FHWA Division Office Survey on State Highway Agency Usage of Reclaimed Asphalt Shingles: Quantities, Trends, Requirements, and Direction - Results from May 2017

Photo of a trommel, a rotary screen, sizing reclaimed asphalt shingles.

Source: FHWA

U.S. Department of Transportation
Federal Highway Administration

Notice

Quality Assurance Statement

1. Report No. FHWA-HIF-18-009	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle FHWA Division Office Survey on State Highway Agency Usage of Reclaimed Asphalt Shingles: Quantities, Trends, Requirements, and Direction - Results from May 2017	5. Report Date February 2018 6. Performing Organization Code
7. Author(s) Tim Aschenbrener	8. Performing Organization Report No.
9. Performing Organization Name and Address Federal Highway Administration Office of Asset Management, Pavements, and Construction 1200 New Jersey Ave. SE Washington, DC 20590	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Organization Name and Address Federal Highway Administration Office of Asset Management, Pavements, and Construction 1200 New Jersey Ave. SE Washington, DC 20590	13. Type of Report and Period Covered Final Report 2018 14. Sponsoring Agency Code FHWA-HIAP-20

15. Supplementary Notes

16. Abstract

In recent years, the economics and supply of petroleum and high quality natural aggregates have increased the need for cost-effective alternatives to virgin paving materials. The use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in the asphalt mixture is increasing because they provide initial cost and material resource benefits. However, they create new challenges for state highway agencies (SHAs) to specify and control the quality of asphalt mixtures for long-term pavement performance.

The FHWA initiated a survey of the Division Offices to gather more information. Although the use of RAP and RAS in asphalt mixtures are often related, the primary focus of the FHWA survey documented by this report was on RAS. The objective of this survey was to collect specific information on the current state-of-the-practice of RAS to:

- Identify quantities, trends, requirements, and performance of RAS usage.
- Obtain opinions on the usage of RAS in asphalt mixtures from the Division Office and state highway agency (SHA) perspective.
- Identify knowledge, engineering, and guidance gaps associated with RAS usage.

The survey questions and summary of findings are provided in four broad RAS categories:

- Usage
- Specifications
- Performance
- Future

17. Key Words RAS, Reclaimed asphalt shingles, asphalt shingles, survey, usage, requirements		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 37	22. Price NA

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Transportation Officials
ARMA	Asphalt Roofing Manufacturer's Association
FHWA	Federal Highway Administration
I-FIT	Illinois Flexibility Index Test
MWAS	Manufactured Waste Asphalt Shingles
NCHRP	National Cooperative Highway Research Program
NHS	National Highway System
OGFC	Open-Graded Friction Course
PCAS	Postconsumer Asphalt Shingles
PG	Performance Grade
RAP	Reclaimed Asphalt Pavement
RAPBR	Reclaimed Asphalt Pavement Binder Ratio
RAS	Reclaimed Asphalt Shingles
RASBR	Reclaimed Asphalt Shingle Binder Ratio
RBR	Reclaimed Binder Ratio
SHA	State Highway Agency
SMA	Stone-Matrix Asphalt
VMA	Voids in the Mineral Aggregate

FHWA Division Office Survey on State Highway Agency Usage of
Reclaimed Asphalt Shingles:
Quantities, Trends, Requirements, and Direction -
Results from May 2017

CHAPTER 1: INTRODUCTION

In recent years, the economics and supply of petroleum and high quality natural aggregates have increased the need for cost-effective alternatives to virgin paving materials. The usage of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in the asphalt mixtures is increasing because they provide initial cost and material resource benefits. These reclaimed materials reduce the amount of virgin aggregates and virgin asphalt binders required to produce asphalt mixtures, resulting in initial cost savings to the producer and the specifying agency. Adding reclaimed materials (assuming appropriate design and construction) into the asphalt mixture conserves natural resources and landfill space, and reduces energy consumption. While RAP and RAS provide opportunities for reduced costs and material resource-conscious applications, they create new challenges for State highway agencies (SHAs) to specify and control the quantity and quality of these materials to ensure responsible use and long-term pavement performance.

FHWA Recycling Policy

Potential material resource, economic, and engineering benefits are driving government agencies and industry to explore the use of more resource responsible materials. To encourage reclaimed materials, the Federal Highway Administration (FHWA) published its *Recycled Materials Policy* (Wright, F.G., Jr., 2002). The policy acknowledges that recycling may not be appropriate in all cases. The policy is at: https://www.fhwa.dot.gov/legsregs/directives/policy/recmatmemo.htm
The policy states:

- Recycling and reuse can offer engineering, economic, and environmental benefits.
- Recycled materials should get first consideration in materials selection.
- Determination of the use of recycled materials should include an initial review of engineering and environmental suitability.
- An assessment of economic benefits should follow in the selection process.
- Restrictions that prohibit the use of recycled materials without technical basis should be removed from specifications.

FHWA has a longstanding position that any material used in highway or bridge construction, be it virgin or recycled, shall not adversely affect the performance, safety or the environment of the highway system. This remains a cornerstone in our policy statement.

RAS Availability, Usage, Benefits, and Risks

Although the usage of RAP and RAS in asphalt mixtures are related and often used together, the primary focus of the FHWA survey of the Division Offices documented by this report was on RAS, which has been used as a component in asphalt mixtures for more than 30 years. Some of the pioneers established the first shingle recycling plants, investigated asphalt mixture designs incorporating RAS, and then published the first technical literature in the late 1980s (Epps and Paulsen, 1986). However, the usage of RAS in the production of asphalt mixtures remains a relatively new application for many agencies. Improvements in RAS processing, along with other economic factors, led to an increased interest in RAS by the pavement community. Best practices for management of RAP and RAS have been documented (West, 2015).

According to the Asphalt Roofing Manufacturers Association (ARMA, 2015), about 13.2 million tons of waste shingles are generated annually in the United States — about 12 million tons of postconsumer asphalt shingles (PCAS) and 1.2 million tons of manufactured shingle waste (MWAS). This is an increase from the commonly cited figure of 11 million tons (NAHB, 1998), reflecting changes in the housing market since 1998.

The usage of RAS offers benefits and risks. A benefit is the angular fine aggregate and fibers. Although the amount of RAS in an asphalt mixture design is generally small, typically 3 to 5 percent, the non-asphalt components (aggregates and fibers) can have a significant effect on the mixture. Voids in the mineral aggregate (VMA) will generally increase due to the hard and angular properties of the RAS granules as well as the presence of fibers. Dust content of the RAS likely causes a reduction in VMA that is generally less than the increase from granules and fibers, resulting in a net VMA increase. According to the American Association of State Highway and Transportation Officials (AASHTO), other properties influenced by the shingles include fine aggregate angularity and dust-to-binder ratio as stated in AASHTO PP 78-14.

On the other hand, there are also engineering risks related to the aged, oxidized, very stiff, and brittle asphalt binder in RAS. The asphalt component of RAS is more aged, more oxidized, much stiffer, and more brittle than typical base asphalt binders (Willis and Turner, 2016). The increased binder stiffness from shingles is likely to decrease the resistance of the asphalt mixture to cracking (Stroup-Gardiner, 2016). Addressing these risks is an engineering challenge to ensure responsible use, long-term pavement performance and safety. SHAs have new challenges to specify and control the quality of asphalt mixtures in their design and field acceptance. There are many other concerns such as the compatibility of RAS and virgin binders, chemical differences in RAS binders compared with virgin binders, and others.

FHWA Survey

This document explores the current state-of-practice regarding usage of RAS in asphalt mixtures and the challenges facing government agencies and the industry. The information comes primarily from the FHWA Division Office survey on SHA usage of RAS as documented in this report.

The primary source of information in this report is from the FHWA survey. Although the RAP and RAS in asphalt mixtures are related and often used together, the primary focus of the FHWA survey of the Division Offices documented by this paper was on RAS. The FHWA survey was accomplished through a survey distributed to its Division Offices. The survey was conducted in April and May 2017. Usage of RAS by each SHA was captured from the 2016 construction season. Responses were obtained from the Division Offices in all 50 states plus the District of

Columbia, Puerto Rico, and the three Federal Lands Highway Divisions (Eastern, Central and Western). There was a total of 55 responses, which reflected a response rate of 100 percent.

Survey Objectives

The FHWA survey collected specific information on the current state-of-the-practice of RAS usage, current specification practices followed by SHAs, and performance. The objectives were to:

- Identify quantities, trends, requirements and performance on RAS usage.
- Obtain opinions on the usage of RAS in asphalt mixtures from the Division Office and SHA perspective.
- Identify knowledge, engineering, and guidance gaps associated with RAS use.

Report Organization

This report is divided into three chapters. Chapter 1 is the introduction, Chapter 2 provides the survey results and analysis, and Chapter 3 presents the summary of findings. Four broad categories were addressed in the survey:

- Usage
- Specifications
- Performance
- Future

The results presented in Chapter 2 are organized by these categories.

Definitions

To be consistent with current terminology in the industry, the following definitions used throughout this report came from AASHTO MP 23-14 and AASHTO M 323-17:

- Manufactured shingle waste— rejected asphalt shingles or shingle tabs that are discarded in the manufacturing process of new asphalt shingles. Often called manufactured waste asphalt shingles (MWAS).
- Postconsumer asphalt shingles (PCAS) — asphalt shingles that are removed from the roofs of residential dwellings or commercial buildings. Postconsumer asphalt shingles are often called “tear-off” shingles.
- Reclaimed asphalt binder ratio (RBR) — the ratio of the RAP and RAS binder in the mixture divided by the mixture’s total binder content.
- Reclaimed asphalt pavement (RAP) – removed and/or processed pavement materials containing asphalt binder and aggregate.
- Reclaimed asphalt pavement binder ratio (RAPBR) — the ratio of the RAP binder in the mixture divided by the mixture’s total binder content.
- Reclaimed asphalt shingles (RAS) — manufactured shingle waste or postconsumer asphalt shingles that have been processed into a product that meets requirements.
- Reclaimed asphalt shingle binder ratio (RASBR) – the ratio of the RAS binder in the mixture divided by the mixture’s total binder content.

CHAPTER 2: SURVEY RESULTS

This chapter presents the current state-of-the-practice of RAS in asphalt mixtures related to usage, current practices followed by SHAs, and performance. The responses from each FHWA Division Office reflect the practice of their local SHA partner. Responses are referenced by the SHA at each Division Office location (e.g., Alabama's SHA usage, Wisconsin's SHA usage, etc.)

This chapter is presented in the following format:

- The survey question is stated.
- The survey results are presented.
- The survey results are interpreted.

The respondents identified themselves along with their contact information. It was thought that clarification or additional information might be needed for some of the responses. Follow-up telephone interviews were conducted with 18 respondents.

To improve the flow of the report, questions have been reorganized from the original survey instrument.

RAS Usage

Survey Question 1: Allowing RAS

Does the SHA currently allow RAS in asphalt mixtures?

- *Yes.* 31 SHAs (56 percent)
- *No.* 23 SHAs (42 percent)
- *No, but allowed in the past.* 1 SHA (2 percent)

Thirty-one SHAs were identified as allowing RAS in asphalt mixtures, as shown in figure 1. Five of these SHAs responded that they only allowed MWAS: District of Columbia, Massachusetts, New Jersey, New York, and Pennsylvania. One respondent, Oklahoma's SHA, indicated that it had used RAS in the past on an experimental basis, but did not currently allow it.

California's SHA noted that it did not allow RAP or RAS at the time of the survey, but was working on specifications for RAS. It was working on a non-standard special provision to be followed by pilot projects where replacement binder could be from RAP and/or RAS. The initial desire was to create RAP specifications first, and then RAS would be next.

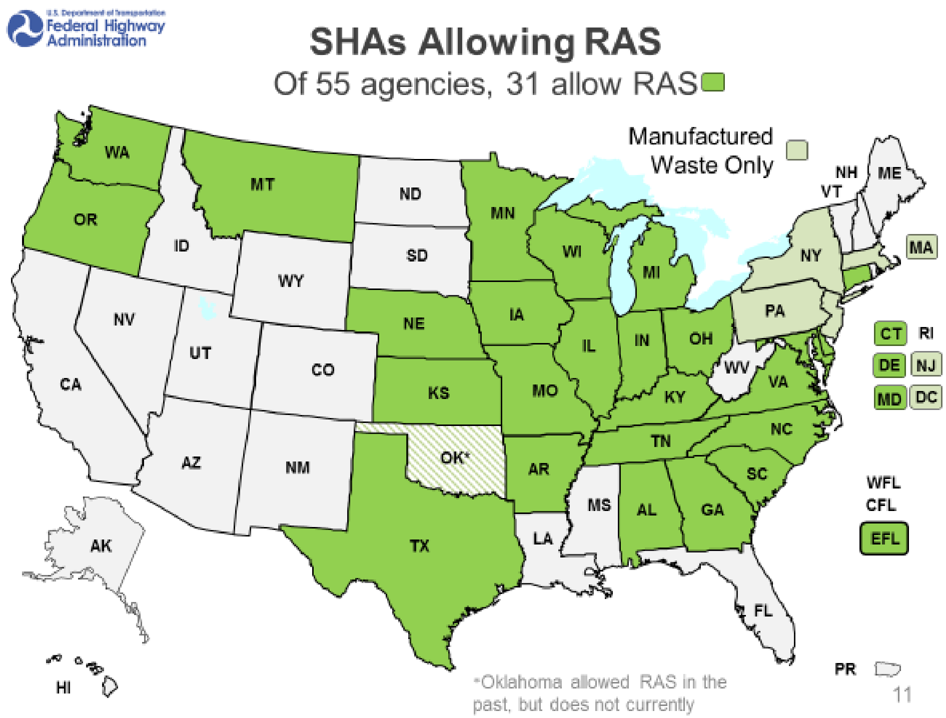


Figure 1. Map of SHAs allowing RAS from the FHWA survey.

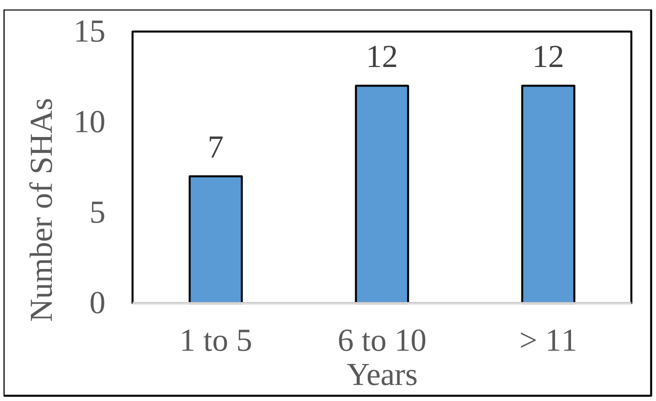


Figure 2. Number of SHAs by years of allowing RAS.

Survey Question 2: Years Using RAS

How many years has the SHA been allowing RAS in asphalt mixtures?

Results are shown in figure 2. Of the 31 SHAs allowing RAS, RAS has been allowed an average of 9.8 years. SHAs allowing RAS for the fewest years were Montana, Connecticut and New York with 1 to 2 years. SHAs allowing RAS for the most years were Minnesota with 22 years and Delaware with 20 years. Also, SHAs in Indiana, Ohio, Pennsylvania, and South Carolina had allowed RAS for 18 years.

Survey Question 3: Tons of RAS Used

*In the 2016 construction season, approximately how many **tons of RAS** were used in asphalt mixtures by the SHA?*

Total tons of RAS used enables the tracking of reclaimed materials use and resource-responsible initiative. The total also may provide an indication of risk, as more tons used is suggestive of agencies tolerating more risk.

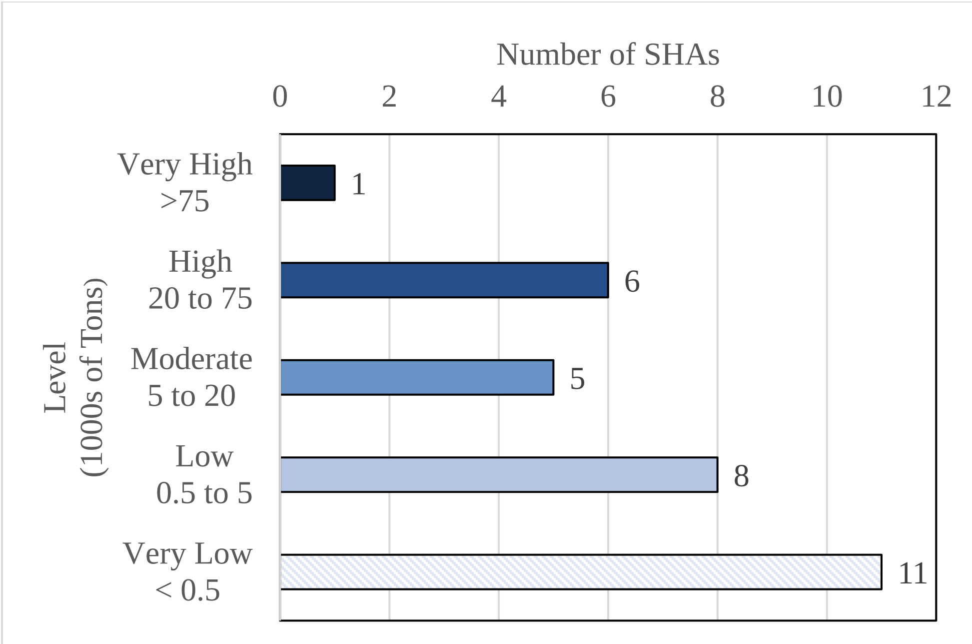
Of the 31 SHAs that indicated they allow RAS, the total tons of RAS used is shown in figure 3 on the following page. RAS tonnage is shown by level of usage and geographic distribution. The levels selected ranged from “very high,” which was greater than 75,000 tons, to “very low,” which was less than 500 tons. The levels used in figure 3 were arbitrary. However, the ranges for each level were based on the database of information as these levels were found to distinguish between different usage levels.

To provide an understanding of the different levels, an example from the “very high” and “low” levels will be provided. North Carolina’s SHA was in the “very high” level with approximately 102,000 tons of RAS used in 2016. North Carolina’s SHA places approximately 8.5 million tons of asphalt mixture per year, 30 percent of which contained RAS. When RAS was used, it averaged 4 percent.

On the other hand, Oregon’s SHA was in the “low” level. Oregon’s SHA has a smaller program, approximately 1.6 million tons of asphalt mixture per year, and using RAS in 6 percent of its asphalt mixture tonnage. When RAS was used, it averaged 2 percent. Oregon’s SHA was in the “low” level with approximately 1,500 tons of RAS in 2016.

Of 31 SHAs allowing RAS, the levels of usage are shown on a map in Figure 3. There were some observations based on the usage levels and geographic distribution.

- In the West, Oregon’s SHA used a “low” level of RAS and reported that RAS was being hauled to its eastern plains as there was no RAP available in that part of the State. It was cost effective to haul shingles for processing.
- In the Northeast, when RAS was used, it was generally “very low.” Of the five States using MWAS, Pennsylvania’s SHA actually used the most at “moderate” levels.
- In the Southeast, several SHAs were using RAS. SHAs in Alabama, North Carolina and Texas were using “high” to “very high” levels.
- In the Midwest, most SHAs used RAS and several were “high” level utilizers including Illinois, Wisconsin, Indiana, and Missouri. One comment of note came from Nebraska’s SHA, a “low” level RAS user. Nebraska’s SHA much preferred optimizing RAP.



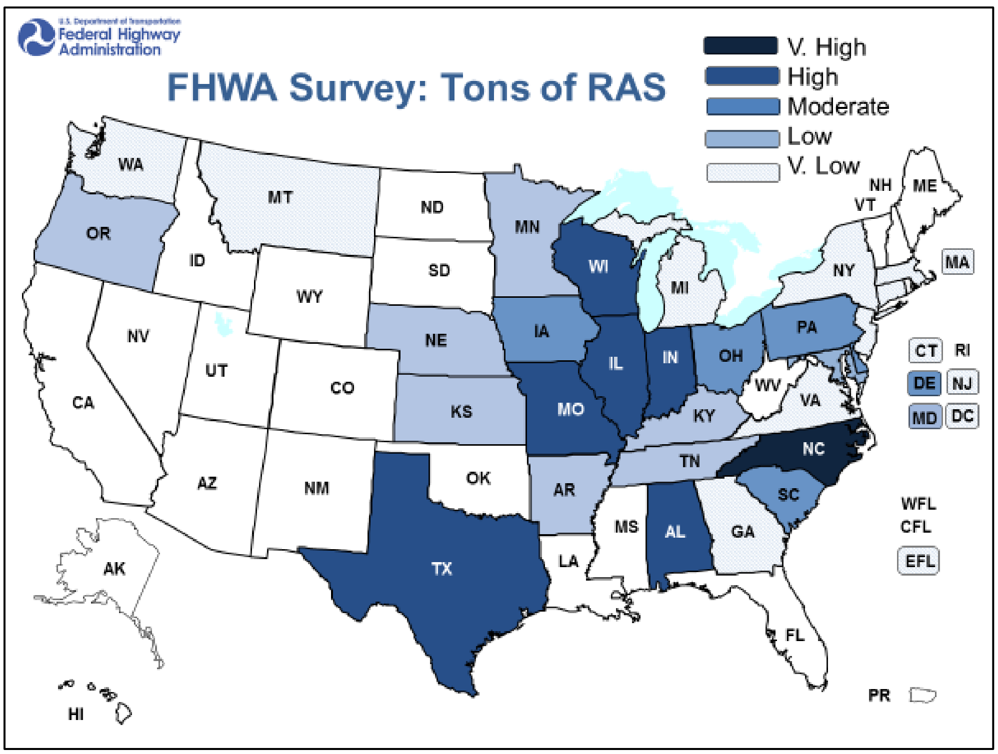


Figure 3. Mapping of reported SHA use of RAS in 2016.

Texas' SHA offered an example of the change in RAS usage over time, as shown in figure 4. RAS usage increased within Texas to address the abundance of shingles due to many storms and associated damage. Then there was a decline in usage of RAS within Texas' SHA from 114,000 tons of RAS in 2012 to 20,000 tons of RAS in 2016. This represented an 80% decline in 4 years.

During that period, Districts in Texas’ SHA were often not using RAS in surface lifts. Additionally, when RAS was used, its concentration was reduced from 5 percent to 3 percent due to performance concerns.

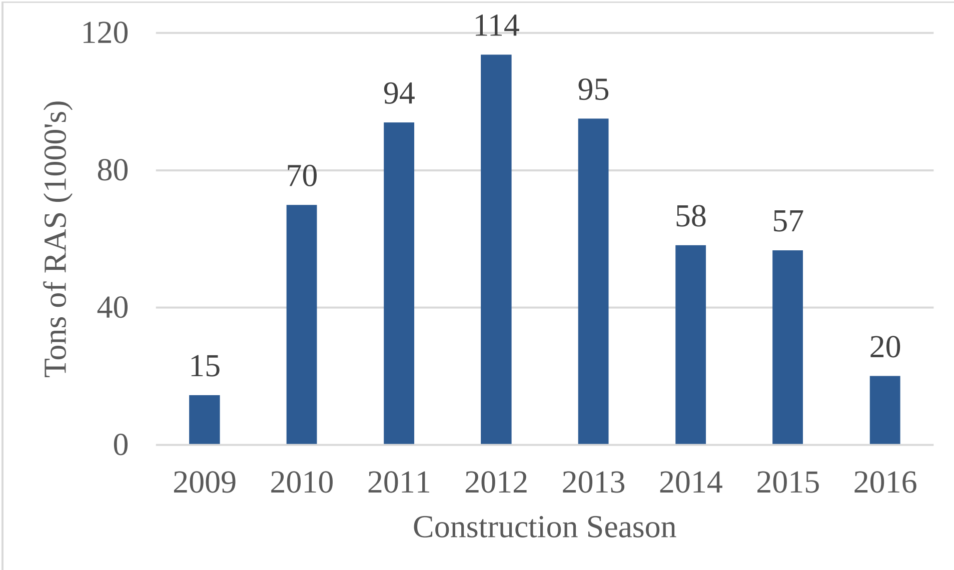


Figure 4. Usage of RAS in Texas from the FHWA survey.

Survey Question 4: Confidence Level

What is your level of confidence in the quantity from the previous question?

Each respondent was asked to determine its level of confidence for several of the quantitative responses. During the pilot testing of the survey, it was recognized that much of the information being requested was not tracked or readily available. So, to encourage more responses, respondents also were requested to provide educated estimates of the quantity. Including a level of confidence was thought to make respondents more comfortable providing estimates.

The level of confidence could range from zero percent to 100 percent. A zero percent level of confidence meant there was no faith at all in the estimates. Therefore, the value was essentially representative of a random number. A 100 percent level of confidence meant there was no doubt in the response. This level of confidence was representative of the use of very good tracking mechanisms. Confidence levels between these two end points represented the balance of "random" versus "well-tracked" in the estimate provided.

For question 3, the average confidence level was 63 percent. Clearly, the total tons of RAS used in asphalt mixtures was not a metric that the SHAs readily tracked.

Survey Question 5: Usage by Other Non-SHA Groups Within the State

Do other non-SHA groups (i.e., local public agencies, airport authorities, tolling authorities, etc.) within the State use notable quantities of RAS in asphalt mixtures?

- *Yes (Please add comments below.)* 10 SHAs (28 percent of respondents)
- *No* 8 SHAs (22 percent)
- *Uncertain* 18 SHAs (50 percent)

Results to this question are shown in figure 5. Total responses were greater than 31 as some respondents not allowing RAS added a response. Eighteen of 36 (50 percent) respondents were uncertain about the usage of RAS by other non-SHA groups within the State and eight (22 percent) were not aware. Only 10 (28 percent) were aware of the RAS usage by other non-SHA groups.

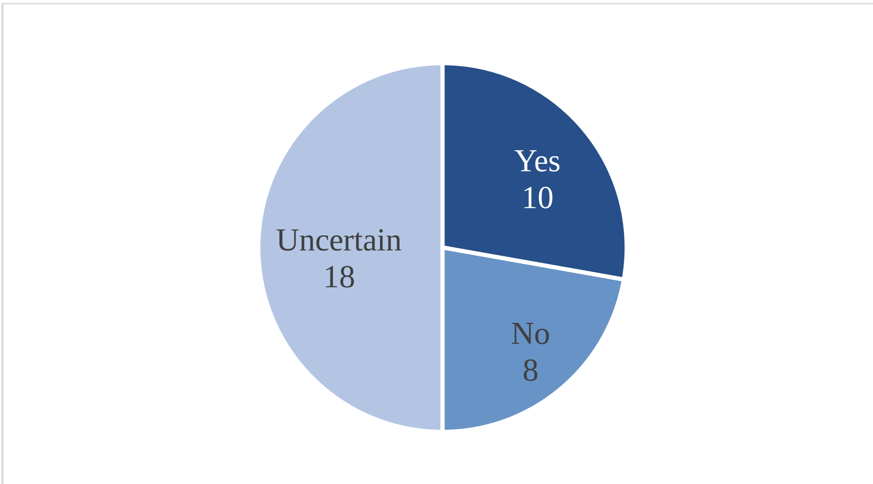


Figure 5. Number of SHAs aware of the usage of RAS by other non-SHA groups within the State.

Oklahoma's SHA, for example, reported that Oklahoma City was using RAS but the SHA was just experimenting with RAS. In another example, Kentucky's SHA usage had been constant, but LPAs such as the City of Louisville had used significant quantities.

Survey Questions 6 and 7: Percent of Asphalt Mixture Containing RAS

In the 2016 construction season, approximately how many ***total tons of asphalt mixtures*** *were used by the SHA?*

In the 2016 construction season, approximately how many ***tons of asphalt mixtures containing RAS*** *were used by the SHA?*

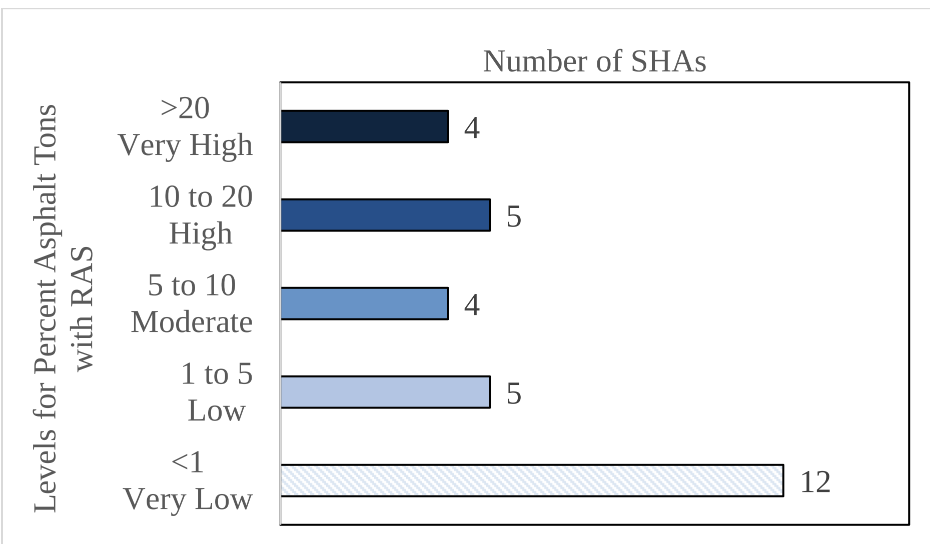
These two questions were designed to obtain the percent of asphalt tons within a SHA's program that used RAS. Percent of asphalt tons within a SHA's program was intended to identify programs with lower tonnages that were using RAS in notable percentages of their asphalt mixture tonnage. Programs using RAS in large percentages of their asphalt mixture tonnage could be an indication of programs with more risk.

Results of percent of asphalt mixture tons with RAS is shown in Figure 6. Figure 6 includes information by level of usage and geographic distribution. Of 31 SHAs that allowed RAS, only 30 responded with figures; one SHA was unsure. The total tons of asphalt mixture produced had an average confidence level of 93 percent. The tons with RAS had an average confidence level of 78 percent.

There were four SHAs that were at "high" levels in terms of the percent of asphalt mixture tons with RAS. Three of the SHAs that used RAS in more than 20 percent of their asphalt tonnage were North Carolina, Illinois, and Wisconsin. These were not surprising as they were in the "very high" and "high" levels of RAS usage by tons.

The fourth SHA that used RAS in more than 20 percent of its asphalt tonnage was Delaware. This was a surprise as it was in the "moderate" level of RAS usage by tons. Delaware's SHA program had 800,000 tons of asphalt mixture per year. Over 25 percent of its asphalt tonnage had RAS in 2016. Delaware's SHA primarily had one major contractor with two production plants. That contractor recently started increasing the amount of RAS. Thus, the percentage of asphalt mixture tons with RAS increased dramatically. Delaware's SHA reported it was conducting mixture performance testing to investigate appropriate limits.

A surprise in the "moderate" level of the percent of asphalt tons with RAS was Texas' SHA. Although the asphalt mixture usage by Texas' SHA was very large, 12.5 million tons per year, RAS was only used in 5 percent of the asphalt mixture tonnage.



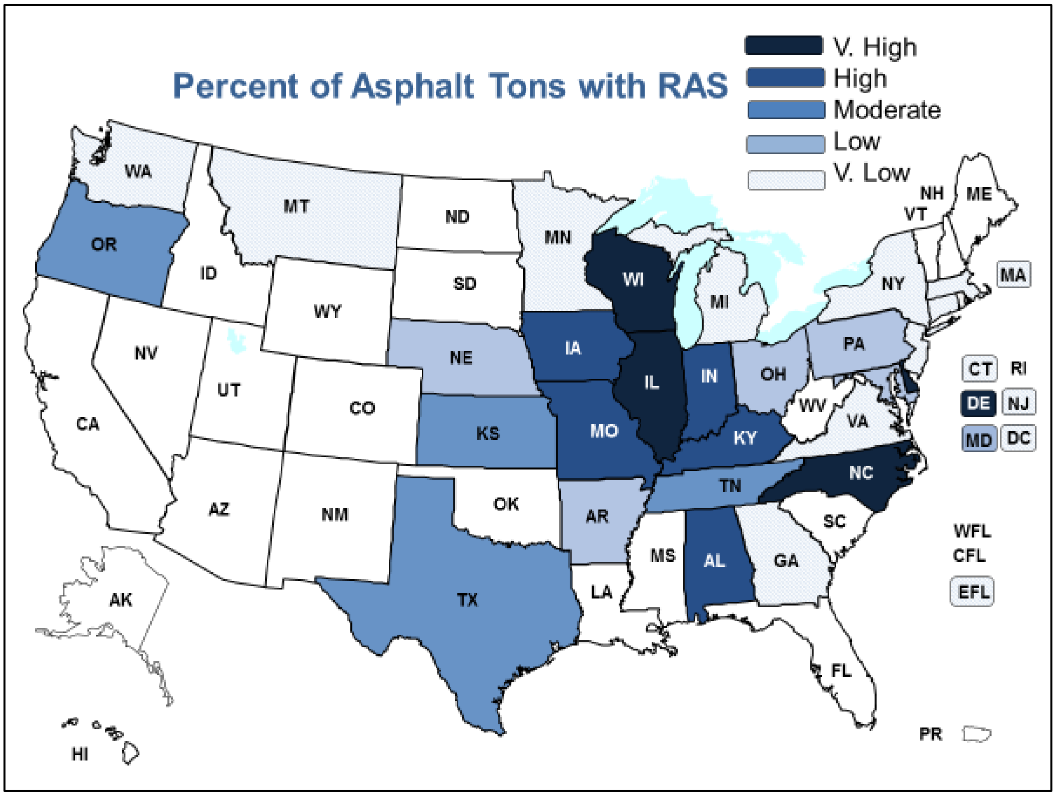


Figure 6. Number of SHAs by percent of asphalt mixture tons with RAS and the geographic distribution from the FHWA survey.

Specifications

Survey Question 8: Maximum Acceptable Limits and Criteria

How does the SHA determine the maximum acceptable limits for RAS in asphalt mixtures and what criteria is used? (Multiple answers are acceptable.)

- *Maximum percent RAS in the mixture (e.g., 5% by weight of aggregate).*
- *Maximum reclaimed binder ratio (e.g., 0.30).*
- *Performance test (cracking and/or rutting test, e.g., bending beam fatigue).*
- *Other (please elaborate).*

Responses are shown in figure 7 along with the geographical distribution. The geographic distribution includes multiple responses as appropriate. The maximum percent RAS was the most popular with 25 respondents. Although not always included in the survey responses, it was most commonly calculated as the percent by weight of asphalt mixture. The maximum RBR was also popular with 20 respondents. Fourteen SHAs had both maximum percent RAS and maximum RBR. When the maximum RBR was used, the SHA almost always included the combined binder from both the RAP and RAS.

Five SHAs reported using asphalt mixture performance testing when using RAS. Texas' SHA used the Hamburg wheel-tracking device and indirect tensile strength for acceptance. Illinois' SHA used the Illinois flexibility index test (I-FIT) for information that held potential for future implementation. Pennsylvania's SHA had one District that used the bending beam fatigue. Montana's SHA used the Hamburg wheel tracking device for acceptance. Delaware's SHA used the overlay tester for information that held potential for future implementation.

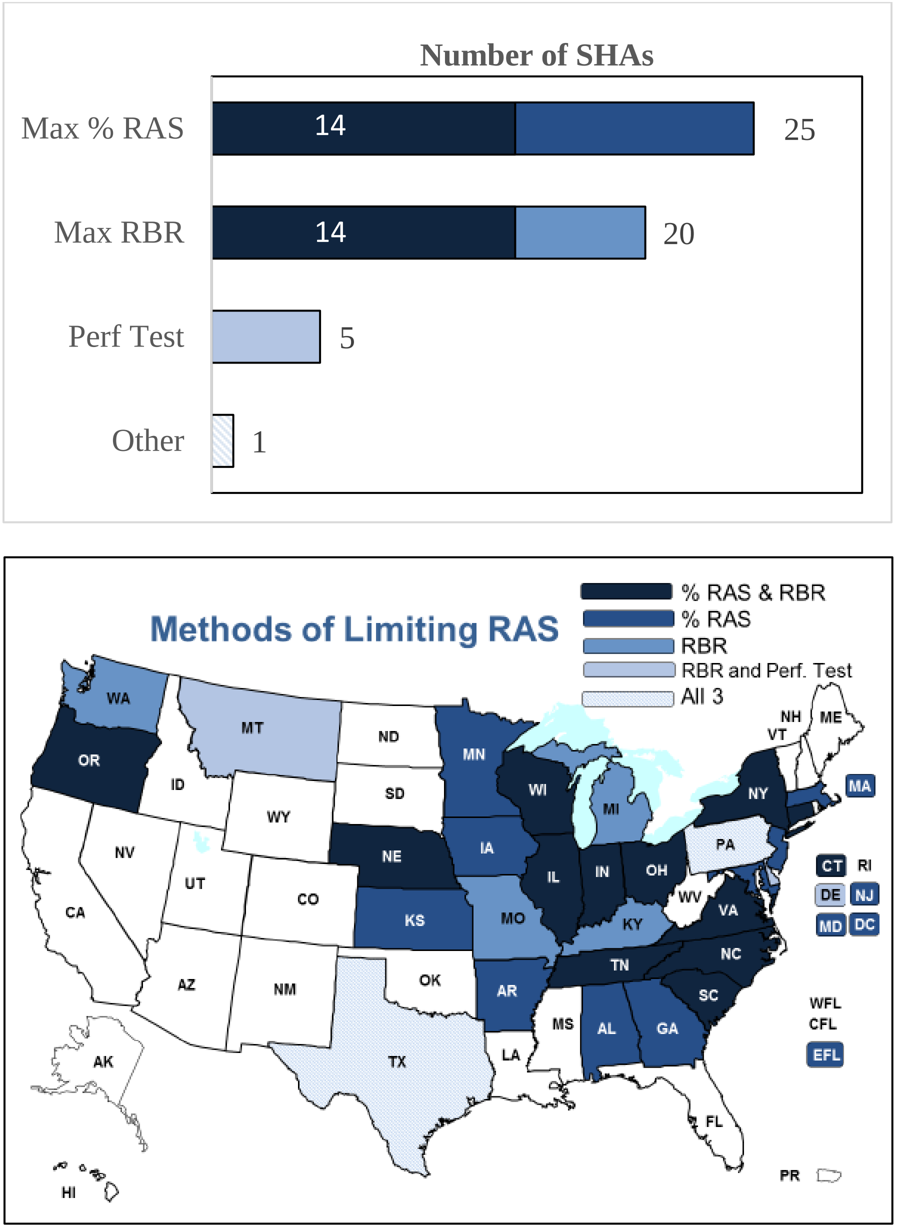


Figure 7. Number of SHAs by the maximum acceptable criteria for RAS and the geographic distribution from the FHWA survey.

Of the 31 SHAs that allowed RAS, examples of the requirements are provided here from the biggest users:

- SHAs in Oregon, Wisconsin, and North Carolina used maximum percent RAS and RBR.
- Illinois' SHA used the maximum percent RAS and RBR and the mixture performance testing was in development for implementation.
- Texas' SHA used maximum percent RAS, RBR and mixture performance testing.
- Pennsylvania's SHA used maximum percent RAS and RBR. One District was using the bending beam fatigue for mixture performance testing. Additionally, Pennsylvania's SHA only allowed MWAS.
- Missouri's SHA was using maximum RBR, but also had project selection guidelines for usage of RAS on low volume routes and shoulders.
- Alabama's SHA used maximum percent RAS, but allowed 3 percent of PCAS or 5 percent of MWAS.

The criteria for maximum RAS usage is summarized in table 1. For the maximum percent RAS, the average restriction was 4.1, the median was 5.0, and the range was from 2.0 to 5.0. For the maximum RBR restriction, the average was 0.25, the median was 0.20, and the range was from 0.15 to 0.50. The criteria for RBR almost always included RAS and RAP, and was often varied based on project selection guidelines.

The highest criteria for RAS was a maximum of 5 percent by weight of mixture. This was the requirement reported by 15 SHAs: District of Columbia, Eastern Federal Lands, Illinois, Indiana, Kansas, Maryland, Massachusetts, Minnesota, Nebraska, New Jersey, Ohio, Oregon, Pennsylvania, South Carolina, and Virginia.

Table 1. Criteria for maximum RAS.

	Maximum Percent RAS	Maximum RBR
Average	4.1	0.25
Median	5.0	0.20
Lowest	2.0	0.15
Highest	5.0	0.50

Note: The maximum RBR often varied depending on RAP quantities, lift, grade bumping, and other factors.

Survey Question 9: Percentage of RAS Most Commonly Used

In the 2016 construction season, when RAS was used, approximately what percent of RAS was most commonly used in the asphalt mixture for the SHA (e.g., 2%, 3%, 5%, etc.)?

From question 8, the average of the SHAs' criteria for the maximum percent RAS was 4.1 with a range of 2.0 to 5.0. What was equally as relevant as the maximum allowed, was the amount contractors were actually using on projects. Survey results are shown in figure 8. The confidence level for the responses was an average of 90 percent.

RAS was not being used on projects within eight SHAs, even though they were allowing it. The average of RAS being used by contractors on SHAs' projects was 3.6 percent for those SHAs that were actually using it.

For the 23 SHAs where contractors were actually using RAS, the lowest amount of RAS commonly used was 2.0 to 2.5 percent within SHAs in Oregon, New York, and Illinois. The highest amount of RAS commonly used was 5.0 percent. The highest amount of RAS commonly used on projects within the SHAs is described below:

- Maryland, Minnesota, and Nebraska observed 5.0 percent RAS being used, but these SHAs used "low" to "moderate" levels of RAS.
- Ohio's SHA observed 5.0 percent RAS being used, but they included requirements for RBR and guidance for usage only in lower lifts.
- Pennsylvania's SHA observed 5.0 percent RAS being used, but they only allowed MWAS.

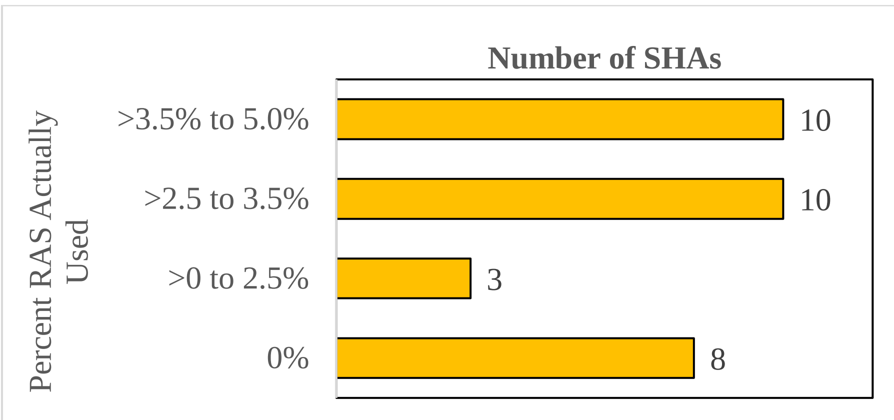


Figure 8. Number of SHAs by the percent of RAS actually used.

When using small quantities of RAS, SHAs in Pennsylvania and Kansas raised concerns about metering RAS into the asphalt mixture production plant. There were questions regarding the ability to accurately add a material that only represented a small percentage (3 or so) of the total asphalt mixture. Three options at the plant to ensure the accuracy of the rate of addition for a material used in small quantities include (Varner, 2016):

- Standard volumetric cold feed bins can work, but the belt must spin quickly. This requires a very narrow opening in the cold feed bin that could result in bridging. It may be necessary to have steep side slopes on the cold feed bin to prevent bridging.
- Weigh belt feeders (gravimetric) can work, but may lack reliability. There is a very small quantity of RAS weighed, and the RAS can stick if wet. The sticking can create gaps and surges in the rate of addition, so scraper plates need to be present and functioning properly.
- Cold feed bins on load cells are very promising, but add cost. This is also called a "reverse weigh" cold feed bin. The weigh belt feeders are also used and act as a secondary check. The "reverse weigh" cold feed bins and weigh belt feeders are both integrated into the plant operations and adjust as production changes.

Additionally, some best practices for processing RAS to help ensure consistency include (Stroup-Gardiner, 2016):

- Uniformly blending RAS with sand minimizes formation of clumping or agglomeration. RAS can also be blended with zeolite or RAP. For example, a RAS processor in Illinois was blending sand with RAS, and a RAS processor in Michigan was blending RAP with RAS.
- Moisture must be kept low to decrease sticking and agglomeration.
- Finer processing is better for adding small quantities of RAS, but increased grinding also results in increased moisture.

Survey Question 10: Selection Guidelines or Restrictions

Does the SHA have any selection guidelines or restrictions for controlling the use of RAS in asphalt mixtures? (Multiple answers are acceptable.)

- *Grade bumping of the PG binder at some level of RAS use (e.g., PG 64-22 is changed to PG 58-28).*
- *Surface mixtures vs. lower lifts.*
- *Specialty mixtures (SMA, OGFC, thin-lift mixtures, etc.)*
- *Traffic levels.*
- *NHS vs. non-NHS.*
- *Shingle source: manufactured waste vs. postconsumer.*
- *Asphalt mixture performance test.*
- *Other (please elaborate).*

Results are shown in figure 9. Grade bumping was the most common guideline as reported by 14 SHAs. The second most common guideline was for the location of the paving lift by 13 SHAs. They made a distinction between the amount of RAS allowed based on the usage in surface and lower lifts. For example, SHAs in Ohio and Texas focused the usage of RAS in lower lifts rather than in surface lifts.

The usage of RAS in specialty mixtures was limited by 11 SHAs. With these limitations, RAS was frequently not allowed in specialty mixture such as open-graded friction course (OGFC), stone-matrix asphalt (SMA), and others. MWAS and PCAS were mentioned seven times, and mixture performance testing was mentioned five times.

Three SHAs had a focus on traffic. As an example of traffic, Missouri's SHA indicated a focus on RAS usage on lower volume routes and shoulders. Those that responded with "other" generally included requirements found in AASHTO MP 23 such as asbestos testing, approved suppliers, and others.

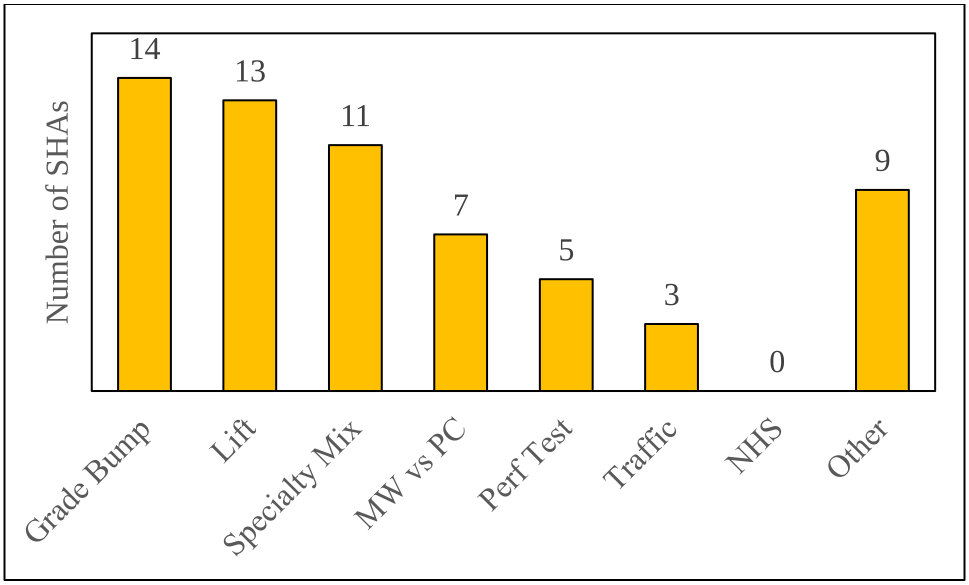


Figure 9. Number of SHAs by the type of guidelines for RAS usage in asphalt mixtures.

In 2014, Maryland's SHA also gathered information regarding requirements for RAS usage. They conducted a survey through AASHTO's Committee on Materials and Pavements (Maryland SHA, 2014). A comparison of the requirements for RAS from Maryland's SHA survey to the FHWA survey is shown in table 2. From 2014 to 2017, there were slight changes to the maximum limits. There were two fewer SHAs allowing RAS, there were no SHAs allowing more than 5 percent RAS, and more SHAs added RBR requirements. Notably, there were more restrictions added such as grade bumping and lift location.

Table 2. Comparison of requirements for RAS by the number of SHAs from Maryland's SHA survey in 2014 to the FHWA survey in 2017.

	2014	**2017**
Allowing RAS	33	31
Allowing 6% RAS	3	0
RBR Requirement	16	20
Grade Bumping	9	14
Restrictions by Lift	7	13
Restrictions by Traffic	6	3

Survey Question 11: Usage of AASHTO PP 78-14

There has been an evolution of AASHTO standard practices related to the usage of RAS. They are:

- Withdrawn standard: AASHTO PP 53
- Current standard: AASHTO PP 78-14
- Proposed standard: AASHTO PP 78-17

Questions 11, 12 and 13 were designed to identify the usage of these standards by the respondents and are summarized in figure 10.

AASHTO PP 78-14 is the Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixture, *which requires adjustment of the asphalt binder grade based on the reclaimed binder ratio. Does the SHA specify the use of PP 78-14 as written?*

- *Yes.* 1 SHA (3 percent)
- *No.* 26 SHAs (84 percent)
- *Uses a modified version.* 4 SHAs (13 percent)

At the time of the FHWA survey, AASHTO PP 78-14, *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures*, was the "current" standard. Results on the usage of AASHTO PP 78-14 are shown in figure 10. Only one SHA reported using it as written. Interestingly, RAS was not used by any contractors on that SHAs' projects.

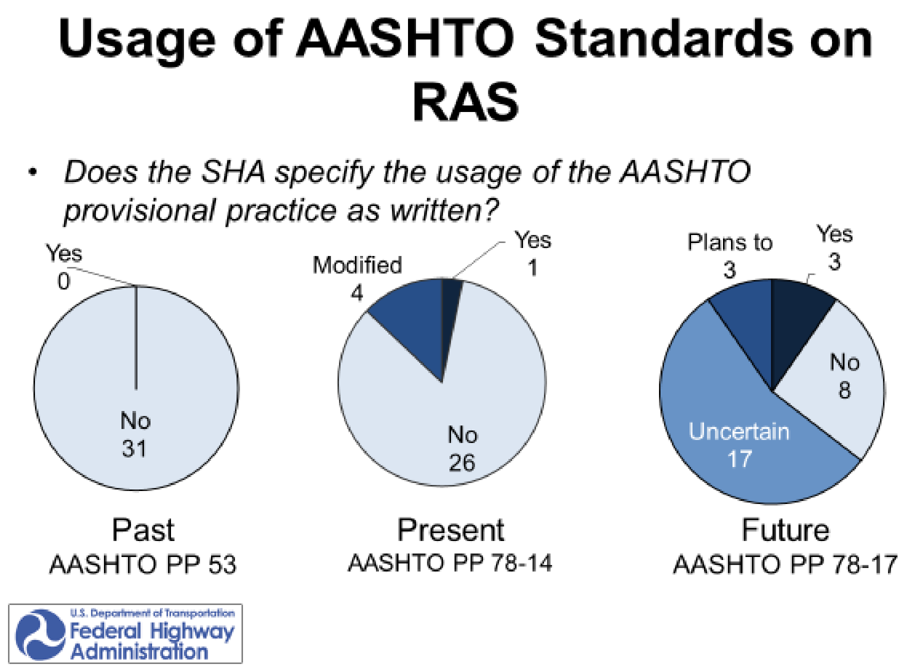


Figure 10. Number of SHAs using various AASHTO standards on RAS.

Survey Question 12: Usage of AASHTO PP 78-17

AASHTO PP 78-17, Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixture, *requires testing of either the asphalt binder (ΔT_c) or a mixture performance test. Will the SHA specify the use of PP 78-17 as written when it is published in Fall 2017?*

- *Yes.* 3 SHAs (10 percent)
- *No.* 8 SHAs (25 percent)
- *Uncertain.* 17 SHAs (55 percent)
- *Plans to use in the future.* 3 SHAs (10 percent)

In August 2017, after the FHWA survey on RAS, a new standard was released, AASHTO PP 78-17. For purposes of the survey, this standard was considered the "future" version. Results are shown in figure 10. It appears that there was more interest in this standard by SHAs. It required either the binder testing to determine the asphalt binder's change in critical low temperature (ΔT_c), or mixture testing using a SHA's performance test, or a maximum limit of 3 percent RAS by weight of mixture.

Survey Question 13: Usage of AASHTO PP 53

The standard prior to AASHTO PP 78 was AASHTO PP 53. Is the SHA using AASHTO PP 53?

- *Yes.* 0 SHAs (0 percent)
- *No.* 31 SHAs (100 percent)
- *Uses a modified version.* 0 SHAs (0 percent)

AASHTO PP 53-09 was withdrawn and then AASHTO PP 78-14 was created. For the FHWA survey, AASHTO PP 53-09 was considered the "past" version. This question was designed to determine if any of the SHAs were still using the outdated standard, PP 53. Results are shown in figure 10 and indicated that no SHAs were using the withdrawn standard.

Survey Question 14: Combinations of RAS and RAP

Does the SHA allow both RAS and RAP to be used in combination in an asphalt mixture?

- *Yes (Please elaborate.)* 27 SHAs (87 percent)
- *No.* 3 SHAs (13 percent)

There were responses from 30 of the 31 SHAs allowing RAS. No trends were identified as there was such a wide variety of methodologies in the requirements when using both RAS and RAP. A few responses from selected SHAs are shown to highlight this:

- **Indiana**
  - Up through 2016, allowed either RAPBR, RASBR, or a blend of both (RBR) up to 0.40 in some mixtures and up to 0.25 in others. A new specification starting in September 2017, will allow either RAPBR, RASBR, or a blend of both (RBR) with no more than 0.25 in any mixture. Additionally, RAS will be $\leq$ 3.0 percent by total mass of mixture and $\leq$ 0.15 by RASBR.

- **Iowa**
    - RAS may be used according to the same requirements as RAP. The percentage of RAS used is considered part of the maximum allowable RAP percentage.
- **Massachusetts**
    - MWAS may be used in leveling courses, base courses, and intermediate courses at a maximum rate of 5 percent by weight only when RAP is not included in the job mix formula.
- **Missouri**
    - Binder ratios are calculated with effective binder contents.
    - When RAP and RAS are used together, an equation is used with the RBR to credit RAS with twice the hardening effect as that of the RAP. The "(RAPBR) + (2 x RASBR)" is used to determine when binder grade changes are needed through extraction, recovery, and grading.
- **Oregon**
    - RAS is allowed at a maximum 5 percent by weight and no more than 0.20 RBR in wearing course and 0.30 RBR in base course.
- **Virginia**
    - Maximum 2 percent RAS with a minimum of 20 percent RAP.
    - Maximum 3 percent RAS with a minimum of 10 percent RAP.
    - Maximum 4 percent RAS with a minimum of 5 percent RAP.
    - Maximum 5 percent RAS with no RAP.

As can be seen from these few examples, there was a wide variety of methodologies in the requirements when using both RAS and RAP. A summary of the variations included:

- RAP and RAS were treated the same;
- RAS only allowed without RAP;
- RAS considered to have twice the stiffening effect of RAP;
- Meet overall binder performance grade (PG) after extraction and recovery;
- Maximum percentage of RAS;
- Maximum percentage of RAS varying with amount of RAP;
- Maximum RBR;
- Maximum RASBR;
- Maximum RASBR varying on amount of RAP and/or RAPBR;
- Maximum RASBR and maximum percentage of RAS;
- Project selection guidelines based on location of lift, traffic, type of RAS (MWAS vs. PCAS) or others; and
- Others.

Performance

As part of the National Cooperative Highway Research Program (NCHRP) Synthesis *495 Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures*, AASHTO State Materials Engineers were surveyed. One of the series of questions related to the perceived influence of RAS on various pavement distresses: rutting, moisture sensitivity, non-thermal cracking, and thermal cracking. Results are shown in table 3 (Stroup-Gardiner, 2016).

Most respondents disagreed or strongly disagreed that RAS increased rutting. This was thought to be from the increased stiffness from the RAS binder. Most respondents were neutral regarding the influence of RAS on moisture susceptibility, but some agreed that RAS may increase moisture susceptibility. This was primarily due to the increased fines. Most respondents agreed and strongly agreed that RAS increased non-thermal and thermal cracking. The increased cracking was thought to be from the increased stiffness created from the RAS binders.

Table 3. Perceived influence of RAS on various pavement distresses.

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Rutting potential is *increased* with increasing percentages of RAS.	0	0	5	5	8
Moisture sensitivity is *increased* with increasing percentages of RAS.	2	6	8	1	0
Cracking potential is *increased* with increasing percentages of RAS.	9	7	2	0	0
Thermal cracking potential is *increased* with increasing percentages of RAS.	4	10	2	0	0

Survey Question 15: Pavement Performance with RAS

Is the SHA having or had any issues with pavement performance that may be related to the use of RAS? Pavement performance was and/or is:

- *Good, very pleased - no changes planned to RAS requirements in the future.*
- *Acceptable - some changes were and/or are considered to the RAS requirements.*
- *Somewhat less than acceptable - some changes were and/or are being considered to reduce the amount of RAS.*

Of the 31 SHAs that allowed RAS, two indicated they were getting “good” performance with the use of RAS, 17 indicated they were getting “acceptable” performance, six indicated that they were getting “somewhat less than acceptable” performance, and six did not respond. Results are shown in figure 11.

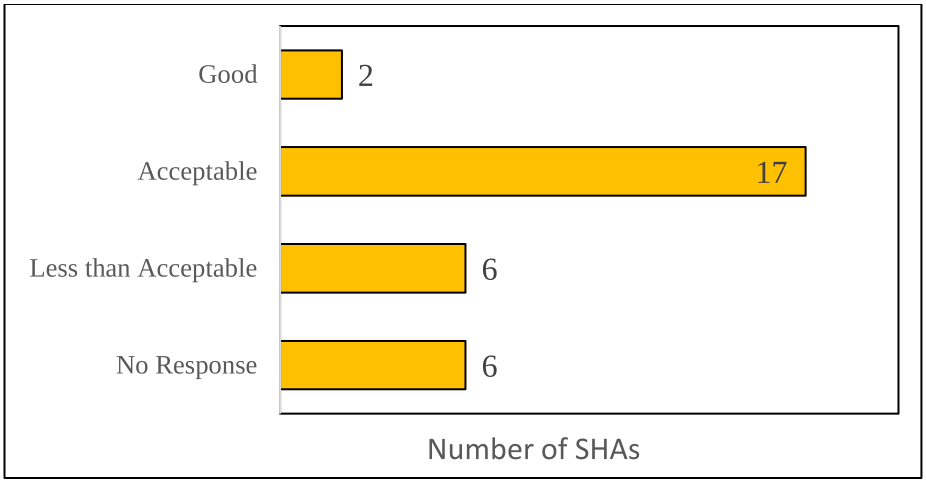


Figure 11. Number of SHAs by the type of pavement performance related to the usage of RAS.

Both SHAs that replied "good" reported using a maximum of 3 percent RAS.

Comments from those that replied "acceptable" often indicated that there were some challenges with pavement performance in the past that led to adjustments in their requirements:

- Reduced service life led to requirements for a maximums of 3 percent RAS and 0.15 RASBR. These requirements resulted in acceptable performance.
- Maximum percent RAS was recently lowered from 5 percent to 3 percent.
- Laydown issues existed at lower placement temperatures.
- The mixtures seemed to crack quickly. Since they were typically used in lower lifts (not surfaces), this was not a major concern.

Comments from those that replied "somewhat less than acceptable" were:

- Studies correlated premature cracking to RAS and RBR levels.
- Recent changes reduced RAP, RAS, and RAP and RAS combinations. Pavement performance will be monitored based on these changes.
- RAP optimization was preferred over use of RAS.
- The current limit of 2 percent RAS was set based on early failures.
- It was not a good idea to use RAS with WMA or in 4.75-mm mixtures.
- Some premature cracking was attributed to the recycled materials and dry mixtures. RAS was a factor in some early warranty project failures.

Within these comments, some trends were observed. Many respondents observed that they were obtaining acceptable performance with usage of RAS at 3 percent or less with the appropriate engineering, design, production, construction, and performance testing controls in place. It was very likely that there could be examples of acceptable pavement performance when using RAS at levels greater than 3 percent by weight by mixture with the appropriate engineering, design, production, construction, and performance testing controls in place.

Survey Question 16: Opinions on RAS Usage

What is the current opinion of the Division and SHA on the use of RAS in asphalt mixtures? (Multiple answers are acceptable.)

- *RAS can have an effective cost-benefit ratio and should be allowed in asphalt pavements.*
- *The effective cost-benefit ratio of RAS is appealing, but still concerned about risk of long-term performance.*
- *There is too great of a performance risk when using RAS that it should not be allowed in asphalt pavements.*

Results are shown in figure 12. With the existing levels of knowledge and experience, most respondents—35—had concerns regarding the usage of RAS in asphalt mixtures. Seventeen respondents expressed that there was too great of a performance risk. Seven identified the usage of RAS had an effective cost-benefit ratio. It should be noted that four of those seven respondents also expressed concern as well.

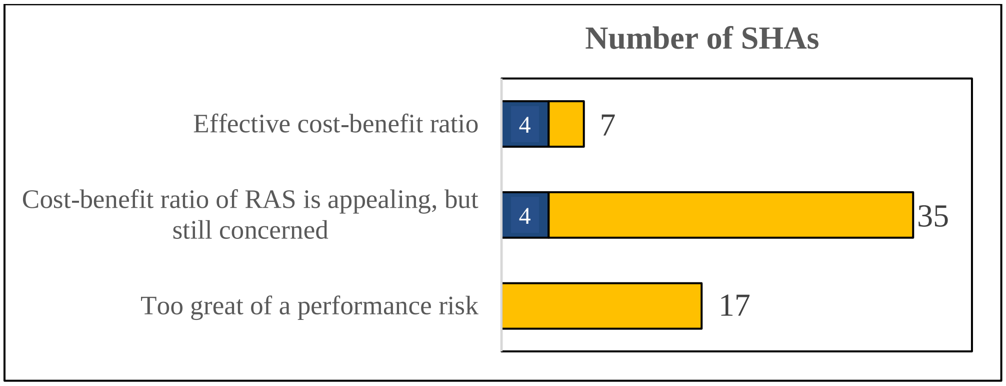


Figure 12. Number of SHAs by the benefits and risks of RAS usage.

Comments included:

- RAS was not readily available. (This was a common theme from the western SHAs.)
- Demand for RAS declined with lower binder prices.
- SHAs reported concern with performance related to fatigue and thermal cracking.
- SHAs reports concerns regarding the ability to write specifications to ensure successful performance (e.g., grade bumping, recycling agents, others).

Survey Question 17: NHS Miles with RAS

Within your State, approximately how many miles (center-line or lane miles) on the National Highway System (NHS) have used asphalt mixtures with RAS?

Results are shown in figure 13. The average level of confidence of the respondents was 65 percent, indicating that this information was not readily tracked and was likely an educated guess.

This question was focused on the total lane miles on the NHS, not just those from the past construction season. Three SHAs reported the most miles. For example, Texas' SHA estimated 4,900 miles and North Carolina's SHA estimated 2,000 miles. For those that reported the largest lane miles using asphalt mixtures with RAS, it was not a significant portion of their overall NHS mileage. Eight respondents reported none, and another 11 respondents were uncertain. Although there was a lot of uncertainty with the responses, it appeared that there was limited exposure on RAS usage on the NHS from those that did respond.

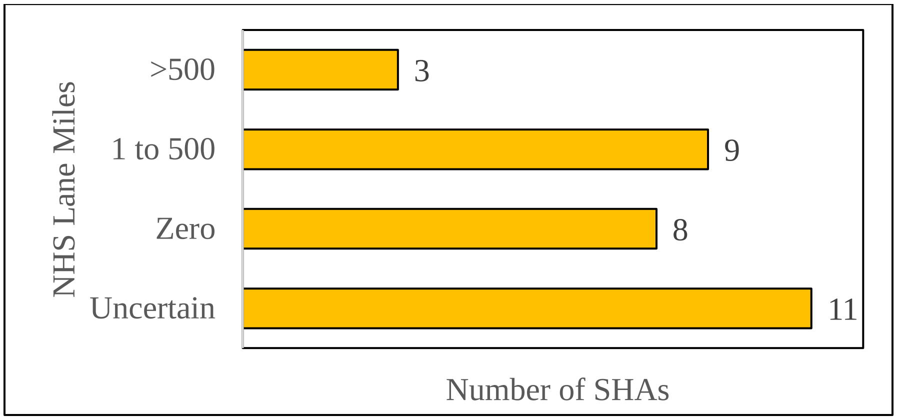


Figure 13. Number of SHAs by lane miles on the NHS with RAS.

Future

Survey Question 18: Need for National Policy and Direction

If the Division and SHA had the opportunity to set national policy and direction for the future usage of RAS in asphalt mixtures, what would be your top priority or priorities? (Multiple answers are acceptable.)

- *Development of AASHTO standards with limits or restrictions on RAS.*
- *No AASHTO standards with limits or restrictions on RAS should be developed.*
- *Development of AASHTO standards with asphalt mixture performance-based specification.*
- *Development of guidance on responsible use of RAS.*
- *No guidance on responsible use of RAS should be developed.*

Results are shown in figure 14. Respondents could select as many responses as they desired. There clearly was a need expressed for national policy and direction. There was virtually an equal need for:

- Guidance on responsible use (35 respondents).
- AASHTO performance-based specification (33 respondents).
- AASHTO standards with limits (28 respondents).

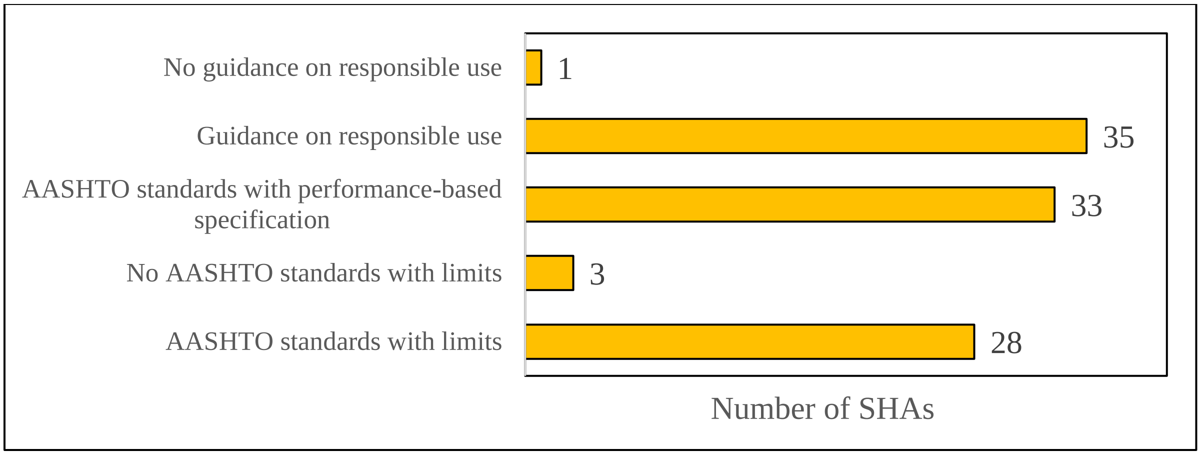


Figure 14. Number of SHAs by type of national policy and direction needed for future usage of RAS.

Survey Question 19: Research with RAS

Does the SHA have any research relating to RAS in asphalt mixtures completed, underway or planned? (Please elaborate and provide report titles or links to research below.)

- *Yes.* 25 SHAs (46 percent)
- *No.* 30 SHAs (54 percent)

As shown on figure 15, fewer than half of the respondents had research completed, underway or planned. In fact, not all the 31 SHAs that allowed RAS had their own research. Only 25 SHAs responded yes. The most common research topics were:

- Pavement performance monitoring.
- Mixture performance testing.
- Binder characterization.
- Recycling agents.

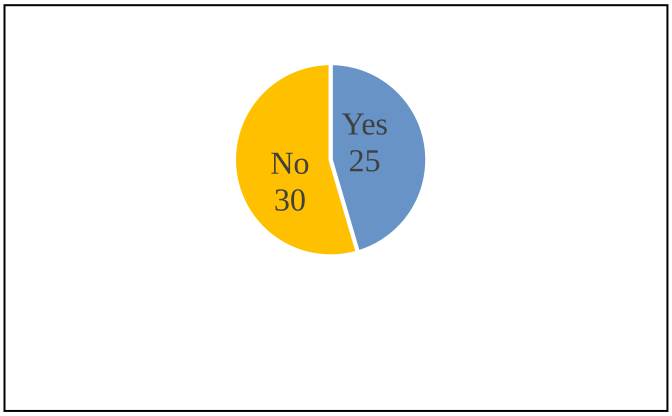


Figure 15. Number of SHAs with completed, existing, or planned research relating to RAS in asphalt mixtures.

Over the last five years, Illinois' SHA appeared to have led the way, conducting over $2.5 million of research related to RAS. A summary is shown in table 4. NCHRP had only had five projects on RAP, RAS, or RAP and RAS totaling $3 million. A summary is shown in table 5.

Table 4. Summary of Illinois' SHA research topics on RAS.

No.	Title
ICT R27 – SP19	Laboratory Evaluation of High Asphalt Binder Replacement with Recycled Asphalt Shingles (RAS) for a Low N-Design Asphalt Mixture
ICT R27 – SP29	Thermodynamics Between RAP/RAS and Virgin Aggregates During Asphalt Concrete Production – A Literature Review
ICT R27 – 128	Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS
ICT R27 - 161	Construction and Performance Monitoring of Various Asphalt Mixes in Illinois: 2015 and 2016 Reports
ICT R27 – 162	Modeling the Performance Properties of RAS and RAP Blended Asphalt Mixes Using Chemical Compositional Information
ICT R27 – 175	Development of Long-Term Ageing Protocol for Implementation of the Illinois Flexibility Index Test (I-FIT), just underway
Complete (Closeout held October 17, 2017)	Joint IDOT/FHWA Process Review on Early-age Cracking of HMA Pavements nearing completion

Table 5. Summary of NCHRP research topics on RAP and/or RAS.

No.	Title	Stage	Funding
09-58	The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios	Due 12-2018	$1,500,000
09-55	Recycled Asphalt Shingles in Asphalt Mixtures with Warm Mix Asphalt Technologies	Due 07-2017	$600,000
46-05	Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures	Synthesis 495 (2016)	$40,000
09-46	Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content	Report 752 (2012)	$400,000
09-12	Incorporation of Reclaimed Asphalt Pavement in the Superpave System	Report 452 (1997)	$460,000

CHAPTER 3: SUMMARY OF FINDINGS

The survey's objective was to collect specific information on the current state-of-the-practice of RAS. The goals were to:

1. Identify quantities, trends, requirements, and performance of RAS usage.
2. Obtain opinions on the usage of RAS in asphalt mixtures from the Division Office and SHA perspective.
3. Identify knowledge, engineering, and guidance gaps associated with RAS use.

The objective was accomplished through a survey distributed to its Division Offices. The survey was conducted in April and May 2017. Usage of RAS by each SHA was captured from the 2016 construction season. Responses were obtained from the Division Offices in all 50 states plus the District of Columbia, Puerto Rico and the three Federal Lands Highway Divisions (Eastern, Central and Western). There was a response rate of 100 percent; tallying 55 responses.

As with survey results and discussion, the summary of findings is presented in four broad categories.

Usage

- Of the 55 respondents, 31 SHAs allow RAS. Twelve of them have been allowing it for more than 11 years, and 7 of them have been allowing it for 1 to 5 years.
- There were lead states and regions that used the most RAS. These were identified by examining both total tons of RAS used and percent of asphalt mixture with RAS within each SHA's program.
- Eight SHAs are using RAS in the "high" to "very high" level in terms of tons or RAS or percent of asphalt tons with RAS. They are: Alabama, Delaware, Illinois, Indiana, Missouri, North Carolina, Texas and Wisconsin.

Specifications

- The maximum percent RAS was the most popular method of specifying RAS.
- The maximum percent RAS and RBR were often used together. RBR was often varied for project selection guidelines.
- Since 2014, SHAs had introduced additional requirements and specifications on RAS usage.
- Guidelines for RAS usage (e.g., grade bumping, restrictions by lower lift, restrictions by traffic, etc.) appeared to be a best practice by many SHAs.
- AASHTO standards on RAS were generally modified to include additional State-specific requirements.
- Requirements vary widely for using combinations of RAS and RAP.
- There was a need identified to define the feeding of RAS in plant operations.

Performance

- Many respondents indicated usage of RAS in asphalt pavements provided acceptable performance.
- There were concerns expressed with field performance and how to write specifications to ensure successful field performance.
- There was a consistent message that using RAS could be effective when done with appropriate controls to ensure mixture performance.

Future

- There was a desire expressed for AASHTO standards and guidance on limits, mixture performance testing, and responsible usage of RAS.
- Exposure on NHS appeared limited although a lot of the responses were "uncertain."
- More national research was needed.

REFERENCES

American Association of State Highway and Transportation Officials. (2017). *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in New Hot Mix Asphalt (HMA)*, AASHTO PP 53, Washington, DC.

AASHTO. (2017). *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures,* AASHTO PP 78, Washington, DC.

AASHTO. (2017). *Standard Specification for Superpave Volumetric Mix Design*, AASHTO M 323, Washington, DC.

AASHTO. (2014). *Standard Specification for Reclaimed Asphalt Shingles for Use in Asphalt Mixtures,* AASHTO MP 23, Washington, DC.

Asphalt Roofing Manufacturers Association. (2015). Personal communication from R.X. Gumucio, ARMA, Washington, DC.

Epps, J.A. and Paulsen, G.L. (1986). *Use of Roofing Wastes in Asphalt Paving Mixtures - Economic Considerations*, Report 709-2, Center for Construction Materials Research, University of Nevada-Reno, NV.

Maryland State Highway Administration. (2014). AASHTO Committee on Materials and Pavements Survey on the Usage of Reclaimed Asphalt Shingles, Baltimore, MD.

McDaniel, R., and Anderson, R. M. (2001). *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual, NCHRP Report 452,* Transportation Research Board of the National Academies, Washington, DC.

National Association of Home Builders. (1998). *From Roofs to Roads... Recycling Asphalt Roofing Shingles into Paving Materials,* NAHB Research Center, Upper Marlboro, MD.

Stroup-Gardiner, M. (2016). *NCHRP Synthesis 495, Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures*, TRB, Washington, DC.

Varner, M. (2016). "Basics of Asphalt Plant Operation," Annual Asphalt Conference, Missouri University of Science and Technology, Rolla, MO.

Willis, J.R., and Turner, P. (2016). *Characterization of Asphalt Binder Extracted from Reclaimed Asphalt Shingles*, National Center for Asphalt Technology, Report 16-01, Auburn University, Auburn, AL.

West, R.C., Willis, J.R., and Marasteanu, M. (2013). *Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content, NCHRP Report 752*, TRB, Washington, DC.

West, R. C. (2015). *Best Practices for RAP and RAS Management* (QIP 129). National Asphalt Pavement Association, Lanham, MD.

Wright, Jr., F.G. (2002). *Formal Policy on the Use of Recycled Materials*, FHWA, Washington, DC, obtained from: https://www.fhwa.dot.gov/legsregs/directives/policy/recmatmemo.htm, last accessed December 27, 2017.