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CASE STUDIES ON SUCCESSFUL UTILIZATION OF RECLAIMED ASPHALT PAVEMENT AND RECYCLED ASPHALT SHINGLES IN ASPHALT PAVEMENTS

Final Report

By

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16. Abstract

Over the past decade, the rapid cost escalation of raw materials used in highway construction has affected the ability of highway and road agencies to maintain their existing pavement system. A common strategy among many highway agencies to offset rising materials costs is to utilize more recycled materials in pavements, particularly Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS). Effective utilization of these and other recycled materials in pavements is also consistent with the desire to use more sustainable construction practices in the transportation infrastructure.

This report describes the development of specifications and practices of a few state highway agencies that have successfully used RAP and RAS. With regard to RAP usage, the Florida Department of Transportation’s and the Ohio Department of Transportation’s programs are highlighted. In Florida, over 75% of all mixes produced for DOT projects contain RAP, with an average RAP content of 22%. The FDOT has found RAP mixes to perform very well. The Ohio DOT also has a long history of recycling asphalt. Like most states, Ohio allows higher RAP contents in lower pavement layers, but allows 5% more RAP when contractor meets additional processing requirements.

Missouri and Texas are leading states in the development of specifications and practices for asphalt mixes containing RAS. MoDOT’s effort led to the use of finer grind RAS. Texas and Missouri were among the first states to allow post-consumer RAS in asphalt mixes. Texas has also developed stringent deleterious materials requirements for RAS.

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ABSTRACT

Over the past decade, cost increases of raw materials used in highway construction has affected the ability of highway and road agencies to maintain their existing pavement system. A common strategy among many highway agencies to offset rising materials costs is to utilize more recycled materials in pavements, particularly Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS). Effective utilization of these and other recycled materials in pavements is also consistent with the desire to use more sustainable construction practices in the transportation infrastructure.

This report describes the development of specifications and practices of a few state highway agencies that have successfully used RAP and RAS and maintained performance. With regard to RAP usage, the Florida Department of Transportation's and the Ohio Department of Transportation's programs are highlighted. In Florida, over 75% of all mixes produced for DOT projects contain RAP, with an average RAP content of 22%. The FDOT has found RAP mixes to perform very well. The Ohio DOT also has a long history of recycling asphalt. Like most states, Ohio allows higher RAP contents in lower pavement layers, but allows 5% more RAP when contractor meets additional processing requirements.

Missouri and Texas are leading states in the development of specifications and practices for asphalt mixes containing RAS. MoDOT's effort led to the use of finer grind RAS. Texas and Missouri were among the first states to allow post-consumer RAS in asphalt mixes. Texas has also developed stringent deleterious materials requirements for RAS.

INTRODUCTION

Although the utilization of recycled materials in asphalt pavements has been a common practice for decades, interest has increased in the last few years due to rising costs of raw materials and the desire of transportation agencies and paving contractors to advance more sustainable pavement construction. Recycled materials used in asphalt pavements have included tire rubber, blast furnace and steel slag, foundry sands, glass, newsprint, and bottom ash. However, the two recycled materials that provide the greatest economic benefit for use in asphalt pavements are recycling of the pavement material itself, referred to as reclaimed asphalt pavement (RAP), and recycled asphalt shingles (RAS). Utilization of RAP and RAS in asphalt pavements is also an important part of the strategy to advance a more sustainable surface transportation infrastructure.

This report provides case studies of programs that have successfully used RAP and/or RAS while maintaining performance of their roads. With regard to RAP, this report details the programs used by the Florida Department of Transportation (FDOT) and the Ohio Department of Transportation (ODOT). These two states' pavement recycling programs have been successful in using higher RAP contents than most agencies while maintaining a high level of pavement performance. Their programs and practices are considered excellent models. This report describes their respective programs and an examination of the impact of the RAP programs in terms of economics, if possible, and pavement performance.

Two agencies that have been very progressive with their use of RAS are the Texas Department of Transportation (TxDOT) and the Missouri Department of Transportation (MoDOT). Both agencies have encouraged the use of RAS in asphalt mixtures over the past decade by constantly evolving their specifications to reflect lessons learned to produce and construct durable RAS asphalt mixtures. This report will approach RAS in a similar methodology to RAP.

BACKGROUND ON RAP USAGE

Recycling of asphalt pavements is one of the great success stories of the highway building industry. Although this practice dates back to 1915 it did not become common until the 1970s, when asphalt binder prices dramatically increased as a result of the Arab oil embargo *(1)*. One way in which the highway construction industry reacted was by developing the asphalt milling machine to remove distressed layers of the pavement and devise methods to recycle the old paving material back into new pavements. Many practices initially developed during that period are still in use today and have become part of routine operations for pavement construction and rehabilitation. Asphalt mixture specifications have also evolved considerably since RAP usage became common practice in the early 1980s.

Over the recent decade, construction material prices have risen and asphalt binder prices have more than tripled (Figure 1). This has affected the ability of most highway and road agencies to maintain their existing pavement system. Numerous transportation agencies have increased allowable RAP contents in many of their most used asphalt mix types. Since 2007, estimates from the National Asphalt Pavement Association indicate that the average RAP content across the US has increased from approximately 12% to 20%.

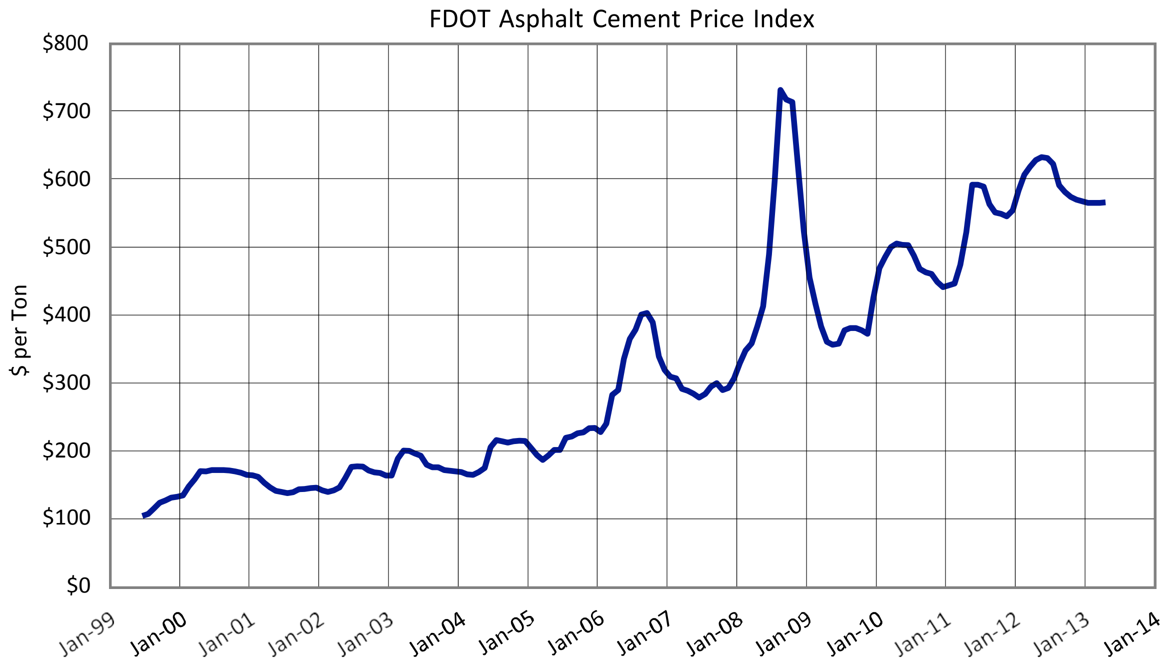

FIGURE 1 Asphalt Binder Price per Ton from Florida DOT Price Index Data

In the past several years, a significant amount of research has continued to focus on the design and performance of asphalt mixes with RAP contents up to 50%. The National Center for Asphalt Technology (NCAT) documented the construction and performance of several high RAP content experiments on the NCAT Test Track *(2)*. In 2006, a group of surface mix test sections containing 20% and 45% RAP were constructed. The four test sections with 45% RAP used different grades of virgin binder, ranging from a "softer" PG 52-28 to a PG 76-22 polymer-modified binder with 1.5% Sasobit. After five years of heavy traffic, all of the test sections had less than 5 mm of rutting. Texture change (an indicator of raveling) was consistent with the grade of virgin binders, with softer binders providing better performance. A small amount of low-severity cracking was evident in all of the sections except for the section containing 20% RAP and PG 67-22 binder, which had less. The amount of cracking was also consistent with the virgin binder grade in the RAP sections. The cracking had no effect on IRI for any of the sections. This five year experiment led to NCAT's recommendation to use a softer virgin binder grade for high RAP content (>25%) mixes and the standard binder grade for low to moderate RAP content mixes (≤25%).

In 2009, an additional 45% RAP content test section was sponsored by the Mississippi DOT. The RAP, gravel, and sand used in the mix designs were from Mississippi. The binder grade used in the Mississippi section was the standard PG 67-22, not a softer grade as was later recommended. At the end of the 25 month trafficking cycle, the Mississippi test section had only 3 mm of rutting (12.5 mm is commonly associated with failure) and 61 feet of low severity cracking. Both were slightly better than the performance of the polymer-modified, 15% RAP mix sponsored by the Mississippi DOT in the previous cycle of the NCAT track. Another group of test sections built in 2009 contained 50% RAP in each of the three layers of the 7-inch asphalt pavement structure. One of the 50% RAP sections used a water-injection asphalt foaming process to produce the mixes as WMA. A virgin mix control section built to the same thickness used a polymer-modified PG 76-22 binder in the top two layers. The sections were instrumented to measure how they responded to loads and environmental conditions throughout the cycle. After four years of heavy traffic, the 50% RAP sections had less rutting and fatigue cracking than the control section. Falling Weight Deflectometer testing of the sections throughout the cycle revealed that the 50% RAP test sections were significantly stiffer than the control section which resulted in significantly lower critical tensile strains and subgrade pressures relative to the control. Despite the increased stiffness, the high RAP mixtures had equivalent cracking performance compared to a virgin mixture test section.

Another noteworthy field study in regards to low temperature performance with 50% RAP mixes was built in 2009 in Manitoba, Canada on Provincial Trunk Highway 8 between Gimli and Hnausa *(3)*. The research project is a joint study by the Manitoba Infrastructure and Transportation and the Asphalt Research Consortium (ARC). The existing pavement was completely removed which resulted in a large supply of RAP. The project included two sections with 50% RAP, a section of 15% RAP, and a section of virgin hot-mix. The two 50% RAP sections used different grades of virgin binder: one was a 150/200 pen asphalt and the other a softer grade 200/300 pen asphalt. The Marshall mix designs targeted 4% air voids, 5.1% total asphalt content, and 13% voids in mineral aggregate (VMA). A primary goal of the project is to compare the laboratory testing with actual field performance. Extensive characterization of the mixtures and materials is currently being conducted by members of the ARC. After nearly three years, the section with 50% RAP and the softer binder has had no thermal cracking. All of the other sections have had just one or two low or moderate severity thermal cracks.

Demonstration projects containing 25% to 50% RAP have also been recently built in numerous other states, including Delaware, Illinois, Florida, South Carolina, Minnesota, Oregon, Missouri, South Dakota, and Idaho.

NCAT and other researchers compared Long Term Pavement Performance (LTPP) sections of pavements containing at least 30% RAP with virgin pavements constructed at the same time (*4*). The pavements were constructed between 1990 and 2000 in 16 states and two Canadian provinces and were regularly monitored to assess rutting, cracking, raveling, and other distresses. Most of the sections exceeded performance expectations for overlays and were still in service after 14 years. From a statistical perspective, test sections containing 30% RAP were found to perform as well as virgin mix sections in terms of IRI, rutting, block cracking, and raveling. Although the sections containing RAP had more cracking (fatigue, longitudinal, and transverse) on some projects, the sections were generally performing well. On several projects where RAP sections had more cracking than virgin counterparts, the LTPP database showed that the RAP mixes had excessive dust contents or low asphalt contents.

FLORIDA DOT'S RECYCLING PROGRAM

Historical Perspective

FDOT's recycling program started with a few experimental projects in the late 1970s. The first project was in Palm Beach County in 1977 which used 25% RAP in a hot-mix asphalt (HMA) base layer. In 1978 a second project was located in Bay County and used 30% RAP in the leveling course. Both of those projects used a batch plant. In 1979, a project in Marion County used 65% RAP in a structural asphalt layer. An asphalt emulsion rejuvenator was used in this mix. The drum mix plant was used to produce the mix. Early performance of these projects was good, which encouraged the agency to move forward with implementation of a RAP recycling specification in 1980.

Gale Page's 1987 account of FDOT's experiences with RAP *(5)* outlined the key elements:

1. The maximum RAP content was set at 60%.
2. RAP obtained from milling of a resurfacing project becomes the property of the contractor.
3. FDOT develops "composition" analyses of the layers to be milled based on cores from the roadway. The composition analysis includes the average asphalt content and recovered aggregate gradation of the layers to be milled as well as the viscosity of the recovered asphalt. The recovered asphalt viscosity is used as part of the mix design to determine the appropriate recycling agent. The composition analysis is provided in project plans to assure that the full value will be given for the reclaimed material.
4. RAP is included in the mix designs at the percentage proposed to be used. The mix design requirements (i.e. volumetric properties and gradation limits) are the same for mixes with and without RAP.
5. Mixes are bid to include the asphalt binder to avoid unbalanced bids.
6. The pavement design structural value for recycled mixes is the same as conventional (virgin) mixes.
7. Testing of plant-produced recycled mixes includes frequent checks of the recovered asphalt viscosity to assure that it is comparable to that of conventional mixes.
8. Placement and compaction requirements for recycled mixes are the same as for conventional mixes.

The study also noted that the performance of mixes containing RAP had been equal or better than the performance of mixes with all virgin materials. One study had found that the in-service hardening rate of binders recovered from asphalt mixes with RAP was slightly less than for standard asphalt binders. On several projects where the existing pavements had extensive cracking, the entire asphalt pavement was removed by milling and repaved using mixes with RAP. The performance of these projects was far superior to conventional overlays which typically led to reflection cracking in a few years.

Through the 1980s and 1990s the average RAP content used in asphalt mixes steadily declined from about 50% to 25%. During these two decades, FDOT implemented a number of specification changes that led to the decline. Investigations of poor rutting performance on several state highways pointed to low in-place air voids as a key indicator of performance. That led to reductions in the maximum allowable P200 content in mix designs, better control of dust during HMA production, and monitoring air voids during mix production using the Marshall method. Since RAP stockpiles typically have high dust contents, the percentage of RAP in mixes was reduced. In the late 1990's when FDOT implemented the Superpave system, the higher laboratory compactive efforts in the Superpave Gyratory Compactor resulted in even lower RAP contents as mix designers struggled to meet the VMA requirements. FDOT also began to use polymer modified asphalts on many high-traffic roadways and set a maximum limit of 15% RAP in those mixes containing the modified binders.

Milling for a Reason

Milling of pavements is now so routine that its benefits are often overlooked, and forgotten is the fact that it was one of the key developments that led to the use of RAP. Through decades of overlays in cities and towns, engineers had to deal with covering curbs and gutters, loss of clearances below bridges, dangerous drop-offs at drainage inlets, and/or building awkward cross sections. For more rural roadways, overlays resulted in a higher roadway grade that had to be matched on the shoulders with additional borrow material. Milling helped maintain desirable roadway cross sections and also provided a means to efficiently remove asphalt layers that were damaged due to rutting, shoving, raveling, cracking, etc. The fact that the removed asphalt pavement material was useful was not a consideration. Today, in most urban areas, so much RAP has accumulated that it seems there are no more good options for storing it. In Florida, a key part of the engineering design process for the rehabilitation of any pavement is determining the appropriate milling depth. All projects scheduled for resurfacing are cored at a frequency of once per lane mile. The primary form of distress on FDOT highways is top-down cracking, so the department examines the cores to determine how far the cracks penetrate the pavement and how deep to mill.

FDOT's RAP Specifications

FDOT's RAP specifications are among the most progressive of all the state transportation agencies. Only mixes requiring polymer or rubber modified binder have a defined maximum RAP content, which is now 20%. FDOT uses polymer modified binders for the upper pavement layers of roadways that carry more than 10 million design ESALs. Projects that have had a history of rutting may also use polymer modified binder. FDOT uses rubber modified binders primarily in open-graded friction courses. Therefore, no maximum limit is specified for most mixes.

The maximum RAP content actually used by contractors is typically about 40%. Asphalt mixes containing RAP must meet all standard mix design, quality control (QC), and acceptance criteria. Typically, the limiting factor for most mixes is the minimum VMA criteria. In some cases, other limitations may include plant constraints, dust-to-binder ratio, or challenges with maintaining pay factors during mix production. One reason VMA commonly controls RAP contents is due to high dust (P200) contents in most RAP materials. High dust contents tend to decrease the VMA of a mix.

For agency mix designs, the RAP aggregate bulk specific gravity $[G_{sb(RAP)}]$ is estimated by first calculating the effective specific gravity of the RAP aggregate $[G_{se(RAP)}]$ using equation 1.

$$G_{se(RAP)} = \frac{100 - P_b}{\frac{100}{G_{mm(RAP)}} - \frac{P_{b(RAP)}}{G_b}} \quad (1)$$

where

$P_{b(RAP)}$ = asphalt content of the RAP, determined by the ignition method using AASHTO T 308
$G_{mm(RAP)}$ = maximum theoretical specific gravity of the RAP, determined using AASHTO T 209
G_b = 1.02 (assumed specific gravity of the RAP binder)

The bulk specific gravity of the RAP aggregate is then determined using Equation 2. The asphalt absorption value (P_{ba}) is estimated based on knowledge of the historical aggregate sources used in the region where the RAP originated with a visual examination of the aggregates recovered from the ignition tests for asphalt content.

$$G_{sb(RAP)} = \frac{G_{se(RAP)}}{\frac{P_{ba} \times G_{se(RAP)}}{100 \times G_b} + 1} \quad (2)$$

Another factor that must be considered in designing mixes containing RAP for FDOT is the selection of the recycling agent or virgin binder grade. Since its early days of recycling, the agency used recycling agents in mixes containing RAP. Historically, the grade of the recycling agent was selected using a viscosity nomograph, similar to the approach described in ASTM D4887. This procedure required that samples of the RAP binder be extracted from the RAP using a solvent, recovered from the solvent, and then tested. As previously noted, FDOT conducted this testing on roadway cores for upcoming resurfacing projects and provided the viscosity of the RAP binder, as well as the asphalt content and aggregate gradation in a composition report that is included with the project plans. Providing this information in the plans helped contractors understand the key characteristics of the salvaged material and used that information in preparing their bids.

The recycling agents used by the agency were produced by blending regular paving grade asphalt binder with a softening agent. This process is managed by binder suppliers in Florida and the resulting recycling agents are required to be tested and meet the agency's quality assurance specifications. There have been very few supply issues for recycling agents thus allowing the agency's RAP program to succeed.

FDOT recently revised its specifications regarding recycling agents for RAP mixtures. In the future, recycling agents will not be used; instead, the virgin asphalt binder is simply based on the following ranges of RAP contents:

- For RAP contents ≤15%, use PG 67-22 (the standard asphalt grade in Florida).
- For RAP contents between 16% and 30%, use PG 58-22 (one and a half grades lower on the high temperature end).
- For RAP contents >30%, use PG 52-28 (low temperature end also lowered by one grade).

These new specifications became effective in 2013. Using the softer grade binders based on the PG grading system is now consistent with the supply requirements for other paving grade binders rather than the viscosity grading system formerly used for their recycling agents. FDOT based the above levels and binder grade changes on an analysis of over 20 RAP stockpiles from around the state. The data showed that the average true grade of the RAP binders was 90.8 - 15.8. The standard deviation for the high true grades was 1.5°C and the standard deviation for the low true grade was 3.2°C.

FDOT allows contractors to use RAP from any source, provided that the stockpile is "reasonably consistent in characteristics" and does not contain deleterious materials. For single-source RAP stockpiles, or RAP obtained from one or more sources that is processed and stockpiled in a continuous manner, FDOT approval requires representative samples at random locations at a minimum frequency of one sample per 1000 tons (with a minimum of six test results) for determining gradation and asphalt content. The RAP must also be tested for Gmm (for Gsb determination) at a minimum frequency of one sample per 5000 tons with a minimum of two test results. Suitability of the stockpiled material is based on a review of the test data and a visual inspection by an FDOT engineer.

A comprehensive study of RAP variability in Florida was completed by the International Center for Aggregate Research in 1998 *(6).* The study analyzed RAP (millings) and aggregate stockpiles (crushed) from 13 asphalt plant locations. Table 1 shows a summary of stockpile statistics from that study. The authors found that RAP stockpiles were less variable than virgin aggregates in Florida and that increasing the percentage of RAP did not increase the variability of the produced mixtures. Therefore, stockpile control and management is critical for using maximum RAP contents.

TABLE 1 RAP Variability Data from ICAR Study in Florida

RAP ID & Description	N	Percent Passing 2.00 mm		Percent Passing 0.075 mm		Asphalt Content (%)	
		Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
A2 Millings	18	51.0	3.23	12.6	1.24	5.7	0.32
B3 Crushed	22	63.2	6.25	8.3	0.87	4.7	0.39
C7 Crushed	28	63.4	5.51	8.9	0.95	5.6	0.55
D8 Crushed	32	63.0	5.36	7.7	1.03	5.2	0.27
D12 Crushed	9	60.5	2.64	7.7	0.48	5.1	0.40
D19 Millings	10	49.9	3.58	9.7	1.63	5.7	0.27
E8 Crushed	9	60.9	4.26	8.8	0.96	5.1	0.44
E13 Crushed	22	64.5	4.68	11.0	1.33	5.1	0.27
E16 Crushed	7	62.1	1.95	11.6	0.45	5.7	0.18
E19 Crushed	11	56.4	5.66	9.5	0.68	5.2	0.50
F3 Crushed	7	72.2	2.81	7.2	0.73	5.8	0.13
G5 Crushed	20	69.7	3.81	8.2	0.69	5.2	0.40
H5 Crushed	12	53.3	1.29	10.6	0.64	5.5	0.12
H7 Crushed	12	56.4	1.62	10.2	0.82	5.8	0.23
I7 Crushed	29	50.1	1.66	9.9	1.36	5.1	0.26
J4 Crushed	51	57.2	5.09	7.8	0.50	5.0	0.34
L6 Crushed	7	70.0	2.08	8.0	0.52	5.2	0.10
M5 Millings	11	51.6	4.59	5.5	1.15	6.1	0.37
M16 Millings	4	59.3	0.50	6.6	0.54	5.7	0.26

Performance of RAP Mixes in Florida

Since RAP usage in asphalt mixtures is such a mainstream practice by FDOT, there have been only a few studies to examine the performance of pavements with and without RAP. However, one experimental project was built in 1996 as part of the national LTPP study to evaluate three factors on the performance of asphalt overlays: overlay thickness, virgin mix versus mixes with 30% RAP, and whether or not the existing pavement was milled before the overlay. This LTPP study is known as SPS-5 (Specific Pavement Study Number 5). As shown in Figure 2, the FDOT test sections were built in Martin County on US-1. Each of the test sections were 500 feet in length. Performance data were obtained from the LTPP performance database, *DataPave Online*.

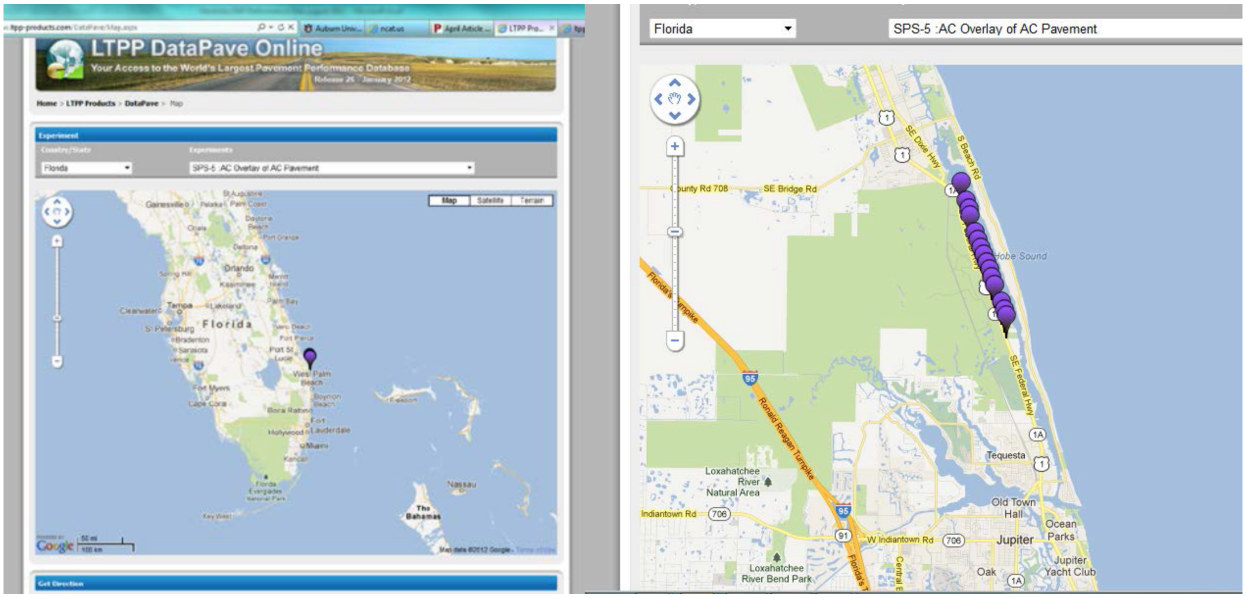

FIGURE 2 Location Maps of the Florida SPS-5 Sections using *LTPP DataPave Online*

As previously noted, the test sections were built in 1996. They are still in service after 16 years. Table 2 shows the latest performance data available for the Florida SPS-5 test sections. FHWA pavement condition criteria defines “Good” ride quality as less than 95 in/mi (1.5 m/km), and “Acceptable” ride quality as ≤170 in/mi (2.68 m/km) *(7)*. Based on those roughness criteria, all of the sections have a “Good” ride quality. All of the sections also have excellent performance with regard to rutting, with rut depths of 5 mm or less. The total length of cracking shown includes both transverse and longitudinal cracking. In the un-milled test sections, the RAP sections had less total cracking than the virgin companion sections; however, the reverse was true for the sections that were milled prior to the overlays. Fatigue cracking just began to appear within the last few years for most of the test sections, but the amount of fatigue cracking is extremely low. Even the thin RAP section with 41 m^2 of fatigue cracking should be considered good performance since that amount represents only 7.3% of the test section area after 16 years of service.

TABLE 2 15-Year Performance Data for the Florida LTPP SPS-5 Experiment in Martin County

Milling Prior to Overlay	Thickness of Overlay	RAP or Virgin	IRI (m/km)	Rutting (mm)	Total Length of Cracking (m)	Fatigue Cracking (m^2)
No	2”	RAP	1.08	5.0	33	41
		Virgin	0.71	4.5	138	6
	5”	RAP	0.94	5.0	62	5
		Virgin	0.82	5.0	81	0
Yes	2”	RAP	0.72	4.0	82	1
		Virgin	0.64	3.5	35	4
	5”	RAP	0.85	5.0	154	1
		Virgin	0.68	4.5	2	0

Another recent study examined the long-term performance of the agency's pavements built using more than 30% RAP. The Florida DOT *(8)* analyzed pavement performance data from 1991-1999 to compare Marshall virgin mixes and mixes with RAP contents ranging from 30% to 50%. All of the pavements analyzed had one or more structural layers that contained RAP and a non-RAP friction course. During this period, RAP was not permitted in friction course layers; therefore, the effect of the RAP in the structural layer(s) was inferred based on surface performance measures: cracking, ride, and rutting. Table 3 shows the results of a preliminary analysis that compared the average age of the pavements at the time they were resurfaced. As can be seen, the pavements with 30% to 40% RAP generally had good service lives. However, there was a trend that higher RAP contents yielded shorter lives.

TABLE 3 Age of Pavements Containing High RAP Contents at the Time They Were Resurfaced

RAP Content	No. of Projects	Avg. Age (years)	Std. Dev. (years)
30	23	17.2	4.0
35	10	16.9	3.2
40	14	15.1	5.5
45	3	11.3	2.3

A further analysis filtered out small tonnage projects (<5000 tons) and normalized the data with regard to truck traffic. Performance data were then analyzed with regard to the time for each pavement to reach one of the FDOT's pavement management distress thresholds. This analysis also indicated a trend that pavement service lives decreased as RAP contents increased from 30% to 50%. However, the authors also noted that the high RAP pavements in that range outperformed pavements that contained no RAP. No data were provided for the performance of projects using RAP contents between 0 and 30 percent.

Economic Savings

The Florida DOT estimates that their recycling program saved over $38 million in materials costs in 2010, the latest year for which comprehensive data is available. In that year, 78.2% of all mixes produced for FDOT projects contained RAP. The average RAP content was 19.9%. Jim Musselman, FDOT's State Bituminous Materials Engineer, suggests that since the FDOT has continued to expand their specifications to RAP usage, the average RAP content in FDOT mixes is now 22%. A recent query of the FDOT Laboratory Information Management System (LIMS) could not find a single virgin structural course mix design. With asphalt and aggregate prices at an all-time high, using RAP to reduce the cost of asphalt mixtures is being good stewards of taxpayer funds and limited non-renewable natural resources. FDOT recognizes that with asphalt binder prices near $700/ton and aggregate prices around $20/ton, the greatest value for RAP is to use it to reduce the demand of those raw materials.

There are also significant energy benefits for using RAP that are the result of reduced mining, processing, and transportation of virgin aggregate and extracting, refining, and transportation of asphalt. FDOT estimates that every ton of asphalt mix containing RAP conserves 200,000 BTUs of energy. With over 4.3 million tons of HMA containing RAP in 2010 for FDOT, the resulting energy savings was over 8.6 billion BTUs.

The other Florida markets for asphalt pavements (cities, counties, commercial development) also utilize high levels of RAP. Most municipalities in Florida simply refer to FDOT specifications for pavement materials and construction.

OHIO DOT'S RAP PROGRAM

Historical Perspective

Ohio is another state transportation agency with a history of successful RAP usage. Recent estimates by Flexible Pavements of Ohio indicates that the average RAP content for all mixes produced in the state is about 23%. Like FDOT, Ohio DOT started exploring RAP in the late 1970s, and began to allow RAP through their standard specification in 1981. Routine usage of RAP in HMA took off in the 1980s, however there was a learning curve and experiences were often gained through trial and error as the department and contractors worked through specification issues and plant issues. Better control of dust contents was one of the key issues addressed during that period.

ODOT's RAP Specifications

ODOT currently sets RAP limits for different mix types based on the type of plant and RAP processing methods. As shown in Table 4, the “standard” RAP limits are used for parallel-flow continuous mix plants and batch plants; whereas “extended” RAP limits are applied to counter-flow drum plants or “mini-drum” batch plants and also require additional RAP processing requirements. Basically, the “extended” RAP limits allow up to 5% more RAP. The “standard” RAP limits have been used in Ohio since the 1980s with a few changes such as increasing the RAP limit in intermediate layers. ODOT's “high-strength, lean base course” (Base Course 302) was also added in the 1990s. The minimum virgin asphalt contents for mixes containing RAP were added more recently to improve their durability.

TABLE 4 Ohio DOT RAP Limits

Asphalt Mix Application	Standard RAP Limits			Extended RAP Limits		
	RAP by Wt. of Mix (%)	Min. Virgin Asphalt Content	Comments	RAP by Wt. of Mix (%)	Min. Virgin Asphalt Content	Comments
Heavy-Traffic Polymer Surface Course	10 max.		For non-polymer virgin binder, allow 20% max.	15 max.	5.0%	For non-polymer virgin binder, allow 25% max.
Medium-Traffic Surface Course	20 max.	5.0%	Polymer or non-polymer virgin binder	25 max.	4.8%	Polymer or non-polymer virgin binder
Light-Traffic Surface Course	20 max.	5.2%	Polymer or non-polymer virgin binder	25 max.	5.0%	Polymer or non-polymer virgin binder
Intermediate Course	35 max.		Any mix type used as an intermediate course	40 max.	3.0%	Any mix type used as an intermediate course
Base Course 301	50 max.		Asphalt content set by ODOT	55 max.		Asphalt content set by ODOT
Base Course 302	40 max.		Max. 30% if poor mixing or coating evident during production	45 max.	1.8%	Max. 40% if poor mixing or coating evident during production

The additional processing required to meet the "extended" RAP limits includes either fractionation or in-line screening of the RAP over a 9/16-inch screen for surface and intermediate mixes, and a 1.5-inch screen for base mixes. When this processing or screening requirement was implemented in the late 1990s, a significant improvement in the uniformity of RAP mixes was evident. "It seemed like a minor change at the time, but looking back on it now it has had a significant influence on quality," says David Powers, head of Ohio DOT's central asphalt laboratory. He also added that very few contractors are fractionating RAP at this time; most are using in-line processing.

ODOT allows the use of RAP from ODOT or Ohio Turnpike roadways, or from other non-DOT sources provided that the RAP is processed, blended into a uniform stockpile, tested, and approved by the department. Testing will include a minimum of four samples tested for gradation and asphalt content. All results for asphalt content shall be within 0.4%, and the percent passing the No. 4 sieve will be within 5%. No deleterious materials are permitted. Once a RAP stockpile is approved by the department, no additional material may be added to it. Table 4 summarizes Ohio's current limitations on RAP contents.

ODOT mix design requirements follow the Asphalt Institute's SP-2 manual with some notable exceptions. ODOT uses 65 gyration of the Superpave Gyratory Compactor (SGC) for all mix designs, a policy that dates back to 2001. An unusual aspect of ODOT specifications is that it allows contractors to add up to 10% RAP to a virgin mix without having to redesign the mix. Powers states that is no longer common practice except in some rural projects where less RAP is available.

When more than 25% RAP is used in a mix design, the RAP binder must be recovered, tested and used to determine the grade of the virgin binder for the mix design. If the mix is produced as warm-mix asphalt, with a production temperature below 275°F, no virgin binder grade change is required for RAP contents up to 40%. One challenge with this specification is checking that contractors actually keep the mix temperature below the 275°F mark. Powers says that about 60% of all asphalt produced for ODOT is now WMA and almost all of it is done with water-injection foaming technologies.

ODOT also has a maximum dust-to-asphalt ratio of 1.2 for Superpave mixes. The use of dust-to-asphalt ratio in ODOT specifications predates Superpave. It was instituted in the 1980's along with other requirements to ensure better control of dust contents during mix production. Marshall mix designs are still used for low-traffic roads. Powers says that most contractors use 40% to 45% RAP in the 301 base mixes, and 35% to 40% in the high-strength base 302 mixes rather than the maximum limits shown in the tables.

Like many states, ODOT is more restrictive on RAP in surface layers for high-traffic roadways. Historically, ODOT's heavy-traffic pavements have performed well with respect to rutting, but suffered from long-term durability issues such as age-cracking, raveling, and freeze-thaw damage. Polymer modified binders, and more specifically, the amount of polymer modified binder in those mixes, has been the principal factor used to improve the resistance of the surface mixes to those problems.

Example Ohio DOT Project Containing RAP

One of the early experimental RAP projects was built by the agency in 1981 on I-71 in Madison and Pickaway counties (project 214-95). The northbound lanes of this interstate highway were built with all virgin materials; the southbound lanes contained 25% RAP in the base course and 45% RAP in the intermediate course. The surface layer was a virgin mix design. In 1983, this project was a runner up for the Sheldon G. Hayes award for the best asphalt pavement in the US by the National Asphalt Pavement Association. In 2005, 24 years after the project was constructed, ODOT examined the project and found no discernible difference in performance between the section containing RAP and the virgin mix section.

Ohio DOT has not conducted any formal analyses of how RAP may affect performance over the long term. Powers says that using RAP has become a routine practice in the state.

SUMMARY OF SUCCESSFUL PRACTICES FOR USING RAP

Over the last few years, most states have increased the maximum allowable RAP contents in asphalt mixtures. Around the country, projects with mixes containing 30% to 50% RAP are becoming more common as confidence grows that these mixes can have acceptable performance as long as recognized best practices are followed. Two states with strong track records with using high RAP contents are Florida and Ohio.

One of the basic principles of a successful RAP program is that, in the end, all stakeholders must benefit including agencies, contractors, and taxpayers/users. The primary benefit for agencies is a stabilization of unit prices for asphalt mixes even when raw materials costs are increasing. Contractors can benefit by being more competitive with the use of RAP when they have a sufficient RAP supply and the opportunity to use it to offset higher cost virgin materials. Users benefit by having more roads maintained at a high level with the same transportation budget. Future generations benefit by having non-renewable natural resources preserved for their use.

Florida DOT, Ohio DOT, and most agencies with a strong RAP history, have found that contractors can be more cost-effective with using RAP when the material salvaged during pavement rehabilitation is part of the cost of milling. Contractors will better manage the qualities of the RAP from the beginning when it becomes their property. Contractors can also make more cost effective decisions when designing mixtures under a permissive type specification that gives them latitude in processing and percentages of RAP to meet the mix design and quality assurance criteria.

The same criteria for mix design and acceptance testing (e.g. air voids, VMA, dust-to-asphalt ratio) should be followed regardless of RAP contents. Current AASHTO standards for Superpave mix design allow high RAP contents. When higher RAP contents are used, additional attention should be given to assuring the RAP characteristics are consistent, the RAP aggregate specific gravity is based on valid tests, and the virgin binder (both high and low temperature requirements) should be selected based on the stiffness characteristics of the RAP and the percentage of the RAP binder relative to the total binder content.

BACKGROUND ON RAS USAGE

Replacing virgin asphalt binder with the asphalt binder from RAS was first considered in the early 1980s *(9)*. As polymer modification became more commonplace with the introduction of the Superpave PG binder specifications in the 1990s, engineers began to look at a way to reduce costs of this more expensive binder and still obtain improved performance. One approach was the concept of replacing the polymer modified binder with an aged or reclaimed binder. This approach was considered advantageous as it would further reduce the materials cost for asphalt mixture contractors and still produce an asphalt binder that would resist rutting in hot weather, but might be a disadvantage in terms of long-term cracking. One approach to improve the resistance of asphalt binder to rutting was to use RAP. Another approach that has been used more recently is to use RAS at a percentage of 5% or less to provide an approximate binder replacement of 10% to 30% *(10).*

It has been estimated that 11 million tons of roofing shingles are available for recycling each year in the United States *(9,11)*. 10 million tons of these roofing shingles are generated as tear-off or post-consumer (PC) shingles. PC shingles come from reroofing structures, homes, and other buildings containing asphalt shingles. The properties of these shingles vary depending on the original composition of the shingles and the amount of time that they have been oxidized in the sun.

The other one million tons of shingles come from manufacturers' waste (MW) or factory rejects which may have some minor deficiency that prevents them from meeting the specifications required for the roofing industry. These MW asphalt shingles have not been exposed to the sun and hence have not experienced additional oxidation after manufacture. Therefore, while the asphalt binder has still been air blown in production, the asphalt binder in MW shingles is not as stiff as that in PC shingles. The MW shingles are also less likely to have contamination from other roofing components such as nails, paper, pieces of wood, etc. *(10)*.

It is difficult to get a true picture of the current practices for RAS usage as state specifications are constantly evolving. Table 5 provides information on the current state practices. Most specifications require the contractor to choose MW or PC shingles for an individual mix and discourage mixing the two materials *(12, 13)*. At the time of this report, RAS had been effectively used in projects throughout Texas, Missouri, North Carolina, Georgia, Minnesota, and Florida *(9,12,14,15,16),* as well as other states shown in Table 5.

TABLE 5 Current RAS Specifications

Specification	State
Allows ≤5% PC RAS	Alabama, California, Georgia, Illinois, Iowa, Nebraska, North Carolina, Oregon, Texas, Virginia
Allows ≤5% MW RAS	Alabama, California, Delaware, Florida, Georgia, Illinois, Indiana, Iowa, Maryland, Massachusetts, Minnesota, Nebraska, New Jersey, North Carolina, Oregon, Pennsylvania, Texas, Virginia
Allows ≤7% RAS	Missouri
Allows ≤8% RAS	South Carolina
Allows 15% to 30% Binder Replacement from RAS	Wisconsin
Allows ≤50% Binder Replacement	Michigan
Follows AASHTO MP-15	Kentucky, New Hampshire
Making Efforts with RAS	Arkansas, Mississippi, Montana, North Dakota
Little to No Use of RAS	Alaska, Arizona, Colorado, Connecticut, Hawaii, Idaho, Kansas, Louisiana, Maine, Nevada, New Mexico, New York, Ohio, Oklahoma, Rhode Island, South Dakota, Tennessee, Utah, Vermont, Washington, West Virginia, Wyoming

MISSOURI DOT'S RAS PROGRAM

Historical Perspective

MoDOT received its first request to use post-consumer RAS in asphalt mixtures in St. Louis, Missouri in 2002. Since MoDOT had no experience using RAS at that time, a literature and specification review was conducted to determine the current state of the practice by agencies, such as Minnesota DOT and North Carolina DOT, which allowed the use of RAS in asphalt mixtures. At the time, only North Carolina permitted the use of post-consumer RAS in their asphalt mixtures; however, due to stringent testing requirements and specifications, it was not practical or economical for the state's contractors to use the material.

In order to give MoDOT a chance to observe the construction and performance of this type of mixture, a demonstration project was conducted in December 2004. MoDOT assessed the mixture for both volumetrics and stripping potential and found the results favorable enough to begin a pilot project *(17)*. This project was constructed in 2005 on Route 61/67 in St. Louis County, Missouri. Four 19.0 mm mixtures were placed as a part of this study: (1) PG 58-28, 20% RAP; (2) PG 58-28, 15% RAP, 5% RAS; (3) PG 64-22, 20% RAP; and (4) PG 64-22, 15% RAP, 5% RAS. After six years, some reflective cracking was noticed on the roadway (Figure 3); however, the pavement's performance was still deemed favorable by the DOT.

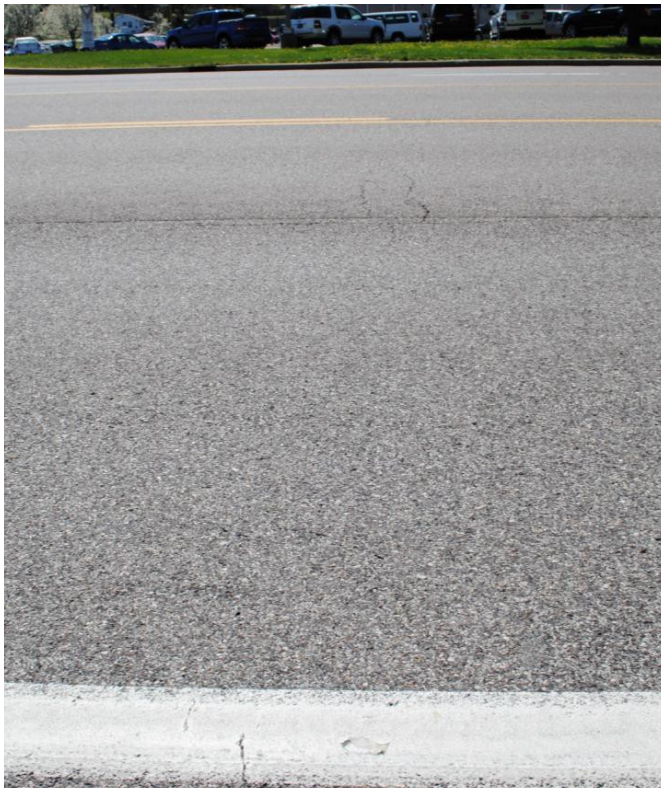

FIGURE 3 MoDOT RAS Pilot Project after Six Years *(18)*

Another field project using manufacturer's waste shingles was constructed in Joplin, Missouri, at approximately the same time with similar results. Due to the initial positive performance of these mixtures, a provisional specification allowing RAS in asphalt mixtures was developed by MoDOT in 2006 followed by a formal specification in 2008.

Every contractor doing work for MoDOT now has mixtures which incorporate the use of either manufacturer's waste or post-consumer RAS. There are more than twenty contractors and recycling organizations that process RAS which can be used effectively in asphalt mixtures. This processing takes place under the guidance of the National Emissions Standards for Hazardous Air Pollutants (NESHAP) which states asbestos testing is not required if the shingles were used in a residential setting; however, as most RAS stockpiles do not delineate RAS source, asbestos testing should always be considered for PC RAS *(17)*.

In addition to encouraging contractors to use RAS, MoDOT has served as the lead state of the Transportation Pooled Fund Study TPF-5(213), *Performance of Recycled Asphalt Shingles in Hot Mix Asphalt*. Other partners in this study include the following agencies: Federal Highway Administration, Minnesota, Iowa, Indiana, California, Colorado, Illinois Tollway, and Wisconsin. This study includes demonstration projects and attempts to understand how RAS affects both the binder and mixture properties of asphalt mixtures by examining quality control practices, grind size of the shingles, and post-consumer and manufacturer's waste shingles *(18)*. The results of this study showed that RAS can be used successfully with warm mix asphalt (WMA) and RAP. The results were promising after two years of field performance that showed no rutting, thermal cracking, or fatigue cracking. Only reflective cracking was noted on five of the projects (*19*).

Due to the aggressive approach MoDOT took in implementing RAS, 20% all of the projects constructed in 2008 contained RAS *(17, 20)*. Since that time the amount of RAS in asphalt mixtures has continued to grow (Figure 4). From 2008 to 2009 there was a 120% increase in the usage of RAS. A 236% increase in the total amount of RAS in asphalt mixtures has been seen since the adoption of the 2008 specifications, when 80,700 tons of RAS were placed in asphalt mixtures in 2011 *(18)*. In 2012, 43% of the newly approved mix designs contained RAS, and 72,300 tons of asphalt mixtures containing RAS were placed in the state. Overall, 2,500 asphalt mixtures have been placed in the state which contain RAS since 2005 *(20)*.

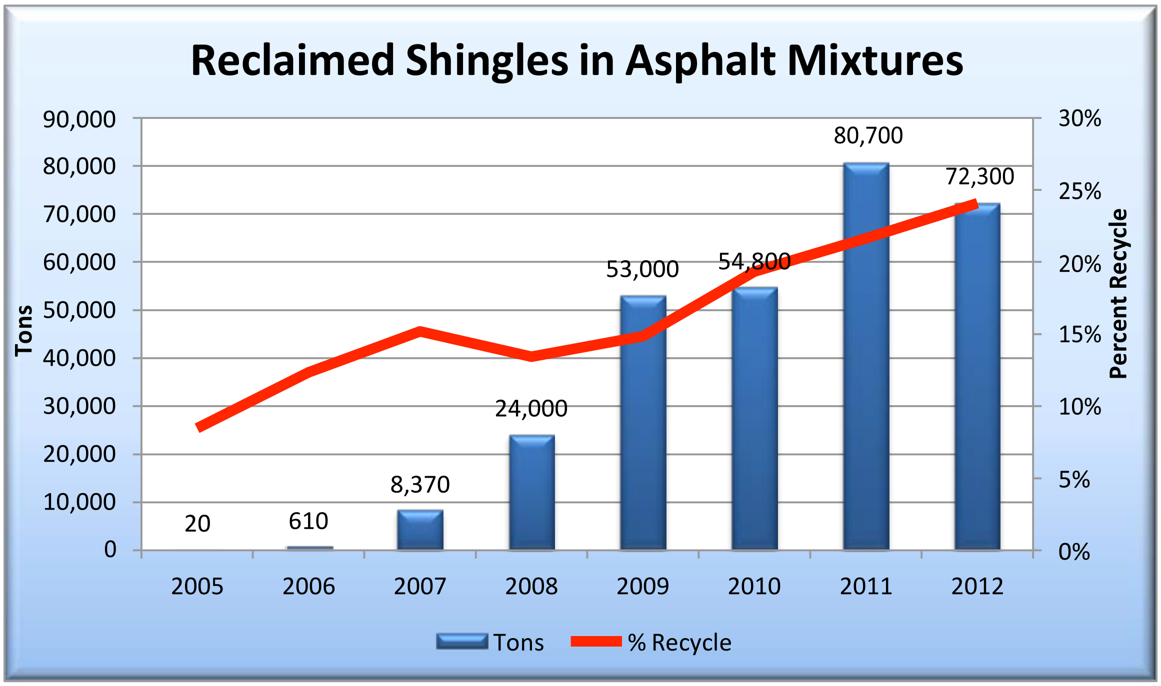

FIGURE 4 MODOT's use of RAS *(20)*

MoDOT's RAS Specifications

MoDOT began developing their initial specifications based on the practices of other states using RAS such as Minnesota and a white paper developed by the Recycled Material Resource Center. However, the specifications have evolved based upon research and performance. The state originally limited the amount of RAS in an asphalt mixture to 5%; however, Missouri now has one of the most progressive specifications allowing contractors to use up to 7% RAS in an asphalt mixture as of 2012.

Despite MoDOT's progressive stance, high RAS mixtures have been shown to be susceptible to specific problems including mixture uniformity (confined to specific plants), placement in cold temperatures, low voids on long hauls, tenderness, and clumping. One cause of these issues can be metering RAS at the plant through a cold feed bin. DOT engineers have noticed metering 5% RAS is pushing the lower limits of the weigh belt's accuracy, and lowering the recycled content makes it even more difficult to produce a consistent mixture. Therefore, contractors must work to ensure uniformity in their mixtures. One way to accomplish this is blending the shingles with RAP through a cold feed bin *(21)*.

One step MoDOT has taken to resolve some other concerns with high RAS mixtures is to require a finer grind on the RAS. Shingles must meet the gradation shown in Table 6 which is a finer grind than currently specified by AASHTO (100% passing the ½-inch sieve). While a coarse grind on the shingles is more expedient and less expensive, a finer grind allows the component materials in shingles to better disperse and contribute to the mixture. In addition to mixing advantages, the finer grind also reduces the chances of shingle clumps or pop-ups on the roadway *(21)*.

MoDOT also allows contractors to determine the asphalt content of their RAS using either an ignition oven or chemical extraction. All of the binder in the RAS is assumed to mix completely with the virgin binder.

TABLE 6 MoDOT Shingle Gradation Requirement

Sieve	⅜"	#4	#8	#16	#30	#50	#100	#200
Percent Passing (%)	100	95	85	70	50	45	35	25

MoDOT's primary concerns associated with incorporating post-consumer shingles in asphalt mixtures have been deleterious materials and premature cracking, as the shingle asphalt is much stiffer than paving-grade asphalts due to the air blown asphalt. Limits on shingle content can minimize the effects of deleterious materials. The original 2008 specification required that all RAS had a deleterious material content less than 0.5%; however, MoDOT later determined that this might not be practical for their contractors. The limit was later raised to 3.0% with wood accounting for less than half of the total deleterious content. Since RAS is generally added to the asphalt mixtures in small percentages, this specification still keeps the deleterious material added by the RAS much lower than allowed in the aggregates. MoDOT found that nails were commonly removed during RAS processing.

To assess how the blended binder was affected by the RAS binder, binder from tear-off shingles, new shingles, and the virgin binder were blended to determine the performance grade, despite knowing that 100% blending probably does not occur in production. The agency determined when more than 70% of the virgin binder was added to the blend, the low temperature grading was not greatly affected by the shingle binder. The effects of the shingle binder became more prominent when less than 70% of the virgin binder was used in the blend. For each mixture using more than 30% reclaimed binder (from RAP and/or RAS), testing of the mixture is necessary to determine the actual required virgin binder grade for the mixture. A PG 58-28 binder is required for mix designs using more than 30% reclaimed binder *(20)*.

MoDOT's Test Project

In 2011, MoDOT resurfaced US Route 50 in Moniteau, Morgan, and Pettis Counties from Sedalia to Tipton, Missouri. Over the 24 miles of this project, a series of test sections were placed over the existing concrete and composite pavements (Figure 5). The existing concrete pavements had longitudinal cracking, mid-panel cracking, and an International Roughness Index (IRI) greater than 150 inches per mile. The composite pavement had reflective cracking through the asphalt layer and severe raveling. The contractor produced and placed three surface and three intermediate layer mix designs for the project. The 19 mm nominal maximum aggregate size (NMAS) mixes were placed 2-inches thick over the existing pavement and 12.5 mm NMAS mixtures were placed 1.75-inches thick as the surface layer. The mix designs included a PG 64- 22 asphalt mix with hydrated lime, a PG 64-22 asphalt mixture with 3% RAS, and a control mixture with a PG 64-22 binder and 28% RAP. The RAS mixture was specifically designed to assess the rutting resistance of the mixture, despite knowing that rutting is not a common issue with RAS mixtures due to the increased stiffness. The six test sections were placed over the 24 miles: three over concrete and three over the composite pavement. Each test section was approximately 500 feet long and is to be observed over a three year period.

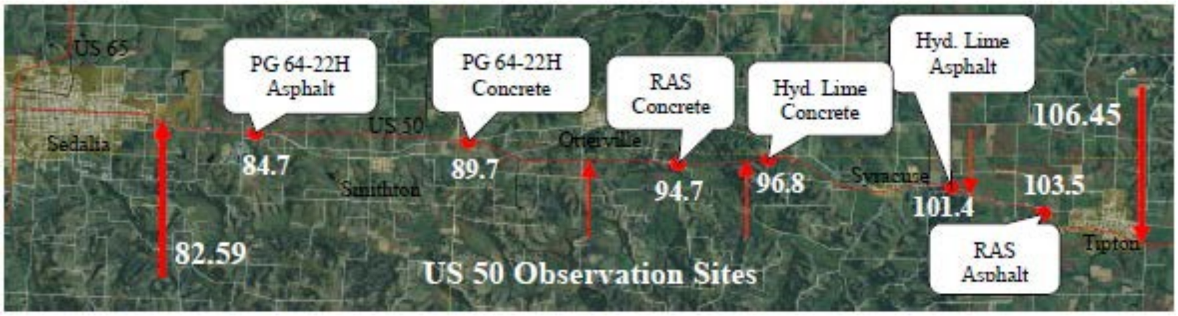

FIGURE 5 MoDOT Case Study Locations

In addition to field testing, QC data and laboratory tests were conducted on the mixtures. Mixture properties and gradations are shown in Tables 7 and 8, respectively. As seen in these tables, the three mixtures for each NMAS had similar volumetric properties such as total binder, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and volume of effective asphalt (VEA). All six mixtures passed the minimum tensile strength ratio (TSR) of 0.80. At two years of trafficking, all of the test sections have performed well.

TABLE 7 Mixture Properties for the MoDOT RAS Test Project

Mixture Properties from Job Mix Formulas						
Mixture	SP125 A	SP125 B	SP125 C	SP190 A	SP190 B	SP190 C
G_{mm}	2.440	2.462	2.474	2.470	2.472	2.476
Total Binder, P_b (%)	5.0	5.2	5.0	4.5	4.6	4.5
Virgin Binder, P_{bv} (%)	3.7	3.7	3.8	3.3	3.2	3.4
P_{bev} Ratio (%)	72	68	74	74	67	75
VMA (%)	14.5	14.5	14.2	13.4	13.7	13.5
VFA (%)	72	72	72	70	71	70
VEA (%)	10.5	10.5	10.2	9.4	9.7	9.5
Dust Ratio, P_{-200}/P_{be}	1.1	1.2	1.4	1.1	1.3	1.4
RAP (%)	28	20	28	25	18	25
RAS (%)	--	3	--	--	3	--
Hydrated Lime (%)	--	--	1.0	--	--	1.0
Anti-strip Liquid (%)	1.4	1.0	1.0	1.4	1.0	1.0
TSR (%)	85	86	92	90	81	87

TABLE 8 Mixture Gradations

Mixture Gradation, Percent Passing by Weight						
Mixture	SP125 A	SP125 B	SP125 C	SP190 A	SP190 B	SP190 C
1”	100.0	100.0	100.0	100.0	100.0	100.0
¾”	99.9	100.0	100.0	100.0	98.1	98.1
½”	95.8	95.5	95.3	82.8	89.5	89.4
⅜”	86.7	89.8	89.3	67.4	81.3	81.0
#4	46.8	60.0	60.4	38.4	53.4	47.6
#8	28.3	31.3	31.9	23.1	28.2	23.8
#16	18.4	18.4	19.2	15.3	16.8	15.3
#30	13.6	12.2	13.2	11.5	11.2	11.0
#50	9.9	8.9	9.8	8.6	8.3	8.5
#100	7.1	6.2	6.7	6.1	5.8	6.0
#200	5.0	4.5	5.1	4.3	4.3	4.5

Economic Savings
MoDOT embraced RAS for two significant reasons. First, incorporating shingles in asphalt mixtures has reduced 146,000 tons of shingles from disposal in landfills, making it an extremely positive environmental practice. Second, using RAS saves the state $3 to $5 per ton of asphalt mixture when used between 5 and 7% RAS. While this may not seem significant, since the average resurfacing project in the state uses 30,000 tons of asphalt, this results in a $90,000 to $150,000 savings per project for the state *(22)*.

Table 9 provides the mixture costs per ton for the mixes placed. As can be seen, using 3% RAS allowed the MoDOT to save $2.11 per ton for the 12.5 mm mixture and $1.83 per ton for the 19.1 mm mixture compared to a 28% RAP mixture.

TABLE 9 Mixture Costs

Mixture Cost per Ton		
Mixture	Component	Cost
SP125 A	PG 64-22H (28% RAP)	$47.99
SP125 B	PG 64-22 w/ RAS (20% RAP, 3% RAS)	$45.88
SP125 C	PG 64-22 w/ Hyd. Lime	$47.79
SP190 A	PG 64-22H (28% RAP)	$44.81
SP190 B	PG 64-22 w/ RAS (20% RAP, 3% RAS)	$42.98
SP190 C	PG 64-22 w/ Hyd. Lime	$44.74

TEXAS DOT’S SHINGLE RECYCLING PROGRAM

Historical Perspective
In 1997, the Texas Department of Transportation (TxDOT) began experimenting with RAS in asphalt mixtures. On State Highway 31 outside of Corsicana, Texas, Duininck Brothers constructed two test sections containing RAS to compare to a common control asphalt mixture using an AC-20 binder. The first test section contained 5% manufacturer’s waste shingles while

the second test section used 5% post-consumer RAS. While there were some initial construction issues with the tear-off RAS section, the performance of both RAS test sections were equivalent to the control and encouraged TxDOT to consider a RAS specification that allowed 5% RAS by weight of mixture *(23)*.

While the first testing began in the late 1990s, TxDOT did little to develop their RAS program until after the 3rd Asphalt Shingle Recycling Forum in Chicago, Illinois, in 2007. At this forum, TxDOT learned of other agencies and contractors who were using 5 to 7% RAS in their asphalt mixtures. TxDOT was then encouraged to return to their state and determine what could be done using the shingles found in Texas. Preliminary investigations were conducted to determine an appropriate shingle content which would allow the mixture to perform well and not adversely affect performance. The value set in the specifications was 5% RAS by weight of the mixture for dense-graded mixtures only, but this produced too high a recycled binder ratio when contractors used RAS in conjunction with RAP.

A significant step towards the use of RAS in asphalt mixtures in Texas was a memo issued by the Texas Commission on Environmental Quality (TCEQ) allowing contractors to use post-consumer RAS *(24)*. TCEQ had previously only allowed manufactured waste shingles from a similar 2006 memo. The 2009 memo stated that all residential roof post-consumer shingles must be certified as asbestos-free. TxDOT requires that every 100 tons of post-consumer shingles be tested for asbestos *(25)*.

TxDOT hosted the 5th Asphalt Recycling Forum in Dallas in October 2011. TxDOT took this opportunity to share with other states and contractors the advancements made over the past fourteen years in the state. In addition to hosting this forum, TxDOT has conducted seminars and meetings to teach contractors and agency employees how to correctly design, produce, and construct asphalt mixtures containing RAS *(26)*.

Two concerns are commonly expressed by the agency and contractors in Texas when discussing RAS mixtures. The first is contractor education. While some contractors study the mixtures and determine how to produce mixtures that are workable and will result in good performance, other contractors do not understand how to design with RAS and solely produce RAS mixtures to stay competitive in a low bid market. This can result in a mixture that is too stiff, unworkable, and prone to premature cracking. The second major concern people associate with RAS is long-term mixture performance due to either dry mixtures or aged binder in the RAS. If a mixture does not have enough asphalt, problems such as premature cracking tend to become evident more quickly. However, while RAS commonly is blamed for the dry mixtures, TxDOT suggests the problem is more widespread than only mixtures using recycled materials.
TxDOT has undertaken efforts such as training courses and workshops to make sure designers understand how to effectively maximize the use of recycled materials.

Economic Savings

While these concerns are legitimate, one of the biggest advantages TxDOT has seen with using RAS are financial. Table 10 shows the costs of four standard mixtures used in Texas. Using 5% RAS can reduce the mixture price by 13%. The combination of RAS and RAP in a mixture even further reduces the cost of the mixture by 20%. Other benefits TxDOT has noticed are increased strength and stiffness, conservation of raw materials, and reduction in consumption of landfill space *(26)*.

TABLE 10 Mix Costs *(26)*

Price ($/ton)			
Type D PG 64-22	With 20% RAP	With 5% Shingles	With 15% RAP and 5% Shingles
$40.70	$36.71	$35.61	$32.62

TxDOT's RAS Specifications

Like MoDOT, TxDOT requires a finer grind of RAS than is recommended by AASHTO. TxDOT initially required 100% of the shingles to pass the ½-inch sieve and 95% to pass the ⅜-inch sieve; however, this was further reduced to increase the activation of the RAS asphalt. TxDOT specifications currently require 100% of RAS pass the ⅜-inch sieve. Since making the change to a finer grind, TxDOT and contractors have noticed better heat transfer and RAS asphalt blending.

TxDOT has developed a unique specification for determining the deleterious material content in its processed RAS. For this specification, a 1000 gram sample of RAS is poured over a specially designed pan (Figure7). A magnet has been placed across the middle of the pan to catch any metal which remains in the processed RAS as the material passes over it. The metal pieces are then weighed to determine how much metal was in the RAS. The remaining RAS is then sieved over the ⅜-inch, No. 4, No. 8, and No. 30 sieves. The minus No. 30 material is discarded. The deleterious materials retained on each sieve are then determined by manual separation and weighed by sieve size. The total percent deleterious materials in the RAS sample is then quantified using Equation 3. Texas requires less than 1.5% deleterious materials in their processed RAS.

$$P = \frac{M + N_{3/8} + N_4 + N_8 + N_{30}}{W_t} * 100 \quad (3)$$

where

P = percent of deleterious matter by weight
M = weight of material retained by magnet, g
$N_{\#}$ = weight of deleterious material on sieve #, g
W_t = total weight of sample, g

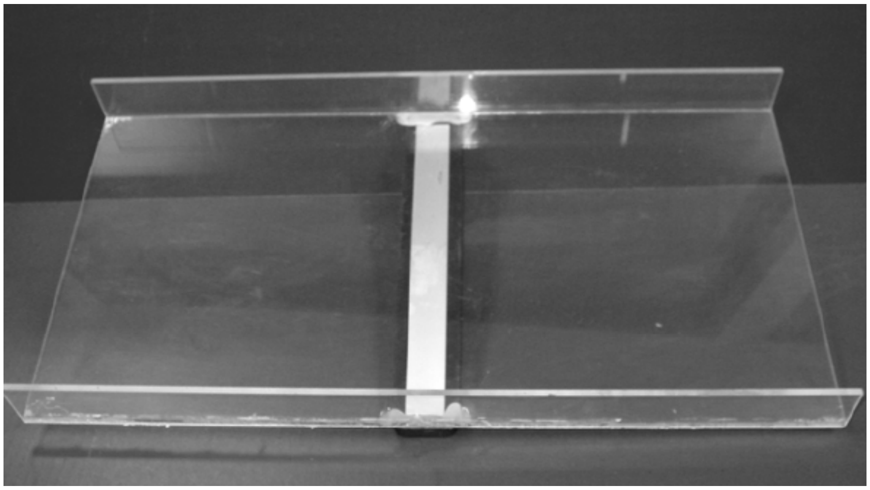

FIGURE 7 TxDOT Deleterious Material Pan

To determine the asphalt content and aggregate gradation of a RAS sample, contractors can use the ignition oven. Zhou et al. *(27)* completed a study for TxDOT showing negligible differences between ignition oven and chemical extraction asphalt content and aggregate gradation values. The small differences in asphalt content results from the two methods were attributed to burning of fibers, loss of fines in the shingles, or chemical extraction not removing all of the stiff binder from the RAS. Therefore, Zhou et al. recommended using the ignition oven for its simplicity and effectiveness. While research is still underway to assess how much the RAS binder blends with the virgin binder, TxDOT assumes 100% of the RAS binder is effective in the new mixture.

A challenge for many contractors in Texas and other southern states is workability of the RAS stockpiles. When RAS stockpiles are exposed to hot weather and solar radiation, the processed RAS tends to agglomerate and stick together. This makes feeding RAS through cold feed bins difficult and may reduce activation of the RAS binder in the plant. TxDOT proposed two options for preventing this problem. First, contractors could cover the stockpile (Figure 8) to minimize moisture and sunlight from reaching the stockpile, or second, the contractor could mix the RAS with either a sand or a fine RAP source. The original intent of this specification was to allow the material to be more workable; however, the agency soon realized contractors were developing RAS/RAP stockpiles which were difficult to assess for quality. To alleviate this problem, the agency asked contractors to use separate cold feed bins for all recycled materials. If a RAP/RAS blend was to be used, the entire blend was considered RAS and limited to 5% by weight of the mixture.

While TxDOT allows 5% RAS in dense-graded mixes, permeable friction courses, Superpave mixtures, and stone matrix asphalt, the department limits the total amount of reclaimed binder which can be put into each mixture by pavement layer and mixture type (Table 11). For example, a dense-graded base mixture can have 40% reclaimed binder, but stone matrix asphalt on the surface of a pavement structure is limited to 15% reclaimed binder. This allows the agency to use mixtures with lower recycled contents at the surface of the pavement structure where they will be exposed to higher shear and thermal stresses *(23)*.

TABLE 11 TxDOT Binder Ratio Specifications

Mix Type	Binder Ratio (%)			Maximum Percent Allowed (Percent by Weight of Total Mixture)								
				Unfractionated RAP			Fractionated RAP			RAS		
	S	I	B	S	I	B	S	I	B	S	I	B
Dense-Graded	30	35	40	10	10	10	20	30	40	5	5	5
PFC	15	-	-	0	-	-	10	-	-	5	-	-
Superpave	25	30	35	10	10	10	20	25	30	5	5	5
SMA	15	20	-	0	0	-	15	20	-	5	5	-

NOTE: S = Surface mixture; I = Intermediate mixture; B = Base mixture

FIGURE 8 RAS Stockpile Covering *(23)*

One change TxDOT has recently made to their specifications related to binder replacement is an attempt to have better controls on the mixtures through QC testing. While contractors are required to monitor the asphalt content of the RAS mixtures, TxDOT can require changes to the mixture if the recycled binder content surpasses the maximum allowable ratio. For example, if based on QC testing the recycled binder content of a dense-graded surface mixture is greater than 30%, the plant must reformulate the mixture through adjustments to ensure that less than 30% recycled binder is going into the mixture. This could be accomplished by increasing the virgin binder content or reducing the overall RAS or RAP content of the design.

Texas Contractor's Experience

APAC-Texas has been one of the leading contractors in the state that uses shingles. In 2008 alone, the company used over 8,000 tons of RAS. In November 2008 alone, it placed more than 3,000 tons of RAP/RAS mixtures in Dallas County. Largely based on experiences of APAC, the following recommendations were made for contractors using RAS mixtures *(26)*:

- Do not exceed recycled binder ratio limits;
- Blend RAS with sand to prevent clumping;
- Verify RAS gradation daily;
- Treat RAS like RAP in laboratory settings;
- Use smaller samples in the ignition oven to determine asphalt content (i.e. 500 to 600 grams); and
- Keep indirect tensile strengths lower than 200 psi, and below 180 psi if possible.

TxDOT's RAS SMA

As shown in Table 11, TxDOT allows contractors to use RAS in SMA mixtures. In accordance with TxDOT specification 346 SMA-D, APAC-Texas produced an SMA mixture containing 5% manufacturer's waste RAS that was placed on IH 30 in Dallas County, Texas, on May 14, 2012. Previously, APAC-Texas had produced a 2400 ft. test section on the eastbound outside lane of this project which was compared to a control SMA mixture. Based on the successful results the trial mixture, the state allowed the contractor to place the entire westbound pavement using the 5% RAS mixture.

PG 76-22 asphalt binders are commonly used for SMA mixtures by TxDOT; however, the RAS- SMA was produced using the combination of 5% RAS and a PG 70-22 binder to reduce the need for a more expensive binder. The RAS for the project was ground finer than the TxDOT specification required. 100% of the RAS passed the ¼-inch sieve. This allowed the material to have better heat transfer between the RAS, aggregate, and virgin binder.

The volumetrics of the mix design, indirect tensile strengths, and Hamburg test results are provided in Table 12. The laboratory tests suggest the mixture will be resistant to both rutting and stripping.

TABLE 12 Mix Design

Property	Test Result
RAS (%)	5.0
Gse	2.736
RAS AC (%)	18.0%
Opt. AC (%)	6.0
Ratio of Recycled to Total Binder (%)	15.0
Air Voids (%)	4.0
VMA (%)	17.8
Fiber Content (%)	0.2
Mixing Temp (°F)	325
Compaction Temp (°F)	300
Indirect Tensile Strength (psi)	162.7
Hamburg, Stripping Inflection Point (cycles)	>20,000
Hamburg Rut Depth (mm)	3.34

Additional Hamburg (TEX-242F) and Overlay Testing (TEX-248-F) was conducted on the mixture during the QC phase of testing to ensure quality mixtures were being placed. The Hamburg Wheel Tracking Test showed the mixture had 4.71 mm of rutting and reached 403 cycles in the Overlay Tester at a crack displacement of 0.025 inches.

During the construction of the mixture, density measurements were always greater than 94% of the theoretical maximum specific gravity. No difficulties were encountered when placing the mixture using a spray paver. To date, the mixtures are performing well in the field in terms of cracking, rutting, and ride.

SUMMARY OF SUCCESSFUL PRACTICES FOR USING RAS

Due to the high amount of asphalt binder in RAS, states have begun to develop specifications which allow contractors to use RAS for binder and virgin aggregate replacement. States which allow RAS commonly have a maximum content of 5%. As research on mix design and long-term performance progresses and contractors become more familiar with these materials, the ability to use this recycled material may continue to grow. Two states with strong track records using RAS are Missouri and Texas.

One benefit of using RAS in asphalt mixtures is the economic savings. As the material cost of asphalt binder increases, the cost of processing and using RAS in asphalt mixtures is relatively constant. In addition, replacing high-cost mixture components such as virgin binder and virgin aggregate in some parts of the United States allows contractors to be more competitive in the market.

Most agencies who use RAS, including MoDOT and TxDOT, understand the importance of RAS source quality. RAS properties such as the grind size or gradation and deleterious materials must be controlled to produce and construct an asphalt mixture which has the capability of performing in the field. The finer the RAS grind, the more RAS binder can be incorporated into the mixture. This requires contractors to manage their RAS properties. Another challenge to using RAS in asphalt mixtures is managing moisture in RAS stockpiles. RAS with high moisture contents wastes energy in the plant by having to dry moisture out of the RAS before the binder can be activated for the mix. When this occurs, the RAS mixture may look dry and be susceptible to early cracking. Covering RAS piles can prove beneficial to preventing high moisture contents.

CONCLUSIONS

While some stakeholders fear that the use of recycled materials in asphalt mixtures may produce inferior mixtures to virgin asphalt mixtures, state agencies who have spent time and resources into understanding material characterization, mix design, and mixture production have seen significant economical and raw material savings. In a similar manner to virgin aggregates and asphalt binders, it is essential that contractors and agencies understand the properties and characteristics of recycled materials used in an asphalt mixture.

When RAS and RAP are processed to yield consistent stockpiles and the materials are properly characterized as part of the mix design process, the resulting asphalt mixtures have been shown to have very good field performance. Agencies considering either beginning or increasing the use of these recycled materials should look to other agencies which have strong recycling programs for guidance and information regarding current practices to avoid early mistakes which might reduce the chances of effectively using both RAP and RAS.

REFERENCES

1. Kandhal. P., Recycling of Asphalt Pavements - An Overview. *Journal of the Association of Asphalt Paving Technologists*, Vol. 66, 1997.
2. West, R., D. Timm, R. Willis, B. Powell, N. Tran, D. Watson, M. Sakhaeifar, R. Brown, M. Robbins, A. Vargas-Nordcbeck, F. Leiva Villacorta, X. Guo, and J. Nelson. *Phase IV NCAT Pavement Test Track Findings*. NCAT Report 12-10, National Center for Asphalt Technology, Auburn, Alabama, 2012.
3. Hajj, E., P. Sebaaly, L. Loria, S. Kadd, S, and T. Liske. Impact of High RAP Content on the Performance Characteristics of Asphalt Mixtures in Manitoba. Presented at 2011 Annual Conference of the Transportation Association of Canada, Edmonton, Alberta, 2011.
4. West, R., J. Michael, R. Turochy, and S. Maghsoodloo Use of Data From Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements, Transportation Research Record No. 2208, 2011, pp. 82-89.
5. Page, G.C. *Florida's Experience in Hot Mix Asphalt Recycling*. Study 87-1, Bureau of Materials and Research, Florida Department of Transportation, 1987.
6. Estakhri, C., C. Spiegelman, B. Gajewski, Y. Guiquin, and D. Little. *Recycled Hot-Mix Asphalt Concrete in Florida: A Variability Study*. ICAR-401-1/98. International Center for Aggregate Research, College Station, TX, 1998.
7. FHWA. Pavement Smoothness. http://www.fhwa.dot.gov/pavement/smoothness. Accessed November 15, 2012.
8. Nash, T., G.A. Sholar, G.C. Page, and J.A. Musselman. Evaluation of High RAP Asphalt Mixture Performance in Florida. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2294, 2012, pp. 16–25.
9. Davis, J. Roofing the Road – Using Asphalt Shingles as Binder. *Asphalt Magazine*, October 2009. http://www.asphaltmagazine.com/news/detail.dot?id=de825f4f-2b6b-4dc4-a12b-dcc3b4c31935. Accessed March 13, 2012.
10. Hansen, K, and D. Newcomb. *Asphalt Pavement Mix Production Survey on Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, and Warm-mix Asphalt Usage: 2009-2010*. IS 138. National Asphalt Pavement Association, Lanham, MD, 2011.
11. McGraw, J., A. Zofka, D. Krivit, J. Schroer, R. Olsen, and M. Marasteanu. Recycled Asphalt Shingles in Hot Mix Asphalt. *Journal of the Association of Asphalt Paving Technologists*, Vol. 77, 2007.
12. Dan Krivit Associates. Recycling Tear-off Asphalt Shingles: Best Practices Guide. Construction Materials Recycling Association, 2007.
13. Mallick, R.B. and W.S. Mogawer. "Evaluation of Use of Manufactured Waste Asphalt Shingles in Hot Mix Asphalt," Technical Report #26, Chelsea Center for Recycling and Economic Development, University of Massachusetts, July 2000.
14. Kandhal, P. *Waste Materials in Hot Mix Asphalt – An Overview*. NCAT Report 92-06. National Center for Asphalt Technology, Auburn, Alabama, 1992.
15. Carolina Asphalt Pavement Association. *Best Practices Guide for Post-Consumer Reclaimed Asphalt Shingles in Asphalt Pavement*. September 2011.

16. Watson, D., A. Johnson, and H. Sharma. Georgia's Experience with Recycling Roofing Shingles in Asphaltic Concrete. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1638, 1998, pp. 129-133.
17. Schroer, J. Missouri's Use of Recycled Asphalt Shingles (RAS) in Hot Mix Asphalt. Presented at 2009 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2009.
18. Schroer, J. Missouri's Use of RAS in Asphalt Pavements. Presented at 2012 Kansas Asphalt Paving Conference, Lawrence, Kansas, 2012.
19. Williams, C., A. Cascione, J. Yu, D. Haugen, M. Marasteanu, and J. McGraw. *Performance of Recycled Asphalt Shingles in Hot Mix Asphalt*. Report TPF-5(213), Iowa State University, August, 2013.
20. Schroer, J. *Use of Reclaimed Shingles in Missouri*. Missouri Department of Transportation, 2013.
21. Schroer, J. Asphalt Shingles in HMA, MoDOT Specification. Presented at RAS in HMA Showcase, September 23, 2008.
22. Missouri Department of Transportation. Roofs to Roads, Missouri Going Green. http://www.modot.org/goinggreen/shingles.htm. Accessed February 3,2013.
23. Lee, R. Recycled Asphalt Shingles in HMA. Presented in Indianapolis, Indiana, November 2012.
24. Texas Commission of Environmental Quality, *Authorization Memo: Recycled Asphalt Shingles as Recycled Asphalt Products in Hot Mix Asphalt Plants*. February 12, 2009.
25. Texas Department of Transportation, *Asphalt Roofing Shingles*. http://www.dot.state.tx.us/business/contractors_consultants/recycling/asphalt_shingles.htm. Accessed November 1, 2012.
26. Krivit, D. Texas Recycles Asphalt Shingles in a Big Way. *C&D World*, 2011. http://www.cdworldmag.com/index.php/features/352-texas-recycles-asphalt-shingles-in-a-big-way. Accessed September 12, 2012.
27. Zhou, F., J. Button, and J. Epps. *Best Practice for Using RAS in HMA*. FHWA/TX-12/0-6614-1, Texas Transportation Institute, College Station, Texas, 2012.