Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice

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FOREWORD

Recycling asphalt pavement creates a cycle of reusing materials that optimizes the use of natural resources. Reclaimed asphalt pavement (RAP) is a useful alternative to virgin materials because it reduces the need to use virgin aggregate, which is a scarce commodity in some areas of the United States. It also reduces the amount of costly new asphalt binder required in the production of asphalt paving mixtures. This report informs practitioners about the state of the practice for RAP use in the United States as well as best practices for increasing the use of RAP in asphalt pavement mixtures while maintaining high-quality pavement infrastructures. High percentage RAP mixtures are achieved with processing and production practices, resulting in cost and energy savings. Based on an evaluation of pavements containing 30 percent RAP through the Long-Term Pavement Performance (LTPP) program, it has been determined that the performance of pavements containing up to 30 percent RAP is similar to that of pavements constructed from virgin materials with no RAP. This report is of interest to engineers, contractors, and others involved in the specification and design of asphalt mixtures for flexible pavements, as well as those involved in promoting the optimal use of RAP.

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16. Abstract

With increased demand and limited aggregate and binder supply, hot mix asphalt (HMA) producers discovered that reclaimed asphalt pavement (RAP) is a valuable component in HMA. As a result, there has been renewed interest in increasing the amount of RAP used in HMA. While a number of factors drive the use of RAP in asphalt pavements, the two primary factors are economic savings and environmental benefits. RAP is a useful alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of HMA. Using RAP greatly reduces the amount of construction debris going into landfills, and it does not deplete nonrenewable natural resources such as virgin aggregate and asphalt binder. Ultimately, recycling asphalt creates a cycle of reuse that optimizes the use of natural resources and sustains the asphalt pavement industry.

More widespread use of higher amounts of RAP in asphalt mixtures requires support from State transportation departments and the HMA industry. State transportation departments have expressed concern over the lack of guidance on the use of high percentages of RAP (high RAP) mixtures, as well as the lack of information on their performance. As a result, there is a need for national guidance on best practices when using RAP and documented information about long-term performance of high RAP pavements.

The intent of this report is to provide state-of-the-practice information on including higher amounts of RAP in asphalt mixtures. The state of the practice for RAP use across the United States, as well as common challenges for increasing the use of RAP, are identified. Best practices applicable for the use of RAP are presented to identify general parameters that must be considered when developing specifications and to provide information on available resources and best practices for sourcing, processing, stockpiling, testing, designing, evaluating, producing, and placing high RAP mixtures, as well as practices to attain the best performance for high RAP mixtures .

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS LIST

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt content
AMPT	Asphalt mixture performance tester
BSG	Bulk specific gravity
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
DOT	Department of Transportation
DSR	Dynamic shear rheometer
ESAL	Equivalent single axle load
ETG	Expert task group
FHWA	Federal Highway Administration
HMA	Hot mix asphalt
IRI	International roughness index
JMF	Job mix formula
LTPP	Long-Term Pavement Performance
MTO	Ministry of Transportation of Ontario
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
ODOT	Ohio Department of Transportation
PG	Performance grade
QC	Quality control
RAP	Reclaimed asphalt pavement
RTFO	Rolling thin film oven
SCDOT	South Carolina Department of Transportation
VMA	Voids in the mineral aggregate
WMA	Warm mix asphalt

Symbols

A	RAP percent binder content
B	RAP percent in mixture
C	Total percent binder content in mixture
$\|E^*\|$	Mix dynamic modulus
G^*	Shear modulus
G_b	Asphalt specific gravity
G_{sb}^{RAP}	Bulk specific gravity of RAP aggregate
G_{se}^{RAP}	Effective specific gravity of RAP aggregate
G_{mm}^{RAP}	Maximum theoretical specific gravity of the RAP mixture
P_b	Asphalt content of the RAP mixture
P_{ba}	Asphalt absorption
T_{Blend}	Critical temperature of blended asphalt binder
$T_c(High)$	Critical high temperature
$T_c(Int)$	Intermediate critical temperature
$T_c(Low)$	Low critical temperature which is the higher of $T_c(S)$ or $T_c(m)$
$T_c(m)$	Critical low temperature based on m-value
$T_c(S)$	Critical low temperature based on s-value
T_{RAP}	Critical temperature of recovered RAP binder
T_{virgin}	Critical temperature of virgin asphalt binder

CHAPTER 1. INTRODUCTION

Over 90 percent of U.S. highways and roads are constructed with hot mix asphalt (HMA). As the U.S. infrastructure ages, these highways and roads must be maintained and rehabilitated. According to the Federal Highway Administration's (FHWA) recycled materials policy:

> The same materials used to build the original highway system can be re-used to repair, reconstruct, and maintain them. Where appropriate, recycling of aggregates and other highway construction materials makes sound economic, environmental, and engineering sense.[1]

With increased demand and limited aggregate and binder supply, HMA producers have began using reclaimed asphalt pavement (RAP) as a valuable component in HMA. As a result, there has been renewed interest in increasing the amount of RAP used in HMA.

While several factors influence the use of RAP in asphalt pavement, the two primary factors are economic savings and environmental benefits. RAP is a useful alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of HMA. The use of RAP also conserves energy, lowers transportation costs required to obtain quality virgin aggregate, and preserves resources. Additionally, using RAP decreases the amount of construction debris placed into landfills and does not deplete nonrenewable natural resources such as virgin aggregate and asphalt binder. Ultimately, recycling asphalt creates a cycle that optimizes the use of natural resources and sustains the asphalt pavement industry.

In order for it to be successful, recycled asphalt pavement must be cost-effective, perform well, and be environmentally sound. To ensure that these requirements are met, FHWA promotes the following:

- The use of recycled material in the construction of highways to the maximum economical and practical extent possible with equal or improved performance.
- The use of RAP in HMA because RAP can have a large economical, environmental, and engineering impact in pavement recycling.

The use of RAP may grow by increasing the number of highway construction and rehabilitation projects that use RAP, as well as by increasing the amount of RAP used in specific projects. To meet these goals, the following tasks were identified:

- Establish a public and industry working group.
- Create funded and coordinated research and demonstrations projects.
- Research deployment and technology transfer for information dissemination and education.

Through the establishment of a public and industry working group known as the RAP Expert Task Group (ETG), one of the top needs for increased RAP use was identified in updated literature on the state of the practice and guidelines for mix design and construction of recycled asphalt pavements.

BACKGROUND

Existing asphalt pavement materials are commonly removed during resurfacing, rehabilitation, or reconstruction operations. Once removed and processed, the pavement material becomes RAP, which contains valuable asphalt binder and aggregate (see figure 1). In the early 1990s, FHWA and the U.S. Environmental Protection Agency estimated that more than 90 million tons of asphalt pavement were reclaimed (i.e., converted into material suited for use) every year, and over 80 percent of RAP was recycled, making asphalt the most frequently recycled material.(2) RAP is most commonly used as an aggregate and virgin asphalt binder substitute in recycled asphalt paving, but it is also used as a granular base or subbase, stabilized base aggregate, and embankment or fill material. It can also be used in other construction applications. RAP is a valuable, high-quality material that can replace more expensive virgin aggregates and binders.

Figure 1. Photo. Milled RAP.

There are four major asphalt production cost categories: (1) materials, (2) plant production, (3) trucking, and (4) lay down (i.e., construction). Materials are the most expensive production cost category, comprising about 70 percent of the cost to produce HMA (see figure 2). The most expensive and economically variable material in an asphalt mixture is the asphalt binder. It is most commonly used in the intermediate and surface layers of flexible pavement to provide tensile strength to resist distortion, protect the asphalt pavement structure and subgrade from moisture, and provide a smooth, skid-resistant riding surface that withstands wear from traffic.(3) As a result, the most economical use of RAP is in the intermediate and surface layers of flexible pavements where the less expensive binder from RAP can replace a portion of the more expensive virgin binder.

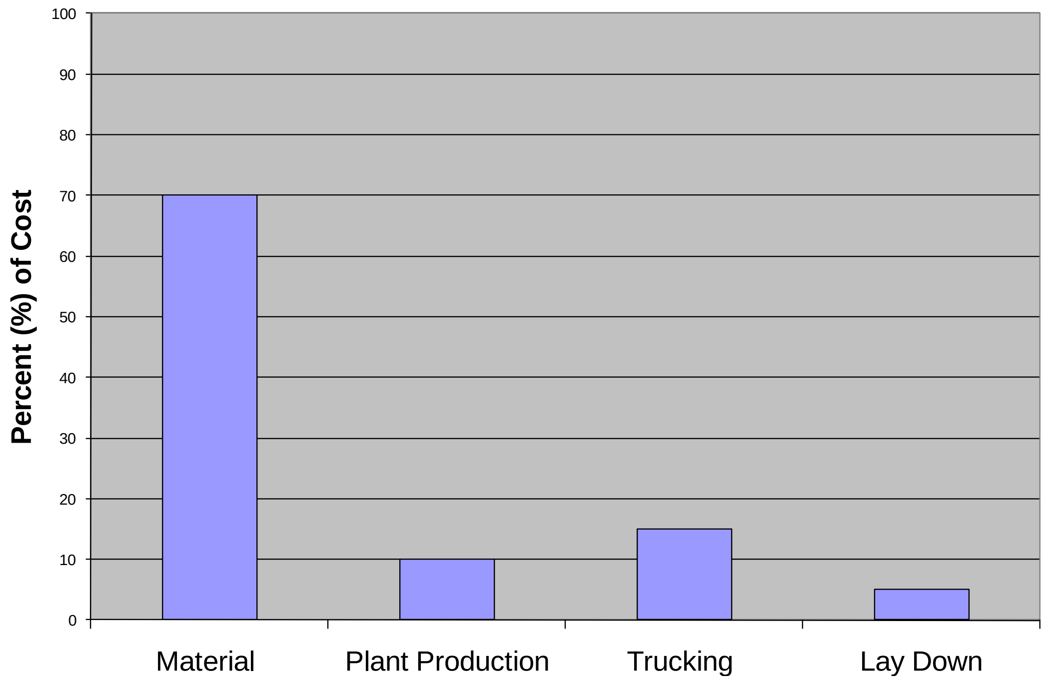

Figure 2. Graph. Estimated asphalt production cost categories.

HISTORICAL PERSPECTIVE

Recycling asphalt pavements became popular in the 1970s due to the high cost of crude oil during the Arab oil embargo. FHWA provided partial funding to State transportation departments through Demonstration Project 39 to construct paving projects using recycled asphalt and to document the effective use of resources in light of increased material costs.(4) As a result, construction practices and technologies quickly evolved to handle RAP. The National Cooperative Highway Research Program (NCHRP) published *Recycling Materials for Highways* in 1978 and *Guidelines for Recycling Pavement Materials* in 1980.(5,6) In the 1990s, FHWA issued further guidance and provided information on the state of the practice regarding pavement recycling by publishing *Pavement Recycling Executive Summary and Report* and *Pavement Recycling Guidelines for State and Local Governments: Participant's Reference Book*.(7,8)

RAP was successfully used by State transportation departments for many years before the implementation of the Superior Performing Asphalt Pavements (Superpave®) mixture design method in the late 1990s. When Superpave® was implemented, the Strategic Highway Research Program did not provide guidance for the use of RAP in HMA. Furthermore, the Superpave® mix design system encouraged the use of coarse-graded mixtures, which, in some cases, limited the amount of RAP that could be used in the mix. In particular, due to the high fines content frequently found in many RAP stockpiles, some of the specified mix design criteria (i.e., voids in the mineral aggregate (VMA), dust to effective binder content, etc.) reduced the use of RAP. Many State transportation departments stopped allowing the use of high amounts of RAP in favor of implementing the Superpave® system with virgin materials to reduce variability. However, since then, there has been an increasing effort to modify the Superpave® design method to more effectively evaluate HMA containing RAP. In the late 1990s, FHWA's Superpave® Mixtures ETG developed interim guidelines for the use of RAP in the Superpave®

mix design method. These guidelines were verified and further developed under NCHRP Project 9-12.[9] The suggested guidelines for specifying agencies are available in *NCHRP Research Results Digest 253: Guidelines for Incorporating RAP in the Superpave System*.[10] Guidance on testing and designing with RAP in the Superpave® method in the lab and field is available in *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*.[11]

Traditionally, many State transportation departments have limited the maximum amount of RAP used in surface layers, certain mixture types, and, in some instances, large or critical projects. Although many HMA producers continued to use RAP, the amount was typically less than 15 percent because there were no binder grade changes or additional tests required for these lower percentages. Additionally, there was no significant economic incentive for using larger percentages of RAP. However, in 2006 and again in 2008, there were sharp increases in asphalt binder costs as well as diminishing supplies of quality aggregate. As a result, utilizing greater amounts of RAP became a priority in the HMA industry once again. With changes in construction materials economics, stricter environmental regulations, and an emphasis on "green" technologies (e.g., warm mix asphalt (WMA)) and sustainable pavements, the highway community is reassessing the economic and environmental benefits of allowing higher percentages of RAP in premium pavements and asphalt surfaces while also maintaining high-quality pavement infrastructures.

More widespread use of higher amounts of RAP in asphalt mixtures requires support from State transportation departments and the HMA industry. State transportation departments have expressed concern over the lack of guidance on the use of high percentages of RAP (high RAP) in mixtures as well as information on their performance. There is a need for national guidance on best practices when using RAP and documented information about long-term performance of high RAP pavements.

PURPOSE AND METHODOLOGY

In 2007, FHWA created an ETG, known as the RAP ETG, for the use of RAP in the construction and rehabilitation of flexible pavements. It is comprised of RAP experts from FHWA, State transportation departments, the American Association of State Highway and Transportation Officials (AASHTO), the National Asphalt Pavement Association (NAPA), the National Center for Asphalt Technology (NCAT), and people from the industry and academia. The purpose of the ETG is to advance the use of RAP in asphalt paving applications by providing State transportation departments and the industry with information emphasizing the production of high-quality high RAP mixtures, the performance of asphalt mixtures containing RAP, technical guidance on high RAP projects, and RAP research activities.

This report is the result of RAP ETG activity to provide state-of-the-practice information for including higher percentages of RAP in asphalt mixtures. For the purpose of this report, *high RAP* is defined as using 25 percent or more RAP in an asphalt mixture by weight of the total mix. The state of the practice for RAP use throughout the United States was determined through a survey conducted by the RAP ETG and sponsored by the AASHTO Subcommittee on Materials (see chapter 2). Several surveys regarding the specification and use of RAP have also been conducted, and the results are also summarized in chapter 2. Common challenges for increasing the use of RAP were identified through these surveys and were used to develop guidance on the best practices.

The best practices discussion presents measures applicable for the use of RAP in asphalt mixtures (see chapter 3). It identifies general parameters to consider when developing specifications. Chapter 3 also provides information on available resources and best practices for sourcing, processing, stockpiling, testing, designing, evaluating, producing, and placing high RAP mixtures, as well as practices to attain the best performance for high RAP mixtures. This information was compiled from current industry reports, State specifications, field projects and demonstrations, and expert knowledge from RAP ETG representatives.

CHAPTER 2. STATE OF THE PRACTICE FOR RAP USE

According to NAPA, the current annual U.S. production of new asphalt pavement material is approximately 500 million tons per year, which includes about 60 million tons of reclaimed material that is reused or recycled directly into pavements.(12) As of 2007, about 40 million tons of RAP is reused or recycled into other pavement-related applications every year for a total use of over 100 million tons of RAP each year. This is an increase from 72 million tons of RAP used each year in the early 1990s. Since most reclaimed asphalt is reused or recycled, asphalt pavement has the highest recycling rate by percentage among recycled materials.

A survey was sent to FHWA division offices to seek information regarding RAP usage by each State transportation department. In total, 18 out of 52 division offices responded, and 17 of the 18 respondents indicated that the use of RAP is optional and depends on the contractor to propose its use based on economic considerations and material availability.

Survey responses confirmed that the use of RAP is primarily driven by the costs of materials and transportation. As stated previously, the most economical use of RAP is in asphalt mixtures where the full benefit of the RAP binder and aggregate is utilized. Most States do not track the amount of RAP used or the cost savings. Only 3 of the 18 respondents indicated that they track the amount of RAP used. A primary challenge in tracking the amount of RAP used is that HMA is not bid based on its components or whether or not it contains RAP; rather, it is bid as a material itself. The New Jersey Department of Transportation tracked the approximate quantities of RAP used. It found a significant increase in the amount of RAP used from 2003–2005, as compared to 2002 (see figure 3). Similarly, other respondents noted increases in the use of RAP (8 out of 18, or about 45 percent), and some noted that contractors requested approval of mixtures with higher percentages of RAP (i.e., more than 25 percent RAP).

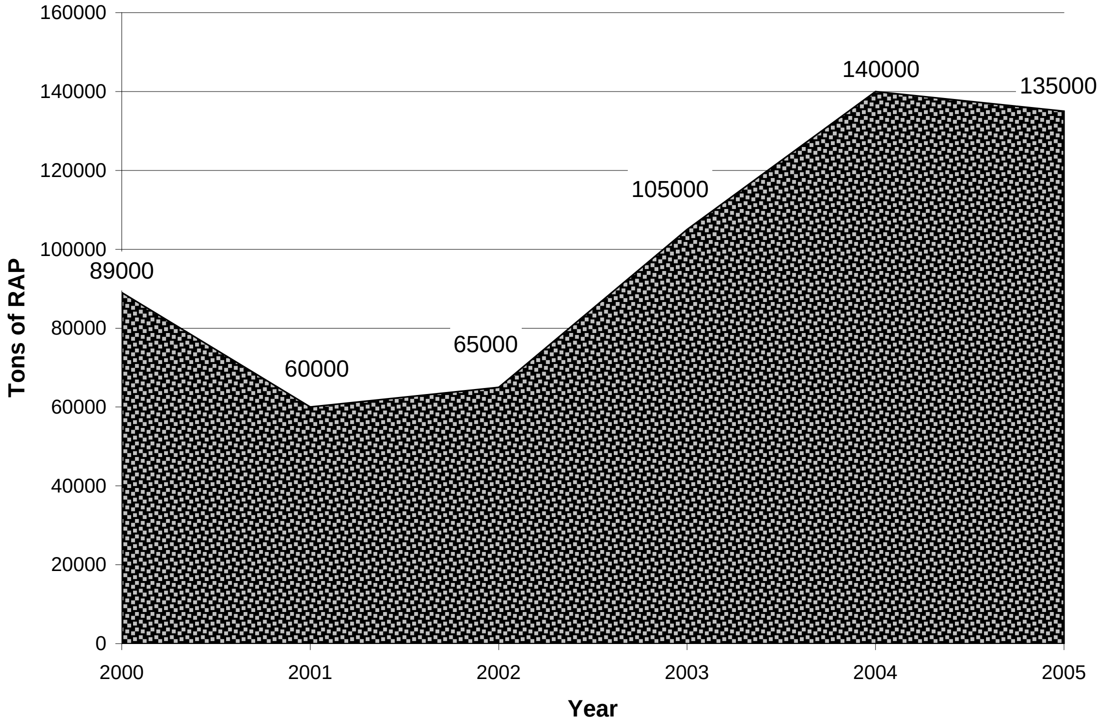

Figure 3. Graph. Approximate tons of RAP used in recycled asphalt in New Jersey per year.

SURVEY OF RAP SPECIFICATIONS AND USE IN THE UNITED STATES

In 2007, a survey was conducted by the North Carolina Department of Transportation (NCDOT) on behalf of RAP ETG and sponsored by the AASHTO Subcommittee on Materials. The survey asked the following questions regarding RAP use:

- How much RAP is permitted in mixtures?
- How much RAP is actually used?
- What are the main roadblocks to greater usage of RAP?

Survey responses were collected from all 50 States as well as Ontario, Canada. The survey showed that the majority of State transportation department specifications allowed the use of RAP in HMA mixtures. The 2007 average national usage rate was estimated to be 12 percent. RAP was typically permitted in subsurface, base, and shoulder mixtures but may have been restricted in surface/wearing courses. Very few States allowed little or no RAP due to concerns regarding performance.

The survey data also indicated the potential for increasing the amount of RAP used across the United States. Figure 4 and figure 5 show the number of State transportation departments that used and permitted a given amount of RAP in the intermediate and surface layers in 2007. There was the potential for more State transportation departments to use up to the amount of RAP that their specifications permitted. For example, in figure 4, only 10 State transportation departments used up to 29 percent RAP in the intermediate layer. However, according to their specifications, there was the potential for over 35 State transportation departments to use up to 29 percent RAP. Similarly, less than 5 State transportation departments used up to 29 percent RAP in the surface layer, while there was the potential for 20 State transportation departments to do so (see figure 5). The data indicated that the maximum amount of RAP that was permitted was not being used on a nationwide basis.

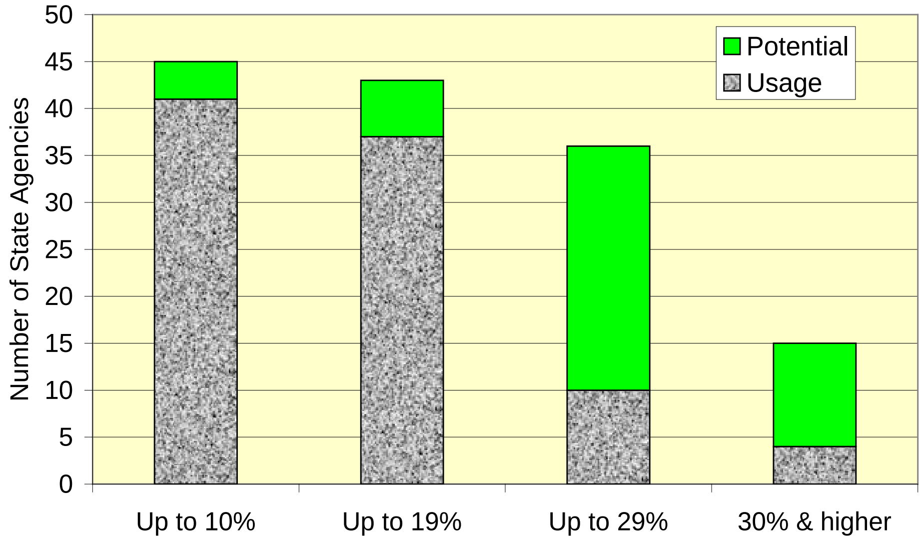

Figure 4. Graph. Usage and potential of various RAP percentages in the intermediate layer.

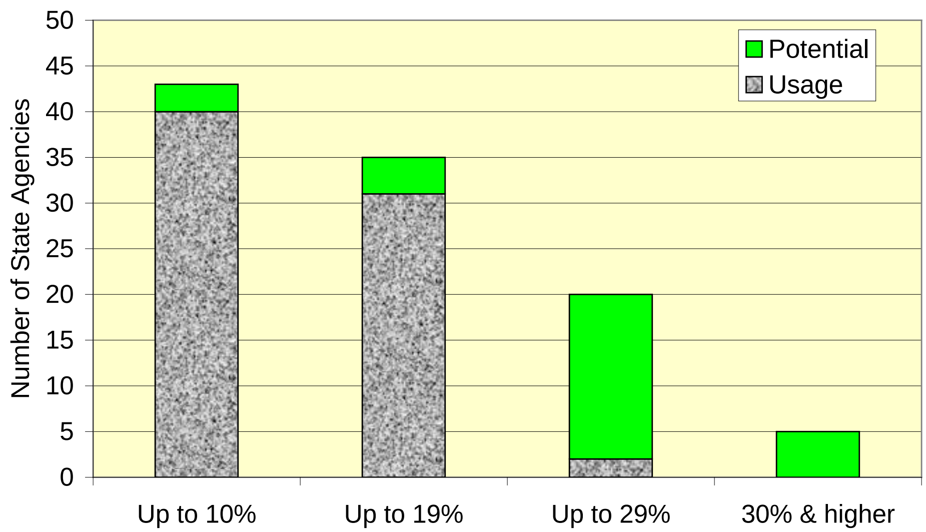

Figure 5. Graph. Usage and potential of various RAP percentages in the surface layer.

A survey of U.S. States conducted by the Materials Engineering and Research Office of the Ministry of Transportation of Ontario, Canada, (MTO) further confirmed the 2007 NCDOT survey results. MTO found that for base and binder courses, 20–50 percent RAP was typically permitted. Permitted levels of RAP were higher in base courses and for light traffic roadways, as compared to medium or heavy traffic roadways. Some States commented that although high amounts of RAP were permitted, contractors typically did not submit mix designs for amounts greater than 25 percent.

Generally, State transportation departments allow between 10 and 20 percent RAP for medium and heavy traffic levels for surface courses. Medium traffic level roads are designed for 3–30 million equivalent single axle loads (ESALs) for a 20-year design. Heavy traffic roads have greater than 30 million ESALs for a 20-year design. For light traffic roads, slightly more RAP is typically allowed in surface courses, and light traffic levels have fewer than 3 million design ESALs for a 20-year design. About 20 percent of the State transportation departments do not allow RAP in surface courses with heavy traffic. Additionally, according to the MTO survey, two State transportation departments did not permit RAP in surface courses and indicated several reasons, such as poor past experiences, lack of expertise/confidence in using RAP in the surface course, and the use of surface mixes with specific aggregate requirements (i.e., frictional characteristics), that may preclude the use of RAP.

Updated Survey Results and Progress

In 2009, another similar survey was conducted by NCDOT on behalf of AASHTO and RAP ETG. The survey asked the following questions:

1. What is the maximum percentage of RAP in HMA allowed by the State?
2. What is the average percentage actually used by contractors?
3. Does the State have special requirements or limitations when higher percentages are used?
4. Has the State experimented with or does it routinely use high RAP mixes?
5. Does the contractor retain ownership of RAP after it is milled?
6. Is the State utilizing WMA technologies in conjunction with increased RAP content?

Figure 6 shows that about half of all States reported increased RAP usage from 2007–2009. Approximately half (23) of the State transportation departments reported experimenting with or routinely using high RAP. While many State transportation departments increased the amount of RAP used in HMA, the use of high RAP mixtures is still not common. As shown in figure 7, many State transportation departments permit more than 25 percent RAP in HMA layers; however, fewer than half of the States actually use more than 20 percent RAP in HMA layers (see figure 8).

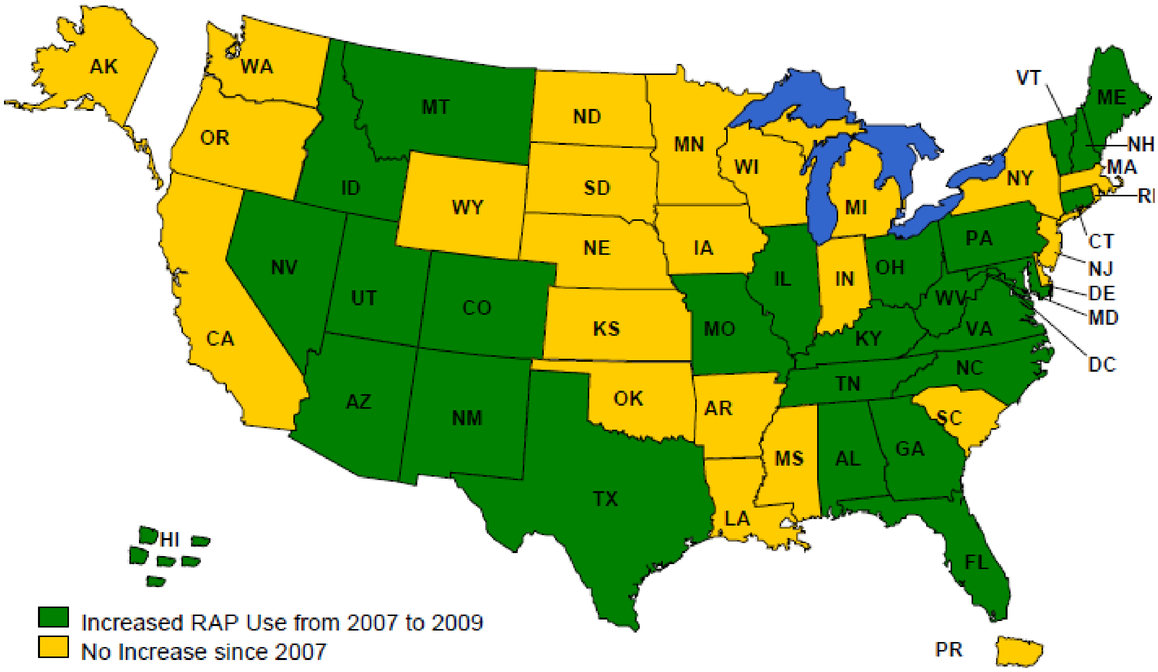

Figure 6. Map. States with increased RAP use since 2007.

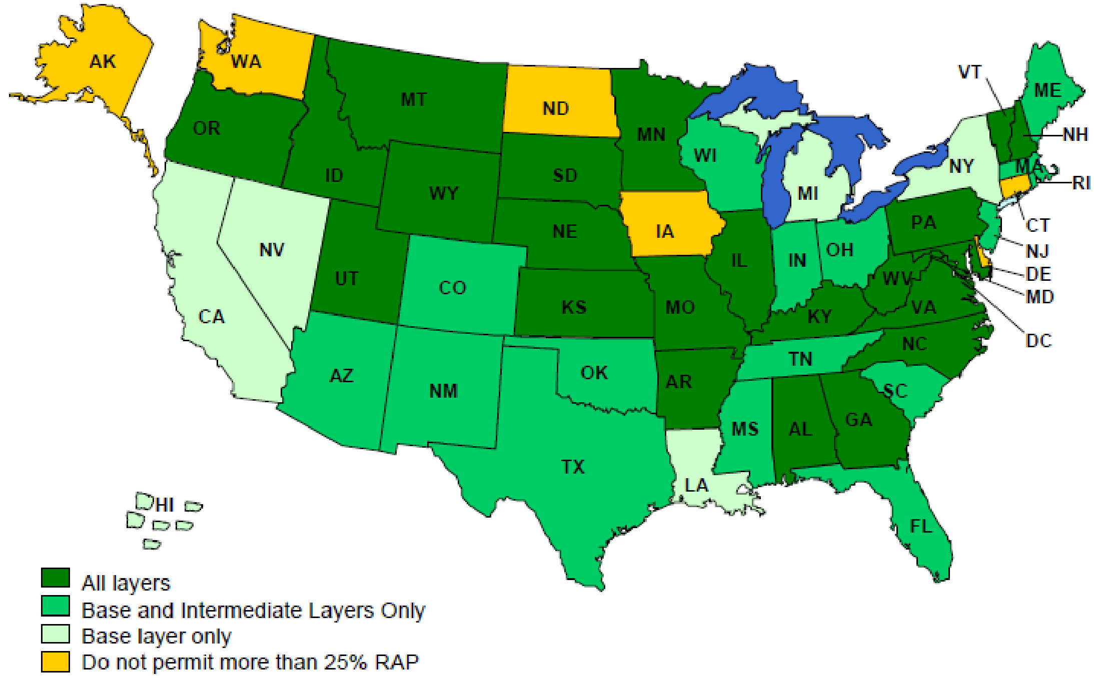

Figure 7. Map. States that permit more than 25 percent RAP in HMA layers.

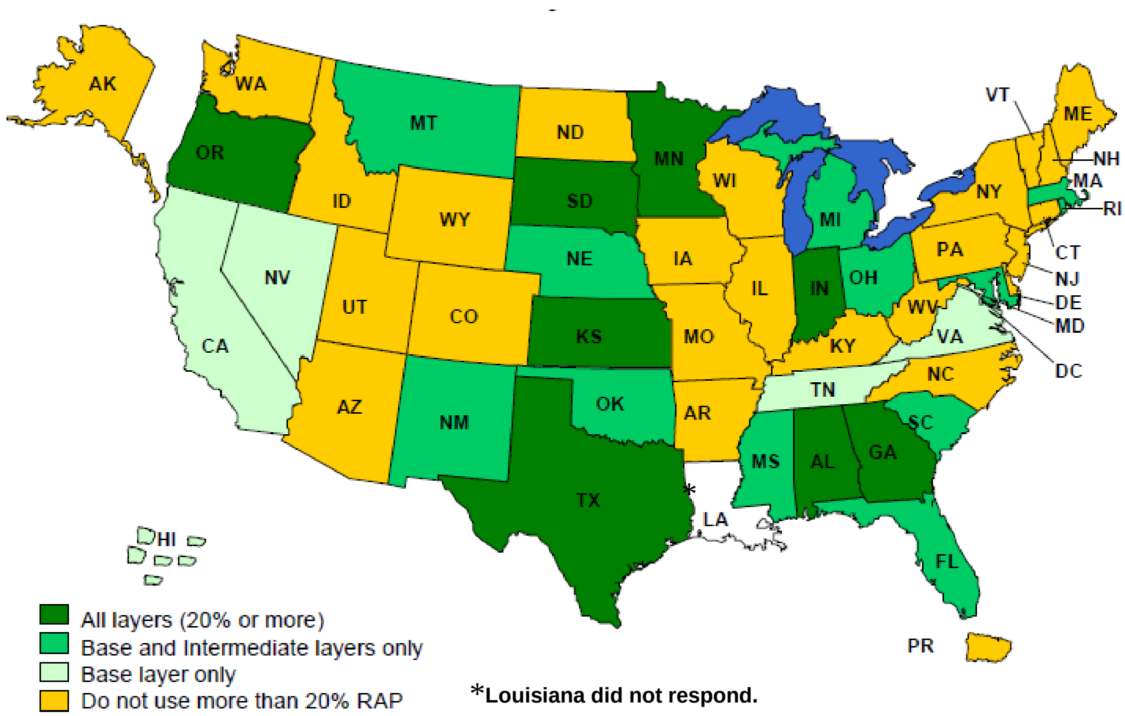

Figure 8. Map. States that use more than 20 percent RAP in HMA layers.

The majority of State transportation departments requires mixtures that incorporate RAP to meet all conventional mix design requirements. However, most State transportation departments place restrictions on the amount of RAP used overall as well as in certain mix types and pavement layers. Conditions may be placed on the asphalt binder grade, aggregate type, and nominal maximum aggregate size for use with RAP. The majority of respondents to a survey conducted by the Ohio Department of Transportation (ODOT) indicated there are no special requirements for high RAP mixtures beyond normal mix design procedures. About half of the States have experimented with high RAP or routinely use high RAP mixes (see figure 9).

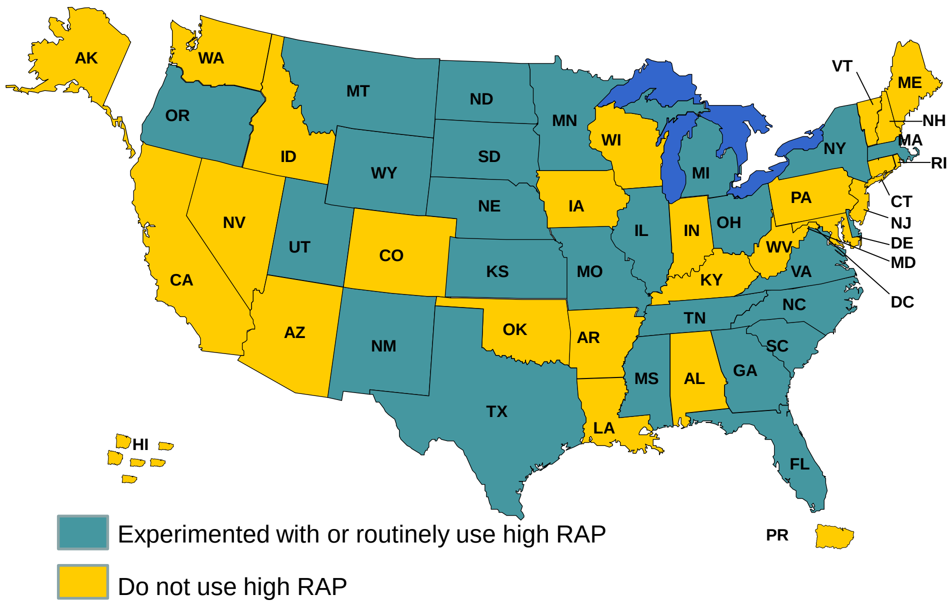

Figure 9. Map. States that have experimented with or routinely use high RAP mixtures.

Many States specify RAP ownership with the contractor retaining RAP the majority of the time (see figure 10). In 20 States, both the State transportation department and the contractor retain ownership of RAP. Only three State transportation departments retain complete ownership of RAP for other applications. RAP ownership depends on the State transportation department's specifications, the individual contract requirements, and utilization by the State transportation department's maintenance departments.

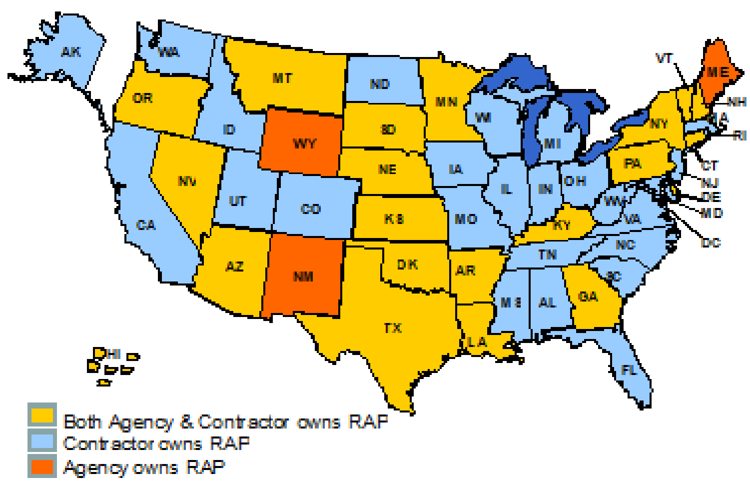

Figure 10. Map. Ownership of RAP by State highway agency.

CHALLENGES FOR INCREASING THE USE OF RAP

Average RAP use is estimated at 12 percent in HMA in the United States. Less than half of State transportation departments use more than 20 percent RAP; however, based on State transportation department specifications, it is possible for States to use up to 30 percent RAP in the intermediate and surface layers of pavements. Currently, it is unknown why over half of the country uses less than 20 percent RAP in HMA.

Despite similarities between producing virgin asphalt mixtures and RAP asphalt mixtures, there are still challenges for maximizing RAP use and routinely using high RAP. According to AASHTO M 323, the current binder selection guidelines for RAP mixtures were formulated based on the assumption that complete blending occurs between the virgin and RAP binders.(13) It is understood that the amount of blending that occurs between the virgin and RAP binder is somewhere between complete blending and no blending at all; however, there is no direct method available to accurately determine the amount of blending that occurs. Currently, researchers are performing ongoing studies to develop methods to determine if proper blending has occurred by using mixture properties such as dynamic modulus to estimate blended binder properties and to compare estimate blended binder properties to measured binder properties.(14,15)

For high RAP mixtures, blending charts can be used to properly determine the virgin binder grade. They can also be used to optimize the amount of RAP used if the virgin binder grade is known. However, blending charts require expensive, time-consuming binder extraction and recovery procedures that use hazardous solvents, which is followed by testing of the recovered binder. Consequently, many State transportation departments are reluctant to permit RAP content that require this testing. Additionally, many contractors are not equipped to perform binder extractions and recoveries or the subsequent binder tests. In general, State transportation departments are concerned with the consistency of RAP materials and whether mixtures with high RAP are inferior and fail earlier than virgin mixtures. In some instances, State transportation departments place limitations on the amount of RAP that can be used based on previous bad experiences with RAP. According to the 2007 NCDOT survey, the four most common factors preventing the use of additional RAP are as follows:

- Specification limitations.
- Lack of processing (i.e., variability of RAP).
- Lack of RAP availability.
- Past experiences.

In the 2009 NCDOT survey, participants were asked to identify major concerns and obstacles that limit or preclude the use of RAP in HMA. The two concerns cited most often regarded the quality of the blended virgin and RAP binder qualities, especially for high RAP mixes and polymer modified binders, and stiffening of the mix from high RAP quantities and resulting cracking performance. Several States were concerned that the use of RAP with polymer-modified binders may reduce the quality of the polymer-modified virgin binder. Furthermore, high RAP may affect binder properties resulting in an “overly stiff” mix that may experience low-temperature cracking. There was also concern that an overly stiff mix may not be as resilient and may crack prematurely for pavements experiencing high deflections.

The most common barriers among State transportation departments are as follows:

- Quality concerns.
- Consistency of RAP.
- Binder grade and blending.
- Mix design procedures.
- Volumetric requirements.
- Durability and cracking performance.
- Use with polymers.

The most common barriers among contractors are as follows:

- State transportation department specifications.
- Control of RAP.
- Dust and moisture content.
- Increased quality control (QC).

ADDITIONAL SURVEY RESULTS

In the past 2 years, several surveys regarding the use of RAP in asphalt mixtures have been compiled. Table 1 presents the survey description, organization, date, and number of responses for each survey summarized in this report.

Table 1. Surveys on RAP usage.

Survey Description	Organization	Date	Number of Responses
FHWA Division Office Pavement Engineers	FHWA	2007	18
FHWA/AASHTO RAP ETG survey	NCDOT	July 2007 and August 2009	51 (including Ontario)
Summary of States extending RAP usage	ODOT	September 2008	29
RAP usage survey	Materials Engineering and Research Office MTO	November 2008	33 (including Ontario)
Nuclear asphalt content (AC) gauge use on HMA mixtures containing RAP	Colorado Department of Transportation (CDOT)	January 2008	29 (including Ontario)
RAP survey	South Carolina Department of Transportation (SCDOT)	April 2009	25 (including Ontario)

RAP Fractionation

Fractionation is the act of processing and separating RAP into at least two sizes, typically a coarse fraction (+$^1/_2$ or +$^3/_8$ inches (+12.5 or +9.5 mm)) and a fine fraction (-$^1/_2$ or -$^3/_8$ inches (-12.5 or -9.5 mm)). According to a survey conducted by ODOT in September 2008 that compiled responses from 29 States, 3 States (South Carolina, Texas, and Alabama) have specifications for fractionating RAP, and 3 States (Ohio, Wisconsin, and Illinois) are currently drafting specifications for fractionating RAP. These six States allow higher amounts of RAP if it has been fractionated. For example, in the Texas specification, unfractionated RAP is limited to 10, 20, and 30 percent by surface, intermediate, and base layers, respectively. However, by special provision, fractionated RAP is allowed at up to 20, 30, and 40 percent in those same layers. In the 2009 survey conducted by NCDOT, 10 State transportation departments reported requiring fractionation. These 10 states are Arizona, Georgia, Illinois, Kansas, North Carolina, Ohio, Texas, Utah, Wisconsin, and Washington, DC. Wisconsin allows an increase of 5 percent binder replacement for surface mixes if fractionation is used. Some States consider crushing and screening RAP over a single screen as fractionation, which is incorrect.

One of the reasons fractionation is required is that it is believed to improve the consistency of RAP. However, data gathered by NCAT in 2008 and 2009 from contractors across the United States showed that fractionated RAP stockpiles were no more consistent than processed unfractionated RAP stockpiles.(16) Therefore, State transportation departments are not advised to invoke a method specification for RAP management. Instead, they should develop an end-result specification for RAP stockpiles that requires routine QC testing of RAP and establishes limits for variability.

Determining AC of RAP

The most common method for determining the AC in a sample of RAP is to use the ignition oven method specified in AASHTO T 308.(17) A CDOT survey compiled in January 2008 includes responses from 29 State transportation departments and shows that almost half of them used the ignition oven to determine the AC of the RAP fraction for mix design purposes. About 30 percent of the respondents used solvent or chemical extraction, while 3 out of the 29 States used both solvent extraction and the ignition oven. The results are provided in figure 11.

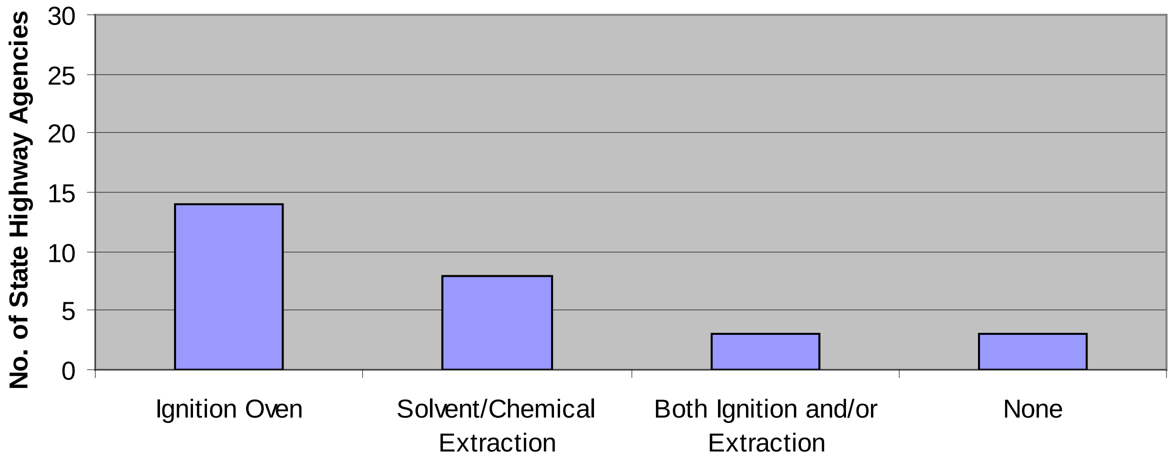

Figure 11. Graph. Quantification of the use of different methods for determining the AC of RAP mixtures.

Mix Design Methods for RAP Mixes

The Superpave® performance grade (PG) binder and volumetric mix design system has become the most widely accepted design system for asphalt mixtures in the United States. According to a survey conducted in 2008 by the Materials Engineering and Research Office MTO, Superpave® is the most common method of mixture design used in the United States for RAP mixes, including those that contain over 20 percent RAP. In total, 25 out of 33 State transportation department respondents use the Superpave® method exclusively or some variation of the Superpave® mix design procedure (i.e., agency-modified Superpave® mix design). Six of the twenty-five also utilize the Marshall or Hveem mix design procedure for certain mix types. According to the MTO survey, four State transportation departments do not use the Superpave® mix design procedure—California and Nevada use the Hveem method for mix design, and Rhode Island and Tennessee use the Marshall method exclusively.

The current Superpave® specification for selecting the virgin asphalt binder grade based on a given RAP percentage is provided in table 2 of AASHTO M 323.[13] Most State transportation departments use this specification. However, 12 out of 33 respondents have raised the lower percent RAP limit for selecting a softer virgin binder grade from 15 to 20 percent or to 25 percent in a few cases. States that have raised the lower limit from 15 percent are Alaska, Colorado, Florida, Illinois, Indiana, Kentucky, Maryland, Michigan, Minnesota, North Carolina, Nebraska, New Jersey, South Dakota, and Washington.

Plant Type Restrictions

The majority of State transportation departments do not place restrictions on the use of RAP in certain plant types. However, in some cases, there are more restrictions when RAP is used in batch plants. According to the ODOT survey of 29 States, 5 State transportation departments place restrictions on the amount of RAP used by plant type. For example, South Carolina does not allow more than 15 percent RAP to be used in a batch plant with a hot elevator. Georgia and New Hampshire limit batch plants to 25 percent RAP but allow up to 30 and 40 percent RAP in drum plants. Massachusetts allows up to 40 percent RAP in a drum plant but limits the amount of RAP used in a batch plant to 20 percent.

RAP and WMA

The majority of State transportation departments responding to a survey conducted by SCDOT and compiled in April 2009 reported no use of WMA; however, as of 2009, WMA projects (i.e., State, private, or local projects) have been constructed in over 40 States. In total, 8 out of 24 State transportation departments are not currently specifying WMA. Additionally, CDOT and the Virginia Department of Transportation do not allow RAP in WMA mixes. According to the NCDOT survey compiled in August 2009, 12 State transportation departments utilized WMA technologies in conjunction with increased RAP contents. These 12 State transportation departments are Alabama, Delaware, Florida, Illinois, Indiana, Mississippi, Nebraska, New Jersey, Ohio, South Carolina, Tennessee, and Texas. As of 2009, at least 14 State transportation departments have adopted specifications to accommodate WMA. Five States (Alabama, Florida, Illinois, Kentucky, and Texas) do not have any differences in allowances for using RAP in WMA mixes compared to using RAP in HMA mixes. Two States (Ohio and South Carolina) have modified their specifications to allow more RAP in WMA. For example, Ohio's recently modified specification allows the use of more RAP before a softer grade of binder is required when using the water injection WMA process. South Carolina allows producers to use up to 10 percent more fractionated RAP in WMA before changing the binder grade. A WMA best practices guide and Web site is available from NAPA, which includes information on using WMA and RAP.[18,19]

Liquid Asphalt

According to the 2009 SCDOT survey, the majority of State transportation departments that responded (18 out of 23) do not pay for asphalt binder separately from the asphalt mixture. Arkansas pays for liquid binder as a separate pay item; however, residual binder in RAP is paid for at the same price as the contract unit bid price for virgin binder. In Colorado, two out of six regions pay for binder separate. However, these regions are rural where RAP capabilities are limited. In Georgia, an index for asphalt binder is paid based on the job mix formula (JMF), and the asphalt binder in the RAP is accounted for in the mix design process. In North Carolina, the asphalt cement is indexed based on the total percent asphalt cement in JMF. The binder from RAP is included in the total binder index; however, in May 2009, North Carolina planned to start indexing based on virgin asphalt cement only. In Utah, there is a separate pay item for liquid binder for open-graded surface courses only. All other HMA products are paid by the mix ton, and RAP is accounted for in the bidding process.

CHAPTER 3. BEST PRACTICES FOR INCREASING RAP USE

This chapter presents some of the current best practices for increasing the amount and frequency of RAP use regarding the management, mix design, production, and placement of RAP asphalt mixtures. The best practices were compiled from existing literature, experience from high RAP projects and trial sections, State specifications, and the advice of experts in the industry. The best practices address some of the specific concerns related to the production of high RAP mixtures. They can be utilized by State transportation departments in preparing specifications and by contractors who will be designing and producing high RAP mixtures. Several different options are available to address potential concerns, and the most appropriate option will depend on various factors such as material properties, plant type, and production rate.

In general, there is little difference in designing asphalt mixtures with RAP compared to virgin asphalt mixtures until high RAP is used. However, the following issues should be considered when increasing RAP use:

- Additional processing and QC.
- Characterizing RAP.
- Changing the virgin binder grade.
- Preparing materials for mix design.
- Blending/comingling the virgin and RAP binders.
- Performance.

Performing QCs throughout the entire processing and production process is critical. Processing and stockpiling best practices are crucial to maintaining the quality and consistency of the RAP stockpile. The RAP material must be properly characterized for mix design purposes. Best practices used in the production of HMA will also address concerns when using high RAP. In fact, it may not be possible to achieve high-quality high RAP mixes without the use of processing and production best practices.

In most cases, it is the contractor’s responsibility to select the amount of RAP included in the mixture, the type of RAP used in the mixture, and the level processing necessary to meet the specifications. State transportation departments may specify the virgin binder grade based on the amount and type of RAP being used. The RAP QC testing requirements and frequency should also be specified or agreed upon by both parties prior to production.

SOURCES OF RAP

RAP will be collected from several sources over time. RAP is usually generated from milling, full-depth pavement removal, and waste HMA materials generated at the plant. An important consideration in RAP management is when to keep RAP from a new source separate and when to combine RAP from different sources.

Milling is an important part of pavement rehabilitation used to remove any distressed upper layer(s) of existing pavement to a given depth. The process involves machines that grind, pick up, and load RAP into a truck for transportation. The mill speed at the job site should be controlled and kept uniform to promote consistency in the resulting RAP. There is an advantage to keeping millings from large jobs in separate stockpiles. Generally, these millings are very consistent and can be used in new mixes without further screening or crushing, saving processing costs. Figure 12 shows a stockpile of unprocessed millings.

Figure 12. Photo. Stockpile of unprocessed RAP millings.

In some cases, it may be beneficial to mill the surface layer or the surface and intermediate layers separately from the asphalt base layer, as the upper layers often contain aggregates with special characteristics such as polishing resistance and/or freeze/thaw durability. The nominal aggregate size in upper pavement layers is also smaller and more suitable for direct use in new surface mixtures without crushing.

Full-depth pavement removal involves the use of heavy equipment to break the pavement structure into slabs. The slabs are then transported to a processing location where they are crushed and processed to a manageable size for recycling. Asphalt mix material that is produced and not used (i.e., “plant waste”) is typically added to the unprocessed RAP stockpile or is kept in a separate stockpile for future processing.

It is critical that materials collected from any source be kept free from contamination. Incoming materials should be visually inspected to avoid dumping of soil, construction debris, or any deleterious material in the stockpile.

RAP CATEGORIES

Some State transportation departments only allow RAP obtained from specific projects or pavement types to be used in their mixes. Such RAP is referred to as classified or traceable source RAP. The restriction to allow only traceable source RAP in new State transportation department asphalt mixes hinders the use of RAP to its full advantage; therefore, State transportation departments should have an engineering basis for this requirement. Rather than prohibiting RAP from non-State transportation department sources, the quality of materials in RAP can and should be verified with routine testing as part of the RAP QC and mix design.

Most State transportation departments allow RAP from multiple sources to be used in recycled asphalt mixes, provided that it is processed into a uniform material, and the aggregates contained in the RAP meet typical source properties. Recommended tests and test frequency information are provided in the RAP Testing and Frequency section below. This type of RAP is referred to as unclassified RAP or multiple sources RAP.

RAP PROCESSING

RAP processing involves one or more steps to create consistent materials that can be used in high percentages and meet standards for high-quality asphalt mixtures. Screening is used to separate sizes. As noted previously, milled material from traceable sources can have very consistent properties and may not require further processing. In some cases, it may be desirable to screen or fractionate traceable source RAP to remove oversize particles or to separate RAP into coarse and fine stockpiles to maximize the amount of RAP that can be used in particular mixes. RAP separation based on size increases control and reduces variability. It also allows for adjustments for variability to be made within the RAP blend rather than just the virgin aggregate blend. An example of specialized RAP fractionation equipment is shown in figure 13 and figure 14. Typically, RAP is sized into two (coarse or fine) or three (oversize, coarse, or fine) piles, as shown in figure 15 and figure 16. With specialized fractionation equipment, it is possible to screen to the -No. 4 sieve size (-0.25 inches (-4.75 mm)) or even to the -No. 8 sieve size (-0.125 inches (-2.36 mm)). In this scenario, it is possible to have three sizes that are all -1 inch (-25 mm).

For stockpiles of RAP from multiple sources, particularly stockpiles containing large chunks of RAP or pavement slabs, it may be necessary to crush the material to produce RAP with a suitable top size for use in new asphalt mixes. Crushing can also improve the consistency of the resulting RAP if the multiple sources RAP is fed into the crushing unit from different locations of the unprocessed stockpile. There are several types of crusher systems available, such as horizontal impact crushers, hammer mill impact crushers, and jaw/roll combination crushers. More information on crushing options is provided in *Recycling Hot Mix Asphalt Pavements*.[20] Choosing the top size (i.e., maximum RAP particle size) for the crushing operation is an important decision. Many contractors select the top size so that the crushed RAP can be used in any type of mix. However, crushing to smaller top sizes will increase the dust content (percentage passing the No. 200 (0.0029-inch (0.075-mm)) sieve) in RAP, which can limit how much RAP can be used in new mix designs while meeting criteria such as VMA and dust-to-binder ratio.

Figure 13. Photo. Specialized fractionation equipment.

Figure 14. Photo. Close-up view of specialized fractionation equipment.

Figure 15. Photo. Fine fractionated RAP stockpile.

Figure 16. Photo. Coarse fractionated RAP stockpile.

Processing RAP may include both crushing and screening to produce a uniform gradation, binder content, and other properties. Agencies should not require specific types of processing operations for RAP. Rather, they should limit the maximum amount of variability in the RAP material that is fed into the plant. This will allow the contractor to utilize the most efficient and cost-effective process for producing a consistent material. The end result type of specification is easier to enforce because it avoids subjective interpretations of the suitability of the various options for RAP processing.

It is recommended that RAP processing occurs prior to feeding to the plant. Earlier RAP systems that included crushing and screening large pieces (2–4 inches (50–100 mm)) of RAP as part of the cold feed system are not recommended. RAP uniformity as well as the ability to characterize RAP during the mix design phase may be inadequate with in-line crushing systems.

STOCKPILING RAP

Normal practice should be used to prevent or limit segregation. Arc-shaped, uniformly layered stockpiles are preferred for storing milled or unprocessed RAP material (i.e., material of various sizes). As with virgin aggregate, conical stockpiles or small, low-sloped piles are preferred for storing processed RAP material. RAP stockpiles should be placed on a base with adequate drainage and constructed in layers to minimize segregation and ensure a workable face. To maximize the percentage of RAP in a mix, consideration may be given to constructing separate stockpiles for each source of RAP based on the category of RAP, the size of processed material, the quality of the aggregate, and the type and quantity of asphalt binder. However, space limitations must be considered.

All RAP stockpiles should be kept clean and free of foreign materials. RAP holds water and does not drain as well as an aggregate stockpile, so efforts should be made to handle and store RAP in such a way as to minimize moisture content. The crust formed on the surface of the stockpile helps to shed water, but other measures can be taken, such as storing RAP on paved sloped surfaces and covering RAP stockpiles with a roof from an open-sided building. In particular, fine RAP holds high moisture content, and it may be desirable to use a building to cover the stockpile. High moisture content in the stockpile may not be detrimental to HMA quality, but it is an issue for the contractor since the moisture must be removed during production and could cause increased fuel usage and reduced production rate.

RAP does not tend to recompact in large piles, but it can form an 8–10-inch (203–254-mm)-thick crust over the surface that is easily broken by a front-end loader. If possible, heavy machinery should not be driven on the RAP stockpile to avoid compaction. The RAP stockpiles should be routinely skimmed to break lumps. An example of a properly maintained RAP stockpile is shown in figure 17.

Figure 17. Photo. RAP stockpile being maintained.

RAP PERCENTAGES AND BINDER GRADE SELECTION

Typically, contractors determine the percentage of RAP to be used and select the binder grade to meet the appropriate specifications. The percentage of RAP used in the mix may be selected by determining the contribution of RAP in the total mix by weight or by determining the contribution of the RAP binder in the total binder in the mix by weight while maintaining volumetric properties requirements. Due to the stiffening effect of the aged binder in RAP, the specified binder grade may need to be adjusted. The current national guideline for determining the binder grade adjustment in HMA mixes incorporating RAP has three tiers.[13] Each tier has a range of percentages that represents the contribution of RAP toward the total mix by weight (see table 2). Some State transportation departments have modified the range of percentages (e.g., increased the RAP percentage that can be used before a softer binder grade must be chosen) based on conditions in that area and/or additional testing.

Table 2. Binder selection guidelines for RAP mixtures according to AASHTO M 323.[13]

Recommended Virgin Asphalt Binder Grade	RAP Percent
No change in binder selection	< 15
Select virgin binder one grade softer than normal (e.g., select PG 58-28 if PG 64-22 would normally be used)	15–25
Follow recommendations from blending charts	> 25

For percentages of RAP greater than 25 percent, procedures for developing a blending chart are provided in the appendix of AASHTO M 323.(13) Based on the desired final blended binder grade, the desired percentage of RAP, and the recovered RAP binder properties, the required properties of the appropriate virgin binder grade can be determined according to blending chart procedures. If a specific virgin asphalt binder grade must be used and the desired blended binder grade and recovered RAP properties are known, the allowable percentage of RAP is determined according to blending chart procedures.

The blending chart process is time-consuming, involves hazardous solvents, and creates disposal issues. It assumes complete blending between the virgin and RAP aggregate. More practical alternate procedures have been suggested for determining the virgin binder PG and ensuring proper blending. Most aged asphalts in a certain region have reached a level of maximum stiffness. With this information, an asphalt grade of RAP can be assumed for 100 percent RAP. For example, in the Southeast and Mid-Atlantic regions, researchers have determined that asphalt in RAP usually has a high temperature grade between 190.4 and 201.2 °F (88 and 94 °C). Thus, using 100 percent RAP, it is assumed that the high temperature grade is 197.6 °F (92 °C). Using the high temperature grade of the virgin asphalt binder as the high temperature grade at zero percent RAP, the RAP content versus high temperature binder grade can be plotted to estimate the effect of RAP on stiffness, specifically the high temperature binder grade (see figure 18). In cold regions, the low temperature grade should also be checked to avoid low temperature cracking.(21)

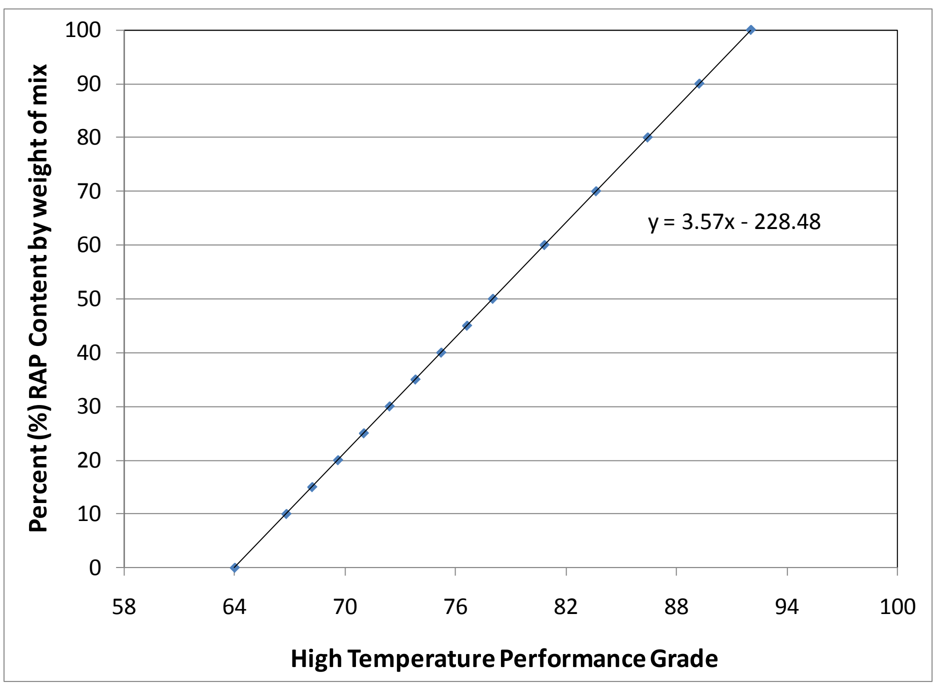

Figure 18. Graph. Percent RAP content versus high temperature PG.

Through years of experience balancing the material quality requirements for the specific application with the market availability and cost, many State transportation departments have standardized the PG binder grade for HMA on a regional, project type, and/or program basis in lieu of determining the project binder grade quality for the specific project location and application. It is recommended that State transportation departments reassess the binder quality requirement for the specific application utilizing the long-term pavement performance (LTPP)Bind protocols to assess specific property requirements based on local environmental conditions and design reliability of the application to gain more insight into the required binder quality.[22]

Bonaquist developed a methodology to evaluate blending in RAP mixtures. The methodology involves measuring the mix dynamic modulus, $|E^*|$, with the asphalt mixture performance tester (AMPT) which is referred to as measured $|E^*|$.[14,23] The binder is extracted and recovered from the mix, during which, the virgin and RAP binders become totally blended. Shear modulus (G^*) of the recovered binder is measured using the dynamic shear rheometer (DSR). The recovered binder's G^* value is used as input into the Hirsch model to estimate the mix $|E^*|$, which is referred to as estimated $|E^*|$.[24] The estimated $|E^*|$ is compared to the measured $|E^*|$, and if the data match, it is assumed there is good blending of the virgin and RAP binders. In addition to using the Hirsch model to estimate mix $|E^*|$, the Witczak model could also be used to estimate mix $|E^*|$.[25,15]

The procedure that uses $|E^*|$ of the mix to estimate blending or the procedure for determining the RAP PG binder grade is not necessarily recommended for individual mix designs. Instead, these approaches are an option for studies on which State transportation department requirements for selection of virgin binder grade may be established.

RAP Percentage Based on Binder

Historically, State transportation department specifications limiting RAP in HMA have been based on RAP percentage by weight of aggregate or by weight of the total mix. However, the primary issue with higher RAP content in asphalt mixes is the amount of binder replacement available since the use of RAP can reduce the need for virgin binder and impact the binder properties. Thus, RAP may also be specified according to percentage binder replacement. The percentage of RAP used in the mix can be selected by determining the contribution of the RAP binder toward the total binder in the mix by weight (i.e., a specified maximum percentage of the binder may come from RAP). In fact, several State transportation departments have specified a minimum percentage of virgin binder content (e.g., 70 percent of the binder content must be virgin binder). The amount of total binder replaced by binder in RAP is computed as follows:

$$Binder\ Replacement,\ \% = \frac{(A \times B)}{C} \times 100\% \tag{1}$$

Where:

A = RAP percent binder content.
B = RAP percent in mixture.
C = Total percent binder content in mixture.

RAP TESTING AND FREQUENCY

Good practice for sampling aggregate applies to the sampling of RAP. Samples may be obtained during production or from a stockpile. Contractors should prepare a plan for sampling and testing

RAP. The sampling plan should meet the minimum testing frequency requirements specified by the owner (i.e., State transportation department, highway agency, etc.) and should detail the procedure used to obtain representative samples throughout the stockpile for testing.

Obtaining Representative Samples

Sampling involves taking a number of random samples from the RAP stockpile, testing a portion of each individual sample, and then combining the remainder of random samples into one representative sample for developing the mix design (see figure 19). A minimum of 5, but preferably 10 or more, individual samples should be used to determine the consistency of a RAP stockpile. Proper sampling procedures normally used for virgin aggregates may also be used to sample RAP aggregate and are provided in AASHTO T 2.[26]

Testing individual samples is required to determine the variability of the AC and aggregate gradation. The size of the sample should be such that the amount of aggregate material recovered will meet the size requirements of the gradation procedure.[27] After testing individual samples is complete, combining the remainder of the individual random samples of each stockpile is necessary to provide a representative sample for conducting mixture design. Projects that use more than one stockpile for RAP require testing of each stockpile.

Figure 19. Photo. Sampling RAP from the stockpile.

Testing and Test Frequency

The representative sample of RAP should be oven dried to a constant mass prior to batching the mix specimens. Moisture content of RAP may be initially determined to facilitate batching for mix design. The sample used to determine the moisture content should not be used for other mix testing since it was overheated.

Testing requirements and testing frequency vary according to the category of RAP and the amount of RAP used in the mixture. RAP from multiple sources may be subject to more rigorous testing than RAP from a single source. The frequency at which to perform tests should be in accordance with agency specifications and should also be adequate to assess variability in RAP. For all RAP stockpiles, the asphalt binder content and aggregate gradation must be determined. The asphalt binder content may be determined according to AASHTO T 308 or AASHTO T 164.[17,28] For the ignition method, an aggregate correction factor will have to be assumed. In many locations, the aggregate correction factor is fairly consistent from mix to mix for the aggregate materials currently being used in mix designs. If the aggregate sources currently being used are the same or reasonably similar to the sources used 10–20 years ago in that location, then it is reasonable to use the current typical correction factor for RAP because it is likely from the same location. For RAP stockpiles containing aggregates of uncertain origins or for RAP containing dolomitic limestone, which often has erratic aggregate correction factors, a solvent extraction procedure may be used to determine the AC of the RAP samples.

If there is a need to test the binder properties of RAP, it is recommended to extract and recover the binder and perform PG testing on the extracted RAP binder. A combined procedure for extraction and recovery is given in AASHTO T 319.[29] This method was recommended in NCHRP 9-12 because it was found to change the recovered binder properties less than other methods.[9]

Gradation of the recovered aggregate is determined using AASHTO T 30.[30] The ignition oven may change the physical characteristics of some aggregates. In general, RAP aggregates must meet the same quality requirements specified for virgin aggregates. This includes evaluating coarse aggregate angularity (ASTM D 5821), fine aggregate angularity (AASHTO T 304), and flat and elongated requirements (ASTM D 4791).[31–33] According to AASHTO M 323, the sand equivalent requirements (AASHTO T 176) are waived for RAP aggregate.[13,34] The Superpave® aggregate consensus property requirements are also provided in AASHTO M 323.[13] Source properties, such as abrasion resistance and frictional properties, may be performed according to agency specifications.

Determining Bulk Specific Gravity of the RAP Aggregate

An important property that needs to be determined is the bulk specific gravity (BSG) of the RAP aggregate, G_{sb}^{RAP}. The BSG of the combined RAP and virgin aggregate is used to calculate the VMA for the mix design. The BSG of the RAP aggregate cannot be directly measured. Studies have shown that the BSG of the RAP aggregate recovered from the ignition oven is typically significantly lower than that of the original aggregate. Furthermore, if solvent extraction is used to remove the RAP aggregate, the aggregate will contain a small amount of unextractable asphalt binder. However, the main issue is wetability and whether water absorption is affected by the solvent residue, which will influence BSG results.

If the source of RAP is known and original construction records are available, the BSG value of the virgin aggregate from the construction records may be used as the BSG value of the RAP aggregate. However, if original construction records are not available, the recommended procedure for estimating BSG of the RAP aggregate is a simple three-step process as follows:

1. Determine the maximum theoretical specific gravity of the RAP mixture, G_{mm}^{RAP}, according to AASHTO T 209.[35]

2. Calculate the effective specific gravity of the RAP aggregate G_{se}^{RAP} using G_{mm}^{RAP}, the AC of the RAP mixture (P_b) and an assumed asphalt specific gravity (G_b) as follows:

$$G_{se}^{RAP} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \tag{2}$$

McDaniel and Anderson recommend a value of 1.020 for G_b.[11] The effective specific gravity of G_{se}^{RAP} could be used as the value for BSG of the RAP aggregate, but this will overestimate the combined aggregate G_{sb}. Furthermore, using higher amounts of RAP may magnify the error in using G_{se}^{RAP} as G_{sb}^{RAP}.

3. Assume a typical value for asphalt absorption, P_{ba}, and use this value to estimate the BSG of the RAP aggregate, G_{sb}^{RAP}, from the calculated G_{se}^{RAP} based on experience with mix designs for the specific location (see equation 3).

$$G_{sb}^{RAP} = G_{se}^{RAP} \Big/ \left[\frac{P_{ba} - G_{se}^{RAP}}{100 G_b} + 1\right] \tag{3}$$

If absorption data are available from past records on similar aggregates, then that value should be used as an estimate for P_{ba}. If historical data are not available, a value for P_{ba} may be estimated as a percentage of the typical water absorption value. For example, P_{ba} may be estimated to be 60–65 percent of the typical water absorption value of the aggregate. This estimate will take into account the fact that the water absorption of aggregate varies based on region or area.

MIX DESIGN CONSIDERATIONS

The standard practice and specifications for designing asphalt mixtures according to the Superpave® mix design system are AASHTO M 323 and AASHTO R 35.[13,36] AASHTO M 323 specifies the quality requirements for binder, aggregate, and HMA for Superpave® volumetric mix design. AASHTO R 35 is a standard for mix design evaluation based on volumetric properties, air voids, VMA, and voids filled with asphalt of the HMA.

The mix design process for mixes incorporating RAP is similar to the mix design for all virgin materials. Once RAP has been characterized, it can be combined with virgin aggregate for calculation of the mix gradation for mix design purposes. RAP is treated like a stockpile of aggregate during this analysis. The composite properties for gradation, specific gravity, and consensus characteristics are used in determining acceptability of the blended aggregates. It should be noted that the gradation of the RAP particles is not the original gradation of the aggregate used in RAP because the binder film on RAP adds to the dimension of the aggregate. However, the original gradation of the recovered RAP aggregate is used for design purposes. Typical design software (i.e., spreadsheet programs) accounts for the differences in the batching material gradation and the "true" gradation of the RAP material as well as for the binder contained in the RAP material. Sand equivalent is tested on the composite aggregate blend according to JMF without the RAP proportion.(34)

RAP material generally contains relatively high percentages of material passing the #200 (0.0029-inch (0.075-mm)) sieve as a result of the milling and/or crushing operations. This can limit the amount of RAP that can be used in a mix design and meet the dust to asphalt ratio, air voids, and VMA. The gradation of the virgin aggregate must compensate for this. Using more of the coarse portion of fractionated RAP may help, as would washing the aggregate or removing dust at the plant during production.

The percentage of asphalt binder in RAP should also be considered when determining the trial asphalt binder content. The asphalt binder content of the total mixture for mix batching includes virgin and reclaimed asphalt binder. The mixture trial AC is calculated or estimated by experience during the trial blend analysis. Thus, the amount of binder in RAP is considered when determining how much virgin asphalt binder is required. It may be necessary to adjust the virgin asphalt binder grade when RAP is used in the mix to achieve the appropriate grade.

High RAP Mix Design

For asphalt mixtures containing high RAP, a method is needed to select the appropriate grade for the virgin binder. A softer virgin binder may be required to balance the stiffer-aged RAP binder. The techniques listed below may be used as part of a State or local transportation department study for the selection of PG asphalt binder. The process involves the use of a blending chart or blending equation to determine the amount of RAP to use if the virgin binder grade is known or to select the grade of virgin binder if the percentage of RAP binder is known. Procedures for using a blending chart are provided in the appendix of AASHTO M 323.(13)

RAP is subjected to a solvent extraction and recovery process to recover the RAP binder for testing.(29) After, the physical properties and critical temperatures of the recovered RAP binder are determined. The critical high temperature ($T_c(High)$) based on the original DSR and rolling thin film oven (RTFO) DSR is determined. The high temperature PG of the recovered RAP binder is the lowest of the original DSR and RTFO DSR critical temperatures. The intermediate critical temperature ($T_c(Int)$) of the recovered RAP binder is determined by performing intermediate temperature DSR testing on the RTFO-aged recovered RAP binder as if the RAP binder were pressure aging vessel-aged. The critical low temperature ($T_c(S)$ or $T_c(m)$) is determined based on bending beam rheometer testing on the RTFO-aged recovered RAP binder, or *m*-value. The low critical temperature ($T_c(Low)$) is the higher of the two low critical temperatures, $T_c(S)$ or $T_c(m)$. The low temperature PG of the recovered RAP binder is based on this low critical temperature value.

Once the physical properties and critical temperatures of the recovered RAP binder are known, there are two options for blending as follows:

- Blending at a known RAP percentage.
- Blending with a known virgin binder grade.

Blending at a Known RAP Percentage

In the case where the desired final blended binder grade, the desired percentage of RAP, and the recovered RAP binder properties are known, the required properties of a virgin binder grade can then be determined at each temperature (high, intermediate, and low) separately as follows:

$$T_{virgin} = \frac{T_{blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \tag{4}$$

Where:

T_{virgin} = Critical temperature of virgin asphalt binder (high, intermediate, or low).
T_{Blend} = Critical temperature of blended asphalt binder (final desired) (high, intermediate, or low).
$\%RAP$ = Percentage of RAP expressed as a decimal.
T_{RAP} = Critical temperature of recovered RAP binder (high, intermediate, or low).

Blending with a Known Virgin Binder Grade

In the case where the final blended binder grade, the virgin asphalt binder grade, and the recovered RAP properties are known, the allowable RAP percentage can be determined as follows:

$$\%RAP = \frac{T_{blend} - T_{virgin}}{T_{RAP} - T_{virgin}} \tag{5}$$

This should be determined at high, intermediate, and low temperatures. The RAP content or range of contents meeting all three temperature requirements should be selected.

NAPA, in partnership with AASHTO and FHWA, has published a guide for designing HMA mixtures with high RAP percentages.[37] The guide includes information on evaluating RAP material, mix design, plant verification, and QC.

Performance Testing

In addition to checking the volumetric properties, it may be desirable to evaluate mixture performance of the designed asphalt mixture containing RAP, especially a high RAP content, to assure that the mixture is able to resist low-temperature and fatigue cracking or rutting if a softer virgin binder was used in the mix design. A variety of performance tests are available.[38]

The possible distress mechanisms that should be evaluated include permanent deformation (i.e., rutting), moisture sensitivity, fatigue, and thermal cracking. Table 3 provides recommended tests for each distress mechanism. More information on performance tests for high RAP mixtures may also be found in *Designing HMA Mixtures with High RAP Content: A Practical Guide*.[37] An NCHRP project 9-46 is underway and will make specific performance test recommendations for high RAP mixtures.[39]

To ensure the long-term performance of RAP mixtures, a paved test strip, similar to conventional virgin mixtures, is recommended to evaluate the in-place properties of the RAP mixture. Also, proper monitoring of the pavement, while in service, and pavement preservation techniques over the service life of the recycled pavement are encouraged.

Table 3. Performance tests for asphalt mixtures.

Distress Mechanism	Test Description	Standard
Permanent deformation	Asphalt pavement analyzer	AASHTO TP63[40] (discontinued)
	Hamburg wheel tracking device	AASHTO T 324[41]
	Repeated load triaxial creep (flow number using AMPT)	AASHTO TP79[42]
Moisture sensitivity	Tensile strength ratio	AASHTO T 283[43]
	Hamburg wheel tracking device (wet)	AASHTO T 324[41]
Fatigue	Four-point bending beam fixture	AASHTO T 321[44]
	Dynamic modulus—continuum fatigue damage (push/pull)	NCHRP 9-29 updated continuum fatigue damage software for AMPT[45]
Thermal cracking	Thermal stress restrained specimen test	No standard available
	Indirect tensile test	No standard available

PLANT CONSIDERATIONS

Similar to the requirements for virgin aggregates, the RAP cold aggregate feed equipment should be capable of accurately proportioning RAP into the mix. Superheated virgin aggregate is used as a heat transfer medium for the ambient temperature RAP. Thus, it is important that RAP and the virgin aggregate have low moisture content. The moisture content of the virgin and RAP aggregates should be determined daily during production or as necessary, and the moisture test results should be recorded. For continuous mix plants, the moisture content is input in the plant's controls to adjust the weight (tons/hour) measured with the belt scales.

When using RAP, a scalping screen or other device should be installed before the weighing system to ensure that large RAP particles are not fed into the drum (see figure 20). It is recommended that screens be installed at the RAP feed to prevent the introduction of particles that are too large. As an alternative, a small crusher may be installed to break the larger RAP particles into smaller sizes (see figure 21).[20]

RAP should be introduced into the drum downstream from the burner and away from the flame and hot gases. Since processing RAP at a HMA facility involves heat transfer techniques, a burner adjustment may be required when using RAP. *Recycling Hot Mix Asphalt Pavements* contains detailed information on processing RAP in an HMA facility and specialized facilities for high percentage recycling.[20]

Figure 20. Photo. Scalping screen for RAP feed.

Figure 21. Photo. Smaller scalping screen for large RAP particles.

PLACEMENT OF RAP MIXES

Construction issues for RAP mixes are not different from issues encountered when paving with conventional HMA produced with virgin materials. However, failure to properly address processing as well as inadequate QC of RAP and an improper mixture design will significantly increase the likelihood of problems in placement and compaction of the new pavement.

No special equipment or techniques are required when placing and compacting mixtures containing RAP (see figure 22 and figure 23). High RAP mixtures may require more attention than conventional mixtures due to increased stiffness as a result of RAP. Achieving density with RAP mixes is typically not a concern, but contractors should be aware that recycled mixtures with high RAP are sometimes stiffer and/or may be produced at slightly higher production temperatures to facilitate blending of RAP with the virgin materials. Like conventional mixes, compaction should be monitored using a nondestructive device calibrated to cores to ensure that adequate density is achieved.

Figure 22. Photo. Placement of a high RAP mixture.

Figure 23. Photo. Compaction of a high RAP mixture.

PERFORMANCE OF RAP ASPHALT MIXTURES

The long-term performance of recycled asphalt pavements, particularly when compared to conventional HMA performance, has not been well documented. State transportation departments that routinely used RAP in HMA production were convinced of its benefits and that recycled asphalt pavement performance was comparable to conventional HMA performance.(7) As a result, LTPP information has not been routinely collected. RAP is primarily used in base and intermediate pavement layers precluding the use of surface condition evaluations and visual observation techniques to assess performance.

In the 1990s, two reports were published evaluating the field performance of recycled asphalt pavements with varying percentages of RAP. Kandhal et al. evaluated virgin and recycled asphalt pavements containing 10–25 percent RAP.(46) After 1–2.5 years of service, there were no signs of rutting, raveling, or fatigue cracking in any of the study sections. This indicated that the virgin and RAP sections performed equally well. In a subsequent analysis, Kandhal et al. expanded the study to more pavement sections including virgin and recycled asphalt pavements with 10–40 percent RAP.(47) Based on visual observations, there was no significant difference in the performance of the virgin and recycled pavement sections. It should be noted, however, that 1–3 years is not sufficient to evaluate the long-term service performance of the pavement sections.(47)

In Louisiana, Paul evaluated the field performance of conventional and recycled asphalt pavements that were 6–9 years old.[48] He analyzed the pavements for condition, serviceability, and structural analysis. The RAP sections contained 20–50 percent RAP. Paul found no significant difference in terms of the pavement conditions and serviceability ratings.[48]

Most recently, NCAT completed a study comparing virgin and recycled asphalt pavements using data from the LTPP program.[49] Data from 18 projects across North America were analyzed to compare paired sections of virgin asphalt mix and recycled asphalt mix containing 30 percent RAP. The projects ranged from 6 to 17 years. The distress parameters that were considered were rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling.

An analysis of variance test indicated that performance of recycled and virgin sections were not statistically different except for fatigue, longitudinal cracking, and transverse cracking, where the virgin sections performed slightly better overall than the RAP sections. Additional statistical analyses using paired *t*-tests showed that the RAP mixes performed better than or equal to virgin mixes for the majority of the locations for each distress parameter. Table 4 summarizes the statistical analyses results for each distress parameter and shows that RAP performed equal (i.e., insignificant difference between RAP and virgin mix, column 4) or better than (column 3) virgin mixes as a majority percentage (column 5). NCAT concluded that, in most cases, using 30 percent RAP in an asphalt pavement can provide the same overall performance as virgin asphalt pavement.[49]

In a separate analysis by FHWA's LTPP program to determine the impact of design features on performance, the majority of the 18 sites did not show significant differences in performance between sections overlaid with virgin and recycled mixes.[50] Hong et al. also investigated the LTPP-specific pavement studies category 5 test sections in Texas with 35 percent RAP.[51] The performance monitoring period in Texas covered 16 years from 1991 to 2007, and the performance indicators included transverse cracking, rut depth, and ride quality (i.e., international roughness index (IRI)). The high RAP sections were compared to virgin sections. Overall, both types of sections had satisfactory performance over the performance monitoring period. Compared with the virgin (no RAP) pavement sections, the sections with high RAP had higher cracking amounts, less rut depth, and similar ride quality (i.e., roughness) change over time. Based on the analysis of field data in this study, Hong et al. concluded that pavement constructed with 35 percent RAP, if designed properly, can perform well and as satisfactorily as a virgin pavement during a normal pavement life span.[51]

In a similar study, the California Department of Transportation (Caltrans) performed a comparative analysis of 47 RAP sections and 7 other different treatments (located within a reasonable distance on the same route) in 3 different environmental zones.[52] Caltrans allowed up to 15 percent RAP to be substituted for virgin aggregate, which is the assumed RAP content for the sections analyzed in this study. Comparisons were made for the following indices: in situ structural capacity, distress condition, roughness condition, and construction consistency. The long-term performance of RAP was found and expected to be comparable to the other treatments based on deterioration models.[52]

Table 4. Summary of statistical analyses from NCAT LTPP study.

Distress Parameter	Virgin Performed Significantly Better than RAP (Percent)	RAP Performed Significantly Better than Virgin (Percent)	Insignificant Difference Between RAP and Virgin (Percent)	RAP Performed Equal or Better than Virgin (Percent)
IRI	42	39	19	58
Rutting	33	29	38	67
Fatigue cracking	29	10	61	71
Longitudinal cracking	15	10	75	85
Transverse cracking	32	15	53	68
Block cracking	3	1	96	97
Raveling	7	15	78	93

A study conducted by the Florida Department of Transportation (FDOT) took a random sampling of mix designs with more than 30 percent RAP content (RAP content ranged from 30 to 50 percent).(53) The pavements were constructed between 1991 and 1999, and the age when the pavements became deficient was noted. Florida's most common mode of distress is cracking, which was the only distress parameter considered in the analyses. Figure 24 shows a comparison of pavement life in age for projects containing at least 5,000 tons of HMA. The average life of virgin mixtures is 11 years. For 30, 35, 40, 45, and 50 percent RAP content mixes, the average age ranges from 10 to 13 years. The primary conclusion of the study is that there does not appear to be a significant difference in pavement life and performance between zero and 30 percent RAP.(53)

RAP has successfully been used for more than 30 years. Based on documented past experience, recycled asphalt mixtures designed under established mixture design procedures and produced under appropriate QC/quality assurance measures perform comparably to conventional asphalt mixtures.

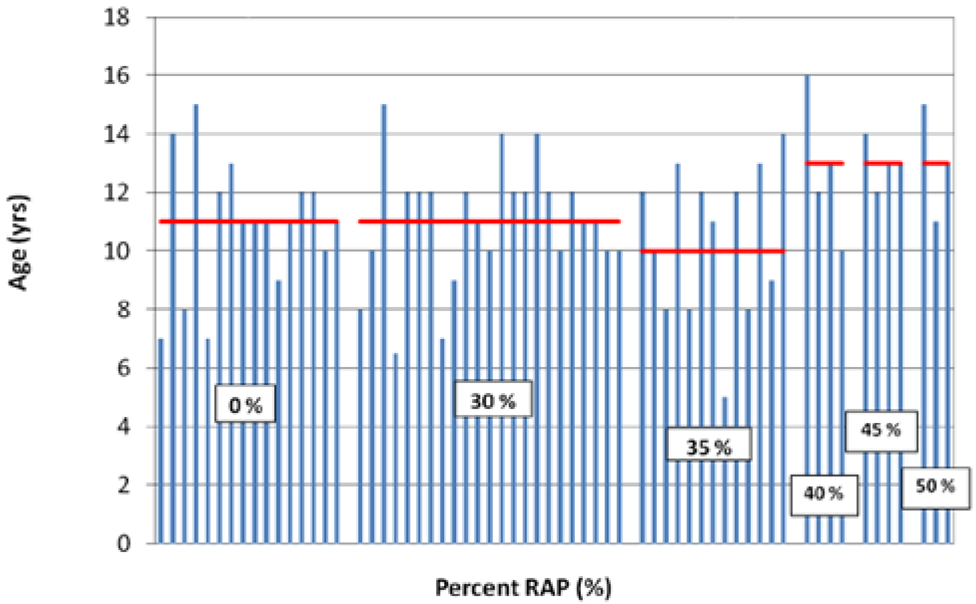

Figure 24. Graph. Pavement age in years versus percent RAP for FDOT projects with greater than 5,000 tons of asphalt mix [53]

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

Based on the information in this report, the following conclusions can be made regarding the state of the practice for RAP:

- RAP is a valuable, high-quality material that can replace more expensive virgin aggregates and binders. The most economical use of RAP is in asphalt mixtures.

- The use of RAP is primarily driven by the costs of virgin materials and transportation. Usage is optional and depends on the contractor to propose its use based on economic considerations, availability of materials, plant site, and production capabilities.

- State transportation departments and contractors are reassessing the economic and environmental benefits of allowing higher percentages of RAP in premium pavements and asphalt surfaces while also maintaining a high-quality, well-performing pavement infrastructure. However, many States are not currently tracking the amount of RAP used or the cost savings associated with the use of RAP.

- More widespread use of higher amounts of RAP in asphalt mixtures requires support from State transportation departments and contractors. State transportation departments have expressed concern over the lack of guidance and information on the performance of high RAP mixtures. Furthermore, some State transportation departments have previously had poor experience with RAP in asphalt mixtures, necessitating contractors to consistently demonstrate the ability to produce high-quality RAP mixes. There is a need for national guidance on best practices when using RAP and documented information about long-term performance of high RAP pavements.

- It is estimated that the average use of RAP across the United States is 12 percent. However, according to State transportation department specifications, there is the potential to use up to 30 percent RAP in the intermediate and surface layers of pavements. As a result, the overall amount of RAP used in asphalt mixtures can be increased.

- RAP mixtures must meet the same mix design specifications required for virgin mixtures. The most common method of mix design for RAP mixtures, including high RAP, is the Superpave® mix design process. For QC purposes, most State transportation departments do not have additional means of determining acceptability of high RAP mixtures.

- The most common challenges to increasing the use of RAP are State transportation department specification limits, lack of processing (i.e., variability of RAP), lack of RAP availability, and past experiences. Furthermore, in regards to performance, the two most common concerns are the quality of the blended virgin and RAP binders, especially for high RAP mixes, as well as stiffening of the mix from high RAP quantities and resulting cracking performance.

- The performance and life of pavement containing up to 30 percent RAP is similar to virgin pavements with no RAP. A survey of LTPP sections containing at least 30 percent RAP showed similar performance to virgin sections. The LTPP pavement sections were located throughout the United States and Canada. An analysis of Florida pavements show similar pavement life for pavements containing no RAP and pavements containing 30 percent RAP.

RECOMMENDATIONS

The following summary of current recommendations is provided to increase the use of RAP and ensure asphalt mixture quality. However, it should be noted that ongoing and future research may lead to refinements of these best practices.

- Proper techniques should be used for obtaining, stockpiling, and processing RAP to maintain its quality. For high RAP mixtures, fractionation of the RAP material should be considered.

- Sampling and testing of the RAP material should be performed. Random samples should be taken to identify the variability of the RAP material properties. Test results, including composition and variability, should be provided to the State transportation department or owner.(7)

- The RAP material should be properly characterized for mix design purposes. The laboratory mixture design should be established using RAP as a component. This is especially important for State transportation departments considering permitting up to 20 percent RAP in mixtures without changing to a softer grade asphalt binder.

- With RAP contents greater than 25 percent, careful consideration should be given to the selection of the grade of asphalt binder added to the recycled asphalt mixture according to State transportation department specifications.

- Production sampling and testing programs should be implemented to verify mixture design assumptions including the asphalt binder blend properties, especially for high RAP mixtures.(7)

- Evaluating mixture performance of the designed asphalt mixture containing RAP, especially high RAP, is recommended. There are a variety of performance tests available for evaluating the probable permanent deformation, fatigue, and thermal cracking performance of compacted asphalt mixtures.

- Plant production best practices used in the production and placement strategies during the construction of HMA will address concerns when using high RAP. The plant production best practices should regularly monitor and adjust for moisture content and scalping screens. High-quality high RAP mixtures are achieved with processing and production best practices, which result in cost and energy savings and reduced emissions.

- Further documentation of the production, construction, and long-term performance of high RAP mixtures is needed.

- Consideration should be given to including documenting RAP use in a pavement management system with details concerning RAP quantities used, sources, and placement details.

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HRDI-10/04-11(WEB)E