accepted in highway construction. A 1991 survey cited its use as the third most popular material following old asphalt and old concrete.(2) This rank was based on material availability, technical suitability, favorable economics, and positive environmental impact. Approximately 35 percent of the States and 2 Provinces use it, and 14 States have specifications that govern its use.(2) Of the various types, air-cooled and granulated are the most widely used. The surveys that have been received from the current requests have not supplied any substantial additional updated usage information at this time.

One of the potential problems associated with its use as granular material is that of leachate production. However, based on test results, the EPA has not to date classified it as a solid waste.(2)

Steel slag is ranked number five, behind fly ash in overall usage.(2) Eighteen States and four Provinces use it. It has been used extensively in HMA's to enhance skid resistance, however currently, southern Ontario is considering excluding this application due to extensive map cracking performance properties.(2,4) It is thought that the cracking is related to deleterious soft lime and/or lime-oxide agglomerations, however this has not been verified. Another restriction that steel slag has, compared to blast furnace slag, is its expansive properties (up to 10 percent by volume due to the hydration of calcium and magnesium oxides). This negates its use in confined applications and in portland cement concrete.

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Paper/Cellulose in Stone Matrix Asphalt (SMA)

Overview

Stone Matrix Asphalt (SMA) is an asphaltic concrete mixture concept developed in Europe primarily to minimize rutting of pavements that carry large volumes of heavy truck traffic. SMA mixtures differ from typical dense-graded hot-mix asphalt (DGHMA) mixtures conventionally used in the U.S. in two important ways: SMA mixtures utilize a coarser aggregate gradation than that used in DGHMA, and SMA mixtures contain a rich stabilized asphaltic mastic to hold the aggregates together compared to simple asphalt cement binders used in conventional DGHMA.

SMA mixtures are now commonly used on many highways in Germany, France, Belgium, Austria, Holland, and the Scandinavian countries.(1) In response to the success of the SMA mixtures in Europe, several States in the U.S. have constructed test pavements with SMA mixtures. The Federal Highway Administration has encouraged the development of the SMA technology. In addition to improved resistance to rutting, other pavement performance benefits of SMA mixtures may include improved skid resistance, greater cracking resistance, and improved durability.(2,3) At the present, the greatest disadvantage of SMA mixtures is a 10 to 30 percent higher cost (European estimates), which is due to the use of asphalt additives and select high-quality aggregates, and increased production costs.(3,4) However, the higher initial cost of SMA mixtures may be offset by a longer pavement service life.

Another potential benefit of SMA mixtures is as an outlet for certain recycled materials. Many SMA mixtures have used cellulose fibers, which can be derived from high-quality waste paper, as a stabilizing agent in the mastic. Recycled plastics and crumb rubber have also been used to improve the mastic in SMA mixtures.(5)

Material Characteristics

- **Aggregates**

The most striking feature of SMA mixtures is the coarse aggregate content. SMA mixtures contain approximately 65 to 70 percent coarse aggregate, which is predominately of one size (> 4.75 mm). By contrast, conventional dense-graded asphalt concrete mixtures contain from 25 to 55 percent coarse aggregate. Typically in an SMA mixture, the maximum particle size is about 11 to 13 mm (~ 1/2 in), and the dominant size is 8 to 10 mm (~ 3/8 in). The coarse aggregate serves as a stone skeleton, or matrix, in which contact between the large particles provides a rigid framework to withstand heavy loads. The fine aggregate fills in gaps in the coarse aggregate skeleton. Approximately one-third of the fine aggregate is mineral filler (> 75 μm), which combines with the stabilized binder to create a stiff mastic.

European aggregate requirements for SMA mixtures have been rather stringent, limiting aggregates to very high-quality, well-crushed materials. Carbonate aggregates such as limestone are prohibited. The restrictive European aggregate specifications are intended in part to minimize wear on the pavement surface due to abrasion by studded tires.(5,6) In the U.S., lesser quality and more economical aggregates will be evaluated. The FHWA has attempted to translate the European specifications into guidelines for aggregate properties using U.S. standard tests.(7) Whether or not the tough European specifications are necessary or if the translated properties are valid is an important issue to be resolved in the U.S. evaluation of the SMA technology.

- **Asphalt Cement**

Although the asphalt cement properties used in SMA mixtures are the same as in conventional dense-graded mixtures, the asphalt content of SMA mixtures is typically higher by 1 to 2 percent of the total mix.(4) The higher asphalt content gives SMA mixtures greater durability and cracking resistance, but makes it necessary to add a stabilizer to the mix to prevent the asphalt from draining through the mixtures during production, transport, and placement.

- **Stabilizing Additives**

The most common form of stabilizing agent used to reduce drainage of the binder in SMA mixtures is some type of fiber. Cellulose fibers are the most economical and the most often used stabilizer.(3) Cellulose fibers are usually added at a rate of 0.3 percent by weight of mix. Mineral fibers such as rock wool and asbestos have been used in Europe, although the use of asbestos is now discontinued. Dosage rates for mineral fibers are often as much as twice that of cellulose fibers. Other stabilizing agents that have been used include carbon black, rubbers, artificial silica, and a number of different polymers.(5) Some of these additives may provide benefits in addition to stabilizing the asphalt. For example, some polymers may improve the resistance of the pavement to deformations at high summer-time temperatures.

Production and Placing of SMA Mixtures

Production of SMA mixtures at hot-mix asphalt facilities is also different than conventional DGHMA production. In Europe, SMA mixtures are nearly always produced in batch plant facilities. Asphalt plants are equipped with additional cold bins to separate aggregates into different size fractions for greater gradation control.(4) Mineral filler and fiber packaged in meltable plastic bags are added at the pugmill. Mixing time is extended to ensure dispersion of the fiber throughout the mixture.(3) The longer mixing time reduces the production rate of the plant.

In the U.S., drum mixer plants are more often used because they have greater production rates and are therefore more efficient than batch plants. To introduce fibers into a drum mixer plant, it is necessary to use fibers in a pelletized form to avoid blowing the loose fibers out through the plant exhaust system. Pelletized fibers, which are fibers encapsulated in an equal amount of asphalt cement by weight, can be added in drum plants through the drum mixer's recycled asphalt pavement (RAP) slot. Since pelletizing more than doubles the cost of the fibers, an alternative technique was developed to inject and blend loose, air-blown fibers into the asphalt cement line just before the asphalt cement enters the drum mixer. This technique has been used on four of the SMA projects constructed in the U.S.

Paving with SMA mixtures is similar to paving with conventional mixtures. Compaction operations are kept close to the paver. Both static and vibratory steel wheel rollers have been used successfully. Pneumatic rollers, however, tend to pump the mastic to the surface and track the mastic on the surface of the pavement. Density levels specified are usually around 94 percent of the theoretical maximum density, which can normally be achieved with four to six roller passes.

SMA Performance

The SMA technology has continually evolved since it was originally developed over 20 years ago. It has been reported that the European SMA pavements have a 12- to 15-year life, which is generally beyond the life of conventional asphalt concrete pavements.(4) Although the U.S. projects are all fairly young, the short-term performance of these projects has been excellent.(8) Initially, five SMA projects were constructed in different States during 1991. Ten more SMA projects were constructed in 1992. Georgia, which has constructed two SMA projects using several material variables and has another major project scheduled to begin soon, is considering the use of SMA throughout the rehabilitation of one of its Interstate highway corridors.(9)

Potential Cellulose Consumption

Cellulose fibers are used extensively in SMA mixtures in Germany and Sweden. Of the 15 SMA projects constructed in the U.S. to date, 11 have contained at least a section with cellulose fibers.(1)

Currently, the primary source of cellulose fibers used in SMA construction comes from a German manufacturing company that derives the fibers from natural raw materials, i.e., wood.(10) However, there appears to be no technical limitation on using recycled paper for making cellulose fibers. In fact, cellulose fibers are currently being produced for use in SMA mixtures by a company in Michigan.(11)

If the SMA technology continues to gain acceptance in this country, and if cellulose fibers continue as the predominant stabilizing agent, the market for the fibers may see tremendous growth. It is estimated that every lane-mile of pavement constructed with a cellulose-stabilized SMA would consume nearly 1.45 Mg (1.6 tons) of fiber. An optimistic forecast of 322 lane-km (200 lane-miles) of SMA construction per State each year would result in an estimated annual U.S. consumption of 14,515 Mg (16,000 tons) of cellulose fiber. However, this amount is insignificant when considering the total yearly generation of waste paper [approximately 50 million Mg (55 million tons)] of which about 33 percent [16 million Mg (18 million tons)] were recycled in 1988.(12-14)

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Carbon Black

Overview

Carbon black is a material derived from petroleum and natural gas furnaces. There are over 40 different grades of carbon black. Only the higher purity carbon black from natural gas furnaces is suitable in the manufacturing of rubber products including truck and automobile tires. Carbon black can also be used as a modifier to improve the properties of paving-grade asphaltic cements.

The pyrolization of used tires—heating in the absence of oxygen—yields gas, liquid fuels, and carbon black. Tires processed this way yield approximately 40 percent carbon black and 60 percent fuels by weight. The gases obtained are used to fuel the pyrolization process and the liquid fuels can be reclaimed leaving a carbon black residue that is free of volatile components such as oils. The carbon black can then be ground to a 60-μm powder suitable for use as an asphaltic cement modifier.(1)

Asphalt Paving Mixtures

Carbon black has been used as a modifier for many years and has been shown to increase stiffness and improve rutting resistance.(1) Other testing of carbon black-modified asphalt has shown increased resistance to low-temperature cracking and longer fatigue life as compared to conventional asphalt.(2)

Since carbon black is nonvolatile, there is little danger of pollution when incorporated into asphalt. Carbon black can be added using mechanical agitation, therefore no special tanks or heaters are necessary for the asphalt or aggregate.

Economic Considerations

The cost of recovering suitable carbon black as an asphalt modifier is estimated at less than $1 per tire. This is compared to the cost of obtaining suitable CRM at $15 per tire. The recovered carbon black has an approximate value of $0.50 to $0.80 per tire.(1) If all of the approximately 242 million waste tires generated in the United States each year were pyrolized, approximately $150 million worth of carbon black would be obtained. It would cost approximately $750 million dollars to realize this same quantity as crumb rubber. These figures do not account for the value of the energy used and obtained from pyrolization.

Assessment

The pyrolization of tires to obtain carbon black appears promising as a method of resource recovery since raw material in the form of useable energy sources and carbon black are produced. Further consideration is necessary to realize the full benefit of the use of carbon black-modified asphalt.

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Recycled Portland Concrete Cement

Overview

The use of recycled portland cement concrete (PCC) has been facilitated in recent years by the increasing costs of hauling and disposing of used PCC. In situ recycling of concrete results in a 45 percent savings compared to transporting and dumping.(1)

Recycling of PCC is currently being practiced by several State and Provincial transportation administrations. In Connecticut, State DOT projects recycle approximately 75 percent of the PCC removed. The remaining 25 percent is disposed. The Manitoba Ministry of Transportation also reports a 75 percent recycling rate for PCC. Michigan DOT projects recycle PCC for use as course aggregate in open-graded drainage courses under pavement and course aggregate for shoulders. Michigan currently recycles 90 recycle of the PCC removed on freeway projects. Ontario employs a riprap gabion filler as reprocessed aggregate. Excess material is made available to commercial recycling facilities.

Applications

- **Aggregate in PCC Pavement**

Recycled PCC aggregate may be preferential to virgin aggregates if careful control is maintained during the crushing operation to ensure uniformity of gradation. The crushed particles tend to be more angular than conventional crushed stones due to the cement mortar adhering to the aggregate surfaces. It should be noted that concrete recycled from PCC pavements makes better aggregate than that derived from structural concrete.(2) The presence of cement mortar decreases the likelihood of failure along the interface between aggregate and mortar that is commonly experienced in PCC with virgin aggregate. Since the chance of this common mode of failure is decreased, the flexural fatigue strength of recycled PCC concrete tends to be higher.(2)

Despite this higher flexural fatigue strength in recycled aggregate concrete, the compressive strength is generally 15 to 40 percent lower. However, the development of strength gain with age is similar to virgin aggregate concrete.(3)

- **Aggregate Base Material**

When applied as a base material, the density of the compacted recycled aggregate will often be lower than that of virgin aggregate, primarily due to the internal voids of the concrete mortar. This can result in a lower initial bearing capacity that will improve, and may exceed, virgin aggregate due to the presence of cement liberated during crushing and compaction.(1)

Research has shown that high fly ash lean concretes with recycled aggregate have potential as a base course. The material shows good workability, strength development, rigidity, and low drying shrinkage.(2)

- **Other Uses**

In a practice commonly known as cracking and seating, a concrete pavement is broken into chunks approximately 0.14 to 0.19 m^2 (1.5 to 2 ft^2) and then seated using a heavy rubber tire roller to serve as a base course for an asphalt overlay. The intent of the process is to prevent the reflective cracking that can be prevalent in asphalt overlays on intact PCC pavement.

The initial step of breaking the pavement into chunks is accomplished with either a standard diesel hammer, a guillotine hammer, or a whip hammer. The chunks are then set using a 30,000- to 45,000-kg (66,000- to 99,300-lb) rubber-tired roller prior to the application of the asphalt overlay.(4)

This in situ use of PCC is more logically called "reuse" rather than recycling since the material is not removed from its place of origin.

Assessments

The potential use of recycled aggregate concrete should not be ignored. The savings in money, landfill space, and reduced virgin aggregate quarrying through increased use of recycled aggregate are adequate to justify expanded use of the material. Although cost data was not located, the minimization of transportation costs by on-site processing may, in many instances, prove to be a cost advantage. Recycling of PCC pavements is undoubtedly effective when cost savings of 40 to 50 percent over the cost of transportation and disposal are realized.

The use of recycled aggregate in base courses has been shown to have better properties than virgin bases. On this basis, the use of recycled aggregate bases will probably be expanded.

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Roofing Materials

Overview

Each year approximately 8,618,000 Mg (9,500,000 tons) of roofing shingles are manufactured in the United States. Approximately 65 percent of these are used for reroofing. Thus, 6,350,400 Mg (7,000,000 tons) of used material is left for disposal. Since roofing shingles contain approximately 33 percent asphalt by weight, approximately 1,814,000 Mg (2,000,000 tons) of asphalt or about 20 percent of the annual usage in the U.S. could be recovered.

The savings in economic terms are also favorable. By incorporating shingles into asphaltic concrete at 5 percent by weight, the cost of the mix can be reduced by $3.08/Mg ($2.79/ton).(1) Manufacturers estimate that the cost of cold-mix patching asphalts with asphaltic shingles can be as much as 50 percent less than standard cold mixes.(2) Recycling of shingles also reduces landfill volume as well as saving landfill disposal fees that range from $19.50 to $49.60/Mg ($18 to $45/ton).

Asphaltic Concrete Paving Mixtures

- **Cold-Mix Patching Compounds**

Cold-mix asphaltic concrete patching compounds are currently manufactured by two companies. These cold mixes are routinely used in eastern municipalities for such applications as patching pot holes, driveways, utility cuts, repairing bridge decks, and as a replacement for aggregate subbase.

Cold-mix patching compounds such as RePave™, which is manufactured by ReClaim Inc., contain as much as 20 percent dry roofing material.⁽²⁾ This shingle material contains asphalt, filler, and fiber, which have been found to perform similarly to many current modifiers, such as polymers and mineral fillers.

- **Hot-Mix Asphalt (HMA)**

The benefits of adding waste roofing material to HMA's are similar to those of cold mix. After the raw waste material is shredded to particles 12.7 mm (½ in) or smaller, it can be easily added to the pug mill in the same manner as is used to introduce recycled asphaltic pavement. An addition of 5 percent to 10 percent by weight has been shown to help pavement resist rutting, shoving, reflective cracking, and aging due to oxidation.

Assessment

The use of waste roofing materials in asphaltic concrete is justified both by the cost savings and the desirable material properties it produces. The material has been used successfully in several projects including high-volume, heavy truck roadways and has shown favorable performance.(2)

For these benefits alone, the recycling of roofing waste could be expanded. By landfilling the approximately 6,350,000 Mg (7,000,000 tons) of roofing waste produced in the U.S. each year, 1,814,000 Mg (2,000,000 tons) of raw asphalt, a non-renewable resource is being wasted.

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Tire Chip and Whole Tire Applications

Overview

In addition to the uses of crumb rubber-modified asphaltic concrete, numerous possibilities exist for the use of tires and tire scraps as lightweight fill, retaining walls, insulator, and other applications. The large quantities of tires available at low cost make their use attractive.

Lightweight Fill Material

In many embankment situations, the weight of the fill used to create the embankment creates a potential for failure. Typical densities for tire chip fill ranges from 480 to 722 kg/m^3 (30 to 45 lb/ft^3) after compaction versus a typical soil density of 1926 kg/m^3 (120 lb/ft^3).(1) By replacing the heavy soils used in many embankments with tire chips—50- to 100-mm (2- to 4-in) gradation—the static weight of the fill is significantly reduced, thus reducing the potential for slope failure.

In areas where roads cross low-strength subgrades such as peats, the weight of a conventional base material will cause substantial long-term settlement. This problem can be alleviated through the use of layers of tire chips that are then covered with compacted structural fill.

One concern in the use of tire fill is leaching of chemicals and oils into the water table. One method of dealing with this problem is to use wood chips below the water table and tire chips above the water table. Using tire chips above the water table also alleviates the problems associated with rotting of wood in the unsaturated zone.(2) After a substantial base has been created using wood and tire chips, 0.6 to 0.9 m (2 to 3 ft) of conventional structural base is added in preparation for the asphaltic surface.

Retaining Walls

Although a tire-surfaced retaining wall may not be as aesthetically pleasing as other conventional materials, in many applications they will not be noticeable to the user. The use of whole tires for retaining walls is enhanced by the fact that used tires are a cheap, nonbiodegradable, ultraviolet-resistant material.

Tire retaining walls are created by placing tires in alternating rows and backfilling in small lifts with a geotextile between lifts to serve as a tie back. The rows of tires are also staggered back from the front edge to add stability and to prevent backfill from falling through the spaces between tires.

The cost of tire retaining walls is significantly lower than the cost of conventional material walls. Tire-faced walls can be constructed for under \$140/m^2 (\$13/ft^2) of face area while the cost of a typical wall can range from \$161/m^2 (\$15/ft^2) to as high as \$323/m^2 (\$30/ft^2).(3)

Insulation Layer Beneath Road Surfaces

In cold weather regions, base-course shrinking and swelling can lead to significant surface cracking. Rubber, which has a significantly lower thermal conductivity than soils, can be used to insulate the base to prevent shrinking and swelling. Research is currently underway in Maine to determine: the thickness of tire chips needed to insulate adequately, the thickness of gravel cover over the tire chips to provide a stable surface, and the effects of tire chips on ground water.(4)

The test section has been subjected to fully loaded double- and triple-axle dump trucks with significant initial rutting. Rutting under subsequent loads was substantially less. The chip layers have shown encouraging results in reducing depth of frost penetration.(4)

Assessment

The potential cost savings available through the use of used tires in retaining walls justifies the continued exploration of usage. However, the low aesthetic value of the tire surface may limit the scope of application.

The value of tire chips, both as insulation and as a lightweight fill, warrants expanded usage—not for economic reasons, but for their structural properties. Tire chips have the potential to provide a cheap, durable substitute for lower-quality materials.

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DISPOSAL, REUSE, AND RECYCLING OF HIGHWAY MATERIALS

Introduction

The results of survey 1 pertaining to the disposal, reuse, and recycling of highway materials are presented in table 17. The original intent of the survey form was to distinguish between materials disposed of by burying on the project, landfilled, sold as scrap metal, or disposed of as contractor property from materials recycled, and functionally reused on the roadway. Unfortunately, there is some degree of confusion between these categories (e.g., recycling or disposal when steel is sold for scrap and recycling or reuse when concrete bridge deck is used for riprap). Descriptive information provided with the survey form by some States and Canadian Provinces proved to be valuable in assessing the actual deposition of highway materials.

Another problem was that exact answers were difficult to provide because of the variations between contracts in specifying reuse, recycling, or in some instances when the contractor is responsible for disposal. In general, the information provided in the discussion of different highway materials and appurtenances provides a realistic overview of current practice for those States and Provinces that provided supplementary detailed information.

The response to this survey indicates that most States are putting forth considerable effort to minimize waste, reduce operational costs, and to improve quality while emphasizing recycling and reuse of materials and appurtenances in their highway maintenance and rehabilitation programs. Numerous comments and letters received from the highway agencies confirmed their concern for effective recycling/reuse of materials. One example provided here is an excerpt from a letter by Richard R. Stapp, State Construction and Materials Engineer, Wyoming Department of Transportation:

> "The decision whether or not to recycle pavements or base materials basically depends upon economics. Our state has many areas in which suitable materials sources are a significant distance from our construction projects, which makes recycling highly attractive. We also have many areas in which aggregate sources are numerous and virgin mixes are less expensive to use than the recycled materials. The haul of the removed material is the significant expense in this case. Very little material is wasted, however. The removed materials are either used as a part of subgrade reconstruction, stockpiled for our maintenance forces to use in their patching and repair work, or used as a portion of various stabilized material tapers along the roadway shoulders. We have even used milled asphalt concrete to stabilize unsurfaced parking lots at various government and civic agency locations. The little material that is disposed of is usually used as landfill material by the contractors."

The ensuing discussion on roadway materials, culverts, guardrail systems, signs, and sign/signal structuring bridges, and other recycling activity provide insight into the diversity of approaches followed by different highway agencies.

Table 17. Summary of disposal/utilization survey.

	ROADWAY MATERIAL Asphalt Concrete						ROADWAY MATERIAL Asphalt Concrete						ROADWAY MATERIAL Stabilized Base					
	1.1.1 Surface Course						1.1.2 Structural or Base Course						1.2					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	5		90		5		5		90		5		0		0		100	
ALASKA	5		15		80		5		15		80		0	N/A	0	N/A	0	N/A
ARIZONA	0		100	(5)	0		0		100	(5)	0		0		100	(5)	0	
ARKANSAS	70	(2.3)	30		0		80	(2,3)	20		0		100	(2,3)	0		0	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	0		75	(5,4)	25	(6)	10	(2)	85	(5,4)	5	(6)	0	N/A	0	N/A	0	N/A
FLORIDA	30	(3)	0		70	(6)	30	(3)	0		70	(6)	50	(3)	50	(5)	0	
GEORGIA	90	(3)	0		10	(6)	90	(3)	0		10	(6)	100	(3)	0		0	
IDAHO	0		80		20		0		80		20		100		0		0	
INDIANA	50		20		30		0		20		80		0		20		80	
KANSAS	0		95	(5)	5		0		95	(5,1)	5		0		100		0	
LOUISIANA	0		20	(5)	80	(6)	0		20		80		0		40	(5)	60	(6)
MAINE	▨	(3)	▨		▨		▨		▨	some	▨		0		0		100	
MASSACHUSSETTS	0		95		5		0		95		5		0		0		100	
MARYLAND	0		100	(5)	0		0		100	(5)	0		100		0		0	
MICHIGAN	5		75		20		5		75		20		30	(3)	0		70	(3)
MISSISSIPPI	80	(3)	20	(5)	0		80	(3)	20	(4)	0		50	(3)	50	(5)	0	
MISSOURI	0		100	(5)	0		0		100	(5)	0		0		100	(5)	0	
NEBRASKA	10		90		0		10		90		0		▨		▨	(5)	▨	(6)
OHIO	0		90		10		0		90		10		100		0		0	
OREGON	10		30		60		10		30		60		0		100	(5)	0	
PENNSYLVANIA	0		100	(5)	0		0		100	(5)	0		0		0		100	(6)
RHODE ISLAND	1		99		0		1		99		0		1		99		0	
S. CAROLINA	▨		10		▨		▨		15		▨		▨		▨		▨	
S. DAKOTA	0		10		90		0		0		100		0		0		100	
TENNESSEE	50	(3)	50	(5)	0		75	(3)	25	(5)	0		20	(3)	0		80	
TEXAS	0		100	(5)	0		0		100	(5)	0		0		100	(5,13)	0	
UTAH	25	(3)	25	(4,5)	50	(6)	25	(3)	25	(4,5)	50	(6)	10		30	(4,5)	60	
VIRGINIA	0		100		0		0		100		0		0		0		100	
VERMONT	0		10		90		0		0		100		▨		▨		▨	
WASHINGTON	32	(2,3)	30	(4,5)	38	(6)	48	(2,3)	16	(4,5)	36	(6)	40	(2,3)	60	(4,5)	0	
WYOMING	50	(3)	30	(5)	20		50	(3)	30	(5)	20		80	(3)	10	(5)	10	
Mean Value	17.7		56.3		24.5		18.1		54.5		26.0		28.5		30.7		34.3	
Range	0, 90		0, 100		0, 94		0, 90		0, 100		0, 100		0, 100		0, 100		0, 100	
No. of Responses	29.		30		29		29		30		29		28		28		28	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	0		100		0		0		100		0		0	N/A	0	N/A	0	N/A
SASKATCHEWAN	0		95		5		0		95		5		0		100		0	
N. BRUNSWICK	5		95		0		5		95		0		0		100		0	
MANITOBA	0		95		5		0	N/A	0	N/A	0	N/A	0		0		100	
ONTARIO	0		100	(5)	0		0		100	(5)	0		0	N/A	0	N/A	0	N/A
Mean Value	1		97		2		1		78		1		0		40		20	
Range	0, 5		95, 100		0, 5		0, 5		0, 100		0, 5		NONE		0, 100		0, 100	
No. of Responses	5		5		5		5		5		5		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

	ROADWAY MATERIAL Crushed Stone Base						ROADWAY MATERIAL Crushed Gravel Base						ROADWAY MATERIAL Granular Subbase					
	1.3						1.4						1.5					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	0		0		100		0		0		100		0		0		100	
ALASKA	0	N/A	0	N/A	0	N/A	0		0		100		0		100	(5)	0	
ARIZONA	0		100	(5)	0		0		100	(5)	0		0		100	(5)	0	
ARKANSAS	30	(2,3)	70	(5)	0		30	(2,3)	70	(5)	0		30	(2,3)	70	(5)	0	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	25	(2)	70	(5,4)	5	(6)	25	(2)	70	(5,4)	5	(6)	25	(2)	70	(5,4)	5	(6)
FLORIDA	50	(3)	50	(5)	0		▨		▨		▨		▨		▨		▨	
GEORGIA	95	(3)	0		5	(6)	0	N/A	0	N/A	0	N/A	100	(3)	0		0	
IDAHO	0		0		100		0		0		100		0		0		100	
INDIANA	0	N/A	0	N/A	0	N/A	100		0		0		100		0		0	
KANSAS	0		100		0		0		100		0		0		0		100	
LOUISIANA	0	N/A	0	N/A	0	N/A	0		90	(5)	10	(6)	25	(6)	75	(5)	0	
MAINE	0		0		100		0		0		100		0		0		100	
MASSACHUSSETTS	0		5		95		0		5		95		0		5		95	
MARYLAND	100		0		0		100		0		0		100		0		0	
MICHIGAN	30	(3)	0		70	(3)	30	(3)	0		70	(3)	30	(3)	0		70	(3)
MISSISSIPPI	0		100	(5)	0		0		100	(5)	0		80	(3)	5	(4)	15	(6)
MISSOURI	0	N/A	0	N/A	0	N/A	80	(3)	5	(4)	15	(6)	0		100	(5)	0	
NEBRASKA	▨		▨	(5)	▨	(6)	▨		▨	(5)	▨	(6)	▨		▨	(5)	▨	(6)
OHIO	50		0		50		50		0		50		50		0		50	
OREGON	0		100	(5)	0		0		100	(5)	0		0		100	(5)	0	
PENNSYLVANIA	0		0		100	(6)	0		0		100	(6)	0		0		100	(6)
RHODE ISLAND	1		99		0		1		19		80		1		9		80	
S. CAROLINA	▨		▨		10		▨		▨		▨		▨		▨		▨	
S. DAKOTA	0		0		100		0		0		100		0		0		100	
TENNESSEE	20	(3)	0		80		20	(3)	0		80		20	(3)	0		80	
TEXAS	0		0		100		0		0		100		0		0		100	
UTAH	0		50	(4,5)	50	(6)	0		50	(4,5)	50	(6)	0		50	(4,5)	50	(4,5)
VIRGINIA	0		0		100		0		0		100		0		0		100	
VERMONT	▨		▨		▨		▨		▨		▨		▨		▨		▨	
WASHINGTON	28	(3)	65	(5)	7	(6)	14	(3)	78	(5)	8	(6)	60	(3)	32	(5)	8	(6)
WYOMING	50	(3)	0		50		50	(3)	0		50		0	N/A	0	N/A	0	N/A
Mean Value	17.1		28.9		38.7		18.5		29.2		48.6		23.0		26.6		46.4	
Range	0, 100		0, 100		0, 100		0, 100		0, 100		0, 100		0, 100		0, 100		0, 100	
No. of Responses	28		28		29		27		27		27		27		27		27	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
SASKATCHEWAN	0		100		0		0		100		0		0		100		0	
N. BRUNSWICK	0		100		0		0		100		0		0		100		0	
MANITOBA	0		0		100		0		0		100		0		0		100	
ONTARIO	0	N/A	0	N/A	0	N/A	0		25	(5)	75	(6)	0		25	(5)	75	(6)
Mean Value	0		40		20		0		45		35		0, 0		45.0		35.0	
Range	NONE		0, 100		0, 100		NONE		0, 100		0, 100		NONE		0, 100		0, 100	
No. of Responses	5		5		5		5		5		5		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

	ROADWAY MATERIAL Stabilized Subbase						ROADWAY MATERIAL Subgrade						ROADWAY MATERIAL Shoulders: Hot Mix					
	1.6						1.7						1.8.1					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	0		0		100		0		0		100		10		0		90	
ALASKA	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	5		15		80	
ARIZONA	0		100	(5)	0		0		100	(5)	0		▨		▨		▨	
ARKANSAS	100	(2,3)	0		0		▨		▨		▨		▨		▨		▨	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	0	N/A	0	N/A	0	N/A	20	(2)	70	(5,4)	10	(6)	0	(2)	75	(5,4)	25	(6)
FLORIDA	10	(3)	90	(5)	0		0		10	(4,5)	90	(6)	20	(3)	70	(5)	10	(6)
GEORGIA	100	(3)	0		0		95	(3)	0		5	(6)	100	(3)	0		0	
IDAHO	100		0		0		0		0		100		0		20		80	
INDIANA	100		0		0		10		0		90		0		5		95	
KANSAS	0		100		0		0		0		100		15		80		5	
LOUISIANA	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0		20		80	
MAINE	0		0		100		0		0		100		0		0		100	
MASSACHUSSETTS	0		0		100		5		0		95		0		95		5	
MARYLAND	100		0		0		0	(9)	0		100	(6)	100		0		0	
MICHIGAN	30	(3)	0		70	(3)	50	(3)	0		50	(3)	5	(3,14)	75	(3,14)	20	(3,14)
MISSISSIPPI	80	(3)	10	(5)	10	(6)	40	(3)	0		60	(6)	80	(3)	20	(5)	0	
MISSOURI	0		100	(5)	0		0		100	(5)	0		0		100	(5)	0	
NEBRASKA	▨		▨	(5)	▨	(6)	0		0		100	(6)	10		90		0	
OHIO	0	N/A	0	N/A	0	N/A	0		0		100		100		0		0	
OREGON	0		100	(5)	0		0		100	(5)	0		0		100	(5)	0	
PENNSYLVANIA	0		0		100	(6)	▨		▨		▨		▨		▨		▨	
RHODE ISLAND	1		99		0		1		99		0		1		99		0	
S. CAROLINA	▨		▨		▨		▨		▨		▨		▨		▨		▨	
S. DAKOTA	0		0		100		0		0		100		0		50		50	
TENNESSEE	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	75	(3)	25		0	
TEXAS	▨		▨		▨		100	(11)	0		0		▨		▨		▨	
UTAH	0		50	(4,5)	50	(6)	0		50	(4,5)	50	(6)	25	(3)	25	(4,5)	50	(6)
VIRGINIA	0		0		100		0		0		100		0		0		100	
VERMONT	▨		▨		▨		▨		▨		▨		0		0		100	
WASHINGTON	44	(3)	44	(5)	12	(6)	14	(2,3)	26	(5)	60	(6)	70	(2,3)	30	(5)	0	
WYOMING	0	N/A	0	N/A	0	N/A	10	(3)	0		90		0	N/A	0	N/A	0	N/A
Mean Value	24.7		25.6		27.4		12.8		20.5		55.6		23.7		38.2		34.2	
Range	0, 100		0, 100		0, 100		0, 100		0, 100		0, 100		0, 100		0, 100		0, 100	
No. of Responses	27		27		27		27		27		27		26		26		26	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
SASKATCHEWAN	0		100		0		0		100		0		100		0		0	
N. BRUNSWICK	0		100		0		▨		▨		▨		▨		80		▨	
MANITOBA	0		0		100		5		0		95		▨		▨		▨	
ONTARIO	0	N/A	0	N/A	0	N/A	▨		▨		▨		0		100	(5)	0	
Mean Value	0.0		40.0		20.0		1.7		33.3		31.7		33.3		45.0		0.0	
Range	NONE		0, 100		0, 100		0, 5		0, 100		0, 95		0, 100		0, 100		NONE	
No. of Responses	5		5		5		3		3		3		3		4		3	

Table 17. Summary of disposal/utilization survey (Continued).

	ROADWAY MATERIAL Shoulders: Raw Aggregate						CULVERTS Concrete						CULVERTS Corrugated Steel Pipe Culverts					
	1.8.2						2.1						2.2					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	10		0		90		100		0		0		100		0		0	
ALASKA	5		15		80		0	N/A	0	N/A	0	N/A	100	(3)	0		0	
ARIZONA							50		0		50		80		0		20	
ARKANSAS							100	(2,3)	0		0		90	(2,3)	0		10	
COLORADO		(3)						(3)						(3)				
CONNECTICUT							75	(2)	25	(5,4)	0		0	(9,2)	95	(5,4)	5	(6)
FLORIDA							90	(2,3)	10	(5)	0		90	(3)	10	(4)	0	
GEORGIA	100	(3)	0		0		100	(3)	0		0		100	(3)	0		0	
IDAHO							100		0		0		100		0		0	
INDIANA							100		0		0		100		0		0	
KANSAS	0		0		100		70		0		30		80		0		20	
LOUISIANA	0		90		10		50	(8)	0		50	(6)	50	(8)	0		50	(6)
MAINE	0		0		100		25		0		75		90	(3)	0		10	
MASSACHUSSETTS	0		95		5		50		0		50		50		0		50	
MARYLAND							100		0		0		100		0		0	
MICHIGAN	20	(3,14)	0	(3,14)	80	(3,14)	50		0		50		90		0		10	
MISSISSIPPI	0		100	(5)	0		70	(3)	30	(5)	0		100	(3)	0		0	
MISSOURI							0		100		0		90		0		10	
NEBRASKA							95		0		5		80		0		20	
OHIO	100		0		0		100		0		0		100		0		0	
OREGON	0		100	(5)	0		100		0		0		100		0		0	
PENNSYLVANIA							100	(3)	0		0		100	(3)	0		0	
RHODE ISLAND																		
S. CAROLINA							90		0		10		90		0		10	
S. DAKOTA							60	(2)	0		40		80	(2)	0		20	
TENNESSEE	95	(3)	0		5		95	(3)	0		5		95	(3)	0		5	
TEXAS										(3)		(6)				(3)		(6)
UTAH							100	(2)	0		0		100	(1,2)	0		0	
VIRGINIA	0		0		100		50		0		50		100	(1)	0		0	
VERMONT							100	(3)	0		0		100	(3)	0		0	
WASHINGTON							81	(2,3)	8	(4,5)	11	(6)	73	(1,3)	7	(4,5)	20	(6)
WYOMING	0	N/A	0	N/A	0	N/A	99		0		1	(6)	95		0		5	(6)
Mean Value	23.6		28.6		40.7		75.9		6.0		14.7		87.0		3.9		9.3	
Range	0, 100		0, 100		0, 100		0, 100		0, 100		0, 75		0, 100		0, 95		0, 50	
No. of Responses	14		14		14		29		29		29		29		29		29	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	0	N/A	0	N/A	0	N/A	100		0		0		100		0		0	
SASKATCHEWAN	0		100		0		0		50		50		0		50		50	
N. BRUNSWICK							25		0		75		40		0		60	
MANITOBA	10		0		90		100		0		0		30		0		70	
ONTARIO	0		100	(5)	0		50		50	(6)	0		90	(3)	0		10	(6)
Mean Value	2.5		50.0		22.5		55		20		25		52		10		38	
Range	0, 10		0, 100		0, 90		0, 100		0, 50		0, 75		0, 100		0, 50		0, 70	
No. of Responses	4		4		4		5		5		5		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

	CULVERTS Wood						CULVERTS Multiplate Underpass or Culvert						GUARDRAIL SYSTEMS Guardrails					
	2.3						2.4						3.1					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	100		0		0		100		0		0		75		0		25	
ALASKA	0	N/A	0	N/A	0	N/A	100		0		0		40	(3)	0		60	
ARIZONA	100		0		0		▨		▨		▨		15		0		85	
ARKANSAS	0	N/A	0	N/A	0	N/A	0	N/A	50	N/A	50	N/A	80	(2,3)	10		10	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	0	N/A	0	N/A	0	N/A	0	(2)	95	(5,4)	5	(6)	0	(2)	50	(5,4)	50	(6)
FLORIDA	▨		▨		▨		10	(3)	10	(5)	80	(6)	40	(3)	30	(4)	30	(6)
GEORGIA	0	N/A	0	N/A	0	N/A	100	(3)	0		0		0		25	(4)	75	(6)
IDAHO	100		0		0		0		50		50		10		0		90	
INDIANA	100		0		0		100		0		0		50		0		50	
KANSAS	100		0		0		0	N/A	0	N/A	0	N/A	50	(9)	0		50	
LOUISIANA	0	N/A	0	N/A	0	N/A	20		80		0		80	(1)	0		20	
MAINE	100		0		0		100	(3)	0		0		30	(3)	0		70	
MASSACHUSSETTS	0	N/A	0	N/A	0	N/A	50		0		50		40		0		60	
MARYLAND	100		0		0		100		0		0		40		0		60	
MICHIGAN	▨		▨		▨		60	(1)	0		40		80	(1)	0		20	
MISSISSIPPI	0	N/A	0	N/A	0	N/A	100	(3)	0		0		100	(3)	0		0	
MISSOURI	100	few	0		0		0	(9)	0		100	few	50	(9)	0		50	
NEBRASKA	100	few	0		0		100		0		0		50		0		50	
OHIO	100		0		0		100		0		0		90		0		10	
OREGON	100		0		0		100		0		0		0		50		50	
PENNSYLVANIA	0	N/A	0	N/A	0	N/A	100	(3)	0		0		60		0		40	
RHODE ISLAND	▨		▨		▨		▨		▨		▨		▨		▨		▨	
S. CAROLINA	100		0		0		100		0		0		80		0		20	
S. DAKOTA	▨		▨		▨		▨		▨		▨		0		0		100	(9)
TENNESSEE	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	90	(3)	0		10	
TEXAS	100		0		0		▨	(3)	▨	(6)	▨		25		0		75	
UTAH	0	N/A	0	N/A	0	N/A	0		100	(5)	0		0		100	(5)	100	
VIRGINIA	0	N/A	0	N/A	0	N/A	100	(1)	0		0		100	(1)	0		0	
VERMONT	100	(3)	0		0		50	(3)	0		50		50	(3)	0		50	
WASHINGTON	100	(3)	0		0		70	(3)	20	(5)	10	(6)	32	(1,3)	42	(4,5)	26	(6)
WYOMING	0	N/A	0	N/A	0	N/A	100	(3)	0		0		10		▨		90	
Mean Value	55.6		0.0		0.0		61.4		15.0		16.1		45.6		10.6		47.5	
Range	0, 100		NONE		NONE		0, 100		0, 95		0, 100		0, 100		0, 50		0, 100	
No. of Responses	27		27		27		27		27		27		30		29		30	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	100		0		0		50		50		0		50		50		0	
SASKATCHEWAN	100	burn	0		0		25	(1)	50		25		90	(1)	0		10	
N. BRUNSWICK	100		0		0		75		0		25		20		80		0	
MANITOBA	100		0		0		0	N/A	0	N/A	0	N/A	0		0		100	
ONTARIO	100		0		0		90	(3)	0	(6)	10	(6)	90	(3)	0		10	(6)
Mean Value	100		0		0		48		20		12		50		26		24	
Range	NONE		NONE		NONE		0, 90		0, 50		0, 25		0, 90		0, 80		0, 100	
No. of Responses	5		5		5		5		5		5		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

	GUARDRAIL SYSTEMS Steel Guardrail Posts						GUARDRAIL SYSTEMS Wood Guardrail Posts						GUARDRAIL SYSTEMS Undesignated Guardrail Posts					
	3.2						3.3						3.4					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA													50		0		50	
ALASKA													80	(3)	0		20	
ARIZONA													95		0		5	
ARKANSAS													90	(2,3)	5		5	
COLORADO		(3)						(3)						(3)				
CONNECTICUT	0		25		75		50	(2)	0		50	(6)						
FLORIDA													50	(3)	0		50	(6)
GEORGIA													0		25	(4)	75	(8)
IDAHO													100		0		0	
INDIANA													50		0		50	
KANSAS	10	(9)	0		90		70	(9)	0		30							
LOUISIANA	10		90	(4)	0													
MAINE													30		0		20	
MASSACHUSSETTS													40		0		60	
MARYLAND													100		0		0	
MICHIGAN													30	(1)	0		70	
MISSISSIPPI													100	(3)	0		0	
MISSOURI													50	(9)	0		50	
NEBRASKA													50		0		50	
OHIO													100		0		0	
OREGON	50		30		20		50		30		20							
PENNSYLVANIA													50		0		50	
RHODE ISLAND																		
S. CAROLINA													80		0		20	
S. DAKOTA													0		0		100	(9)
TENNESSEE													90	(3)	0		10	
TEXAS													75		0		25	
UTAH													100	(2)	0		0	
VIRGINIA													50		0		50	
VERMONT																		
WASHINGTON																		
WYOMING													10		0		90	(6)
Mean Value	17.5		36.3		46.3		56.7		10.0		33.3		60.3		2.6		35.2	
Range	0, 50		0, 90		0, 90		50, 70		0, 30		20, 50		0, 100		0, 33		0, 100	
No. of Responses	4		4		4		3		3		3		26		26		26	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA													100		0		0	
SASKATCHEWAN													100	(1)	0		0	
N. BRUNSWICK													90		0		10	
MANITOBA													10		0		90	
ONTARIO													90	(3)	0		10	(8)
Mean Value	0		0		0		0		0		0		78		0		22	
Range	NONE		NONE		NONE		NONE		NONE		NONE		0, 100		NONE		0, 90	
No. of Responses	0		0		0		0		0		0		5		0		5	

Table 17. Summary of disposal/utilization survey (Continued).

	SIGNS Advisory & Regulatory						SIGNS Sign Posts						SIGNS Sign or Signal Poles and Structures					
	4.1						4.2						4.3					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	30		70		0		30		0		70		50		0		50	
ALASKA	60		10		30		75		5		20		100	(3)	0		0	
ARIZONA	5		5		90		10		5		85		5		5		90	
ARKANSAS	10	(2,3)	85		5		80	(2,3)	10		10		5	(2,3)	80		15	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	0		90		10		0		90		10		0		90		10	
FLORIDA	10	(3)	0		90	(6)	50	(3)	0		50	(6)	50	(3)	10	(4,5)	40	(6)
GEORGIA	75	(1)	25	(4)	0		100	(1,10)	0		0		50	(3)	50	(4)	0	
IDAHO	40		60		0		100		0		0		50		0		50	
INDIANA	0		100		0		60		40		0		60		40		0	
KANSAS	20		30		50		60		0		40		85		0		15	
LOUISIANA	50	(1)	50	(4)	0		40	(1)	0		60		90	(1)	0		10	
MAINE	25		0		75		25	(3)	0		75		25	(3)	0		75	
MASSACHUSSETTS	80		0		20		50		0		50		50		0		50	
MARYLAND	100		0		0		100		0		0		0		20		80	
MICHIGAN	50	(1)	0		50		80	(1)	0		20		▨		▨		▨	
MISSISSIPPI	100	(3)	0		0		100	(3)	0		0		100	(3)	0		0	
MISSOURI	0		60		40		25	(9)	0		75		25	(9)	0		75	
NEBRASKA	▨		▨	(4)	▨	(6)	▨		▨	(4)	▨	(6)	95		0		5	
OHIO	100		0		0		100		0		0		100		0		0	
OREGON	50		50		0		20		50		30		20		50		30	
PENNSYLVANIA	50		0		50		20		0		80		95		0		5	
RHODE ISLAND	▨		▨		▨		▨		▨		▨		▨		▨		▨	
S. CAROLINA	▨		▨		▨		▨		▨		▨		▨		▨		▨	
S. DAKOTA	0		100		0		0		0		100		5	(2)	0		95	
TENNESSEE	95	(3)	0		5		95	(3)	0		5		75	(3)	0		25	
TEXAS	0		100	(12)	0		0	(9)	0		100	(6)	100	(11)	0		0	
UTAH	50	(1,2)	5	(5)	0		50	(1,2)	50	(5)	0		0		80	(5)	20	(6)
VIRGINIA	100	(1)	0		0		100	(1)	0		0		75		0		25	
VERMONT	25	(3)	25		50		25	(3)	25		50		50	(3)	0		50	
WASHINGTON	27	(1,3)	62	(4,5)	11	(6)	68	(2,3)	17	(4,5)	15	(6)	42	(3)	28	(4,5)	30	(6)
WYOMING	100	(3)	0		0		100	(3)	0		0		50	(3)	0		50	(6)
Mean Value	44.7		33.1		20.6		55.8		10.4		33.8		51.8		16.2		32.0	
Range	0, 100		0, 100		0, 90		0, 100		0, 90		0, 100		0, 100		0, 80		0, 95	
No. of Responses	28		28		28		28		28		28		28		28		28	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	30		70		0		10		90		0		10		90		0	
SASKATCHEWAN	100	(1)	0		0		50		0		50		75	(10)	0		25	(10)
N. BRUNSWICK	20		40		40		20		0		80		10		0		90	
MANITOBA	0		0		100		5		0		95		25	n-type	0		75	n-type
ONTARIO	20	(1)	30		50		10	(10)	30	(10)	60	(10)	0		0		100	
Mean Value	34		28		38		19.0		24.0		57.0		24.0		18.0		58.0	
Range	0, 100		0, 70		0, 100		5, 50		0, 90		0, 95		0, 75		0, 90		0, 100	
No. of Responses	5		5		5		5		5		5		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

	BRIDGES Steel Railings						BRIDGES Aluminum Railings						BRIDGES Non-designated Railings					
	5.1						5.2						5.3					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	▨		▨		▨		▨		▨		▨		90		0		10	
ALASKA	▨		▨		▨		▨		▨		▨		100	(3)	0		0	
ARIZONA	▨		▨		▨		▨		▨		▨		0		0		100	
ARKANSAS	▨		▨		▨		▨		▨		▨		40	(2,3)	50		10	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	▨		▨		▨		▨		▨		▨		0	(9,2)	100	(5,4)	0	
FLORIDA	▨		▨		▨		▨		▨		▨		60	(3)	20	(4)	20	(6)
GEORGIA	▨		▨		▨		▨		▨		▨		0		100	(4)	0	
IDAHO	▨		▨		▨		▨		▨		▨		80		20		0	
INDIANA	▨		▨		▨		▨		▨		▨		50		0		50	
KANSAS	▨		▨		▨		▨		▨		▨		0		99		1	
LOUISIANA	▨		▨		▨		▨		▨		▨		85	(1)	0		15	
MAINE	▨		▨		▨		▨		▨		▨		60	(3)	0		40	
MASSACHUSSETTS	▨		▨		▨		▨		▨		▨		50		0		50	
MARYLAND	100		0		0		50		0		50		▨		▨		▨	
MICHIGAN	90	(1)	10	(4)	0		0		50	(4)	50	(6)	▨		▨		▨	
MISSISSIPPI	▨		▨		▨		▨		▨		▨		100	(3)	0		0	
MISSOURI	▨		▨		▨		▨		▨		▨		10	(9)	0		90	
NEBRASKA	▨		▨		▨		▨		▨		▨		100		0		0	
OHIO	▨		▨		▨		▨		▨		▨		100		0		0	
OREGON	▨		▨		▨		▨		▨		▨		▨		▨		▨	
PENNSYLVANIA	▨		▨		▨		▨		▨		▨		100	(3)	0		0	
RHODE ISLAND	▨		▨		▨		▨		▨		▨		▨		▨		▨	
S. CAROLINA	▨		▨		▨		▨		▨		▨		100		0		0	
S. DAKOTA	▨		▨		▨		▨		▨		▨		0		95		5	
TENNESSEE	▨		▨		▨		▨		▨		▨		100	(3)	0		0	
TEXAS	▨		▨		▨		▨		▨		▨		0		100		0	
UTAH	▨		▨		▨		▨		▨		▨		0		80	(5)	20	(6)
VIRGINIA	▨		▨		▨		▨		▨		▨		90	(1)	0		10	
VERMONT	10	(3)	0		90		90	(3)	0		10		▨		▨		▨	
WASHINGTON	▨		▨		▨		▨		▨		▨		80	(1,3)	11	(4,5)	9	(6)
WYOMING	▨		▨		▨		▨		▨		▨		25	(3)	0		75	(6)
Mean Value	66.7		3.3		30.0		46.7		16.7		36.7		54.7		25.9		19.4	
Range	10, 100		0, 10		0, 90		0, 90		0, 50		10, 50		0, 100		0, 100		0, 100	
No. of Responses	3		3		3		3		3		3		26		26		26	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	▨		▨		▨		▨		▨		▨		10		90		0	
SASKATCHEWAN	▨		▨		▨		▨		▨		▨		0		100		0	
N. BRUNSWICK	▨		▨		▨		▨		▨		▨		10		0		90	
MANITOBA	▨		▨		▨		▨		▨		▨		0		0		100	
ONTARIO	▨		▨		▨		▨		▨		▨		90	(3)	0		10	
Mean Value	0		0		0		0		0		0		22		38		40	
Range	NONE		NONE		NONE		NONE		NONE		NONE		0, 90		0, 100		0, 100	
No. of Responses	0		0		0		0		0		0		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

	BRIDGES Steel Superstructure						BRIDGES Concrete Beams						BRIDGES Concrete Decks					
	5.4						5.5						5.6					
U.S. SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
ALABAMA	75		0		25		90		0		10		90		0		10	
ALASKA	100	(3)	0		0		100	(3)	0		0		100	(3)	0		0	
ARIZONA	85	(3)	5		10	(6)	85		10	(5)	5	(6)	50		50	(5)	0	
ARKANSAS	5	(2,3)	75		20		95	(2,3)	0		5		100	(2,3)	0		0	
COLORADO	▨	(3)	▨		▨		▨	(3)	▨		▨		▨	(3)	▨		▨	
CONNECTICUT	0	(9,2)	80	(5,4)	20	(6)	30	(2)	70	(5,4)	0		40	(2)	60	(5,4)	0	
FLORIDA	100	(3)	0		0		50	(3)	50	(5)	0		50	(3)	50	(5)	0	
GEORGIA	0		90	(4)	10	(6)	100	(3)	0		0		100	(3)	0		0	
IDAHO	50		0		50		50		0		50		100		0		0	
INDIANA	100		0		0		100		0		0		100		0		0	
KANSAS	0		90		10		100		0		0		100		0		0	
LOUISIANA	95	(1)	0		5		100		0		0		100		0		0	
MAINE	60	(3)	0		40		0	N/A	0	N/A	0	N/A	100		0		0	
MASSACHUSSETTS	80		0		10		▨		▨		▨		90		0		10	
MARYLAND	99		0		1		100		0		0		100		0		0	
MICHIGAN	0		50		50		50		0		50		90		10		0	
MISSISSIPPI	100	(3)	0		0		100	(3)	0		0		80	(3)	20	(5)	0	
MISSOURI	50		0		50		0		100	(5)	0		0		60	(5)	40	
NEBRASKA	95		0		5		100		0		0		75		25	(5)	0	
OHIO	100		0		0		100		0		0		100		0		0	
OREGON	▨		▨		▨		▨		▨		▨		▨		▨		▨	
PENNSYLVANIA	100	(3)	0		0		100	(3)	0		0		100	(3)	0		0	
RHODE ISLAND	▨		▨		▨		▨		▨		▨		▨		▨		▨	
S. CAROLINA	90		0		10		100		0		0		100		0		0	
S. DAKOTA	0		90		10		100	(2)	0		0		100	(2)	0		0	
TENNESSEE	100	(3)	0		0		100	(3)	0		0		100	(3)	0		0	
TEXAS	50	(1)	0		50		▨		▨		▨		▨		▨		▨	
UTAH	0		100	(5)	0		100	(2)	0		0		100	(2)	0		0	
VIRGINIA	100	(1)	0		0		100		0		0		100		0		0	
VERMONT	0		0		100		100	(3)	0		0		100	(3)	0		0	
WASHINGTON	68	(3)	31	(5)	(11)	(6)	88	(2,3)	0		12	(6)	100	(2,3)	0		0	
WYOMING	99	(3)	0		1	(6)	100	(3)	0		0		100	(3)	0		0	
Mean Value	62.1		21.1		16.8		82.8		8.5		4.9		88.0		9.8		2.1	
Range	0, 100		0, 90		0, 100		0, 100		0, 100		0, 50		0, 100		0, 60		0, 40	
No. of Responses	29		29		29		27		27		27		28		28		28	
CANADA SOURCE:	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes	% Dispos	Notes	% Recycl	Notes	% Reused	Notes
NOVA SCOTIA	30		70		0		0	N/A	0	N/A	0	N/A	100		0		0	
SASKATCHEWAN	0		50		50		100	(2)	0		0		100	(2)	0		0	
N. BRUNSWICK	10		0		90		0	N/A	0	N/A	0	N/A	0	N/A	0	N/A	0	N/A
MANITOBA	25		0		75		100		0		0		75		25	(5)	0	
ONTARIO	90	(3)	0		10		90		10	(5)	0		30	(2)	70		0	
Mean Value	31		24		45		58		2		0		61		19		0	
Range	0, 90		0, 70		0, 90		0, 100		0, 10		NONE		0, 100		0, 70		NONE	
No. of Responses	5		5		5		5		5		5		5		5		5	

Table 17. Summary of disposal/utilization survey (Continued).

Legend

NOTE	DESCRIPTION
DISPOSAL:	
1	Sold as scrap.
2	Disposed of in landfill, etc.
3	Material becomes contractor's property to be recycled, reused, or sold as scrap.
8	Becomes property of others.
9	Only unusable items are disposed of.
11	Only unsuitable material is removed.
RECYLED:	
4	Reused, or stored for subsequent use after straightening, painting, or minor repair.
5	Crushed, broken, or modified for recycling for use in a different highway application.
REUSED:	
6	Used in the same application or function.

NOTE	DESCRIPTION						
OTHER:							
10	Entry applicable to steel only. For wood:						
	State/Province	% Dispos	Notes	% Recyc	Notes	% Reused	Notes
	Georgia	50	(2)	50	(2)	0	
	Saskatchewan	25	burned	0		75	
	Ontario	80		10		10	
12	Wood	75		0		25	
	Aluminum	0		100		0	
13	Concrete Shoulder	10		90		0	
14	Asphalt Cement						
N-Type	New type of poles.						
▨	Not responded to, or specific type not responded to.						

Roadway Materials

Roadway materials are comprised of different material layers extending from the asphalt pavement's surface course to the subgrade and those material layers used to construct the shoulders. Ten different material/application layers are identified in table 17. The response to the survey indicated that, on the average, at least 75 percent of all roadway materials were either reused or recycled. The ensuing discussion presents a more detailed evaluation for each category of roadway materials.

Most States and Provinces do not distinguish between asphalt surface and asphalt structural layer/base course for pavement recycling purposes. The majority of the highway agencies recycle between 75 and 100 percent of their asphalt surface and asphalt base courses and the remainder is reused except for a small percentage (e.g., 5 to 10 percent) of RAP that is disposed of because it was not recoverable from stockpile or was of poor quality. Several States (e.g., Oregon, Alaska, Vermont) recycle less than 30 percent and primarily reuse the RAP for embankment fill. In Vermont, the contractor, with written approval, may use on the project such stone, gravel, sand, and other materials as may be found in the excavation, for other construction items, providing the materials meet the specifications. Alaska removes asphalt pavement and stockpiles about 80 percent for later use or for local reuse. The Province of Alberta often provides designs for pavement rehabilitation that allow for the use of all the RAP excluding that which is of poor quality.

The amount of recycling performed by the highway agencies is affected by the cost and availability of commercial aggregates, the type or category of highway, the pavement design, and existing policy and specifications for recycling of asphalt pavements. Table 18 provides a summary of specifications for hot-mix recycling in 50 States and the District of Columbia.(1) Typically, most States allow a maximum of 50 percent or less RAP, except Arkansas and Utah where the maximum amount of RAP allowed in surface or binder courses is 70 percent.

Other roadway materials such as crushed stone base, crushed gravel base, and granular subbase are commonly reused or disposed of into embankments or fills. In Louisiana, 90 percent of old crushed gravel base courses are improved by stabilization. Granular subbase is used as fill, although 25 percent is used as aggregate in HMA and approximately 25 percent is donated to adjacent property owners. Crushed stone is used in Kansas as a subgrade modifier or stabilized subbase.

Stabilized base course materials are conventionally used in embankments, although other methods have been adopted by several States. Louisiana pulverizes and restabilizes about 40 percent of the time. When cement-treated bases are encountered in Idaho, they are disposed of rather than attempting to recycle. Arizona breaks all stabilized base materials and incorporates them into embankment fills where future excavation is not anticipated. In Alberta, stabilized base containing 4 percent asphalt and/or crushed gravel is reused to improve the properties of subgrade and granular bases on the rehabilitation project. Stabilized subbases are generally reused or disposed of in embankments.

Table 18. Summary of recycling specifications of 50 States and the District of Columbia (from reference 3).

STATE	MAX RAP %—BATCH			MAX RAP %—DRUM			TOP SIZE FOR RAP	BLENDED STOCKPILE ALLOWED?	RECYCLING AGENTS		NOTES
	BASE	BIND	SURF	BASE	BIND	SURF			A/C	MOD.	
Alabama	40	40	12	50	50	12	2 in	YES	AC 5-20	NO	RAP must meet specs.
Alaska	(Developmental projects only at this time — no standard specifications)										
Arizona	40	40	40	40	40	40	1½ in	NO	AC 10-20	NO	100% RAP must pass 1½-in screen. Oversize must be crushed.
Arkansas	70	70	70	70	70	70	3 in	NO	YES	YES	
California	50	50	50	50	50	50	2 in	NO	YES	YES	Only RAP milled from rehabilitation project can be used in recycled mix on that project.
Colorado	30	30	30	30	30	30	1½ in	OPEN	YES	YES	In most cases, less than 30% used.
Connecticut	40	40	40	40	40	40	95% < 2 in	YES	YES	NO	15% RAP may be routinely used after notifying DOT.
Delaware	35	35	25	50	50	30	See note #1	See note #2	AC 10	NO	Note #1: 100% RAP must pass 2-in sieve with 90% passing 1-in sieve. Note #2: When using blended stockpile, maximum RAP allowable is 10%.
District of Columbia	60	60	NO	60	60	NO	1 in	NO	AC 10	YES	When RAP contains sheet asphalt, the practice is to limit the RAP to 20%.
Florida	60	50 See note #1	50	60	50 See note #1	50	See note	YES	YES	YES	Note #1: All mixes must meet standard spec requirements. Note #2: Equal to top size of mix used.
Georgia	25	25	25	40	40	40	2 in	YES	YES	NO	Specs allow use of contractor's stockpile of RAP; RAP stockpile must be approved by DOT.

Table 18. Summary of recycling specifications of 50 States and the District of Columbia (Continued).

STATE	MAX RAP %—BATCH			MAX RAP %—DRUM			TOP SIZE FOR RAP	BLENDED STOCKPILE ALLOWED?	RECYCLING AGENTS		NOTES
	BASE	BIND	SURF.	BASE	BIND	SURF			A/C	MOD.	
Hawaii	30	NONE	NONE	40	NONE	NONE	1½ in	NO	AR6000	OPEN	Limited to AC base.
Idaho		OPEN			OPEN		2 in	OPEN	YES	OPEN	Specs tailored to each project 20% to 40% max.
Illinois	25 See note #1	25	15 See note #2	25 See note #1	25	15 See note #2	See note	NO	AC 2.5 to 20	NO	Grizzly required for RAP bin. Note #1: No Interstate use. Top size for RAP, maximum size allowed in mixture. Note #2: For ADT less than 2,000.
Indiana	50	50	See note	50	50	See note	2 in	NO	AC 2.5 to 20	AE60 AE90	Open to modifying specs for given project. Surface recycling is by special provision only. RAP percentage limited to 20% when not salvaged from DOH project. Homogenous stockpile required.
Iowa	OPEN						1½ in	NO	YES	OPEN	At least 70% of asphalt cement in final surface course mix shall be new material.
Kansas	50	50	50	50	50	50	See note	YES	YES	YES	100% must pass 2¼-in scalper; 10% RAP routinely may be used.
Kentucky	30/20	30/20 See notes #1, #2	30/20	30/20	30/20 See notes #1, #2	30/20	NONE	OPEN See note #2	YES	OPEN	Note #1: RAP used in open-graded portion, sand surface asphalt, or any surface course must meet aggregate requirements when originally placed. Same is true with mixes requiring polish-resistant sand. Note #2: When RAP not salvaged from DOT projects, RAP percentage limited to 20%.
Louisiana	30	30	NO	30	30	NO	2 in	OPEN	AC 10, 30	NO	Shoulder-wearing course maximum of 20%.

Table 18. Summary of recycling specifications of 50 States and the District of Columbia (Continued).

STATE	MAX RAP %—BATCH			MAX RAP %—DRUM			TOP SIZE FOR RAP	BLENDED STOCKPILE ALLOWED?	RECYCLING AGENTS		NOTES
	BASE	BIND	SURF	BASE	BIND	SURF			A/C	MOD.	
Maine	40	40	NO	40	40	NO	1½ in	NO	AC 5, 10	NO	20% max RAP allowed in all base and binder mixtures on all projects. Up to 40% RAP on specific projects only.
Maryland	50	50	30	50	50	30	See note #1	See note #2	YES	YES	Note #1: All mixes must meet JMF. Note #2: Not after the approval of mix design.
Massachusetts	20	20	10	40	40	10	1½ in	NO	AC 5, 10	NO	No for open-graded friction course.
Michigan	50	50	50	50	50	50	2-in Base 1-in Top	YES	AC 1-10	NO	
Minnesota									Modifiers not required		All salvaged asphaltic pavement materials to be used in type 32 mix, no particle greater than 3 in; for type 42, none greater than ¾ in.
Type 32 Mix	50	50	30	50	50	30	See note	YES	AC120/150		
Type 42 Mix	50	30	30	50	30	30	See note	YES			
Mississippi	30	30	NO	30	30	NO	2 in	NO	YES	NO	
Missouri	50	50	50	50	50	50	1½ in	OPEN	YES	NO	30% minimum RAP required.
Montana	50	50	0	50	50	0	2 in	YES	85-100 120-150 200-300	NO	Specifications tailored to each project. May be less to meet air quality requirements.
Nebraska	Batch plants not commonly used			50	50	50	2 in	OPEN	YES	NO	RAP percentage may vary if order for combined gradation is to meet standard specs.
Nevada	50	50	15	50	50	15	1½ in	NO?	YES	YES	Modifier required when RAP percentage is between 35 and 50%.
New Hampshire	35	35	0	50	50	0	See note	NO	YES	NO	Gradation must meet standard specs.

Table 18. Summary of recycling specifications of 50 States and the District of Columbia (Continued).

STATE	MAX RAP %—BATCH			MAX RAP %—DRUM			TOP SIZE FOR RAP	BLENDED STOCKPILE ALLOWED?	RECYCLING AGENTS		NOTES
	BASE	BIND	SURF	BASE	BIND	SURF			A/C	MOD.	
New Jersey	50	50	10	50	50	10	2½ in	YES	AC 20, 10	NO	Specs are for RAP used from same reconstruction project; otherwise, from blended stockpile, 10% RAP in surface and 50% in base and binder courses allowed.
New Mexico		OPEN* See note #1			OPEN See note #1		2 in	NO	YES	YES	RAP must be screened and stockpiled 2 in to ⅜ in. Note #1: By mix design.
New York	50	50	NO	70	70	NO	2 in	NO	YES	NO	Maximum RAP % linked to RAP moisture content.
North Carolina	60	60	60	60	60	60	2 in	YES See note	YES	NO	Subject to approval. AC-20 may be allowed with 15% or less RAP, subject to approval.
North Dakota	50	50	50	50	50	50	1½ in	NO	YES	OPEN	
Ohio	50	50	30	50	50	30	Base 95% < 2 in, ¾ in for surface	NO	YES	YES	When RAP % is less than 10%, Marshall mix design not required. These figures okay for contractor mix designs.
Oklahoma	25	25 See note	25, 0	25	25 See note	25, 0	95% < 2 in	YES	AC-20	NO	25% for low volume roadways (less than 1,000 ADT); 0% for all other roadways.
Oregon	30	20 See note #1	20	30	20 See note #1	20	1 in	NO	YES	OPEN	20% RAP allowed in shoulders. The combination of RAP, new materials, and recycling agents must produce mixture with recovered asphalt properties equal to new asphalt. Note #1: Non-Interstate jobs; 0% RAP on Interstate projects.
Pennsylvania	OPEN	OPEN	10	OPEN	OPEN	10	95% < 2 in	YES	YES	YES	Minimum 11% RAP required for base and binder, 5% for surface.

Table 18. Summary of recycling specifications of 50 States and the District of Columbia (Continued).

STATE	MAX RAP %—BATCH			MAX RAP %—DRUM			TOP SIZE FOR RAP	BLENDED STOCKPILE ALLOWED?	RECYCLING AGENTS		NOTES
	BASE	BIND	SURF	BASE	BIND	SURF			A/C	MOD.	
Rhode Island	35	35	NO	50	50	NO	1¼ in	NO	YES	Optional	Minimum 10% RAP required.
South Carolina	20	15	10	20	15	10	2 in	NO	YES	NO	
South Dakota	Batch plants not commonly used.			50	50 See note	50	1½ in	NO	YES	NO	Percentage specified on project basis by plan note.
Tennessee	OPEN See note		0	OPEN See note		0	NONE	OPEN	YES	YES	At least 65% of asphalt cement in final mix shall be new material.
Texas	OPEN See note			OPEN See note			2 in	OPEN	YES	YES	Specification limits RAP percentage to 20% when not salvaged from TxDOT project. Only RAP from TxDOT projects allowed in surface courses. RAP percentages above 20% require analysis of blended asphalt quality.
Utah	70	70	70	70	70	70	95% < 1½ in 100% < 2 in	NO	YES	YES	Minimum 50% RAP Required: recovered asphalt after recycling has to meet same requirements as if new asphalt was used, and gradations have to meet same requirements as new material. Up to 15% RAP allowed without recovered analysis of aggregate gradation and asphalt cement.
Vermont	See note			See note			N/A	NO	YES	NO	All recycled mixes must meet standard specifications.
Virginia	25 (see note)			25 (see note)			2 in	YES	YES	NO	Unless otherwise approved in writing by the engineer.
Washington	OPEN See note #1			OPEN See note #1			OPEN See note #1	YES	YES	YES	Up to 20% RAP allowed without analyzing gradation of RAP. Mixture containing RAP must conform to standard specs. Note #1: By mix design.
West Virginia	OPEN			OPEN			OPEN	OPEN	OPEN	OPEN	Penetration not less than 60.

Table 18. Summary of recycling specifications of 50 States and the District of Columbia (Continued).

STATE	MAX RAP %—BATCH			MAX RAP %—DRUM			TOP SIZE FOR RAP	BLENDED STOCKPILE ALLOWED?	RECYCLING AGENTS		NOTES
	BASE	BIND	SURF	BASE	BIND	SURF			A/C	MOD.	
Wisconsin		OPEN			OPEN		1 in	NO	YES	NO	RAP source limited to reconstruction project for surface courses.
Wyoming	50	50	50	50	50	50	2 in	NO	YES	NO	Percent of RAP specified by State on a project basis.

1 in = 25.4 mm

Subgrade materials are always reused except in certain situations where the material is wet or contaminated and does not meet the agency's specifications.

Shoulders constructed with HMA are mostly reused and recycled. Very little is disposed of except into fills. Similarly, compacted aggregate shoulders are reused, possibly stabilized, or re-manipulated most of the time.

Culverts

The primary function of a culvert is to transfer surface drainage water from one side of a roadway to the other and to provide structural support for the overlying roadway fill, pavement, and vehicular traffic. In some cases, large culverts also function as vehicle or pedestrian underpasses. The materials used in the construction of small culverts usually range from wood, concrete pipe, corrugated steel pipe, to concrete box. Larger culverts and underpass structures are often constructed using multiplate.

The information on culverts from the survey indicated 100 percent disposal of wood culverts. In most States, multiplate underpasses were disposed of 100 percent of the time, either being sold as scrap or as the contractor's property for reuse, recycling, or disposal or scrap. A few States and Provinces indicated reuse ranging from 10 to 50 percent (one State cited 100 percent reuse). The limited demand for multiplate structures and the difficulties encountered in erection using bent, damaged, or rusted plates and fittings often make it more practical to sell as scrap or designate as contractor salvage. One State mentioned that the lack of storage space made it impractical to recycle or reuse multiplate units.

About one-half of the respondents indicated that they dispose of 90 to 100 percent of the concrete culvert pipe. Missouri crushes all old concrete pipe and recycles it into roadway fill. Arizona and Manitoba recycles about 50 percent in this manner and disposes of the remaining 50 percent in other ways. In general, in the remaining one-half of those responding to the survey, concrete culvert reuse ranged from 10 to 75 percent. One State donated about half of the old concrete culverts to property owners and the remainder were used as temporary culverts. Recycling usually involved use in roadway fill, but in Ontario, 30 percent is consumed as riprap, 20 percent is reused, and 50 percent is buried or used as fill.

Corrugated steel culvert pipe is predominantly disposed of directly or by the contractor as scrap for recycling into steel products. On the average, 87 percent is disposed of as compared to 74 percent for concrete culverts. About 15 percent (ranging from 5 to 70 percent) was reused on State highways, given to local municipalities for local roads, or either sold or donated to landowners, sometimes as part of right-of-way negotiations for use as storage bins or culverts. In numerous instances, scrap steel is the property of the contractor.

Guardrail Systems

The survey form did not identify the different types of guardrails. Although the implication was for conventional rolled steel, there was one or two responses that indicated aluminum and steel cable. Similarly, the guardrail posts were generally steel posts, however, aluminum and wood posts were utilized in three and five States, respectively.

As would be expected, on the average, 57 percent of wood guardrail posts were disposed of by the contractor or maintenance crew. Wood posts may be landfilled, used as landscaping timbers, sold to landscapers, or disposed of by the contractor. Salvageable wood posts are generally reused when guardrails are raised, but are seldom stockpiled for reuse except in regions where rotting is not a major problem and wood is predominately used.

Steel posts are reused or recycled depending upon conditions and State highway agency procedures. In some States and Provinces, the removed material becomes the property of the contractor (e.g., 100 percent disposal), which may be reused elsewhere or sold as scrap and recycled into new steel products. On the average, the States reuse about 37 percent of the steel guardrail posts and recycle about 5 percent. These values are not truly representative because of the variability in which the different States handle contractor salvage. One State recycles about 90 percent of the steel posts removed from the highways for construction of storage racks. Most States reuse steel posts, or if damaged, sell it for scrap rather than recycle (refurbish) damaged posts. Similarly, damaged aluminum posts are sold for scrap since it is not practical to straighten them.

Typically, guardrails are reused and recycled about 50 percent of the time and the remaining 50 percent are sold as scrap or contractor salvaged. However, cable guardrails in Connecticut are 100 percent recycled. Most States and Provinces reuse guardrails unless they are damaged excessively. A few States straighten (recycle) bent guardrail. In some instances, the recycled or removed guardrails are stockpiled in maintenance yards for subsequent use in guardrail repair. In Michigan, aluminum and galvanized guardrails are used by maintenance crews but Cor-Ten™ guardrail is scrapped. Similarly, in Oregon, ungalvanized guardrail is sold for scrap. In Canada, the policy varies between Provinces, such as removed steel becoming the property of the contract (agency) to reuse unless bent or damaged excessively.

Comments received from States having high wind and snowfall conditions indicate they have encountered a major problem with guardrails causing snow drifts. The guardrail is considered a roadside hazard in these conditions. Therefore, except for those locations where a guardrail is essential, there is a tendency to minimize guardrail installation.

In summary, State highway agency policies, climate conditions, type of material used in guardrails and posts, availability of facilities for straightening, and probably the degree of corrosion produced by deicing salts or saltwater spray influences the amount of disposal, recycling, and reuse of guardrail systems.

Signs and Sign Signal Structures

Sign and sign post replacement is usually the responsibility of maintenance and operations with the State highway agencies. On the average, about 46 percent of all signs are disposed of, 34 percent are recycled, and the remaining 20 percent are reused. The actual values for each State vary substantially because of different materials used in sign construction and operational procedures. Arizona and Maine predominantly reuse their signs. Maine disposes of 15 percent, reuses 75 percent, and recycles 10 percent as scrap metal. Oregon and Louisiana recycle (resurface and reuse) 50 percent of their signs and dispose of the remaining signs as scrap metal. All plywood signs in Oregon are discarded. In Missouri, 40 percent of the signs are reused and the remaining 60 percent resurfaced (recycled) in the sign reclamation plant. Similarly, the Province of Alberta recycles 60 percent of their aluminum-backed signs by removing old reflective sheeting and sign messages from the aluminum blank which is then covered with new sheeting and message. In some cases, States and Provinces dispose of all signs either by selling as scrap metal or by becoming the property of the contractor.

The disposal, recycling, and reuse of sign posts varied depending upon material type and highway agency. Ohio, Wisconsin, Wyoming, and Virginia dispose of 100 percent of their sign posts either through maintenance forces or as contractor's property. About one-half of the respondents reuse between 50 to 100 percent of their sign posts. In Saskatchewan, 75 percent of wood posts are reused, the remainder are burned, and 50 percent of the steel sign posts are reused, the remainder are disposed of as scrap steel. Ontario was similar except they recycled approximately 30 percent of the metal posts.

Sign and signal poles or structures, usually aluminum or steel, are disposed of about 50 to 95 percent of the time by most of the responding States. This material is sold as scrap except in those States (e.g., Alaska, Virginia, Vermont) where it is designated as the contractor's property for subsequent sale as scrap (recycling) or reuse. The amount of reuse tends to be associated with type and age of the sign structures. Ontario reuses 100 percent of their new type poles and sign structures whereas only 20 percent of the older type is reused, the remainder being property of the contractor. Saskatchewan disposes of 75 percent as scrap metal, but reuses about 25 percent of all sign poles and structures. Wyoming and Alberta primarily reuse sign poles unless structurally unsound, and recycle about 50 percent of the sign structures, the rest being scrapped.

It is apparent that the amount of disposal, recycling, and reuse is dependent upon each State's policy, type of materials used, and regional conditions that affect suitability for recycling or reuse. Transportation and competitive cost of new signs, posts, poles, and sign structures make it impractical to recycle in some areas.

Bridges

The survey response for major bridge components (railing, steel superstructure, concrete beams, and concrete deck) indicated that most States dispose of 80 percent or more of the concrete obtained from the rehabilitation and demolition of bridges. Similarly, over half of the States dispose of 80 percent or more for the steel superstructure and bridge railings. At least five States and one Province indicated that almost all bridge materials were the contractor's property for reuse, recycling, or disposal, as considered appropriate by the contractor.

Bridge railings are reused or recycled unless they are excessively damaged, corroded, or do not meet current standards. The amount of reuse ranges from between 1 and 15 percent, although Indiana, Maine, and Wyoming indicated 50, 40, and 75 percent reuse, respectively. Missouri and Arizona essentially reused all bridge railings (90 to 100 percent), except where the condition required sale as scrap. In Alberta, steel tube railings are commonly recycled by sand blasting and galvanizing in their shop. The excessively corroded railings are disposed of in landfills. Only three States differentiated between steel and aluminum railings. Maryland and Michigan reuse 50 percent of their aluminum railings, but dispose of almost all steel railings. No comments were provided to identify the difference in reuse between aluminum and steel, although it may be related to the corrosion resistance of aluminum.

Steel superstructure members and trusses were reused by about two-thirds of the respondents. The amount of reuse generally varied between States from 1 to 50 percent. The response may be misleading because reuse may involve being reused by local or municipal agencies. For example, Missouri reuses about 50 percent of its steel bridges, but part of this is sold to counties. Similarly, in the Province of Alberta, steel trusses with insufficient load capacity are either sold through Government Services Surplus sales or sold to the public for reuse or recycling. Otherwise, they reuse trusses at other suitable locations or put them into salvage steel truss inventory for repair or modification of inservice trusses. Occasionally, they are reused on similar bridges by doubling the trusses to increase load capacity.

Those States that indicated a high percentage of recycling were in several instances disposing of the steel as scrap for recycling into new steel products. This, combined with disposal practices in many States, suggests that most bridge superstructure steel is removed and sold as scrap by either the contractor or the highway agency.

Concrete beams and concrete bridge decks are, for the most part, disposed of with very little recycling or reuse. Broken concrete is frequently used as embankment fill or buried within limits of construction. Reinforcing steel is generally removed and sold as scrap. In Pennsylvania, all bridge materials are the contractor's property, but when concrete bridge demolition is near suitable commercial facilities, the concrete rubble is generally recycled. In Alberta, concrete beams are occasionally used in storage yards for stockpiling planks and other materials or sold to the public for use as sleepers or in small bridge construction for landowner access. Concrete bridge decks are reused by some States and Provinces for slope protection (Missouri) or riprap (Nebraska, Manitoba, Ontario).

Other Recycling Activities

Traffic paint and cracksealer are supplied, in accordance with the Alberta Transportation Department's specifications, in returnable drums with plastic liners. After the material is used, the liner and drum are returned to the manufacturer.

Arizona recycles about 95 percent of chain-link fences and posts. Sidewalk/curb and gutter concrete is used in embankments.

Summary

The results of this survey would have been enhanced had the knowledge gained here been applied in the development of an improved survey form or questionnaire. However, the results obtained and inferred suggest that numerous regional or local factors influence the operational aspects of maintenance and rehabilitation. In some cases, policies and specifications governing the disposal, recycling, and/or reuse of highway materials have evolved to fit these situations. It seems that substantial effort has been and is being exerted by the agencies to find more effective ways to utilize highway materials. Finally, since highway materials often differ from one locality to the next, there are, as evidenced by this survey, different approaches to materials utilization that are effective under a specific set of conditions.

References

1. "Three States OK More RAP in Recycling Specs," *Roads and Bridges*, October 1992, pp. 31-34.

CHAPTER 4. SUMMARY OF FINDINGS

ENVIRONMENTAL ASSESSMENT

Crumb Rubber Modifier

Environmental and Human Health Effects

The available data are inadequate to develop a quantitative characterization of absolute or relative human health or environmental risks associated with the production, application, recycling, or disposal of paving asphalt modified with CRM. Critical data gaps are as follows.

There are no environmental monitoring data that can be used to define "mixtures of concern" or "similar mixtures," or to assess exposure to humans or other organisms to components of these mixtures. Data on emissions are limited to a few studies of stack emissions from asphalt mixing plants and two preliminary studies of occupational exposure. The results of these studies and other similar studies of emissions from conventional asphalt production suggest that, in general, the addition of CRM to the mix does not significantly contribute to changes in emissions of major classes of pollutants (e.g., polyaromatic hydrocarbons (PAH), volatile organic compounds, etc.). However, at least one chemical, 4-methyl-2-pentanone (methyl isobutyl ketone or MIBK), may be released in greater quantities during mixing of asphalt pavements modified with CRM. Although the source of MIBK has not been identified, a plausible source is thermal degradation of isoprene, a component of rubber. This is consistent with the observation of higher rates of emission of MIBK at higher mixing temperatures.

The significance of the detection of MIBK in the emissions from mixing of asphalt pavements modified with CRM is that it suggests that components of rubber and reaction products of these components may be emitted during asphalt production (and perhaps at other stages in the life of the asphalt product). If this is the case, then mixing temperature may be an important factor in determining relative risk associated with modified asphalt pavement production vs. conventional asphalt production. It also is possible that other components of rubber and thermal reaction products may be emitted in the production of modified asphalt paving mixtures. Consideration should be given to conducting studies in which emissions of rubber chemicals and probable reaction products are monitored. Once the emission profile for rubber chemicals has been defined, it might be possible to define potential "mixtures of concern" or "similar mixtures" that could be used in risk characterization.

It needs to be emphasized that measurements of stack emissions such as those conducted in the Thamesville (Ontario), Haldimand-Norfolk (Ontario), Parmer County (Texas), and San Antonio (Texas) studies provide only a rough index of potential exposures resulting from production of asphalt pavements. They do not provide information about exposures that might result from leaching of materials from pavement, or from emissions during removal, recycling, or disposal of paving. Such information can be obtained from environmental monitoring in the vicinity of these operations.

In the absence of environmental monitoring studies, some limited estimates of exposure potential can be made from evaluations of environmental fate. For example, it may be possible to evaluate the potential for MIBK to be transported to various environmental media and to estimate its persistence in these media. Such evaluations depend on the availability of high-quality data on the composition of modified asphalt pavement and the environmental fate of the chemicals of greatest concern. The chemical composition of asphalt pavements modified with CRM has not been adequately defined to support a comprehensive "components" approach to environmental fate assessments. Furthermore, although there is information on the environmental fate and toxicity of some of the major hazardous components of conventional asphalt cement and rubber, this data has not been evaluated to assess the adequacy of the data base for estimating exposure potential.

Dose-response assessments have not been developed for "mixtures of concern" or "similar mixtures" since these have not been defined. Dose-response assessments are available for some of the major components of asphalt cement and rubber. The toxicologic interactions that occur between the chemical components of modified asphalts have not been adequately characterized.

Recycling

A characterization of relative risk associated with recycling of asphalt paving mixtures modified with CRM vs. conventional asphalt pavement is not feasible at this time.

Other Recycled Materials

Environmental and Human Health Effects

The available data are inadequate to develop a characterization of absolute or relative human health or environmental risks associated with the production, application, recycling, or disposal of asphalt pavements modified with other recycled materials.

Recycling

The available data are inadequate to develop a characterization of absolute or relative human health or environmental risks associated with the recycling of asphalt pavements modified with other recycled materials.

ENGINEERING ASSESSMENT

Crumb Rubber Modifier (CRM)

Approximately 242 million tires that are comprised of over 1.8 million Mg (2 million tons) of rubber are discarded annually. Currently, about 11 percent of these scrap tires are used as a tire-derived fuel (TDF) source for heat or power generation. About 5 percent are exported and less than 7 percent are recycled or processed for other products. Of this 7 percent, about 2 percent is used in tire manufacturing, 3 percent is turned into rubber products, and 2 percent is used as crumb rubber in asphalt pavements.

The answer to the question of whether the CRM technology is viable and cost-effective is not readily apparent. States located in the hot, dry, southwestern U.S. have extensive experience with rubber-modified asphalt membranes and mixtures. In general, they have had only a few failures and are generally satisfied with the constructability and performance of pavements containing CRM. However, highway agencies in the northern States, where wet and cold weather is more prevalent, have not observed any major improvement in performance over their conventional HMA pavements.

The major unknown in using these materials is the potential for their influence on the recycling process. Experience with the recycling of RAP containing CRM is limited. The greatest deterrents from the use of CRM is the high initial cost and the variable performance that seems to be associated with climate and selection of proper application, mix design, and construction.

There is an urgent need to evaluate the recyclability of asphalt concrete pavements containing CRM. The investigation should encompass the use of recycled asphalt pavement (RAP) that contains stress-absorbing membrane (SAM), stress-absorbing membrane interlayer (SAMI), and other asphalt rubber (AR) paving mixtures, including combinations (e.g., SAMI, asphalt concrete, SAM).

There is also a need to develop mixture design methods to accommodate the use of CRM using either dry or wet processing methods. The combined influence of CRM particle size and aggregate gradation needs to be evaluated and suitable criteria needs to be established for selection of amount and size of CRM and total binder content for each application.

The CRM/asphalt cement interaction needs to be evaluated to establish absorption of malthenes, degree of rubber particle swell or solubility, and influence on binder properties in relation to size and amount of CRM. Processing methods, both wet and dry, should be evaluated to determine the effects of time, temperature, pressure, mechanical mixing, etc., on the CRM/asphalt interaction. Process (reaction) time, storage time, or equilibrium conditions must be established for wet processing methods. It should be determined whether or not the dry process is equivalent to the wet process once a certain fineness and amount of CRM is achieved.

Recycling of Pavements Using 80 Percent RAP

Currently, there are only three asphalt recycling processes that can utilize successfully at least 80 percent RAP. They are: (1) cold in-place recycling, (2) hot in-place recycling, and (3) hot central plant recycling by means of the proprietary CYCLEAN® process.

Cold in-place recycled materials are usually used as a stabilized base course to be covered with a chip seal in low volume roads, or overlaid with a hot or cold surface mix. Pavements with excessive patching, weak subgrade due to water damage, or stripping problems are not recommended for cold in-place recycling.

Hot surface recycling is usually used to correct surface defects such as roughness and weathering of pavements that are structurally adequate. The recycling process is also limited to a depth of 50 mm (2 in).

Among these three recycling processes, the hot central plant recycling can produce mixes of the highest quality. The hot recycled mixes are usually used as surface structural mixes. However, due to the problem with smoke emission, utilization of greater than 80 percent RAP in the recycled mix has been limited to the CYCLEAN® process that uses the microwave technology. For a RAP material that has been substantially aged and deteriorated, adequate amounts of virgin aggregate and recycling agent are required to be added to the RAP to produce a high-quality hot mix. This will limit the percentage of RAP that could be incorporated into the recycled mix. Recycling specifications of State highway departments have set limits on the maximum allowable percentage of RAP to be used in hot-mix recycling.

Crushed Glass

The quantity of crushed glass is relatively small with respect to potential uses in the highway network. Also, the availability of crushed glass for highway construction is limited to areas near cities that are major generators of glass. Because of its value, glass that has been sorted is best suited for recycling back into glass products.

Crushed glass has been used successfully as an aggregate replacement in base and subbase course materials, as a drainage media, and in asphalt pavements subjected to light traffic volumes. The use of glass as an aggregate supplement should be considered experimental in the surface coarse since its performance in this capacity is unknown.

In summary, glass has been used in portions of the highway pavement structure. Its use may not be cost-effective nor may it impart any beneficial attributes to a pavement other than reflectivity. It can generally be considered as being nonbeneficial to the properties of conventional construction materials and to the performance of highway pavements.

Plastic

In summary, recycled plastic guardrail posts and other experimental posts that are not currently a manufactured product, have insufficient performance data to evaluate their suitability for use in highway construction. Impurities that affect strength properties and densities that are greater than wood products suggest that it may be impractical to use recycled plastics in certain applications. Also, costs that may be four times greater than wood may result in life-cycle costs that are excessively high.

However, it seems reasonable to assume that State highway agencies can utilize currently manufactured recycled plastic products provided they meet their requirements/specifications. Although many manufacturers label their products with the recycled content, all producers should have similar labeling to facilitate purchasing of products according to specifications.

The use of virgin polymers for modification of asphalt cements is not a new technology. Other than differences in processing and type of polymer, those processes using recycled plastics (Novophalt® and Polyphalt™) are similar and should be expected to provide greater resistance to rutting and possibly greater life provided the properties of the binder and mixture are suitable for the imposed traffic and climatic conditions. The approximate 30 percent increase in cost for polymer-modified hot-mix asphalt appears justifiable based upon life-cycle costs.

Other Materials

Coal Ash

Coal-fired power generating plants produce as byproducts, fly ash and bottom ash. Both have been used extensively in highway construction. Fly ash in particular is one of the most abundant and useful "waste" products available.

For over 50 years, fly ash has been used as a replacement/additive in portland cement concrete where it enhances sulfate resistance, raises strength, and reduces permeability. Forty-five States either incorporate it in or have specifications governing its use. Another benefit derived is the potential cost savings of \$1.3 to \$2.6/m^3 (\$1 to \$2/yd^3) when used as a cement replacement.

Fly ash added to aggregates has been used to produce a high-quality base course in flexible pavement systems, and a high-quality subbase in rigid pavement systems. Lime-fly ash-aggregate mixtures are also commonly used as a base or subbase course. Other uses include mineral filler in HMA pavements, fine aggregate, embankment material, soil stabilizer, and flowable backfill component.

Bottom ash accounts for 15 percent of total coal ash production (fly ash is 85 percent). It has been extensively used as an anti-skid material, granular backfill and embankment material, as a coarse aggregate in asphalt paving, and as a component of cement-stabilized base material.

Slag

As is the case with fly ash, blast furnace (primarily iron) slag has been used extensively as an all purpose aggregate material for over 30 years. There are four primary types of slag: air-cooled, expanded, granulated, and pelletized. The other types include steelfurnace, nickel, and copper slags.

Air-cooled slag is used as an aggregate in a variety of materials such as concrete (both plain and reinforced) and bituminous pavements (enhances skid-resistance). It has been used as a high-stability base course for macadam surfaces and bases, dense-graded aggregate, bituminous stabilized bases, and as a soil-aggregate base.

Expanded slag and pelletized slag are lightweight aggregates, and are not used extensively in highway construction, except for producing lightweight concrete products.

Granulated slag gains strength with time and it exhibits good compaction characteristics. It is used frequently for embankment fill or highway bases. When used as a base material, it exhibits excellent insulative properties and can be used effectively in frost prone areas. Due to its strength-gaining characteristics, it has also been used as an additive/replacement for cement in slag cement.

Steel furnace slag, produced in the making of steel, exhibits high bulk densities, and is frequently used as base course and for highway shoulders. The additional unit weight produces higher skid resistance when used in asphalt mixes for wearing surfaces. Other benefits derived from its use in both dense and open-graded HMA include high stability and good stripping resistance.

Nickel and copper slags are usually combined into a single category since they are both iron silicate, nonferrous materials. Their use is not widespread; however, there is interest in using it in blended cement, base stabilization, and fine aggregate in HMA.

The use of blast furnace slag is generally accepted in highway construction. It is the third most popular material following recycled or reused asphalt and concrete. Its popularity is based on its availability, technical suitability, favorable economics, and positive environmental impact. Approximately 35 percent of the States and 2 Provinces use it, and 14 States have specifications that govern its use. Of the various types, air-cooled and granulated are the most widely used.

The only potential problem associated with the use of slags as granular material is leachate production. However, based on test results, the EPA has not, to date, classified it as a solid waste.

Steel slag is ranked behind coal fly ash in overall usage. Eighteen States and four Provinces use it primarily in HMA to enhance skid resistance. Caution is advised when using steel slag due to its expansive properties, and thus, it should not be used in confined applications or in portland cement concrete.

Municipal Solid Waste Ash (MSW)

Approximately 15 percent of the 181 million Mg (200 million tons) of domestic waste produced each year is burned in incineration plants. The 7.8 million Mg (8.6 million tons) of residue or ash left (bottom - 90 percent and fly - 10 percent) have been successfully used as a partial replacement for coarse aggregate in asphalt paving mixes as well as combined with portland cement in base courses. Currently five States have used MSW either as subbase, embankment material, or as aggregate in asphalt or concrete.

During the late 1970's, several research projects were conducted to evaluate the use of MSW in highway construction. Several researchers found that the material, when used as an aggregate in a bituminous base (termed "littercrete"), performed as well as conventional aggregates. Thus, in terms of engineering properties, it appears to be promising.

The primary concerns with the use of this material however, are the variability of the product and the potential for leachate problems associated with excess lead and cadmium present in the fly ash. Most plants combine the two ashes together, thereby reducing the concentrations to acceptable limits. Nevertheless, the concern for leachate contamination—primarily heavy metals—has prevented the widespread use of this material in highway construction.

Paper/Cellulose in Stone Matrix Asphalt

Cellulose fibers are used extensively in SMA mixtures in Germany and Sweden. Currently, the primary source of cellulose fibers used in SMA construction comes from a German manufacturing company that derives the fibers from natural raw materials, e.g., wood. However, there appears to be no technical limitation on using recycled paper for making cellulose fibers. Cellulose fibers are currently being produced for use in SMA mixtures by a company in Michigan. If the SMA technology continues to gain acceptance in this country, and if cellulose fibers continue as the predominant stabilizing agent, the market for the fibers may see tremendous growth. An optimistic forecast of 322 lane-km (200 lane-miles) of SMA construction per State each year would result in an estimated annual U.S. consumption of 14,500 Mg (16,000 tons) of cellulose fiber. However, this amount is insignificant when considering the total yearly generation of waste paper, which is approximately 65 million Mg (72 million tons).

Carbon Black

The pyrolization of tires to obtain carbon black appears promising as a method of resource recovery since raw material in the form of useable energy sources and carbon black are produced. Further consideration is necessary to realize the full benefit of the use of carbon black-modified asphalt.

Recycled Portland Cement Concrete

Recycled portland cement concrete (PCC) can be used as aggregates in PCC pavement or as a base material. Recycled PCC aggregate may be preferential to virgin aggregates if careful control is maintained during the crushing operation to ensure uniformity of gradation. The use of recycled PCC aggregate in base courses has been shown to have better properties than virgin bases.

Roofing Materials

The use of waste roofing materials in asphalt concrete is justified both by the cost savings and the desirable material properties it produces. The material has been used successfully in several projects, including high-volume, heavy truck roadways, and has shown favorable performance.

Tire Chip and Whole Tire Applications

Tires and tire scraps have been used as retaining walls, lightweight fill, and insulation layers beneath road surfaces. The use of whole tires for retaining walls is enhanced by the fact that used tires are a cheap, nonbiodegradable, ultraviolet light-resistant material. The value of tire chips, both as insulation and as a lightweight fill, warrants expanded usage not only for economic reasons, but for their structural properties.

Roadway Materials

Roadway materials are comprised of different material layers extending from the asphalt pavement's surface course to the subgrade and those material layers used to construct the shoulders. The response to the survey indicated that, on the average, at least 75 percent of all roadway materials were either reused or recycled. The majority of the highway agencies recycle between 75 and 100 percent of their asphalt surface and asphalt base courses. Crushed stone base, crushed gravel base, and granular subbase are commonly reused or disposed of into embankments or fills. Stabilized base course materials are conventionally used in embankments. Subgrade materials are always reused except in certain situations where the material is wet or contaminated and does not meet the agency's specifications. Shoulders constructed with HMA are mostly reused and recycled. Compacted aggregate shoulders are reused, possibly stabilized, or re-manipulated most of the time.

Culverts

The materials used in the construction of small culverts usually range from wood, concrete pipe, corrugated steel pipe, to concrete box. Larger culverts and underpass structures are often constructed using multiplates. The information from the survey indicated wood culverts and multiplate units are usually disposed of as scrap. Concrete culverts have been used as roadway fill or riprap. Corrugated steel culvert pipe is predominantly disposed of as scrap for recycling into steel products.

Guardrail Systems

Guardrail posts are generally made of steel. However, a few States also use aluminum and wood posts. Most States reuse steel posts, or if damaged, sell it for scrap rather than recycle (refurbish) damaged posts. Similarly, damaged aluminum posts are sold for scrap since it is not practical to straighten them. Wood posts may be landfilled, used as landscaping timbers, sold to landscapers, or disposed of by the contractor.

Signs and Sign Signal Structures

Sign and signal poles or structures, usually aluminum or steel, are either reused or disposed of as scrap. The amount of disposal, recycling, and reuse is dependent upon each State's policy, type of materials used, and regional conditions that affect suitability for recycling or reuse. Transportation and competitive costs of new signs, posts, poles, and sign structures make it impractical to recycle in some areas.

Bridge

Major bridge components include railing, steel superstructure, concrete beams, and concrete deck. Bridge railings are reused or recycled unless they are excessively damaged, corroded, or do not meet current standards. A small portion of steel superstructure members and trusses were reused. Most bridge superstructure steel is removed and sold as scrap by either the contractor or the highway agency. Concrete beams and concrete bridge decks are, for the most part, disposed of with very little recycling or reuse.

APPENDIX A. LETTER OF TRANSMITTAL AND SURVEY FORM NO. 1

November 20, 1992

345 Weil Hall

Tel.: (904) 392-6590
FAX: (904) 392-3394

1~

Dear 2~:

We are currently working on the documentation of information on the Use of Recycled Materials in Highway Construction. This investigation is being conducted for the Federal Highway Administration to address certain aspects of the Intermodal Surface Transportation Efficiency Act (ISTEA).

The information that I am requesting relates to the use of materials, structural units, appurtenances, etc., that are removed from the highway system for disposal, recycling, or reuse. Table 19 provides a general guide (not necessarily complete) as to the materials/ appurtenances that may be removed in the process of rehabilitation, reconstruction, or removal of abandoned structures. Please furnish any documented information and comments relating to how the materials are reused, recycled, or disposed of. The table may be used to furnish the relative percentage of reuse, recycling, or disposal for each type of removed material, structural element, or appurtenance.

In the event that the utilization of disposed materials is unknown, then please furnish the names, addresses, and telephone numbers of two or three contractors that have recently been involved in the removal and disposal of highway materials. Examples of disposal include landfilling, land reclamation, reclaimed for building materials, etc.

Your assistance in providing this information will be greatly appreciated. If possible, send the information to me by mail or FAX prior to January 8, 1993.

The information you provide will be compiled with the responses from other State highway agencies in the final report that should be available before the fall of 1993.

Thank you again for your consideration in this matter.

Sincerely,

Byron E. Ruth
Highway Engineer/Professor

BER/ckl

Table 19. Disposal/utilization of materials removed from highways.

Material/Appurtenance Type	Percent of Material, Structural Unit, or Appurtenance Disposed, Recycled, or Reused		
	Disposed %	Recycled %	Reused %
Asphalt Concrete: Surface Course			
Structural or Base			
Stabilized Base (Specify)			
Crushed Stone Base			
Crushed Gravel Base			
Granular Subbase			
Stabilized Subbase			
Subgrade			
Shoulders (Specify Type)			
Concrete Culverts			
Corrugated Steel Pipe Culverts			
Wood Culverts			
Multiplate Underpass or Culvert			
Guardrails			
Guardrail Posts			
Signs - Advisory and Regulatory			
Sign Posts			
Sign or Signal Poles and Structures			
Bridges: Aluminum or Steel Railing			
Steel Members for Super-Structure, Deck, etc.			
Concrete Beams			
Concrete Deck			

Use the following code numbers as applicable:

Disposal: (1) sold as scrap; (2) disposal in landfill, etc.; (3) contractor's property—recycled, revised, or scrap
Recycled: (4) reused or stored for subsequent use after straightening, painting, or minor repair
(5) crushed, broken, or modified for recycling for use in a different highway application
Reused: (6) used in the same application or function

APPENDIX B. LETTER OF TRANSMITTAL, SURVEY FORM NOS. 1 AND 2, AND ONE-PAGE QUESTIONNAIRES

December 4, 1992

345 Weil Hall

Tel. 904-392-6590
FAX 904-392-3394

1~

Dear 2~:

We are currently working on the documentation of information on the Use of Recycled Materials in Highway Construction. This investigation is being conducted for the Federal Highway Administration to address Section 1038 of the Intermodal Surface Transportation Efficiency Act (ISTEA).

Attached are copies of two (2) one-page questionnaires relating to "Crumb Rubber-Modified Asphalt Paving Mixtures," and to "Recycling of Pavements Containing Crumb-Rubber," Please complete a questionnaire for each test project within your jurisdiction (State, municipality, etc.). These forms may be duplicated if additional copies are needed.

The information you provide is critical in establishing the status, feasibility, and/or future needs of this technology. In the event your agency has not constructed or planned to construct crumb rubber-modified test sections, so note on the form after filling in lines 1 and 2 (similarly for recycling with RAP containing crumb rubber). It is essential that I receive the requested information as soon as possible, but no later than January 15, 1993. Please mail all responses in the attached self-addressed envelope.

In addition to these one-page questionnaires, I have enclosed one copy or packet of each of the following questionnaires (spread sheets) for the purpose of acquiring more detailed information on utilization of waste/byproduct materials in highway construction:

A1A	Crumb Rubber-Modified Asphalt Paving Mixtures
A1B	Crumb Rubber-Modified Spray Applications
A1C	Recycling of Pavements Containing Crumb Rubber
B1A	Recycling of Pavements Using Over 80 Percent RAP
B1B	Plastics in Highway Construction
B1C	Crushed Glass in Highway Construction
B1D	Reuse, Recycling, and Disposal of Other Recycled Materials Used in Highway Construction

The detailed information requested in these packets will be analyzed to establish current practice, types of technologies being used, feasibility of utilization/technology, and future research needs. These packets may be duplicated as necessary to provide sufficient copies for each project. Please return the completed forms to me no later than February 5, 1993.

In the event that test projects have been thoroughly documented in published or in-house reports for any of the subject areas (A1A through B1D), please furnish copies of these reports along with the questionnaire (spread sheets) for each project.

Your assistance in providing this information will be greatly appreciated. Contact me by telephone or FAX if you need clarification of any questions in the packets.

Thank you again for your consideration in this matter.

Sincerely,

Byron E. Ruth
Highway Engineer/Professor

BER/ckl
enclosures

INFORMATION URGENTLY NEEDED AND CRITICAL TO OUR SURVEY OF CRUMB RUBBER MODIFIED (CRM) ASPHALT PAVING MIXTURES

1. State DOT/Agency (Specify): ______________________________

2. State Agency Contact Name: ______________________________

Phone: ____________________ FAX: ____________________

3. Project Location:

Route Number __________, Beginning Milepost __________, Ending Milepost __________

Project between or at what cities: ______________________________

Project No. (Research or Constr. I.D.): ______________________________

4.

	Date Constructed	Age yrs/mos.
Control Section	__/__/__	__/__
CRM Test Sections	__/__/__	__/__

5. Control section for comparison:

Same mixture without addition of crumb rubber (✓): ____

Mixture that is conventionally used by the State (✓): ____

Does control have same aggregate and gradation as test section (Y/N): ____

6. General assessment of performance compared to control:

(1) worse, (2) slightly substandard, (3) no difference, (4) slightly improved, (5) improved

Rutting ____, Cracking ____, Raveling ____, Stripping ____, Overall ____

7. Wet Processing Technology Used (✓): McDonald ____, Continuous (Rouse) ____

8. Dry Processing Technology Used (✓): PlusRide® ____, Generic ____, Chunk Rubber ____

9. Application Used (✓): Dense ____, GAP ____, OGFC ____, SAM ____, SAMI ____

10. Do you anticipate the test sections being overlaid in the near future (✓): yes ____, no ____

11. Would your agency consider including the test sections as part of a long-term national study (✓): yes ____, no ____

12. Can your agency provide construction records and a complete performance history of the test section (✓): yes ____, no ____

INFORMATION THAT IS NEEDED AND CRITICAL TO OUR SURVEY ON RECYCLING OF PAVEMENTS CONTAINING CRUMB RUBBER

1. State DOT/Agency (Specify): ____________________

2. State Agency Contact Name: ____________________
   Phone: ____________ FAX: ____________

3. Project Location:
   Route Number ________, Beginning Milepost ________, Ending Milepost ________
   Project between or at what cities: ____________________
   Project No. (Research or Constr. I.D.): ____________________

4.

	Date Constructed	Age yrs/mos.
Control Section	__/__/__	__/__
Test Sections	__/__/__	__/__

5. Control section for comparison:
   Same aggregate, gradation, and binder content as test sections (✓): ____
   Mixture that is conventionally used by the State (✓): ____

6. General assessment of performance compared to control:
   (1) worse, (2) slightly substandard, (3) no difference, (4) slightly improved, (5) improved
   Rutting ____, Cracking ____, Raveling ____, Stripping ____, Overall ____

7. Type of Plant (✓)
   Batch: ____
   Continuous: ____
   Drum Mixer: ____ (Single Drum) ____ (Dual Drum) ____

8. Type/Method used for recycling of pavements containing crumb rubber
   Hot-mix recycling (✓): ____
   Cold-mix recycling (✓): ____
   Surface recycling/traveling plant (✓): ____
   Other (specify): ____________________
   ____
   ____

9. Application Used (✓): Dense ____, GAP ____, OGFC ____, Other (Specify): ____________
10. Do you anticipate the test sections being overlaid in the near future (✓): yes ____, no ____
11. Would your agency consider including the test sections as part of a long-term national study (✓): yes ____, no ____

12. Can your agency provide construction records and a complete performance history of the test section (✓): yes ____, no ____

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