A Field Review: Successful Practices and Lessons Learned When Using Reclaimed Asphalt Shingles in Asphalt Mixtures

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Abstract

The use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in asphalt mixtures can provide initial cost savings through the replacement of a portion of the aggregate and virgin asphalt binder in a mixture for use in highways and trails. This keeps the reclaimed material from being discarded in landfills. Improvements in mixture design and materials processing and handling have increased the amount of RAP and RAS that can be used in asphalt mixtures today. The performance history of RAP mixtures over the past 40 years and RAS over the past 20 years, when properly engineered, produced, and constructed, can provide comparable levels of service as asphalt mixtures with no reclaimed materials, referred to as virgin asphalt mixtures. However, in some cases durability of asphalt mixtures containing RAS has been poor. Additionally, agency rationale for using RAS can be for very different reasons with different goals. Field visits of six agencies regularly using RAS in asphalt mixtures took place in the Summer of 2019. This effort showed that agencies with detailed policy and specifications on RAS use had the best control and performance. Field performance reviews of in-service pavements up to 9 years old containing RAS or RAP and RAS revealed that with appropriate policy, mixture design and control of quality, good performance can be obtained. This was typically obtained through the following comprehensive steps: 1) regular and diligent review of specifications and mixture design procedures, 2) monitoring pavement performance, 3) working with industry and 4) performing research as a basis for changes.

Key Words: RAS, RAP, RBR, pavement performance, implementation, RAS processing, asphalt plants with RAS, specifications
# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

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

AASHTO – American Association of State Highway and Transportation Officials
AC – Asphalt Content
a.k.a. – also known as
AP – Asphalt Pavement
APA - Asphalt Pavement Analyzer
AV – Air Voids
BOL – Bill of Lading
COC - Certificates of Compliance
DelDOT – Delaware Department of Transportation
DNREC - Delaware Department of Natural Resources and Environmental Control
DOT – Department of Transportation
EPA – Environmental Protection Area
FHWA – Federal Highway Administration
FRAP – Fractionated Reclaimed Asphalt Pavement
GHG – Greenhouse Gas
GTR – Ground Tire Rubber
Gmm – Mixture Theoretical Maximum Specific Gravity
Gsb – Aggregate Bulk Specific Gravity
Gse – Aggregate Effective Specific Gravity
HMA – Hot Mix Asphalt
HWT – Hamburg Wheel Track
ICT – Illinois Center for Transportation
IDEAL-CT – Ideal Cracking Test
IDOT – Illinois Department of Transportation
I-FIT – Illinois Flexibility Index Test
JPC – Jointed Plain Concrete Pavement
JSP – Job Special Provision
LTA – Long Term Aging
MoDOT- Missouri Department of Transportation
MWAS – Manufactured Waste Asphalt Shingles
NAPA - National Asphalt Pavement Association
NCHRP - National Cooperative Highway Research Program
NMAS – Nominal Maximum Aggregate Size
ODOT – Oregon Department of Transportation
PCAS – Post-Consumer Asphalt Shingles (a.k.a., tear offs)
PCCP – Portland Cement Concrete Pavement
PennDOT – Pennsylvania Department of Transportation
PG – Performance Graded
PWL – Percent Within Limits
QA – Quality Assurance
QC - Quality Control
RAM – Reclaimed Asphalt Material
RAP - Reclaimed Asphalt Pavement
RAS - Reclaimed Asphalt Shingles
RBR - Reclaimed Binder Ratio
RTR – Recycled Tire Rubber
SEA - State Environmental Agency
SHA - State Highway Agency
SMA – Stone Matrix Asphalt
TDF – Tire Derived Fuel
TxDOT – Texas Department of Transportation
TxOL - Texas Overlay Test
TFHRC – Turner-Fairbank Highway Research Center
VMA – Voids in Mineral Aggregate
WMA – Warm Mix Asphalt
Executive Summary

The use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in asphalt mixtures can provide initial cost savings through the replacement of a portion of the aggregate and virgin asphalt binder in a mixture for use in highways and trails. This keeps the reclaimed material from being discarded in landfills. Improvements in mixture design and materials processing and handling have increased the amount of RAP and RAS that can be used in asphalt mixtures today. The performance history of RAP mixtures over the past 40 years and RAS over the past 20 years, when properly engineered, produced, and constructed, can provide comparable levels of service as asphalt mixtures with no reclaimed materials, referred to as virgin asphalt mixtures. However, in some cases durability of asphalt mixtures containing RAS has been poor. Additionally, agency rationale for using RAS can be for very different reasons with different goals.

Field visits of six agencies regularly using RAS in asphalt mixtures took place in the Summer of 2019. The objectives of the visits were to:

- Learn more regarding the details of best practice recommendations implemented by agencies for using RAS.
- Collect and communicate experiences, lessons learned and performance information.
- Identify gaps for creation of research needs statements for the Turner-Fairbank Highway Research Center (TFHRC) and/or the National Cooperative Highway Research Program (NCHRP) on use of recycled materials in asphalt pavements.
- Identify other uses for RAS than in asphalt mixtures.

Initially, documents were reviewed prior to the visit. The visits included agency, RAS producer, and contractor interviews, as well as some RAS processing facility and asphalt mixture plant tours. Finally, pavements with RAS in the surface mixtures were inspected in each state visited.

This effort showed that agencies with detailed policy and specifications on RAS use had the best control and performance. Field performance reviews of in-service pavements up to 9 years old containing RAS or RAP and RAS revealed that with appropriate policy, mixture design and control of quality, good performance can be obtained. This was typically obtained through the following comprehensive steps: 1) regular and diligent review of specifications and mixture design procedures, 2) monitoring pavement performance, 3) working with industry and 4) performing research as a basis for changes.

A wide range of criteria used by agencies which specify and design mixtures and pavements incorporating RAS were identified and summarized. They were then compared to pavement performance to assess their effectiveness and identify opportunities for improvement. Important considerations for implementing the use of RAS were identified and described or illustrated that could be of benefit to other agencies. This included agencies that may want to start using RAS or agencies currently using RAS that may want to make some refinements to their process. They included programmatic, mixture design, mixture production, mixture acceptance, RAS production, and quality control considerations. Collectively, this illustrated that care must be taken during design, production, and construction to ensure desired performance. It also revealed that there are opportunities for future improvements that can be accomplished through research needs identified.
Introduction
Since the 2008 peak in asphalt binder price, the desire to increase use of reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) has continued. It has been driven by the need for cost-effective alternatives to virgin asphalt binder and the desire to make asphalt pavements more sustainably. However, the use of RAS has created challenges for some state Departments of Transportation (DOTs) to specify, design, and control the quality of asphalt mixtures containing RAS to assure good long-term pavement performance. The primary concern with mixtures containing RAS is assuring that the high stiffness RAS binder in the mix does not lead to long-term pavement durability issues such as raveling and cracking.

Use of Recycled Materials in Asphalt Pavements
The most common materials recycled into asphalt pavements include RAP, RAS and recycled tire rubber (RTR). When RTR is ground and recycled into asphalt pavement applications (asphalt mixture and binder), it is often referred to as ground tire rubber (GTR). A summary of the recent annual use of each of these three recycled materials is provided in Table 1.

| Table 1. Approximate Annual Generation, Re-Use and Disposal of Several Recycled Materials. |
|---------------------------------------------|----------------|----------------|---------------|
| Annual Tons (1,000’s) | RAP | RTR | RAS |
| Generated | 101,100 | 4,189 | 13,200 to 17,000 |
| Landfilled | 12 | 670 | 12,000 to 16,000 |
| Recycled into Asphalt Binder and/or Mixtures | 82,200 | 121 | 1,053 |
| Recycled Elsewhere | 8,500 | 3,398 | 50 |
| Stockpiled | 10,200 | N/A | N/A |
| No. of DOTs Allowing (including D.C. and Puerto Rico) | 52 | 11 | 31 |

According to the National Asphalt Pavement Association (NAPA), the amount of RAP accepted in 2018 was 101.1 million tons, and the RAP used increased to 82.2 million tons in asphalt mixtures (1). This was an increase of 7.9 percent from 2017. The average percent RAP used in asphalt mixtures was 21.1 percent. About 8.5 million tons of RAP were used as aggregate, cold mix or other pavement applications. Only about 12,100 tons of RAP was landfilled. The remainder was stockpiled for future use providing an approximate 1.4 years of inventory based on usage in 2018. More than 97 percent of asphalt mixture reclaimed from old asphalt pavements was being put back to use in new pavement and the remaining 3 percent being used in other civil engineering applications, such as unbound aggregate bases. RAP is allowed by 52 DOTs including the District of Columbia and Puerto Rico.

According to the U.S. Tire Manufacturers Association (USTMA), the amount of scrap tires generated was 4.189 million tons (2). Of the scrap tire market, ground tire rubber accounted for 1.013 million tons of which 12 percent (0.121 million tons) was used in asphalt (2). There are many other aftermarket applications for RTR such that only 16 percent (0.67 million tons) were reported to be landfilled. Over the last 5 years between 9 and 14 DOTs reported use GTR in asphalt applications, but this number has not been consistent (1).

The U.S. Environmental Protection Agency (EPA) reported that in 1990, over 77 percent of scrap tires were landfilled, stockpiled or illegally dumped (3). In 2018, the USTMA reported that only about 16 percent of scrap tires were land disposed (2). Strong markets for scrap tires have developed over the past thirty years. Figure 1 illustrates the distribution of current markets. The markets specifically include:
• Tire derived fuel (TDF) (about 43 percent) whose markets include the cement industry (46 percent), pulp and paper mills (29 percent), and electric utility boilers (25 percent).
• Ground rubber applications (about 25 percent) whose markets include molding and extruding (38 percent), playground mulch (24 percent), sports surfaces (23 percent) and asphalt (12 percent).
• Civil engineering applications (about 8 percent) which encompass applications where scrap tire material replaces some other material currently used in construction, such as soil, drainage aggregate or lightweight fill materials.
• Export (whole discarded tires) (about 3 percent).
• Land disposed (about 16 percent).
• Other applications (about 5 percent).

According to the Asphalt Roofing Manufacturers Association, about 13.2 million tons of waste shingles were generated each year in the United States — about 12 million tons of post-consumer asphalt shingles (PCAS) and 1.2 million tons of manufactured waste asphalt shingles (MWAS) (4). According to the Construction & Demolition Recycling Association, there are up to 17.0 million tons of waste shingles generated each year which would be increased with the inclusion of illegal dumping (5). The amount of RAS used in 2018 increased to 1.053 million tons in asphalt mixtures (1). This was an increase of 12.5 percent from 2017. About 0.05 million tons of RAS were used as aggregates. In 2018, DOTs and asphalt mixture producers diverted about 10 percent of the total available supply of waste shingles from landfills. RAS is allowed by about 31 DOTs (6).

**FHWA Recycling Policy Usage**
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* (7). 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.

**Benefits and Risks of Using Reclaimed Asphalt Shingles**

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 78-17 (9).

On the other hand, there are also engineering risks related to binder quantity requirements for effective asphalt content and binder quality requirements for binder embrittlement. Regarding binder embrittlement, the RAS binder is aged, oxidized, very stiff, and brittle. The asphalt binder component of RAS is more aged, more oxidized, much stiffer, and more brittle than typical base asphalt binders (10). The increased binder stiffness from shingles is likely to decrease the resistance of the asphalt mixture to cracking (11). Addressing these risks is an engineering challenge to ensure responsible use, long-term pavement performance and safety. DOTs have new challenges to specify and control the quality of asphalt mixtures in their design and field acceptance. There are other concerns such as the compatibility of RAS and virgin binders, chemical differences in RAS binders compared with virgin binders, actual RAS binder availability and others.

**Background on Reclaimed Asphalt Shingles**

In May 2017, FHWA published FHWA-HIF-18-009, “FHWA Division Office Survey on State Highway Agency Usage of Reclaimed Asphalt Shingles: Quantities, Trends, Requirements, and Direction - Results from May 2017” (6). It summarized the findings, which aimed to:

1. Identify quantities, trends, requirements, and performance of RAS usage,
2. Obtain opinions on the usage of RAS in asphalt mixtures from FHWA Division Offices and DOTs perspective, and
3. Identify gaps associated with RAS usage.

The survey quantified the current state-of-the-practice of RAS usage. It indicated that nationally about 2 million tons of RAS have been used in asphalt mixtures in the previous 4 years. Lead states and regions
using RAS were identified. The report also indicated that individual DOTs were rapidly adjusting policy and practices. While some DOTs were increasing RAS use, others were decreasing it including one of the largest users, the Texas Department of Transportation. Finally, it indicated that some DOTs had learned lessons that were leading to changes to improve long-term performance, while others were at a higher risk of poor future pavement performance. In summary, the state-of-the-practice for RAS use was identified. The state-of-the-practice does not always equate to best practices and for responsible use of RAS, best practice recommendations were needed from an FHWA and DOT perspective.

Scope and Objective
The 2017 FHWA RAS survey identified a need for some additional information gathering (6). The scope of this report is to:

1. Learn more regarding the details of best practice recommendations implemented by agencies.
2. Collect and communicate experiences, lessons learned and performance information.
3. Identify gaps for creation of research needs statements for the Turner Fairbanks Highway Research Center (TFHRC) and/or the National Cooperative Highway Research Program (NCHRP) on use of recycled materials in asphalt pavements.
4. Identify other uses for RAS than in asphalt mixtures.

A primary objective of this overall effort was to identify and put forth practices implemented by DOTs for responsible use of RAS in asphalt mixtures. This will compliment National Asphalt Pavement Association (NAPA) publications: IS-136 “Guidelines for the Use of Reclaimed Asphalt Shingles in Asphalt Pavements;” QIP-129 “Best Practices for RAP and RAS Management;” and SR-213 “Use of RAP & RAS in High Binder Replacement Asphalt Mixtures: A Synthesis,” which provide contractors with management practices and guidelines for the designing and use of high RAP and RAS mixtures (12, 13, 14). To accomplish this objective information was collected through agency site visits.

Agency Site Visits
Site visits and interviews of key public agencies, along with material producers and contractors that serviced the agencies, was the mechanism used to learn more regarding the details of best practice recommendations implemented by DOTs. The participating agencies were geographically dispersed across the U.S. and are shown in Figure 2. Additionally, the following characteristics were used to select the agencies:

- City of Eugene: local agency with high percentage of RAP and RAS use.
- Delaware DOT: top 3 state DOT in percent of asphalt mixture tonnage with RAS at 25 percent.
- Illinois DOT: top 2 state DOT in tons of RAS used (about 30,000 to 40,000 tons) in asphalt mixtures.
- Missouri DOT: top 5 state DOT in tons of RAS used (about 20,000 tons) in asphalt mixtures and recent specification changes based on pavement performance.
- Pennsylvania DOT: top 5 state DOT in tons of RAS used (about 10,000 tons) in asphalt mixtures.
- Texas DOT: top 5 state DOT in tons of RAS used (about 20,000 tons) in asphalt mixtures and recent specification changes based on pavement performance.
The scope of each field visit included: a pre-visit kickoff web meeting and review of agency documents (policy, specifications, research reports, etc.); and two-day, on-site visits to obtain detailed understanding of agency processes, best practices, lessons learned and pavement performance. The on-site visits included RAS processing and asphalt mixture plants that illustrated best practices also. The outcomes of each visit included a brief report to each FHWA Division Office and DOT visited on the observations, best practices and lessons learned identified. The reports summarized the information collected through interactions with agency and any industry personnel agencies included in the visits. A brief summary of each agency visit is presented highlighting RAS use, key specification items, pavement performance and production facility visits. This is followed by a summary of key observations from all of the agency visits presented in three categories:

- Observations from document reviews and agency interviews.
- Field performance observations.
- Observations from RAS processing and asphalt plant visits.

Finally, important considerations for specifying RAS, designing mixtures containing RAS, producing RAS, producing asphalt mixture containing RAS, and controlling the quality of mixtures containing RAS are provided along with research needs identified.

**Reclaimed Binder Ratio**

Reclaimed binder ratio (RBR) is now being used by agencies, researchers, and engineering consultants to specify the amount of reclaimed binder from RAP and RAS to total binder in the mixture. The following equation explains the reclaimed binder ratio concept (15):

\[
RBR = \frac{\text{Reclaimed Binder from RAP or RAS}}{\text{Total Binder in Mixture}}
\]
Because the RBR concept accounts for the varying binder content and properties in the RAP and RAS sources used which impact the binder grade, it is a better method for specifying allowable amounts of RAP and RAS rather than the total combined RAP plus RAS content by weight. A higher reclaimed binder ratio may impact the embrittlement properties (stiffness and relaxation) of the total binder in a mixture, which is a consideration for the performance of asphalt mixtures containing RAP and RAS.

The RBR method is used to specify a minimum amount of virgin asphalt binder relative to reclaimed asphalt binder. Currently, many agencies consider RAP and RAS binder ratios as equivalent and additive to set a maximum total reclaimed binder ratio or content. This practice is no longer encouraged, as Note 13 in AASHTO PP 78-17 Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures states, these two quantities are not additive because the RAS binder will cause the combined asphalt binder to stiffen approximately twice as much as a similar amount of RAP binder, and limits should be set separately (8, 9).

**Pennsylvania Department of Transportation (PennDOT)**

PennDOT is approximately 2nd in annual asphalt mixture tonnage placed in the U.S. at about 9 million tons per year. It is also among the top 10 DOTs in annual RAS tonnage used with 2 to 3 percent of all asphalt mixture containing RAS (about 228,000 tons of mixture with RAS per year) and over 1 percent contains RAP and RAS. In 2018, about 65 percent of asphalt mixture produced for PennDOT contained approximately 15 percent recycled asphalt materials and about 20 percent contained 20 percent or more. PennDOT has over 35 years of experience with the use of RAP and 28 years of experience with the use of RAS in asphalt mixtures.

Integration of RAS into asphalt mixtures in Pennsylvania is market driven and only manufactured waste asphalt shingles (MWAS) were allowed, though industry is requesting the ability to use tear-off shingles. Use is common in Engineering District 8 and Engineering District 12. There is a GAF/Elk shingle manufacturing plant in Engineering District 8 within a few miles of a contractor’s shingle processing facility. Processed MWAS used in Engineering District 12 are imported from Ohio, which requires approximately a 200-mile one-way haul.

Interviewed PennDOT materials and construction staff overwhelmingly reported positive performance of mixtures containing 5 percent RAS by weight. No RAP was used in the pavements reviewed. They also indicated that 100 percent of asphalt mixture produced for PennDOT is warm mix asphalt (WMA), made using approximately 50 percent plant foaming and 50 percent chemical additives, though much is produced at typical hot mix asphalt (HMA) temperatures. Inspected pavements containing 5 percent RAS exhibited good durability and performance.

**Pavement Performance**

Table 2 is a summary of inspected pavement sections information and observed performance. The pavements are performing well after up to 7 years of service. Figure 3 shows the good performance after 7 years of service and Figure 4 shows good performance of an asphalt overlay on Portland cement concrete pavement (PCCP) that was sawn and sealed to control reflective cracking.
Table 2. Pennsylvania inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Route</th>
<th>%RAM (by weight)</th>
<th>Reclaimed Binder Ratio (RBR)</th>
<th>Mix Type</th>
<th>Asphalt Binder</th>
<th>Thickness (inches)</th>
<th>Observed Pavement Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 SR 22</td>
<td>5% RAS</td>
<td>0.19 RAS</td>
<td>12.5mm Surface</td>
<td>PG64-22</td>
<td>2.0 Overlay</td>
<td>• Performing well, only maintenance activity is crack sealing of longitudinal construction joints.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Low severity, high extent longitudinal joint separation (may be reflective).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• No other visible distress.</td>
</tr>
<tr>
<td>2015 SR 382</td>
<td>5% RAS</td>
<td>0.17 RAS</td>
<td>9.5mm Surface</td>
<td>PG64-22</td>
<td>1.5 Overlay</td>
<td>• Some of the pavement is PCC with asphalt overlay that is saw cut and sealed over transverse joints.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Low severity high extent longitudinal joint separation due to reflective cracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• No other visual distress.</td>
</tr>
<tr>
<td>2018 SR 30</td>
<td>5% RAS</td>
<td>0.17 RAS</td>
<td>12.5mm Surface</td>
<td>PG64-22</td>
<td>2.0 Overlay</td>
<td>• Acceptance was by PWL and a joint incentive/disincentive provision was included.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• No visual distress observed.</td>
</tr>
</tbody>
</table>

Image: University of Nevada Reno

Figure 3. PennDOT SR22 constructed in 2012.
Plant Visits
The one contractor RAS processing facility located in Engineering District 8 was visited. The contractor used typical RAS shredding equipment and noted that a significant amount of water was used to maximize production and enhance grinding, while minimizing clumping and equipment wear. The finely ground RAS was blended with fine aggregate at a rate of 50/50 to prevent clumping as illustrated in Figure 5. The fact that moisture impacts production and fuel consumption at the asphalt plant was discussed and the contractor indicated that the RAS/fine-aggregate blend was stored on paved sloped stockpile areas that were covered to reduce moisture prior to use in the asphalt plant as shown in Figure 6. The contractor had a very robust quality control (QC) program in place that was not required by specification. It included daily inspection of the MWAS delivered to the facility. It also included asphalt content (AC), gradation, and moisture content on shredded RAS (prior to blending) and RAS/fine-aggregate blends moisture content, asphalt content and gradation of the blended RAS and fine aggregate.
Figure 5. Finely ground RAS blended with sand to prevent clumping.

Figure 6. Paved and tented RAS stockpile cover near asphalt plant.
Practices Observed
Throughout the visit, identified PennDOT practices of note which included:

1. Multiple binder sources can be submitted for a single mixture design. A requirement to evaluate moisture sensitivity when a source change occurs during production is in the PennDOT standard specifications and this can be addressed at the time of mixture design, rather than during construction which could cause a delay while the testing is performed.

2. If recycled materials (RAS, RAP, or RAS and RAP) are used, PennDOT standards assure the binder in a mixture containing recycled materials is not too brittle for the environment.
   a. When only RAS is used, the amount of RAS must be 5 percent by weight and the virgin binder grade remains the same as the specified performance graded (PG) binder for the environment.
   b. When only RAP is used and the amount of RAP is less than or equal to 15 percent by weight, the virgin binder grade remains the same as the specified PG binder for the environment.
   c. When only RAP is used and the RAP is greater than 15 percent by weight, the RAP binder is extracted and recovered, and a blending chart analysis is performed to determine the appropriate virgin PG binder to ensure the blend of materials meets the PG binder requirement for the environment.
   d. If RAS and RAP are proposed in the same asphalt mixture, regardless of the RAP percentage, the asphalt binder from a lab blend of the RAP and RAS is extracted, recovered, and analyzed and a blending chart analysis is performed to determine the appropriate virgin PG binder to ensure the blend of materials meets the PG binder requirement for the environment.

3. An Engineering District 12 Standard Special Provision requires flexural beam fatigue testing when a RBR greater than 0.25 for binder course and 0.30 for base course mixtures exists. The fatigue testing must demonstrate that the addition of recycled materials does not reduce the fatigue resistance of the mixture by more than 15 percent.

4. The PennDOT mix design standard requires minimum design VMA of 0.5 percent higher than AASHTO M323. In production, VMA must be no less than 0.5 percent of the minimum design VMA requirement (i.e., the AASHTO M323 minimum design VMA) which is a practice that leads to increased virgin binder content for mixtures incorporating recycled materials (16).

5. If blended with aggregate, RAS is blended 50/50 on a weight basis with fine aggregate to reduce clumping and improve flow, handling, and uniform plant feeding characteristics.

6. Research is planned for identification and selection of asphalt mixture performance testing of mixture containing RAP and/or RAS.

7. Historical video logging of the pavement network on a regular basis captured very useful information to compare the existing pavement condition to that prior to overlay.

Some key observations regarding positive practices from PennDOT include:
- Type of shingles allowed were only MWAS.
- An RBR of 0.20 with only MWAS at 5 percent was effective.
- Criteria for PG binder grade bumping and use of blending charts.
- Mixture performance testing.
- Increased optimum asphalt content in the mixture design and controls during plant production.
- Blending RAS and fine aggregate at a rate of 50/50.
City of Eugene, Oregon
The City of Eugene’s program goal is to reduce CO₂ emissions. In fact, there is a City Climate Recovery Ordinance on CO₂ emissions reduction that is the driver for many of the decisions made in the pavement program and the impetus for regularly pushing program goals to the next step. The City’s goal is accomplished through a combination of best practices described in detail below. The City staff’s disposition is to be a leader in embracing environmental stewardship. This has led to the City Principal Civil Engineer, being invited to share the City’s pavement engineering practices at a West Coast Climate & Materials Management Forum.

About 40,000 tons of asphalt mixture is placed in the City annually, that is used for all pavements including 2 to 4-inch mill and fill through full depth reclamation. The mixtures reviewed for this field visit were all ½” nominal maximum aggregate size (NMAS), Level 2 dense graded warm mix asphalt (WMA) with a minimum reclaimed binder ratio (RBR) of 0.35. The Level 2 mix is the City’s workhorse and a standard special provision exists for it. The Lane County laboratory performs all testing for the City and is staffed with technicians that are qualified in the Oregon Department of Transportation’s (ODOT) technician certification program. ODOT representatives participated in the visit and shared a process for reconciliation of meters and scales for all raw materials and end products.

A strong partnership with local producers exists to develop best practices to accomplish environmental goals. The balance of RAP and RAS used is market driven as the contractors develop their mix designs. Material costs, processing, hauling, and availability are all factors which contractors include in their decision-making process.

Pavement Performance
Table 3 is a summary of inspected pavement sections information and observed performance. Four pavement sections, of various ages, containing 3 to 5 percent RAS and 15 to 30 percent RAP were inspected. The observed performance was very positive, with the exception of greater than expected longitudinal and block cracking on the Conger/Wilson project, which is likely due to the use of PG70-22 with a high RAM percentage as shown in Figure 7. Note that the City specification was changed after construction of this project to require the use of PG58-28. Figure 8 illustrates the positive field performance observed on Centennial Loop project constructed in 2016.
Table 3. City of Eugene, Oregon inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Route</th>
<th>%RAM (by weight)</th>
<th>Reclaimed Binder Ratio (RBR)</th>
<th>Mix Type</th>
<th>Asphalt Binder</th>
<th>Thickness (inches)</th>
<th>Observed Pavement Performance</th>
</tr>
</thead>
</table>
| 2011 Conger/Wilson  | 5% RAS + 15% RAP | 0.21 RAS + 0.13 RAP          | ¾” L2 Dense Wearing | PG64-22 and PG70-22\(^1\) | 5.5 Re-construction | • Only maintenance activity is very limited crack filling.  
• Moderate severity, high extent longitudinal cracking.  
• Low to moderate severity, low to moderate extent block cracking.  
• Limited localized striping. |
| 2016 Centennial Loop| 3.6% RAS + 30% RAP| 0.15 RAS + 0.25 RAP          | ¾” L2 Dense Wearing | PG58-34         | 7.0 Re-construction | • Performing well.  
• No visual distress observed. |
| 2019 Charnelton     | 2.7% RAS + 30% RAP| 0.12 RAS + 0.26 RAP          | ¾” L2 Dense Wearing | PG58-28         | 6.0 - 8.0 Full-depth Reclamation | • Performing well.  
• No visual distress observed. |
| 2019 W. 19th Ave.   | 2.7% RAS + 30% RAP| 0.12 RAS + 0.26 RAP          | ¾” L2 Dense Wearing | PG58-28         | 6.0 Full-depth Reclamation | • Performing well.  
• No visual distress observed. |

\(^1\)As time passed, it was realized that PG 70-22 was too stiff for Eugene’s climate with high RAM levels.

Image: University of Nevada Reno

Figure 7. Conger/Wilson project with high RAM and PG70-22 constructed 2016.
Plant Visits

One asphalt mixture plant was visited in Corvallis, Oregon. The contractor was progressive and doing in-house research related to responsible use of recycled materials on-site, while also performing production testing and QC. The plant was well equipped to produce mixture with both RAS and RAP. RAS was a blend of MWAS and PCAS. RAP and RAS were both stored under covers on paved floor for moisture management as shown in Figure 9. The counterflow drum had a late entry RAP collar and anytime RAS is used it is produced as warm mix asphalt with goal of not mobilizing the asphalt in the RAS. With the lower production temperatures required for WMA, it is believed that less RAS binder is heated enough to blend with the virgin binder. The recycled material conveyor belt to the RAP collar was equipped with a weigh bridge which the contractor indicated needed special equipment and attention due to the low percentage of RAS being fed to the plant. The conveyor was also completely covered to minimize environmental impacts. All three of these items are shown in Figure 10.
Figure 9. Covered RAS and RAP stockpiles.

Figure 10. Counterflow drum with RAP collar and covered RAP feed belt with weigh bridge.
Practices Observed
Throughout the visit several City of Eugene positive practices were identified. They included the following:

1. The City’s specification has evolved over time e.g., asphalt binder grade selection, from the amount of RAM allowed to a required amount of RAM, and others. A continuous quality improvement philosophy was important to allow for the continued innovation.
2. The City has categories of RAM criteria. Depending on the type of mixture, the RAM criteria varies. The most commonly used mixture, the “workhorse mix” is used on collector/local roadways (i.e., Level 2). It is used for both base and wearing courses.
3. The City requires an RBR of 0.35, and RAS is limited to a maximum of 5 percent by weight. The actual composition of RAP and RAS is market driven.
4. Level 2 mixtures will have a slightly higher asphalt content than mixtures designed per AASHTO M323-17 because a lower gyration level (65) is used. Additionally, the mixture design requirements force identification and the need to reject baghouse fines to meet graduation requirements.
5. Asphalt binder grade bumping down one full PG grade from PG64-22 to PG58-28 is required.
6. WMA by plant foaming is required for all paving with a maximum discharge temperature of 275°F.
7. Items 4, 5, and 6 lead to increased binder content and assurance that the potential for binder embrittlement is minimized.
8. If a change in asphalt binder sources occurs there is a requirement to re-evaluate moisture sensitivity with the TSR test.
9. All high RAM projects are visually inspected annually and the observations are put in MicroPaver.
10. Active participation in the Asphalt Pavement Association of Oregon (APAO) and American Public Works Association (APWA) keeps City staff well informed about the latest technology transfer. Specification development is done by the City in partnership with industry.
11. All capital improvement project (CIP) designs include a greenhouse gas generation analysis for alternatives.

Some key lessons learned from the City of Eugene include:
- Grade bumping down from PG70-22 to PG58-28 improved pavement performance.
- Blending MWAS and PCAS during processing can limit the amount of shingles a contractor can use to meet the asphalt mixture’s acceptance criteria for asphalt content.

Some key observations regarding positive practices from City of Eugene include:
- An RBR of 0.35 which included about 3 percent RAS (blended MWAS and PCAS) was effective.
- Criteria for PG binder grade bumping down one grade.
- Required use of WMA at lower temperatures.

Illinois Department of Transportation (IDOT)
IDOT is in the top 5 DOTs in annual asphalt mixture tonnage placed in the U.S. at about 7 million tons per year. It is also among the top 2 DOTs in annual RAS tonnage used at 30,000 to 40,000 tons of RAS used in asphalt mixture per year. IDOT also uses 700,000 to 800,000 tons of RAP in asphalt mixture annually. Over half of the RAP used is fractionated. The average RAP used is 25 percent by weight. In 2018, 66 percent of the RAS used in the state was in District 1 (Chicago) and 27 percent was used in District 8 (East St. Louis). IDOT has over 40 years of experience with the use of RAP and over 10 years of experience with the use of RAS in asphalt mixtures.
The RAS criteria is percent by weight. In addition, there is RAP and RAS criteria based on reclaimed binder ratio (RBR). It is the contractor’s option to use them in all asphalt mixtures. The criteria are a function of lift type, traffic level, mixture type, RAP type (fractionated or not), binder type and Illinois Flexibility Index Test (I-FIT) performance test. IDOT also uses a RAS binder availability factor of 0.85, which is similar to the RAS binder availability factor defined in AASHTO PP78-14, *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures* which sunset when AASHTO PP 78-17 *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures* was published (8, 9). However, the RAS binder availability factor used by IDOT is more rigorously defined resulting in a more accurate estimate.

Integration of RAS into asphalt mixtures in Illinois is market driven with both MWAS and PCAS allowed. There are shingle manufacturers and multiple RAS processors. A strong partnership with the University of Illinois at Urbana-Champaign (UIUC) through the Illinois Center for Transportation (ICT) exists, and IDOT coordinates research with ICT to assure rational implementation of material specifications.

**Pavement Performance**

No field pavement performance observations were made as part of the field visit. However, recently completed ICT Research Project R27-161, documented in FHWA-ICT-17020 report titled, “Utilizing Lab Tests to Predict Asphalt Concrete Overlay Performance” was reviewed (17). A series of five experimental and three demonstration projects were constructed. The objective was to understand the performance of pavement overlays using various levels of reclaimed binder ratios (RBR) from RAS and RAP. Pavement performance was monitored and transverse cracking was found to be more pronounced in thin asphalt overlays than in thick overlays. Flexibility Index was found to correlate to transverse cracking and confirmed the validity of using this performance test parameter in mixture design development.

**Positive Practices Observed**

Throughout the visit several IDOT positive practices were identified. They included the following:

1. IDOT’s specification has evolved over time based on field performance and research.
2. IDOT has very clear documentation including a Special Provision for RAP and RAS, a Policy Memorandum on RAS Sources, and a Determination of Aggregate Specific Gravity Procedure (Appendix B.21 of Reference 18). The clear documentation also includes the Annual Highway Material Sustainability Efforts Report which documents quantities of recycled and reclaimed materials used annually.
3. IDOT has a very robust VMA requirement for mixture design and acceptance. There is a strong Quality Assurance (QA) program for virgin and recycled aggregate bulk specific gravities (Gsb).
4. RAS is limited to a maximum of 5 percent by weight. In addition, the RBR criteria (referred to in Illinois as Asphalt Binder Replacement (ABR)) for RAP and RAS are shown in Table 4 and Table 5. The criteria were developed over time based on research, field performance and negotiation.

| Table 4. IDOT’s Maximum RBR for RAS and RAP by asphalt mixture type. |
|-----------------|-----------------|-----------------|-----------------|
| **Asphalt Mixture N设计** | **Binder Course Maximum RBR for RAS and RAP** | **Surface Course Maximum RBR for RAS and RAP** | **Polymer Modified Maximum RBR for RAS and RAP** |
| 30 | 0.30 | 0.30 | 0.10 |
| 50 | 0.25 | 0.15 | 0.10 |
| 70 | 0.15 | 0.10 | 0.10 |
| 90 | 0.10 | 0.10 | 0.10 |
Table 5. IDOT’s Maximum RBR for RAS and FRAP.

<table>
<thead>
<tr>
<th>Asphalt Mixture</th>
<th>Binder Course without I-FIT Maximum RBR for RAS and FRAP</th>
<th>Binder Course with I-FIT Maximum RBR for RAS and FRAP</th>
<th>Surface Course without I-FIT Maximum RBR for RAS and FRAP</th>
<th>Surface Course with I-FIT Maximum RBR for RAS and FRAP</th>
<th>Polymer Modified without I-FIT Maximum RBR for RAS and FRAP</th>
<th>Polymer Modified with I-FIT Maximum RBR for RAS and FRAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>0.55</td>
<td>0.40</td>
<td>0.45</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>50</td>
<td>0.40</td>
<td>0.45</td>
<td>0.35</td>
<td>0.40</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>70</td>
<td>0.40</td>
<td>0.45</td>
<td>0.30</td>
<td>0.35</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>90</td>
<td>0.40</td>
<td>0.45</td>
<td>0.30</td>
<td>0.35</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>SMA</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>IL-4.75</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.30</td>
<td>0.35</td>
</tr>
</tbody>
</table>

5. When RBR is greater than 0.20 a softer binder is required with both the high and low performance grade (PG) temperatures lowered by one grade. Observations from performance tests have identified that this is effective. However, this one grade bump may not be sufficient when RBR exceeds 0.30.

6. When polymer modified asphalt is specified, maximum RBR is at lower levels than when neat binders are specified based on performance test results and consistent with other national research.

7. Specifications include mixture performance testing for rutting using the Hamburg Wheel Track Test (HWTT) and cracking using the I-FIT for both mixture design and production.

8. The importance of long-term aging for performance testing has been identified, and research has been completed that will provide the basis for future specification changes.

9. A rigorous QC Plan requirement for RAS sources was developed in partnership with the Illinois Environmental Protection Agency, which approves and authorizes the RAS suppliers beneficial use determination (BUD) application. The QC Plan and corresponding activities leads to RAS sources being on the IDOT qualified producer list.

10. A QC Plan for RAS and RAS blended with manufactured sand is the contractor’s responsibility. It includes frequencies, tolerances, and acceptance criteria for gradation on four sieves and asphalt binder content.

11. RAS stockpiles are dedicated and rigorous criteria must be met in order to supplement a dedicated stockpile.

12. Asphalt plants must be capable of automatically recording and printing the production recordation which includes all proportioning. IDOT believes this, coupled with the percent within limits (PWL) acceptance specification, leads to good quality.

13. IDOT identified other potential beneficial uses of RAS: 1) dust suppressant on gravel roads (e.g., in a blend of RAS and aggregates), and 2) a component in flowable fill (Controlled Low-Strength Material (CLSM)) for use around utilities.

Some key observations regarding positive practices from Illinois DOT include:

- The maximum RAS was 5 percent.
• The maximum RBR varied from 0.10 to 0.50 based on traffic (i.e., number of design gyrations), lift, use of polymer modified asphalt, type of RAP (fractionated or not) and mixture performance.
• Criteria for PG binder grade bumping existed when the RBR was greater than 0.20.
• Mixture performance testing was used.
• Minimum asphalt content was controlled by robust mixture design and acceptance criteria.
• Rigorous QC requirements existed for RAS and RAP stockpiles. Once meeting requirements, they became “dedicated,” and no additional material can be added.

Missouri Department of Transportation (MoDOT)
MoDOT’s asphalt mixture tonnage placed is about 3 million tons per year. It is among the top 5 DOTs in annual RAS tonnage at about 20,000 tons of RAS used in asphalt mixture per year. MoDOT also uses about 600,000 tons of RAP in asphalt mixture annually. The distribution of percentage of mix designs with the different material types is illustrated in Figure 11. The average RAP used is about 20 percent by weight. In metropolitan areas, RAP is the primary recycled material used as it is readily available. In rural areas, RAS is the more prevalent recycled material used as RAP is not as readily available. MoDOT has over 20 years of experience with the use of RAP and over 15 years of experience with the use of RAS in asphalt mixtures.

Of all the mixture designs in one year, 3 percent had RAS only, 64 percent had RAP only, 30 percent had RAP and RAS, and only 3 percent had no recycled materials. When RAS is used it is typically 3 percent, and when RAP is used it is typically about 27 percent in asphalt mixture designs. MoDOT standard specifications include three asphalt mixture items. They are:
• 401 Plant Mix Bituminous Base and Pavement (about 30 percent of the annual tonnage).
• 402 Plant Mix Bituminous Surface Leveling (about 20 percent of the annual tonnage).
• 403 Asphalt Concrete Pavement (about 50 percent of the annual tonnage but very limited RAS usage).

The RAS and RAP criteria is by reclaimed binder ratio (RBR) using the weight of the effective virgin asphalt content. There is RBR criteria for RAP only, RAS only and a combination of RAP and RAS. It is the contractor’s option to use RAP and RAS in all asphalt mixtures, although RAS can only be used in mixtures specifying a contract asphalt binder of PG 64-22. When RAS is used it normally results in MoDOT requiring a softer PG binder. The option for RAS usage only when PG 64-22 is specified, limits RAS by lift and traffic as shown in Table 6. Six hundred trucks per day separate medium and heavy volumes of traffic. MoDOT mix type selection guidelines are presented in Table 7.

Table 6. MoDOT asphalt binder selection criteria, RAS only allowed when PG64-22.

<table>
<thead>
<tr>
<th>Type of Corridor</th>
<th>Traffic Level</th>
<th>Type of Mix</th>
<th>Asphalt Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstates and Other Freeways</td>
<td>All</td>
<td>Surface Mixture (SP125 or SMA) and First Underlying Lift</td>
<td>PG 76-22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remaining Underlying Lifts</td>
<td>PG 76-22</td>
</tr>
<tr>
<td>Other Remaining Major Routes</td>
<td>Heavy</td>
<td>Surface Mixture (SP125) and First Underlying Lift</td>
<td>PG 70-22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remaining Underlying Lifts</td>
<td>PG 64-22</td>
</tr>
<tr>
<td>Medium or Low</td>
<td></td>
<td>Surface Mixture (SP125 or BP)¹</td>
<td>PG 64-22</td>
</tr>
<tr>
<td>Minor Routes</td>
<td>All Levels</td>
<td>All Mixtures (Generally BP-1 as Surface Mix)</td>
<td>PG 64-22</td>
</tr>
</tbody>
</table>

¹Requires JSP to include appropriate smoothness requirements.

Table 7. MoDOT mixture selection guidelines.

<table>
<thead>
<tr>
<th>Corridor Designation</th>
<th>Traffic</th>
<th>Recommended Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate and Other Freeways</td>
<td>All Traffic</td>
<td>Superpave</td>
</tr>
<tr>
<td>Remaining Major Routes</td>
<td>Total Average 24 Hour Commercial Truck Traffic: 600 or greater</td>
<td>Superpave</td>
</tr>
<tr>
<td>Remaining Major Routes</td>
<td>Total Average 24 Hour Commercial Truck Traffic: less than 600</td>
<td>BP-1 (Sec 401)¹,²</td>
</tr>
<tr>
<td>Minor Routes</td>
<td>Total Average 24 Hour Commercial Truck Traffic: 600 or greater</td>
<td>Superpave²</td>
</tr>
<tr>
<td>Minor Routes</td>
<td>AADT&gt;3500 and Total Average 24 Hour Commercial Truck Traffic &lt; 600</td>
<td>BP-1 (Sec 401)</td>
</tr>
<tr>
<td>Minor Routes</td>
<td>AADT&lt;3500 and Total Average 24 Hour Commercial Truck Traffic &lt; 600</td>
<td>BP-1 or BP-2³</td>
</tr>
</tbody>
</table>

¹Requires JSP to include appropriate smoothness requirements.

⁴Consideration should be given to alter mix type for overlays based upon existing conditions.

³The selection of which mix to use is left to the district’s discretion based upon past field performance.

In addition to the binder grade, lift, and traffic; criteria are a function of mixture type (i.e., bid item). Additionally, RAS is not allowed in stone matrix asphalt (SMA) at this time, but experimentation is ongoing.

Integration of RAS into asphalt mixtures in Missouri is market driven with both MWAS and PCAS allowed. However, MoDOT reports that only PCAS are used to produce RAS in Missouri. There are multiple RAS processors in the state. A strong partnership with the asphalt pavement industry in Missouri as well as
the University of Missouri System exists, and it is leveraged to continually improve and implement recycled materials specifications in the state.

**Pavement Performance**

Two types of field performance observations were made. The first was electronic review, and the second was on-site pavement inspections. The electronic review included Long-Term Pavement Performance (LTPP) data collected on the Specific Pavement Study (SPS)-10: warm mix asphalt (WMA) experiment. The LTPP SPS-10 test sections were constructed in 2016 and reviewed with Google Earth images along with MoDOT pavement condition survey from ARAN video imaging. The pavement sections did not exhibit any distress and appeared to be performing well. All of the pavements reviewed were 2 to 3 years old. Additionally, video logs of pavement performance from Route 61 in St. Charles County, Route 5 in Camden County, Route MM, TT, F in Camden County and I-435 were reviewed. These pavements also showed very good results. However, they have only been in service for 2 years.

Six pavement sections, of various ages, containing either RAS, RAP, or RAP and RAS were physically inspected. Table 8 is a summary of information about the sections inspected. Figure 12 shows an SMA placed over PCC on I55 that contains 4 percent RAS (RBR = 0.18) which is performing very well, with only low severity low extent transverse cracking after 9 years of service. Figure 13 shows an SMA on the mainlines and a BP-1 dense graded mixture on the shoulders of I-44, with no visible distress in the SMA but low severity moderate extent transverse cracking in the BP-1 shoulders after only 2 years of service. Figure 14 shows a BP-1 dense graded mixture on a low volume road (Route 94) that contains 3 percent RAS and 28 percent RAP (RBR = 0.48) which is performing poorly with high severity high extent longitudinal, block, and localized fatigue cracking after just 3 years of service.

*Image: University of Nevada Reno*

Figure 12. I-55 SMA, constructed 2010 with low severity low extent longitudinal and transverse cracking.
Table 8. MoDOT inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Route</th>
<th>%RAS/RAP (by weight)</th>
<th>Reclaimed Binder Ratio (RBR)</th>
<th>Mix Type</th>
<th>Asphalt Binder Grade</th>
<th>Pavement Thickness (inches)</th>
<th>Observed Pavement Performance</th>
</tr>
</thead>
</table>
| 2016 Route 94  | 3% RAS + 28% RAP      | 0.16 RAS + 0.32 RAP\(^1\)    | 12.5mm BP-1 | PG 46-34              | 1.75                        | • High severity high extent longitudinal and block cracking. Some is likely reflective.  
• High severity low extent fatigue cracking. |
| 2014 Route D   | 5% RAS + 25% RAP      | N/A                           | 12.5mm BP-1 | N/A                  | 1.75                        | • High severity high extent longitudinal and block cracking. Some is likely reflective.  
• High severity low extent fatigue cracking. |
| 2018 Wood Lake Drive | 0% RAS + 25% RAP     | N/A                           | 12.5mm BP-1 | N/A                  | 2.5                         | • No visible distress.  
• Performing well. |
| 2015 MoDOT Facility | 0% RAS + 25% RAP    | N/A                           | 12.5mm BP-1 | N/A                  | N/A                         | • Very low severity low extent longitudinal cracking.  
• Performing well. |
| 2017 I-44      | 0% RAS + 0% RAP       | N/A                           | 12.5mm SMA Surface | N/A              | 2.0                         | • No visible distress.  
• Performing well. |
| 2017 I-44      | N/A/N/A               | N/A                           | 12.5mm BP-1 | N/A                  | 2.0                         | • No visible distress.  
• Low severity, moderate extent transverse cracking. |
| 2010 I-55      | 4% RAS + 0% RAP       | 0.19 RAS                       | 12.5mm    | PG 76-22             | 1.75                        | • Low severity, low extent longitudinal cracking and reflective cracks.  
• No other visible distress, performing very well for age/loading. |

\(^1\)calculated using effective virgin asphalt content.  
\(^2\)N/A is not available as the information could not be obtained by MoDOT.
Figure 13. I-44 SMA and BP-1 shoulder, constructed 2017 with no visible distress in the SMA and low severity moderate extent transverse cracking in the BP-1 shoulders.

Figure 14. Route 94, constructed 2016, high severity high extent longitudinal, block, and localized fatigue cracking.
Plant Visits

A RAS processing facility located in the St. Louis District was visited. About 15,000 tons of PCAS are processed at the facility annually. The operator indicated that it costs $50 per ton to send shingles to a landfill, but the tipping fee at this location was only $35 per ton. Additionally, the cost of processing shingles is about 50 percent higher than the cost of processing other recycled materials due to equipment wear. The shingles with the debris removed are ground to minus #4 sieve size. There was a stockpile of approximately 1,000 tons on site at the time of the visit. The stockpile was noticeably dry and did not possess an excessive amount of moisture. At the current time, processing costs are approximately $20 per ton and they are sold for approximately $12 per ton. MWAS from a nearby manufacturing facility are sent to the landfill. There is not the capacity to accept MWAS at this facility. Shingles are undesirable in landfills as they trap methane gas and create issues. The recycler visited indicated it blended RAP and RAS with emulsion which it sells as base course material and is another beneficial use of RAS. Figure 15 shows a Beast Recycler that is a horizontal grinder being used to process RAS at the recycle center along with some PCAS. Figure 16 shows an approximately 1,000-ton stockpile of processed RAS.

One contractor’s asphalt plant operation was visited. The plant was a counterflow 600 tons per hour drum mix plant with 8 coldfeed bins, 2 recycled material coldfeed bins, and 4 storage silos. The plant includes 2 mineral filler silos and 1 baghouse fines return silo. Several positive observations were made at the asphalt plant. There was an on-site QC laboratory and staff. Recycled materials coldfeed bins had scalping screens over them to eliminate clumps and cameras mounted on them so the operator could continuously monitor bin levels. Air cannons were installed on the RAP coldfeed bin and vibrators on the RAS coldfeed bin to improve flow as shown in Figure 17. The RAS coldfeed bin had a gate installed to assist with uniform feed of as little as 2 percent RAS shown in Figure 18. The plant operator indicated that several smaller vibrators worked more effectively than one larger air cannon. The mineral filler and baghouse fines silos were all equipped with weigh pods for accurately metering and feeding material to the mixing chamber of the drum shown in Figure 19. A small horizontal impact crusher and single deck screen was installed at the intersection of the recycled materials collector belt and the drop point to the collector belt to the RAP collar on the drum shown in Figure 20. The contractor used this to process all millings to ½” minus and feed milling directly to the plant. The belt scale on the coldfeed collector belt was covered to prevent environmental impacts on its performance.
Figure 15. PCAS being processed with a shredder.

Figure 16. Finely ground RAS stockpile in Missouri.
Figure 17. Air cannon and vibrators on RAS coldfeed bins.

Figure 18. Gate installed on the RAS coldfeed bin to allow for consistent low flow.
Figure 19. Mineral filler and baghouse fines silos with weigh pods.
Figure 20. Horizontal impact crusher and screen on the recycled materials feed belt.
Information Gathering Meeting with Field Practitioners

An open discussion was held with staff from MoDOT, paving contractors, consultants, and academia to identify successful practices and challenges with the use of RAS. Observations identified included the following related to mixture design, performance, and RAS processing.

Mixture Design and Performance Comments:
- When RAP is available, the most cost-effective mixture seemed to be 40 percent RAP and a PG 58-28 binder. RAP is not always available.
- An observation was shared that the use of recycling agents led to cracking sooner than if additional binder was used.
- An observation was shared that when there was cracking in RAS mixtures, the crack did not increase in severity over time.
- Keys to success include a combination of increased asphalt content, use of softer binder, fine gradation, and lower dust to asphalt ratio. A minimum amount of virgin binder is needed to be successful.

RAS Processing Comments:
- Just in time RAS processing is beneficial to prevent clumping.
- It is preferred to have RAS ground to 3/8 inch. When ground finer to a fine powder, laboratory results indicated that there was not an improvement in rutting in the HWTT and the PG binder range was limited. Size matters, 3/8 inch is preferred to a powder.
- Each plant is different. There is not one “best” way to produce RAS. Some have found blending RAS with sand can be done to minimize clumping, whereas others use zeolite, etc.
- The use of weigh depletion bins is an accurate method to measure the small quantities of RAS.
- Air cannons and vibrators on RAS cold feed bins are beneficial to keep the RAS from bridging.

Positive Practices Observed

Throughout the visit several MoDOT positive practices were identified. They included the following:

1. MoDOT’s specification has evolved based on field performance observations, partnering with industry, and research. There were two distinct “eras” of specification changes identified as shown below:
   a. The first significant change occurred in approximately 2009 as there was an unacceptable level of cracking. In some cases, 7 percent RAS was being used. Changes were made to increase the amount of virgin binder by accounting for the absorption of virgin binder and requiring a higher VMA.
   b. The second significant change occurred in approximately 2014 as there was an unacceptable level of cracking. The current specification evolved with more emphasis on limits of RAS and combinations of RAS and RAP, use of softer virgin binders, and more virgin binder.
2. MoDOT uses VMA requirement for mixture design and acceptance. There is a strong QA program for virgin and recycled aggregate bulk specific gravities (Gsb).
3. RAS, RAP and combinations of RAP and RAS are limited by RBR as shown in the Table 9 for Item 401. The criteria were developed over time based on research, field performance and negotiation.
Table 9. Illustration of RAS, RAP and RAS/RAS Limitations based on RBR for Item 401.

<table>
<thead>
<tr>
<th>Binder</th>
<th>RAP RBR Using Effective Asphalt Content</th>
<th>RAS RBR Using Effective Asphalt Content</th>
<th>RAS and RAP RBR Using Effective Asphalt Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract PG</td>
<td>0.00 – 0.20</td>
<td>0.00 – 0.10</td>
<td>RAP + (2*RAS) ≤ 0.20</td>
</tr>
<tr>
<td>PG softened one grade</td>
<td>0.21 – 0.40</td>
<td>0.11 – 0.20</td>
<td>0.20 &lt; RAP + (2*RAS) ≤ 0.40</td>
</tr>
<tr>
<td>Blend chart</td>
<td>0.00 – 1.00</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Extraction and grading of binder from final mixture</td>
<td>0.00 – 1.00</td>
<td>0.00 – 1.00</td>
<td>0.00 – 1.00</td>
</tr>
</tbody>
</table>

4. When using a combination of RAP and RAS, the RBR is calculated using a relative weighting of “two” for the RAS to account for the additional binder stiffness.

5. When RBR from RAS is greater than 0.10 a softer binder is required with either the low temperature or both the high and low PG lowered by one grade. Observations from performance tests have identified that this is effective. In fact, this may be more effective than using a recycling agent.

6. When RBR from RAS is greater than 0.20, blending charts are not applicable. The actual grading from the binder extracted from the aged mixture is required.

7. Recycling agents are allowed and about 15 to 25 percent of the asphalt mixtures contain them. They are selected by the contractor. Some examples of recycling agents that have been used include Evoflex and Hydrogreen.

8. Specifications will soon include mixture performance testing for rutting using the Hamburg Wheel Track Test (HWTT) and cracking using either the Illinois Flexibility Index Test (I-FIT) or Ideal Cracking Test (IDEAL-CT) for both mixture design and production. In 2020 there will likely be approximately ten projects statewide with pilot performance testing requirements.

9. At the end of each day's operation, the contractor shall furnish to the engineer a total tonnage of mixture produced by the asphalt plant in sufficient detail to determine the amount of asphalt binder used in that day's operation.

Some key lessons learned regarding practices from MoDOT include:
- Early on there was significant cracking when up to 7 percent RAS was being used.
- An RBR of 0.50 with 3 to 5 percent RAS produced significant cracking.

Some key observations regarding positive practices from MoDOT include:
- The RBR for RAP and RAS is combined by weighting the RBR from RAS by a factor of 2.
- There is an effort to use more virgin binder:
  - The RBR is calculated based on the effective virgin asphalt content.
  - The VMA criteria have been increased.
  - Minimum asphalt content was controlled by robust mixture design and acceptance criteria.
- The maximum RBR varies based on binder grade, lift, traffic and mixture type.
- With lower amounts of RAS and, RAP and RAS, criteria for PG binder grade bumping existed.
- With higher amounts of RAS and, RAP and RAS, blending charts were not used. The actual material was extracted and graded from the final mixture.
- Recycling agents were allowed and used in about 15 to 25 percent of the mixtures to meet blending chart requirements.
- Mixture performance testing will soon be required.
Delaware Department of Transportation (DelDOT)

Uniquely, DelDOT owns and maintains nearly 90 percent of the state’s roadways. DelDOT’s asphalt mixture tonnage placed is about 750 to 850 thousand tons per year. As a smaller state, it makes sense that the asphalt mixture tonnage is smaller. However, it is among the top 3 DOTs in annual percent of asphalt mixture tonnage with RAS at about 25 percent. DelDOT uses approximately 9,000 tons of RAS per year in asphalt mixtures. DelDOT also uses about 200,000 tons of RAP in asphalt mixture annually. The average RAP used is about 25 percent by weight. DelDOT has about 30 years of experience with the use of RAP and about 14 years of experience with the use of RAS in asphalt mixtures. RAS use increased significantly after Hurricane Sandy in 2013.

When RAS is used it is typically 4 percent and always with RAP. When RAP is used it is typically about 25 percent in asphalt mixture designs. It is the contractor’s option to use RAS and RAP in all asphalt mixtures. The RAS and RAP criteria is by reclaimed binder ratio (RBR). There is RBR criteria for RAP only (0.40), RAS only (0.20) and a combination of RAP and RAS (0.40). DelDOT does allow an RBR of 0.10 from RAP in SMA. It also specifies the use of ground tire rubber (GTR) modified binder in some SMA when placed on rigid pavements treated with Novachip prior to the SMA to minimize reflective cracking.

In addition to the RBR requirements, a blending chart is used. Data used in the blending chart comes from a statewide running average of 1 to 2 years of data. There is a spreadsheet used to calculate the PG of the virgin binder and reclaimed material. It is called the “2009 RAP Calculator.” The RAP Calculator only works for blended and processed RAP piles. It makes the RAP sufficiently uniform across the state to use an average. The RAP average is based on the running average of blended and processed RAP. Single sources of RAP cannot be used in the calculator since the properties are too variable. Single sources of RAP are not part of the RAP Average. When using a combination of RAP and RAS, the binder stiffness uses a relative weighting of “two” for the RAS to account for the additional binder stiffness. It assumes 100 percent binder availability from the reclaimed materials. A higher upper temperature grade than specified in the contract can be used. Use of recycled materials cannot raise the low temperature properties of the combined binder above -23°C. No grade change is allowed with polymer modified binders (PG 76 and 70). Some plants use of recycled materials is limited by emissions testing conducted by Delaware Department of Natural Resources and Environmental Control (DNREC). DelDOT is in the process of reviewing the 2009 RAP Calculator and may be considering updates relative to the binder availability and rheological parameters.

There are no other limitations for lift or traffic. The use of chemical and foaming WMA technologies are at the contractor’s option and it is typically used as a compaction aid with the mixture produced at hot mix temperatures. Integration of RAS into asphalt mixtures in Delaware is market driven with the primary supply being PCAS. There is a RAS manufacturing plant in Delaware, and a large asphalt mixture producer processes both PCAS and MWAS RAS in the state. The RAS is supplied to two asphalt plants within the state. A strong partnership between DelDOT and the asphalt pavement industry in Delaware exists, and it is leveraged to continually improve and implement recycled materials specifications in the state.

Pavement Performance

Three pavement sections constructed in 2015 built with the same mixture produced by Tri-county Materials containing 25 percent RAP and 4 percent RAS which had an RBR of 0.37 were physically inspected. The team carpooled and visually inspected the pavements together. The representative length of each project was windshield surveyed. Additionally, the vehicle was stopped in a safe location and close inspection was performed. The inspected sections were all relatively low volume local roads. The surface mixture was all the same, the existing structures varied. Table 10 is a summary of information about the
sections inspected and observations made during the inspection process. Figure 21 shows moderate severity high extent fatigue cracking (likely load related) and moderate severity high extent block and transverse cracking on Brairbush after 4 years of service. Figure 22 shows Plaindealing Road exhibiting low severity moderate to high extent block cracking after 4 years of service.

Table 10. DelDOT inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Route</th>
<th>%RAS/RAP (by weight)</th>
<th>Reclaimed Binder Ratio (RBR)</th>
<th>Mix Type (100 gyration)</th>
<th>Asphalt Binder Grade</th>
<th>Pavement Thickness (inches)</th>
<th>Observations</th>
</tr>
</thead>
</table>
| 2015 Brairbush | 4% RAS + 25% RAP     | 0.19 RAS + 0.18 RAP          | 9.5mm Superpave          | PG64-22              | 2.0 on 6.0 FDR              | • Moderate severity high extent fatigue cracking (likely load related).  
• Moderate severity high extent block and transverse cracking. |
| 2015 Plaindealing Road | 4% RAS + 25% RAP | 0.19 RAS + 0.18 RAP          | 9.5mm Superpave          | PG64-22              | 2.0 on 4.0 CIPR             | • Low severity moderate to high extent block cracking. |
| 2015 Andrews Lake | 4% RAS + 25% RAP     | 0.19 RAS + 0.18 RAP          | 9.5mm Superpave          | PG64-22              | 2.0 on 6.0 FDR              | • Low severity high extent block and transverse cracking.  
• Low severity low extent deleterious materials. |

Image: University of Nevada Reno

Figure 21. Briarbush, constructed 2015, moderate severity high extent fatigue cracking (likely load related) and moderate severity high extent block and transverse cracking.
Figure 22. Plaindealing Road, constructed 2015, low severity moderate to high extent block cracking.

Plant Visits
One contractor’s asphalt plant operation site was visited in Dover. It had been in operation for approximately 5 years and was on the same site as an aggregate pit. RAP and recycled Portland cement concrete base were also produced on the site. RAS was imported to this plant facility from a RAS processing facility in Wilmington about a 90-minute haul from the north. The shingles with the debris removed are ground to minus ¼-inch sieve size. There was only an approximately 500-ton stockpile of RAS on site at the time of the visit. The stockpile contained 12-17 percent moisture. The stockpile was not covered, but the plant operator indicated it is tarped at night. It was intentionally small to prevent clumping. At the current time, processing costs are approximately $20 per ton.

The asphalt plant was a counterflow 400 tons per hour drum mix plant with an external mixing drum (a.k.a., “mini-mixer”) to which the asphalt binder and baghouse fines are injected. The drum mix plant has an exterior drum for adding RAP and RAS to the heated aggregate. There are 5 coldfeed bins, 2 recycled material coldfeed bins, and 3 three-hundred-ton storage silos. The plant includes 2 mineral filler silos and 1 baghouse fines return silo. There are 3 asphalt binder tanks. One 40-ton horizontal tank dedicated to PG76-22, one 30-ton vertical tank dedicated to PG64-22 and one 30-ton vertical tank for PG58-28. A recycling agent tank containing a vegetable-based recycling agent used at a dose of 2-3% by total weight of binder was at the plant. The Contractor and DelDOT shared a laboratory and staff that performed the following QC checks:

- Daily on RAP and RAS stockpile moisture content, asphalt binder content and gradation.
- Daily asphalt mixture asphalt binder content, gradation, and volumetric properties.
- Quarterly measurement of aggregate specific gravities.
Recycled materials coldfeed bins had scalping screens over them to eliminate clumps. Air cannons were installed on all coldfeed bins to improve flow. The RAS coldfeed bin had a gate installed to assist with uniform feed of as little as 4 percent RAS, as well as a limit switch to assure positive flow shown in Figure 23. Figure 24 shows the dryer drum and external mixing drum, a.k.a., “mini-mixer.” Figure 25 shows well coated asphalt mixture with high RBR and recycling agent on discharge from the external mixing drum. The mineral filler and baghouse fines silos were all equipped with weigh pods for accurately metering and feeding material to the external mixing chamber. The belt scale on the coldfeed collector belt was covered to prevent environmental impacts on its performance. Figure 26 shows the recycling agent pump and metering system at the plant.

Figure 23. RAS feed bin with a gate to limit flow and a limit switch.
Figure 24. Dryer drum and external mixing drum, a.k.a., “mini-mixer.”
Figure 25. Well coated asphalt mixture with high RBR and recycling agent on discharge from the external mixing drum.

Figure 26. Recycling agent pump and metering system.
Positive Practices Observed
Throughout the visit several DelDOT positive practices were identified. They included the following:

1. DelDOT’s specification has evolved over time based on field performance observations and partnering with industry.
2. RAS, RAP and combinations of RAP and RAS are limited by RBR. There is RBR criteria for RAP only (0.40), RAS only (0.20) and a combination of RAP and RAS (0.40).
3. The “2009 RAP Calculator” is used to ensure the PG of the binder is acceptable when RAP and RAS are used. The higher temperature of the contract PG can be up to one grade higher. Recycled materials cannot raise the low temperature properties of the combined binder above -23°C. The calculator relies on blending charts. To make the process more efficient, typical base binder grade properties, RAP and RAS are used in the blending charts that are averages obtained from a statewide database. When using a combination of RAP and RAS, the binder stiffness uses a relative weighting of “two” for the RAS to account for the additional binder stiffness. The low temperature PG grade is protected with the use of blending charts and the PG grade of the blended materials is also estimated based on them.
4. Asphalt binder contents of RAS and RAP stockpiles are measured by DelDOT each season and the contractor is required to use the values provided by DelDOT.
5. A combination of reduced number of gyrations (75 for dense graded mixtures and 100 for SMA) and a minimum VMA requirement that is 0.5 percent above the AASHTO M323 minimum has led to an increase of about 0.2 percent asphalt binder in DelDOT mixtures (16).
6. The bulk specific gravity of recycled material aggregates (Gsb) is estimated from effective specific gravities (Gse) with an adjustment for an assumed asphalt absorption. The Gse is obtained from theoretical maximum specific gravity measurements during mix design and during production.
7. Recycling agents are voluntary being used by a major contractor to improve mixture performance. This is based on binder and mixture performance testing.
8. APA rutting, as well as Texas Overlay and Ideal-CT tests before and after long-term aging are being performed by DelDOT to evaluate the quality of its asphalt mixtures, particularly with recycled materials. The performance tests are being evaluated for potential implementation in the mixture design and/or acceptance.

Recommended Research
DelDOT suggested research to:
1. Improve the ability to accurately measure RAS binder properties and/or create a database of typical properties by region that could be used by DOTs, and
2. Establish correlations between simple performance tests and field performance that can practically be used for mix design and acceptance accounting for the influence of lab versus plant production.

Some key lessons learned regarding practices from DelDOT include:
- An RBR of 0.40 with 4 percent RAS produced significant cracking.

Some key observations regarding positive practices from DelDOT include:
- The maximum RBR when using only RAS is 0.20.
- The maximum RBR when using RAP and RAS is controlled by ensuring the PG of the binder is acceptable. This is done with blending charts using statewide averages in the “RAP Calculator.”
- The RBR for RAP and RAS is combined by weighting the RBR from RAS by a factor of 2 when using the “RAP Calculator.”
• There is an effort to use more virgin binder by using lower design gyrations and increasing VMA requirements by 0.5. This has increased optimum asphalt contents by about 0.2 percent.
• Recycling agents were allowed.
• Mixture performance testing is being conducted for potential implementation.

Texas Department of Transportation (TxDOT)
TxDOT had about 16 million tons of asphalt mixture placed in fiscal year 2019, which is the most of all SHAs. It is among the top 10 DOTs in RAS use at about 20,000 tons per year (Fiscal year 2019 use was 6,000 tons). Both MWAS and PCAS are used for RAS in Texas. RAS usage peaked for mixtures used by TxDOT in 2012 at just over 110,000 tons of RAS in asphalt mixtures. This was part of the “pennies to pavements” program. Since 2016, it has stabilized at about 20,000 tons of RAS in asphalt mixtures. TxDOT also uses about 2 million tons of RAP in asphalt mixture annually (1.7 million tons in fiscal year 19). The average RAP used is about 17 percent by weight. TxDOT has nearly 50 years of experience with the use of RAP and over 15 years of experience with the use of RAS in asphalt mixtures.

The TxDOT workhorse asphalt mixtures are specified in standard specification Items 341, Dense-Graded Hot-Mix Asphalt and Item 344, Superpave Mixtures. Item 341 is used for approximately 35 percent of the asphalt mixture placed by TxDOT, Item 344 for approximately 46 percent, and specialty mixtures account for the remainder. The primary differences in the specifications are Item 341 allows for either Texas Gyratory or Superpave Gyratory; gradation bands are different between Item 341 and 344; incentive/disincentive tolerances are tighter for Item 344 and it has higher VMA requirements typically leading to higher asphalt contents than Item 341. The payment incentives and disincentives associated with Item 344 are also rigorous (narrower tolerances and greater payment incentives/penalties) than with Item 341.

Figure 27 is excerpts of Table 4, Table 5, and Table 8 of the current Item 341, Dense-Graded Hot-Mix Asphalt specification. Figure 28 is excerpts of Table 4, Table 5, and Table 8 of the current Item 344, Superpave Mixtures specification. It is important to note that these specifications are under modification that will be used for lettings starting in January 2020. Thus Figure 29 and Figure 30 are the versions that will be used in future for comparison purposes. A description of the common Tables in each of the Figures follows.

• Table 4 in both figures indicate the maximum allowable percentage of RAP on a weight basis, as a function of location in the pavement structure, and whether the RAP is fractionated or not. The tables also have three important notes. One indicates that regardless of the percent by weight of RAP used, the maximum reclaimed binder ratios (RBR) in Table 5 also have to be met. The second important note indicates that up to 5 percent RAS can be used separately or as a replacement for a fraction of the allowable RAP. Planned changes will not permit RAS in surface mixtures unless otherwise shown on the plans with a general note from a District and RAS will be allowed in intermediate and base mixtures at 3 percent. The third note indicates that unfractionated RAP may not be combined with fractionated RAP or RAS. Fractionated RAP is currently defined as either coarse or fine RAP processed over a 3/8-inch or 1/2-inch screen. The coarse RAP is retained on either of these sieves; the fine RAP is passing either of these sieves. Planned changes will not allow unfractionated RAP and fractionated RAP will be defined as a stockpile containing RAP with a minimum of 95.0 percent passing the 3/8-inch or 1/2-inch sieve prior to burning in the ignition oven. It is the contractor’s option to use RAS, RAP or a combination of them in all asphalt mixtures (except RAS in the surface mixes that will be determined by the District moving forward).
• Table 5 in both Figure 27 and Figure 28 indicates the allowable PG grade substitutions and RBR based on location of the mixture in the pavement structure and originally specified PG binder grade. The contractor has the option for an allowable substitute for the PG required by contract for some of the binders. The planned changes are not allowing binder substitution for some originally specified binders and reducing the RBR in surface mixtures.

• Table 8 in both figures indicates gradation requirements for different NMAS mixtures, as well as minimum mixture design and production VMA requirements which are different for Item 341 and 344. Although the VMA requirements in Table 8 of Figure 28 are higher than those in AASHTO M 323 “Standard Specification for Superpave Volumetric Mix Design,” the VMA is calculated using the effective specific gravity of the aggregate. It is important to note that both the Item 341 and 344 specifications are undergoing significant revisions with research on-going to support the changes. Asphalt mixture durability and skid resistance were identified as current hot topics.

Integration of RAS into asphalt mixtures in Texas is market driven with both MWAS and PCAS allowed. There are multiple RAS manufacturing plants and RAS processors in the state. A very strong partnership between TxDOT and the asphalt pavement industry in Texas, as well as the University of Texas, University of Texas El Paso and Texas A&M University is leveraged.
Figure 27. Current Item 341, Dense Grade Mixtures, Table 4 and Table 5 and Table 8.
### Table 4. Maximum Allowable Amounts of RAP

<table>
<thead>
<tr>
<th>Maximum Allowable Fractionated RAP (%)</th>
<th>Maximum Allowable Unfractionated RAP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Intermediate</td>
</tr>
<tr>
<td>20.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

1. Must also meet the recycled binder to total binder ratio shown in Table 5
2. Up to 5% RAS may be used separately or as a replacement for fractionated RAP
3. Unfractionated RAP may not be combined with fractionated RAP or RAS

### Table 5. Allowable Substitute PG Binders and Maximum Recycled Binder Ratios

<table>
<thead>
<tr>
<th>Originally Specified PG Binder</th>
<th>Allowable Substitute PG Binder for Surface Mixes</th>
<th>Maximum Ratio of Recycled Binder to Total Binder (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
<td>Intermediate</td>
</tr>
<tr>
<td>76-22&lt;sup&gt;2&lt;/sup&gt;</td>
<td>70-22 or 64-22</td>
<td>20.0</td>
</tr>
<tr>
<td>70-22&lt;sup&gt;2&lt;/sup&gt;</td>
<td>70-28 or 64-28</td>
<td>30.0</td>
</tr>
<tr>
<td>64-22&lt;sup&gt;2&lt;/sup&gt;</td>
<td>64-22</td>
<td>20.0</td>
</tr>
<tr>
<td>76-28&lt;sup&gt;1&lt;/sup&gt;</td>
<td>70-28 or 64-28</td>
<td>20.0</td>
</tr>
<tr>
<td>70-28&lt;sup&gt;1&lt;/sup&gt;</td>
<td>64-34</td>
<td>30.0</td>
</tr>
<tr>
<td>64-28&lt;sup&gt;1&lt;/sup&gt;</td>
<td>58-28</td>
<td>20.0</td>
</tr>
<tr>
<td>76-28&lt;sup&gt;1&lt;/sup&gt;</td>
<td>58-34</td>
<td>30.0</td>
</tr>
<tr>
<td>70-28&lt;sup&gt;1&lt;/sup&gt;</td>
<td>70-22 or 64-22</td>
<td>30.0</td>
</tr>
<tr>
<td>64-22&lt;sup&gt;1&lt;/sup&gt;</td>
<td>64-22 or 58-28</td>
<td>30.0</td>
</tr>
<tr>
<td>64-28&lt;sup&gt;1&lt;/sup&gt;</td>
<td>58-28</td>
<td>30.0</td>
</tr>
<tr>
<td>64-34&lt;sup&gt;1&lt;/sup&gt;</td>
<td>58-34</td>
<td>30.0</td>
</tr>
</tbody>
</table>

1. Combined recycled binder from RAP and RAS.
2. Use no more than 20.0% recycled binder when using this originally specified PG binder.
3. WMA as defined in Section 341.2.6.2., "Warm Mix Asphalt (WMA)."
4. When used with WMA, this originally specified PG binder is allowed for use at the maximum recycled binder ratios shown in this table

### Table 8. Master Gradation Limits (% Passing by Weight or Volume) and VMA Requirements

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>SP-A Base</th>
<th>SP-B Intermediate</th>
<th>SP-C Surface</th>
<th>SP-D Fine Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&quot;</td>
<td>100.0&lt;sup&gt;1&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1-1/2&quot;</td>
<td>98.0–100.0</td>
<td>100.0&lt;sup&gt;1&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1&quot;</td>
<td>90.0–100.0</td>
<td>98.0–100.0</td>
<td>100.0&lt;sup&gt;1&lt;/sup&gt;</td>
<td>–</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>Note&lt;sup&gt;2&lt;/sup&gt;</td>
<td>90.0–100.0</td>
<td>98.0–100.0</td>
<td>100.0&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>–</td>
<td>Note&lt;sup&gt;2&lt;/sup&gt;</td>
<td>90.0–100.0</td>
<td>98.0–100.0</td>
</tr>
<tr>
<td>5/8&quot;</td>
<td>–</td>
<td>–</td>
<td>Note&lt;sup&gt;2&lt;/sup&gt;</td>
<td>90.0–100.0</td>
</tr>
<tr>
<td>#4</td>
<td>19.0–90.0</td>
<td>23.0–90.0</td>
<td>28.0–90.0</td>
<td>32.0–90.0</td>
</tr>
<tr>
<td>#8</td>
<td>19.0–45.0</td>
<td>23.0–49.0</td>
<td>28.0–58.0</td>
<td>32.0–67.0</td>
</tr>
<tr>
<td>#16</td>
<td>1.0–45.0</td>
<td>2.0–49.0</td>
<td>2.0–58.0</td>
<td>2.0–67.0</td>
</tr>
<tr>
<td>#50</td>
<td>1.0–45.0</td>
<td>2.0–49.0</td>
<td>2.0–58.0</td>
<td>2.0–67.0</td>
</tr>
<tr>
<td>#50</td>
<td>1.0–45.0</td>
<td>2.0–49.0</td>
<td>2.0–58.0</td>
<td>2.0–67.0</td>
</tr>
<tr>
<td>#200</td>
<td>1.0–7.0</td>
<td>2.0–3.0</td>
<td>2.0–10.0</td>
<td>2.0–10.0</td>
</tr>
</tbody>
</table>

Design VMA, % Minimum

| –        | 13.0     | 14.0    | 15.0 | 16.0 |

Production (Plant-Produced) VMA, % Minimum

| –        | 12.5     | 13.5    | 14.5 | 15.5 |

1. Defined as maximum sieve size. No tolerance allowed.
2. Must retain at least 10% cumulative.

Figure 28. Current Item 344, Superpave Mixtures, Table 4 and Table 5 and Table 8.
Table 4. Maximum Allowable Amounts of RAP

<table>
<thead>
<tr>
<th>Surface</th>
<th>Intermediate</th>
<th>Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>25.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

1. Must also meet the recycled binder to total binder ratio shown in Table 5.

Table 5. Allowable Substitute PG Binders and Maximum Recycled Binder Ratios

<table>
<thead>
<tr>
<th>Originally Specified PG Binder</th>
<th>Allowable Substitute PG Binder for Surface Mixes</th>
<th>Allowable Substitute PG Binder for Intermediate and Base Mixes</th>
<th>Maximum Ratio of Recycled Binder to Total Binder (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76-22-5</td>
<td>70-22</td>
<td>70-22</td>
<td>10.0 20.0 25.0</td>
</tr>
<tr>
<td>70-22-5</td>
<td>N/A</td>
<td>64-22</td>
<td>10.0 20.0 25.0</td>
</tr>
<tr>
<td>64-22-5</td>
<td>N/A</td>
<td>N/A</td>
<td>10.0 20.0 25.0</td>
</tr>
<tr>
<td>76-28-5</td>
<td>70-28</td>
<td>70-28</td>
<td>10.0 20.0 25.0</td>
</tr>
<tr>
<td>70-28-5</td>
<td>N/A</td>
<td>64-28</td>
<td>10.0 20.0 25.0</td>
</tr>
<tr>
<td>64-28-5</td>
<td>N/A</td>
<td>N/A</td>
<td>10.0 20.0 25.0</td>
</tr>
</tbody>
</table>

1. Combined recycled binder from RAP and RAS. RAS is not permitted in surface mixtures unless otherwise shown on plans.
2. Binder substitution is not allowed for surface mixtures.
3. Binder substitution is not allowed for intermediate and base mixes.
4. Use no more than 10.0% recycled binder in surface mixtures when using this originally specified PG binder.
5. Use no more than 20.0% recycled binder when using this originally specified PG binder for intermediate mixtures. Use no more than 25.0% recycled binder when using this originally specified PG binder for base mixes.

Table 8. Master Gradation Limits (% Passing by Weight or Volume) and VMA Requirements

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>B Fine Base</th>
<th>C Coarse Surface</th>
<th>D Fine Surface</th>
<th>F Fine Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&quot;</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1 1/2&quot;</td>
<td>100.0(^a)</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1&quot;</td>
<td>98.0-100.0</td>
<td>100.0(^a)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>84.0-98.0</td>
<td>95.0-100.0</td>
<td>100.0(^a)</td>
<td>–</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>–</td>
<td>–</td>
<td>98.0-100.0</td>
<td>100.0(^a)</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>60.0-80.0</td>
<td>70.0-85.0</td>
<td>85.0-100.0</td>
<td>98.0-100.0</td>
</tr>
<tr>
<td>#4</td>
<td>40.0-60.0</td>
<td>45.0-63.0</td>
<td>50.0-70.0</td>
<td>70.0-90.0</td>
</tr>
<tr>
<td>#8</td>
<td>29.0-43.0</td>
<td>32.0-44.0</td>
<td>35.0-46.0</td>
<td>38.0-48.0</td>
</tr>
<tr>
<td>#50</td>
<td>13.0-28.0</td>
<td>14.0-28.0</td>
<td>15.0-29.0</td>
<td>12.0-27.0</td>
</tr>
<tr>
<td>#50</td>
<td>6.0-20.0</td>
<td>7.0-21.0</td>
<td>7.0-20.0</td>
<td>6.0-19.0</td>
</tr>
<tr>
<td>#200</td>
<td>2.0-7.0</td>
<td>2.0-7.0</td>
<td>2.0-7.0</td>
<td>2.0-7.0</td>
</tr>
</tbody>
</table>

Design VMA, % Minimum

| – | 13.0 | 14.0 | 15.0 | 16.0 |

Production (Plant-Produced) VMA, % Minimum

| – | 12.5 | 13.5 | 14.5 | 15.5 |

Figure 29. Future Item 341, Asphalt Mixtures, Table 4, Table 5 and Table 8.
Table 4. Maximum Allowable Amounts of RAP¹

<table>
<thead>
<tr>
<th>Maximum Allowable Fractionated RAP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
</tr>
<tr>
<td>20.0</td>
</tr>
</tbody>
</table>

1. Must also meet the recycled binder to total binder ratio shown in Table 5.

Table 5. Allowable Substitute PG Binders and Maximum Recycled Binder Ratios

<table>
<thead>
<tr>
<th>Originally Specified PG Binder</th>
<th>Allowable Substitute PG Binder for Surface Mixes</th>
<th>Allowable Substitute PG Binder for Intermediate and Base Mixes</th>
<th>Maximum Ratio of Recycled Binder¹ to Total Binder (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76-22ʰ,³,⁵</td>
<td>70-22</td>
<td>70-22</td>
<td>15.0</td>
</tr>
<tr>
<td>70-22ʰ,³,⁵</td>
<td>N/A</td>
<td>64-22</td>
<td>15.0</td>
</tr>
<tr>
<td>64-22ʰ,³</td>
<td>N/A</td>
<td>N/A</td>
<td>15.0</td>
</tr>
<tr>
<td>76-28ʰ,³,⁵</td>
<td>70-28</td>
<td>70-28</td>
<td>15.0</td>
</tr>
<tr>
<td>70-28ʰ,³,⁵</td>
<td>N/A</td>
<td>64-28</td>
<td>15.0</td>
</tr>
<tr>
<td>64-28ʰ,³</td>
<td>N/A</td>
<td>N/A</td>
<td>15.0</td>
</tr>
</tbody>
</table>

1. Combined recycled binder from RAP and RAS. RAS is not permitted in surface mixtures unless otherwise shown on the plans.
2. Binder substitution is not allowed for surface mixtures.
3. Binder substitution is not allowed for intermediate and base mixtures.
4. Use no more than 15.0% recycled binder in surface mixtures when using originally specified PG binder.
5. Use no more than 25.0% recycled binder when using this originally specified PG binder for intermediate mixtures. Use no more than 30.0% recycled binder when using this originally specified PG binder for base mixtures.

Table 8. Master Gradation Limits (% Passing by Weight or Volume) and VMA Requirements

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>SP-B Intermediate</th>
<th>SP-C Surface</th>
<th>SP-D Fine Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>2²</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>1 1/2&quot;</td>
<td>100.0³</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>1&quot;</td>
<td>90.0–100.0</td>
<td>100.0³</td>
<td>−</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>90.0–100.0</td>
<td>90.0–100.0</td>
<td>100.0³</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>Note²</td>
<td>90.0–100.0</td>
<td>90.0–100.0</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>−</td>
<td>Note²</td>
<td>90.0–100.0</td>
</tr>
<tr>
<td>#4</td>
<td>23.0–90.0</td>
<td>28.0–90.0</td>
<td>32.0–90.0</td>
</tr>
<tr>
<td>#8</td>
<td>23.0–34.6</td>
<td>28.0–37.0</td>
<td>32.0–40.0</td>
</tr>
<tr>
<td>#16</td>
<td>2.0–28.3</td>
<td>2.0–31.6</td>
<td>2.0–37.6</td>
</tr>
<tr>
<td>#30</td>
<td>2.0–20.7</td>
<td>2.0–23.1</td>
<td>2.0–27.5</td>
</tr>
<tr>
<td>#50</td>
<td>2.0–13.7</td>
<td>2.0–15.5</td>
<td>2.0–18.7</td>
</tr>
<tr>
<td>#200</td>
<td>2.0–8.0</td>
<td>2.0–10.0</td>
<td>2.0–10.0</td>
</tr>
</tbody>
</table>

Design VMA, % Minimum

| − | 15.0 | 15.0 |

Production (Plant-Produced) VMA, % Minimum

| − | 13.5 | 14.5 | 15.5 |

1. Defined as maximum sieve size. No tolerance allowed.
2. Must retain at least 10% cumulative.

Figure 30. Future Item 344, Superpave Mixtures, Table 4 and Table 5 and Table 8.
**Pavement Performance**

Three pavement sections containing RAS were inspected. The inspected sections were on US 180 and I-30 in the Fort Worth District, and US 175 east of downtown Dallas in the Dallas District. The section of I-30 inspected in the Fort Worth District was under construction, so it wasn’t possible to assess performance. This mixture was also used as a bond breaker for a future concrete overlay. Table 11 is a summary of information about the two sections inspected that had been in service for up to 7 years. Figure 31, Figure 32 and Figure 33 illustrate the field performance observed for these pavements. The US 180 project included overlays on jointed plain concrete pavement (JPCP) and asphalt pavement (AP). The section on AP exhibited some fatigue cracking, while the section on JPCP did not. The US 175 pavement appeared to be performing well for its intended purpose and 7 years of service. The US 175 project with a lower RBR and 3 years of service was not performing as well potentially due to the underlying structure. The distresses on US 175 were likely not related to the binder embrittlement from high amounts of RAM.

Table 11. TxDOT inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Route</th>
<th>%RAS/RAP (by weight)</th>
<th>Reclaimed Binder Ratio (RBR)</th>
<th>Mix Type</th>
<th>Asphalt Binder Grade</th>
<th>Pavement Thickness (inches)</th>
<th>Observed Performance</th>
</tr>
</thead>
</table>
| 2016 US 180    | 5% RAS + 0% RAP      | 0.19 RAS                    | ½” Type C | PG58-28              | 2.0 on JPCP or AP           | • Moderate severity low extent longitudinal cracking, and transverse cracking.  
• low severity low extent fatigue cracking.  
• Localized high severity low extent fatigue cracking. |
| 2012 US 175    | 5% RAS + 13% RAP     | 0.19 RAS + 0.16 RAP         | ½” Type C | PG64-22              | 1.5 on JPCP                 | • Moderate severity high extent longitudinal and block cracking. Some is reflective cracking from JPCP.  
• High severity low extent fatigue cracking. |
Figure 31. US 180 constructed 2016, longitudinal and transverse cracking on JPCP.

Figure 32. US 180 constructed 2016, longitudinal, transverse and fatigue cracking on AP.
Plant Visits

One asphalt mixture plant facility located east of Dallas was visited. It had been in operation for approximately 5 years and was equipped to run both RAS and RAP. The contractor uses approximately 35,000 tons of RAS annually with approximately 60 percent in TxDOT mixtures and 40 percent in commercial mixtures. MWAS are processed at the plant site by a subcontractor. The equipment used by the subcontractor is a shredder followed by a trommel to produce ¼-inch minus RAS. Figure 34 shows the trommel used to produce RAS passing the ¼-inch sieve. Figure 35 shows a MWAS stockpile showing whole shingles and tab punch outs prior to processing.

A relatively small amount, about 1,000 tons, of finished RAS is stockpiled at the asphalt plant to minimize clumping. Though it was not covered, the moisture content was very low. The contractor indicated the three keys to successful use of RAS at an asphalt plant were:

1. A consistent supply of RAS (which was why they indicated MWAS was used).
2. Fine grind of RAS (1/4-inch minus).
3. Managing moisture to the lowest level possible.

The asphalt plant visited was a counterflow drum mix plant with 5 coldfeed bins, 2 recycled material coldfeed bins, and 3, three-hundred-ton storage silos. The plant is equipped with 4 horizontal asphalt binder tanks, though only 2 grades of asphalt are used at the facility. The plant baghouse fines return system was a screw auger feed which included the primary dust collector (cyclone) material with the baghouse fines. Several positive observations were made at the asphalt plant. They included an on-site QC laboratory and staff. The recycled materials coldfeed bins feeding RAS and RAP were specifically made for feeding these recycled materials as shown in Figure 36. They were not conventional aggregate
coldfeed bins with add-ons (chop gates, cannons, etc.). They had steep sides and sloped bottoms. The bins also had scalping screens on them. The recycled material feed belt going to the RAP collar of the drum had a covered belt scale and it was covered to prevent environmental impacts on its performance as shown in Figure 37.

Image: University of Nevada Reno

Figure 34. RAS processing trommel used to produce RAS passing ¼-inch sieve.

Image: University of Nevada Reno

Figure 35. MWAS stockpile showing whole shingles and tab punch outs.
Figure 36. Coldfeed bin specifically manufactured to feed recycled materials with scalping screen to remove RAS clumps.

Figure 37. Cover on belt scale on conveyor to the RAP collar on the drum.
**Positive Practices Observed**

Throughout the visit several TxDOT positive practices were identified. They included the following:

1. TxDOT’s specifications have evolved over time based on field performance observations, partnering with industry, and research. The specifications are evolving toward all Superpave gyratory compaction. In fact, the primary asphalt mixture specifications TxDOT Item 341, Dense-Graded Hot-Mix Asphalt and Item 344, Superpave Mixtures are both currently undergoing significant revisions.

2. RAS and RAP are each limited by percent weight in the mixture and RBR criteria. The amount of recycled materials increases with depth in a pavement structure. The revisions to both specifications pertaining to the allowable RAP ranges from 15 to 35 percent, while the allowable RBR ranges from 0.10 to 0.30 depending on location in the pavement structure. Unfractionated RAP is not allowed in the new specification.

3. RAS is currently allowed in SMA, PFC, Superpave, dense-graded, and thin bonded friction course mixtures. RAS is allowed, and 5 percent is used by a large environmentally conscious producer in every SMA mix it produces. Based on proposed changes for the future, RAS will not be allowed in any surface mixtures, unless otherwise shown on the plans.

4. There is an allowable substitute for the PG binder required by contract for some of the binders. However, only the high temperature PG is lowered and not the low temperature PG.

5. The RBR is flagged on the test result report template if the design RBR is exceeded and used to stop production until it is within specification.

6. TxDOT uses a VMA requirement for mixture design and acceptance. However, VMA is calculated with the effective specific gravity of the virgin and recycled aggregates.

7. TxDOT specifications currently require the Hamburg Wheel Track (HWT) rutting test and Texas Overly Test (TxOL) cracking performance test in mix design. The HWT has to meet specification criteria, while the TxOL test is currently used for information gathering. In the near future HWT, TxOL and Ideal-Cracking Test (IDEAL-CT) will be required with the goal of correlating TxOL used in design and Ideal-CT used in production for acceptance. A new special provision for pilot projects is being used for this.

8. Partnering with academia and industry is integral to continual improvement of asphalt mixture performance in Texas.

**Recommended Research**

TxDOT suggested research to:

1. Determine how to use RAS as “black rock” in asphalt mixture and obtain mixture performance similar to virgin asphalt mixture.

2. Evaluate the use of RAS in cold in-place and cold central plant recycling.

3. Identify the use of RAS for other applications, e.g., base layers for concrete pavements, and unprocessed shingles that could be used as soil replacement for expansive soils.

4. Address two common issues when using RAS in asphalt mixtures: 1) clumping and 2) identifying the actual amount of shingles entering the asphalt mixture. Methods to improve these should be identified. One example could be the use of a screw auger to feed the shingles.

Some key lessons learned regarding practices from TxDOT include:

- Based on the preference from the Districts, planned changes will not permit RAS in surface mixtures unless otherwise shown on the plans with a general note from a District.

Some key observations regarding positive practices from TxDOT include:

- An RBR of 0.35 with 5 percent RAS had good performance.
• RAS will be allowed in intermediate and base mixtures at 3 percent.
• The amount of recycled material increases with depth.
• During production, the RBR is flagged if it exceeds the maximum. That information is used to stop production until it is within specification.
• Mixture performance testing is currently required in the mixture design. A specification is being piloted for use during production for acceptance.

Observations from Document Reviews and Agency Interviews
U.S. agency experience with using RAS in asphalt mixture dates back to the 1970’s and interest in using it has historically been greatest when significant increases in virgin asphalt binder cost have occurred. For example, in the early 1970’s and in the past 10 years. Integration of RAS into asphalt mixtures is market driven and influenced by cost, availability, customer allowance for use, and sustainability ambition. A decision to use RAS will often only be considered if the cost of RAS is significantly less than the cost of virgin asphalt binder that can be replaced with RAS.

Pavement Design and Performance Strategy Considerations
Each state has a strategy that relates the quality of their asphalt mixtures and overlay design methodology to the expected time for future rehabilitations. Further, each state has different funding levels to support its asphalt overlay program. Some states have very high-quality asphalt mixture requirements with a strong overlay design program and routinely obtain 15 to 18 years before the next overlay. Other states emphasize a lower cost asphalt mixture with a “pave it thin” approach, but only expected to obtain 7 to 8 years of service before the next overlay. DelDOT is a good example of the former and MoDOT is a good example of the latter. Both had very good pavement performance while using different philosophies. These are considerations when reviewing the information in this report; whether comparing the information from agency to agency within this report or comparing it to your own program.

Lessons Learned
There was one common lesson learned observed at multiple agencies that led to optimizing use of RAS and thus pavement performance. It was to diligently: review mixture design requirements, specifications and test methods and inspect pavement performance. This information was used to make course corrections and changes to improve performance based on those observations while working with industry and research.

The City of Eugene, MoDOT, TxDOT, and IDOT are all examples. The City of Eugene now requires lower stiffness virgin asphalt binder based on observation of earlier than anticipated block cracking of mixtures having RBR up to 0.40. A relatively minor change in specifications addressed the issue and performance improved significantly.

MoDOT’s specification has evolved over time based on field performance observations, partnering with industry, and research. There were two distinct “eras” of specification changes identified. The first significant change occurred in approximately 2009 as there was an unacceptable level of cracking. In some cases, 7 percent RAS was being used. Changes were made to increase the amount of virgin binder by accounting for the absorption of virgin binder and requiring higher VMA. The second significant change occurred in approximately 2014 as there was this an unacceptable level of cracking occurring. The current specification evolved with more emphasis on limits of RAS and combinations of RAS and RAP, use of softer virgin binders, and more virgin binder. Work to improve the specification continues with research intended to integrate performance tests into the specifications.
TxDOT was historically the leader in RAS use in the U.S. It has two workhorse asphalt mixture specifications, Item 341 and Item 344. Unacceptable levels of cracking associated with RAS use led to partnering with industry, coupled with extensive research, to make significant changes in both Items 341 and 344. The revised specifications will be effective in January 2020 and will essentially reduce the maximum allowable RAP/RAS and RBR. The use of RAS in surface mixtures will also be removed from the specifications, though allowed by note on plans at the discretion of District Engineers. TxDOT also uses simple performance tests and will be piloting specifications in 2020 with new performance tests that will likely be required in both mix design and acceptance in the future. TxDOT also has research underway assessing the impact of not directly accounting for asphalt absorption when determining VMA.

IDOT is another agency that has made changes to specifications and design requirements over time based on performance. The changes have been based on extensive research that has led to improved performance. Like TxDOT, IDOT has integrated simple performance tests into its specifications to achieve the desired performance with the use of recycled materials.

Range of Some Typical RAS and RAP Quantities Observed
When visiting each of the agencies, various projects and asphalt mixture designs were reviewed. There was a wide range in quantities of recycled materials used among them. Some examples of the quantities of RAS and RAP observed are shown in Table 12.

<table>
<thead>
<tr>
<th>Agency</th>
<th>RAS and RAP Content</th>
<th>RBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Eugene</td>
<td>3% RAS and 30% RAP</td>
<td>0.15 RAS and 0.25 RAP</td>
</tr>
<tr>
<td>DelDOT</td>
<td>4% RAS and 25% RAP</td>
<td>0.19 RAS and 0.18 RAP</td>
</tr>
<tr>
<td>MoDOT with RAS</td>
<td>3% RAS and 27% RAP</td>
<td>0.16 RAS and 0.32 RAP¹</td>
</tr>
<tr>
<td>MoDOT without RAS</td>
<td>40% RAP</td>
<td>0.46 RAP¹</td>
</tr>
<tr>
<td>PennDOT</td>
<td>5% RAS</td>
<td>0.20 RAS</td>
</tr>
<tr>
<td>TxDOT</td>
<td>3% RAS and 10% RAP</td>
<td>0.20 RAS and 0.15 RAP</td>
</tr>
</tbody>
</table>

¹Calculated with effective asphalt content.

Some contractors in Missouri reported that the most cost-effective asphalt mixture was using 40 percent RAP with PG58-28 binder without RAS. However, those quantities of RAP were not always available, so some contractors would then use RAS to make up the difference to meet the RBR requirements. Again, it should be noted that it is difficult to directly compare the RAS and RAP quantities from agency to agency. Each agency has a different process in designing its asphalt mixture, designing its pavement overlay program, and writing its specifications when using RAS and RAP. The information provided is intended to provide an overview of existing practices.

Summary of Observations:
Each agency has its own methodology to accommodate the use of RAS and RAP. Their standard mixture design requirements and specifications were modified to accommodate high quantities of recycled materials. Methodologies, mixture design requirements, and specifications can be broken down into categories to allow for a better understanding. A list of the categories is provided below and shown in Table 13. Not every agency has requirements in each category. Further, requirements for an agency apply from multiple categories in combination.

- Rationale and location for using RAS.
- Type of RAS allowed.
- Criteria for RAS by weight and/or RBR.
- Use of softer binder.
- Additional asphalt content.
- Use of additives.
- Criteria for RAS based on other factors.
- Mixture performance tests.
- Other keys.

Table 13. Categories of requirements used by various agencies for RAS usage.

<table>
<thead>
<tr>
<th>Requirements of Agencies for RAS Use</th>
<th>City of Eugene</th>
<th>DelDOT</th>
<th>IDOT</th>
<th>MoDOT</th>
<th>PennDOT</th>
<th>TxDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWAS RAS Type</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X(^1)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>PCAS RAS Type</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X(^1)</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>% RAS Criteria</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X(^2)</td>
<td>X(^3)</td>
<td>X</td>
</tr>
<tr>
<td>RBR Criteria</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X(^2),(^3)</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Softer Binder by Grade Bump</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X(^4)</td>
<td>X(^5)</td>
<td>X</td>
</tr>
<tr>
<td>Softer Binder by Blending Chart</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Softer Binder by PG of Actual Blend</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional Asphalt by Design</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional Asphalt by Acceptance</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Recycling Agent Additive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WMA Additive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift Location Criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic Criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specialty Mixture Criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAP Type Criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binder Type Criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance Test(s)</td>
<td>Evaluating</td>
<td>X</td>
<td>Soon</td>
<td>X</td>
<td>Soon</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Only PCAS used.
\(^2\)RAS portion weighted twice RAP.
\(^3\)RBR calculated with effective asphalt content.
\(^4\)RAP only.
\(^5\)Required with recycled materials use at lower temperatures.

**Rationale and Location for Using RAS**

There are a variety of rationales for the use of RAS and some examples are described below.

- City of Eugene uses RAS and RAP due to a sustainability ambition with a City Climate Recovery Ordinance on CO\(_2\) emissions reduction. That is the driver for many of the decisions made in their pavement program. This has led to RBR of up to 0.40 with up to 0.15 from RAS on the city’s streets.
- DelDOT has one large asphalt contractor with multiple asphalt plants who has invested in processing both MWAS and PCAS. This contractor has been very proactive in using innovations for including RAS in their asphalt mixture design.
- IDOT has observed that over 90 percent of the RAS used in asphalt mixtures is used within the two, large-metropolitan districts: Chicago and East St Louis.
- MoDOT has observed that RAP is the primary recycled material used in metropolitan areas as it is readily available. In rural areas, RAS becomes more prevalent as RAP is not as readily available.
PennDOT has observed two contractors that use RAS. There is a shingle manufacturing plant within a few miles of one asphalt contractor’s shingle processing facility. The other is an asphalt mixture producer importing shingles from Ohio who does not have a supplier source code.

**Type of RAS Used**
Some agencies only allow the use of both MWAS and PCAS, while others only allow MWAS. Availability of shingles is influenced by the location of shingle manufacturing plants, the type of roofing materials used in specific geographies and how far it can economically be hauled. Some examples of the type of RAS encountered are described below.

- City of Eugene allows either MWAS or PCAS. Interestingly, the contractor processing the RAS combines both MWAS and PCAS as part of the grinding process. This minimizes wear on their equipment. However, this creates high variability in the asphalt content of the combined RAS. Asphalt contractors are limited in the amount of these combined shingles they can use to meet the agency’s asphalt content acceptance specification. This is an example why MWAS and PCAS should not be combined as AASHTO MP 23 “Standard Specification for Reclaimed Asphalt Shingles for Use in Asphalt Mixtures” indicates (19).
- IDOT and MoDOT allow either MWAS or PCAS. They cannot be combined.
- PennDOT allows only MWAS.
- TxDOT allows either MWAS or PCAS. The Dallas-Ft. Worth area has three different shingle manufacturing companies. As a result, MWAS were primarily used in that area.

**Criteria for RAS by Weight and/or RBR**
When an agency allows the use of both RAS and RAP it is important that policy, materials selection, mixture design and specifications clarify how to integrate both together. Examples of the criteria used for RAS and RAP are summarized in Table 14 and described below.

<table>
<thead>
<tr>
<th>Agency</th>
<th>Percent by Weight</th>
<th>RBR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Eugene</td>
<td>≤ 5% RAS</td>
<td>RAS + RAP ≥ 0.35</td>
<td></td>
</tr>
<tr>
<td>DelDOT</td>
<td>N/A</td>
<td>RAS only ≤ 0.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAS + RAP ≤ 0.40</td>
<td></td>
</tr>
<tr>
<td>IDOT</td>
<td>≤ 5% RAS</td>
<td>Summary: RAS + RAP ≤ 0.10 to 0.30</td>
<td>This is a summary as the criteria has many different categories.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAS + FRAP ≤ 0.10 to 0.50</td>
<td></td>
</tr>
<tr>
<td>MoDOT</td>
<td>N/A</td>
<td>RAS ≤ 0.10</td>
<td>Effective asphalt content is used to calculate RBR.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAP ≤ 0.20</td>
<td>When calculating RBR with RAS and RAP, the RAS percentage must be</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAS + RAP ≤ 0.20</td>
<td>doubled.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAP (PG*) ≤ 0.40</td>
<td>*Softer binder requirements apply.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAS + RAP (PG*) ≤ 1.00</td>
<td></td>
</tr>
<tr>
<td>PennDOT</td>
<td>= 5% RAS</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>TxDOT</td>
<td>≤ 3% RAS (not on surface)</td>
<td>RAS + RAP ≤ 0.15 in Surface 0.15 in Intermediate 0.25 in Intermediate 0.30 in Base</td>
<td>Proposed changes for Item 344 Superpave mixtures. All RAP is fractionated.</td>
</tr>
</tbody>
</table>
• The City of Eugene allows a maximum of 5 percent RAS and a minimum RBR of 0.35 from RAS and RAP.
• DelDOT allows a maximum RBR of 0.20 for just RAS and 0.40 from RAS and RAP. The binder must also meet blending chart requirements.
• IDOT allows a maximum of 5 percent RAS and a maximum RBR from RAS and RAP varies based on many other considerations. These other considerations are discussed further in the section “Criteria for RAS Based on Other Factors” below.
• MoDOT allows a maximum RBR calculated with effective asphalt content. MoDOT’s requirements for RAS, RAP and combinations of RAS and RAP are limited by RBR as shown in Table 15 for Item 401. The criteria were developed over time based on research, field performance and negotiation. When RAS and RAP are used, the RBR from RAS is doubled to account for the stiffer binder in RAS. When the RBR exceeds 0.20 from RAS and RAP, a softer binder must be used. When the RBR exceeds 0.40 from RAS and RAP, the aged and extracted binder must meet the contract PG requirements.

<table>
<thead>
<tr>
<th>Binder</th>
<th>RAP RBR Using Effective Asphalt Content</th>
<th>RAS RBR Using Effective Asphalt Content</th>
<th>RAS and RAP RBR Using Effective Asphalt Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract PG</td>
<td>0.00 – 0.20</td>
<td>0.00 – 0.10</td>
<td>RAP + (2*RAS) ≤ 0.20</td>
</tr>
<tr>
<td>PG softened one grade</td>
<td>0.21 – 0.40</td>
<td>0.11 – 0.20</td>
<td>0.20 &lt; RAP + (2*RAS) ≤ 0.40</td>
</tr>
<tr>
<td>Blend chart</td>
<td>0.00 – 1.00</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Extraction and grading of binder from final mixture</td>
<td>0.00 – 1.00</td>
<td>0.00 – 1.00</td>
<td>0.00 – 1.00</td>
</tr>
</tbody>
</table>

• PennDOT allows 5 percent RAS only, no more or less. Blending charts are used to determine the virgin binder grade. An Engineering District 12 Standard Special Provision requires Bending Beam Fatigue comparison testing for asphalt mixture designs containing both RAP and RAS, and containing greater than 0.25 RBR for binder and 0.30 for base mixtures.
• TxDOT allows a maximum of 3 percent RAS although no RAS is allowed in the surface. A maximum RBR from RAS and RAP varies based on many other considerations such as lift and type of RAP.

**Use of Softer Binder**

MWAS contain approximately 20 to 30 percent asphalt binder which is greater than PCAS due to the loss of aggregate granules over time (12). (The binder of MWAS is less stiff than the binder in PCAS since they have not been exposed to the environment for years. Typical RAS PG binder high temperatures greatly exceed 100°C with low temperatures as warm as 40°C (15).)

Using a softer binder has been a very effective method for using RAS and higher quantities of RAP. This can be done by bumping the PG binder’s low and high temperature down, using blending charts or extracting and grading the binder from final mixture. Examples of the criteria used for softer binder are summarized in Table 16 and described below.
- City of Eugene requires bumping down both the PG binder’s high and low temperature one grade from PG 64-22 to PG 58-28. Initial projects were built without grade bumping down and there was noticeable cracking. Since the change to requiring grade bumping, the performance has improved.
- DelDOT requires a blending chart. Data used in the blending chart comes from DelDOT’s statewide testing and uses a running average from 1 to 2 years of data. There is a spreadsheet used to calculate the PG of the virgin binder and reclaimed material. It is called the “2009 RAP Calculator.” It assumes 100 percent binder availability from the reclaimed materials. A higher upper temperature grade than specified in the contract can be used. Use of recycled materials cannot raise the low temperature properties of the combined binder above -23°C. DelDOT primarily uses a PG 64-22. No grade change is allowed with polymer modified binders (PG 76 and 70).
- IDOT requires a softer binder with both the PG binder’s high and low temperatures lowered by one grade when the RBR is greater than 0.20. IDOT observations from performance tests have identified that this is effective. However, this one grade bump may not be sufficient when RBR exceeds 0.30.
- MoDOT requires a softer binder with either the PG binder’s low temperature or both the high and low temperature lowered by one grade when the RBR either from RAS is greater than 0.10 or from RAS and RAP is greater than 0.20. The actual grading from the binder extracted from the aged mixture is required when RBR from either RAS is greater than 0.20 or from RAS and RAP is greater than 0.40.
- PennDOT requires no adjustment to the binder grade when 5 percent RAS is used. If RAP is proposed to be used with 5 percent RAS in the same asphalt mixture, regardless of the RAP percentage, the asphalt binder from a lab blend of the RAP and RAS is extracted, recovered, and analyzed. In the majority of cases will require a softer binder grade. The blend of binder materials must meet the PG binder requirement for the environment.

Table 16. Summary of criteria for using softer binder from various agencies.

<table>
<thead>
<tr>
<th>Agency</th>
<th>Softer Binder</th>
<th>Blending Chart</th>
<th>Actual PG of Blended Asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>City of Eugene</td>
<td>Asphalt binder grade lowered one full grade from PG 64-22 to PG 58-28.</td>
<td>Low temperature PG cannot be raised. High temperature PG can be raised one grade.</td>
<td></td>
</tr>
<tr>
<td>DelDOT</td>
<td>RBR &gt; 0.20: softer binder is required with both the low and high PG temperatures lowered by one grade.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IDOT</td>
<td>RBR from RAS &gt; 0.10: softer binder required with either the low or both the low and high PG lowered by one grade.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoDOT</td>
<td>RBR from RAS &gt; 0.20: actual grading from the binder extracted from the aged mixture is required to meet the contract PG.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PennDOT</td>
<td>PennDOT requires analysis by Blending Chart for all RAP and RAS combinations.</td>
<td>Any amount of RAP and 5% RAS requires extraction and must meet PG for the environment.</td>
<td></td>
</tr>
</tbody>
</table>
**Additional Asphalt Content**

Two items commonly mentioned were the type and quantity of binder. The previous section discussed the type of binder as related to the grade of the virgin binder used in the mixtures. Softer virgin binder is often selected to minimize embrittlement. This results in grade bumping down one or two grades. It is also important that the asphalt mixtures contain adequate amount of virgin asphalt binder. To emphasize the importance of the virgin binder content, a couple of agencies also mentioned the emphasis on meeting dust to asphalt content ratio requirements. Examples of effective methods to ensure that there is an adequate amount of virgin asphalt content are described below.

- DelDOT has increased the asphalt content by about 0.2 percent with a combination of reduced number of gyrations (75 for dense graded mixtures and 100 for SMA) and a minimum VMA requirement that is 0.5 percent above the AASHTO M323 minimum (16).
- IDOT has a very robust VMA requirement for mixture design and acceptance. VMA is calculated using the virgin and recycled aggregate bulk specific gravities (Gsb) as determined by IDOT. Although IDOT uses the same VMA criteria as AASHTO M 323 “Standard Specification for Superpave Volumetric Mix Design,” there is strict enforcement of that minimum VMA for acceptance (16). A percent within limits (PWL) specification includes VMA as a quality characteristic that impacts payment.
- PennDOT’s mixture design requires minimum design VMA of 0.5 percent higher than AASHTO M323 (16). In production for acceptance, VMA must be no less than 0.5 percent of the minimum design VMA requirement (i.e., the AASHTO M323 minimum design VMA). This practice leads to increased virgin binder content for mixtures incorporating recycled materials.
- TxDOT uses the minimum RBR to set the lower tolerance limit of asphalt content for acceptance. Indirectly, the minimum RBR is part of the acceptance. This is done to ensure that there is enough virgin binder in the mixture during production.

**Use of Additives**

Some agencies are using additives to support their recycling with RAS and RAP. These include WMA additives and recycling agents. Examples of the requirements for additives used are described below.

- City of Eugene requires WMA using foaming at lower temperatures. The maximum temperature at mixing is 275°F and the maximum temperature behind the paver is 215°F. They reported that WMA at lower temperatures was specified to minimize the activation or mobilization of RAS binder. Consideration is being given to requiring WMA chemical additives.
- DelDOT allows recycling agents at the contractor’s option. Recycling agents are voluntarily being used by a major contractor to improve mixture performance. This is based on their performance testing results on binders and mixtures.
- MoDOT allows recycling agents. They are used to meet the requirement that the actual grading of the binder extracted from the aged mixture meets the contract PG. About 15 to 25 percent of MoDOT’s asphalt mixtures contain recycling agents. Some contractors suggested that additional virgin asphalt binder might be more effective than a recycling agent.

**Criteria for RAS Based on Other Factors**

There are many other factors that agencies use to allow an increase in the amount of RAS. For example, it is not uncommon for agencies to allow greater amounts of RAS in base and intermediate pavement layers than in surface courses. Examples of additional criteria when using RAS are described below.

- IDOT allows a maximum of 5 percent RAS by weight. In addition, the RBR criteria are shown in Table 17 for RAS and RAP and Table 18 for RAS and fractioned RAP (FRAP). It also includes criteria
for specialty mixtures such as SMA and a small NMAS mixtures (IL-4.75). The criteria were developed over time based on research, field performance and negotiation.

Table 17. IDOT’s Maximum RBR for RAS and RAP by asphalt mixture type.

<table>
<thead>
<tr>
<th>Asphalt Mixture</th>
<th>Binder Course Maximum RBR for RAS and RAP</th>
<th>Surface Course Maximum RBR for RAS and RAP</th>
<th>Polymer Modified Maximum RBR for RAS and RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{design}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.10</td>
</tr>
<tr>
<td>50</td>
<td>0.25</td>
<td>0.15</td>
<td>0.10</td>
</tr>
<tr>
<td>70</td>
<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>90</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 18. IDOT’s Maximum RBR for RAS and FRAP.

<table>
<thead>
<tr>
<th>Asphalt Mixture</th>
<th>Binder Course without I-FIT Maximum RBR for RAS and FRAP</th>
<th>Binder Course with I-FIT Maximum RBR for RAS and FRAP</th>
<th>Surface Course without I-FIT Maximum RBR for RAS and FRAP</th>
<th>Surface Course with I-FIT Maximum RBR for RAS and FRAP</th>
<th>Polymer Modified without I-FIT Maximum RBR for RAS and FRAP</th>
<th>Polymer Modified with I-FIT Maximum RBR for RAS and FRAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{design}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>0.55</td>
<td>0.40</td>
<td>0.45</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>50</td>
<td>0.40</td>
<td>0.45</td>
<td>0.35</td>
<td>0.40</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>70</td>
<td>0.40</td>
<td>0.45</td>
<td>0.30</td>
<td>0.35</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>90</td>
<td>0.40</td>
<td>0.45</td>
<td>0.30</td>
<td>0.35</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>SMA</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>IL-4.75</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.30</td>
<td>0.35</td>
</tr>
</tbody>
</table>

- IDOT also uses a RAS binder availability factor of 0.85, which is similar to the RAS binder availability factor defined in AASHTO PP78-14, *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures* which sunset when AASHTO PP 78-17 *Standard Practice for Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures* was published (8, 9). However, the RAS binder availability factor used by IDOT is more rigorously defined resulting in a more accurate estimate.

- MoDOT allows RAS in mixtures specifying a contract PG64-22. This requirement impacts the allowable RAS by lift and traffic. PG64-22 is the asphalt binder used for the following types of corridors and mixtures:
  - Interstates: below the surface and first underlying lift.
  - Heavy volume (more 600 trucks per day): below the surface and first underlying lift.
  - Medium and low volume (less than 600 trucks per day): surface and underlying lifts.

Criteria for RAS usage are also a function of mixture type (i.e., bid item). Additionally, RAS is not allowed in SMA at this time, but experimentation is ongoing to change this.

**Mixture Performance Tests**

Ideally, a mixture performance test whose results relate to field performance is desired. This would allow contractors room for innovation with their selection of various types of materials and their proportions. Some states have a performance test and others are moving in that direction as described below. The addition of recycled materials makes an asphalt mixture more susceptible to cracking. Since cracking is related to long-term aging (LTA), it is important for cracking tests to be conducted on aged materials.
DelDOT is evaluating the Asphalt Pavement Analyzer (APA) for rutting, as well as Texas Overlay Test (TxOL) and IDEAL-Cracking Test (IDEAL-CT) before and after LTA. They are evaluating the quality of their asphalt mixtures, particularly with recycled materials. The performance tests are being evaluated for potential implementation in the mixture design and/or acceptance.

- IDOT specifications include mixture performance testing for rutting using the Hamburg Wheel Track (HWT) test and cracking using the Illinois Flexibility Index (I-FIT) test for both mixture design and production.
- MoDOT specifications will soon include mixture performance testing for rutting using the HWT and cracking using either the I-FIT or IDEAL-CT for both mixture design and production. In 2020 there will likely be approximately ten projects statewide.
- PennDOT’s District 12 uses a Standard Special Provision that requires flexural beam fatigue testing when an RBR is greater than 0.25 for binder and 0.30 for base mixtures exists. The fatigue testing must demonstrate that the addition of recycled materials does not reduce the fatigue resistance of the mixture by more than 15 percent.
- TxDOT specifications will soon include mixture performance testing for rutting using the HWTT and cracking using the TxOL for mixture design and IDEAL-CT for production. It will also include binder testing for the change in the critical low temperature (ΔTc). This was based on research, and a new special provision is available for pilot sections to be built from 2019 to 2021.

Other Keys

- Contractors in Missouri and Texas emphasized the importance of the quantity of binder in a mixture. They both mentioned the importance of a minimum virgin binder content and the need for appropriate dust to asphalt content ratios.
- IDOT has a strong partnership with the University of Illinois at Urbana-Champaign (UIUC) through the Illinois Center for Transportation (ICT). IDOT coordinates research with ICT to assure rational implementation of material specifications. Research directly relates to implementation in specifications.
- IDOT requires a rigorous QC Plan for RAS sources which was developed in partnership with the Illinois Environmental Protection Agency, which approves and authorizes the RAS suppliers beneficial use determination (BUD) application. The QC Plan and corresponding activities leads to RAS sources being on the IDOT qualified producer list.
- IDOT requires a QC Plan for RAS and RAS blended with manufactured sand. It is the contractor’s responsibility. It includes frequencies, tolerances, and acceptance criteria for gradation on four sieves and asphalt content.
- IDOT has clear documentation in the Annual Highway Material Sustainability Efforts Report which documents quantities of recycled and reclaimed materials used annually.

Field Performance Observations

Each agency site visit included informal pavement condition surveys of in-service mixtures containing RAS or RAS and RAP. The team carpooled and visually inspected the pavements together. The length of each project was windshield surveyed. Additionally, the vehicle was stopped and close inspection was performed at two or more locations per project that could safely be inspected. A total of 19 pavements were inspected across the country that had been in service for up to 10 years. The asphalt mixtures were either 9.5 or 12.5mm NMAS and dense graded or SMA. Fifteen of them were overlays ranging in thickness from 1.5 to 2.5 inches. Three of the overlays were on PCC pavements. Four were reconstruction or full-
depth reclamation projects with the asphalt mixture ranging in thickness from 5.5 to 8.0 inches. RBR of the mixtures ranged from 0.17 to 0.48. RAS dose ranged from 0 to 5 percent while RAP dose ranged from 0 to 30 percent. RAS/RAP dose combinations by weight ranged from 3/30 to 5/25. Table 19 is a summary of information about the sections inspected and performance observations made during the inspections.

Table 19. Inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Agency</th>
<th>%RAS/%RAP</th>
<th>RBR</th>
<th>Mix Type</th>
<th>Asphalt Binder</th>
<th>Thickness (inches)</th>
<th>Observed Pavement Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 PennDOT</td>
<td>5/0</td>
<td>0.19 RAS</td>
<td>12.5mm Surface</td>
<td>PG64-22</td>
<td>2.0</td>
<td>Overlay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Performing well, only maintenance activity is crack sealing of longitudinal construction joints.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Low severity, high extent longitudinal joint separation (may be reflective).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- No other visible distress.</td>
</tr>
<tr>
<td>2015 PennDOT</td>
<td>5/0</td>
<td>0.17 RAS</td>
<td>9.5mm Surface</td>
<td>PG64-22</td>
<td>1.5</td>
<td>Overlay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Some of the pavement is PCC with asphalt overlay that is saw cut and sealed over transverse joints.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Low severity high extent longitudinal joint separation due to reflective cracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- No other visible distress.</td>
</tr>
<tr>
<td>2018 PennDOT</td>
<td>5/0</td>
<td>0.17 RAS</td>
<td>12.5mm Surface</td>
<td>PG64-22</td>
<td>2.0</td>
<td>Overlay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Acceptance was by PWL and a joint incentive/disincentive provision was included.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- No visual distress observed.</td>
</tr>
<tr>
<td>2011 City of Eugene</td>
<td>5/15</td>
<td>0.21 RAS + 0.13 RAP</td>
<td>½” L2 Dense Wearing</td>
<td>PG64-22 and PG70-22(^1)</td>
<td>5.5</td>
<td>Re- construction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Only maintenance activity is very limited crack filling.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Moderate severity, high extent longitudinal cracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Low to moderate severity, low to moderate extent block cracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Limited localized striping.</td>
</tr>
<tr>
<td>2016 City of Eugene</td>
<td>3.6/30</td>
<td>0.15 RAS + 0.25 RAP</td>
<td>½” L2 Dense Wearing</td>
<td>PG58-34</td>
<td>7.0</td>
<td>Re- construction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Performing well.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- No visual distress observed.</td>
</tr>
<tr>
<td>2019 City of Eugene</td>
<td>2.7/30</td>
<td>0.12 RAS + 0.26 RAP</td>
<td>½” L2 Dense Wearing</td>
<td>PG58-28</td>
<td>6.0 - 8.0</td>
<td>Full-depth Reclamation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Performing well.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- No visual distress observed.</td>
</tr>
</tbody>
</table>

\(^1\)As time passed, it was realized that PG 70-22 was too stiff for Eugene’s climate with high RAM levels.

\(^2\)RBR calculated using effective virgin asphalt content.
### Table 19 (continued). Inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Agency</th>
<th>%RAS/ %RAP</th>
<th>RBR</th>
<th>Mix Type</th>
<th>Asphalt Binder</th>
<th>Thickness (inches)</th>
<th>Observed Pavement Performance</th>
</tr>
</thead>
</table>
| 2019 City of Eugene | 2.7/30 | 0.12 RAS + 0.26 RAP | ½” L2 Dense Wearing | PG58-28 | 6.0 | Full-depth Reclamation | • Performing well.  
• No visual distress observed. |
| 2016 MoDOT | 3/28 | 0.16 RAS + 0.32 RAP | 12.5mm BP-1 | PG 46-34 | 1.75 | | • High severity high extent longitudinal and block cracking. Some is likely reflective.  
• High severity low extent fatigue cracking. |
| 2014 MoDOT | 5/25 | N/A | 12.5mm BP-1 | N/A | 1.75 | | • High severity high extent longitudinal and block cracking. Some is likely reflective.  
• High severity low extent fatigue cracking. |
| 2018 MoDOT | 0/25 | N/A | 12.5mm BP-1 | N/A | 2.5 | | • No visible distress.  
• Performing well. |
| 2015 MoDOT | 0/25 | N/A | 12.5mm BP-1 | N/A | N/A | | • Very low severity low extent longitudinal cracking.  
• Performing well. |
| 2017 MoDOT | 0/0 | N/A | 12.5mm SMA Surface | N/A | 2.0 | | • No visible distress.  
• Performing well. |
| 2017 MoDOT | N/A/N/A | N/A | 12.5mm BP-1 | N/A | 2.0 | | • No visible distress.  
• Low severity, moderate extent transverse cracking. |
| 2010 MoDOT | 4/0 | 0.19 RAS | 12.5mm | PG76-22 | 1.75 | | • Low severity, low extent longitudinal cracking and reflective cracks.  
• No other visible distress, performing very well for age/loading. |
| 2015 DelDOT | 4/25 | 0.19 RAS + 0.18 RAP | 9.5mm Superpave | PG64-22 | 2.0 on 6.0 FDR | | • Moderate severity high extent fatigue cracking (likely load related).  
• Moderate severity high extent block and transverse cracking. |
| 2015 DelDOT | 4/25 | 0.19 RAS + 0.18 RAP | 9.5mm Superpave | PG64-22 | 2.0 on 4.0 CIPR | | • Low severity moderate to high extent block cracking. |
| 2015 DelDOT | 4/25 | 0.19 RAS + 0.18 RAP | 9.5mm Superpave | PG64-22 | 2.0 on 6.0 FDR | | • Low severity high extent block and transverse cracking.  
• Low severity low extent deleterious materials. |

1As time passed, it was realized that PG 70-22 was too stiff for Eugene’s climate with high RAM levels.  
2RBR calculated using effective virgin asphalt content.
Table 19 (continued). Inspected pavement sections summary information.

<table>
<thead>
<tr>
<th>Year and Agency</th>
<th>%RAS/ %RAP</th>
<th>RBR</th>
<th>Mix Type</th>
<th>Asphalt Binder</th>
<th>Thickness (inches)</th>
<th>Observed Pavement Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 TxDOT</td>
<td>5/0</td>
<td>0.19 RAS</td>
<td>½” Type C</td>
<td>PG58-28</td>
<td>2.0 on JPCP or AP</td>
<td>-Moderate severity low extent longitudinal cracking, and transverse cracking. -low severity low extent fatigue cracking. -Localized high severity low extent fatigue cracking.</td>
</tr>
<tr>
<td>2012 TxDOT</td>
<td>5/13</td>
<td>0.19 RAS + 0.16 RAP</td>
<td>½” Type C</td>
<td>PG64-22</td>
<td>1.5 on JPCP</td>
<td>-Moderate severity high extent longitudinal and block cracking. Some is reflective cracking from JPCP. -High severity low extent fatigue cracking.</td>
</tr>
</tbody>
</table>

1As time passed, it was realized that PG 70-22 was too stiff for Eugene’s climate with high RAM levels. 2RBR calculated using effective virgin asphalt content.

It is important to consider all of the factors that can influence the performance of a surface mixture when looking at pavement performance. In the context of this effort one could focus simply on RAS dose or RBR. However, that alone could be very misleading because other individual factors or combinations of factors could have a greater impact on performance than just RAS dose or RBR. Some of the factors that need to be considered include:

- Type of underlying pavement - Portland cement concrete or asphalt concrete.
- Condition of the pavement pre-overlay – significant distress with minimal repairs or limited distress with appropriate repairs.
- Roadway classification or traffic – Interstate with heavy traffic or rural with light traffic.
- Relative virgin binder quality – amount, stiffness, sensitivity to aging.
- Mixture design criteria – use of G_{sb} or G_{se} for recycled materials, minimum VMA, amount of asphalt binder.
- Acceptance criteria – mixture meeting design minimums or allowance for less than, inclusion of a dust to asphalt ratio, maximum RBR.
- Construction quality – in place density and joint construction.

It is also important to consider the types of pavement distress directly related to the recycled material dose or RBR. Poor durability is the primary concern and is observed as cracking, raveling and stripping (moisture sensitivity). Durability related cracking includes block, fatigue, and longitudinal cracking that is not at construction joints or reflecting due to cracks or joints in underlying pavement. It is worth noting that none of the 19 pavements inspected exhibited any rutting.

The performance observed ranged from good to poor. Interestingly, some agencies had good performance, while others had good and poor performance. No agency visited had only poor performance. The observed performance is summarized in Table 20 along with relevant pavement section information. Figure 38 shows RAS and RAP RBR levels with pavement performance indicated. The figure illustrates that as increases in the amount of RAP added to mixtures with RAS it becomes difficult to
maintain good performance. There is a fine line separating good and poor performance when using combinations of RAP and RAS.

PennDOT pavements inspected with 5 percent RAS are performing particularly well. All were thin overlays. Figure 39 and 40 are good examples of pavements in service up to 7 years exhibiting little or no durability related distress. Note that one is on JPCP. PennDOT only allows 5 percent MWAC RAS, no more or less resulting RBR approximately 0.20. It also requires additional asphalt binder through VMA requirements in mixture design and acceptance that are greater than the AASHTO M323 minimum.

Table 20. Summary of observed pavement performance and pavement section information.

<table>
<thead>
<tr>
<th>Agency</th>
<th>Year</th>
<th>Route</th>
<th>RAP RBR</th>
<th>RAS RBR</th>
<th>Performance</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>PennDOT</td>
<td>2012</td>
<td>SR 22</td>
<td>0.00</td>
<td>0.19</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>PennDOT</td>
<td>2015</td>
<td>SR 382</td>
<td>0.00</td>
<td>0.17</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>PennDOT</td>
<td>2018</td>
<td>SR 30</td>
<td>0.00</td>
<td>0.17</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Eugene</td>
<td>2011</td>
<td>Conger/Wilson</td>
<td>0.13</td>
<td>0.21</td>
<td>Noticeable Cracking</td>
<td>Stiffer Binder</td>
</tr>
<tr>
<td>Eugene</td>
<td>2016</td>
<td>Centenial Loop</td>
<td>0.25</td>
<td>0.15</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Eugene</td>
<td>2019</td>
<td>Charnelton</td>
<td>0.26</td>
<td>0.12</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Eugene</td>
<td>2019</td>
<td>W. 19th Ave.</td>
<td>0.26</td>
<td>0.12</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>MoDOT</td>
<td>2016</td>
<td>Route 94</td>
<td>0.32</td>
<td>0.16</td>
<td>Noticeable Cracking</td>
<td></td>
</tr>
<tr>
<td>MoDOT</td>
<td>2014</td>
<td>Route D$^1$</td>
<td>0.32</td>
<td>0.16</td>
<td>Noticeable Cracking</td>
<td></td>
</tr>
<tr>
<td>MoDOT</td>
<td>2010</td>
<td>I-55</td>
<td>0.00</td>
<td>0.19</td>
<td>Good</td>
<td>SMA</td>
</tr>
<tr>
<td>MoDOT</td>
<td>2015</td>
<td>MoDOT Facility$^1$</td>
<td>0.25</td>
<td>0.00</td>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>DelDOT</td>
<td>2015</td>
<td>Briarbush</td>
<td>0.18</td>
<td>0.19</td>
<td>Noticeable Cracking</td>
<td></td>
</tr>
<tr>
<td>DelDOT</td>
<td>2015</td>
<td>Plaindealing</td>
<td>0.18</td>
<td>0.19</td>
<td>Noticeable Cracking</td>
<td></td>
</tr>
<tr>
<td>DelDOT</td>
<td>2015</td>
<td>Andrews Lake</td>
<td>0.18</td>
<td>0.19</td>
<td>Noticeable Cracking</td>
<td></td>
</tr>
<tr>
<td>TxDOT</td>
<td>2016</td>
<td>US 180</td>
<td>0.00</td>
<td>0.19</td>
<td>Good with some cracking</td>
<td></td>
</tr>
<tr>
<td>TxDOT</td>
<td>2012</td>
<td>US 175</td>
<td>0.16</td>
<td>0.19</td>
<td>Good</td>
<td></td>
</tr>
</tbody>
</table>

$^1$Estimated.
Figure 38. RAS and RAP RBR levels with a pavement performance indicated.

Figure 39. PennDOT SR22 constructed in 2012.
The City of Eugene uses surface mixtures with RBR between 0.34 to 0.40 from combinations of about 3 percent RAS and 25 to 30 percent RAP that have been in service up to 8 years. All of the projects observed were reconstruction or full-depth reclamation with thick mixtures. Poor performance on one early RAS project led to requiring one or two full PG bumps down (softer binders) and good performance has been observed since. Figure 41 is the early project exhibiting block cracking and Figure 42 is a pavement that has been in service for 3 years and is performing well with the binder specification change in place. The city specifications include requirements for percent RAS and RBR, softer binder, additional asphalt binder in design and acceptance, and only allows warm mix asphalt at warm mix production temperatures.
Figure 41. Conger/Wilson project with high RAM and PG70-22 constructed 2016.

Figure 42. City of Eugene Centennial Street constructed 2016.
More pavement sections were inspected in Missouri than on any other site visit and a range of performance was observed. MoDOT specifications allow for different levels of recycled materials in different mix types and locations. Figure 43 shows an SMA containing 4 percent RAS (RBR = 0.18) placed over PCCP on an interstate which is performing very well, with only low severity low extent transverse cracking after 9 years of service. Figure 44 shows an SMA on the mainlines and a dense graded mixture on the shoulders of an Interstate, with no visible distress in the SMA but low severity moderate extent transverse cracking in the shoulders after only 2 years of service. Figure 45 shows a dense graded mixture on a low volume road containing 3 percent RAS and 28 percent RAP (RBR = 0.48) which is performing poorly with high severity high extent longitudinal, block, and localized fatigue cracking after just 3 years of service. MoDOT allows RAS from either MWAS or PCAS and the use of recycling agents with criteria for RBR, softer binder, additional asphalt binder, lift, traffic, specialty mixtures. The allowable RBR on the low volume and dense graded mixtures is much higher than on specialty mixtures.

Figure 43. I-55 SMA, constructed 2010 with low severity low extent longitudinal and transverse cracking.
Figure 44. I-44 SMA and BP-1 shoulder, constructed 2017 with no visible distress in the SMA and low severity moderate extent transverse cracking in the BP-1 shoulders.

Figure 45. Route 94, constructed 2016, high severity high extent longitudinal, block, and localized fatigue cracking.
In Delaware three pavement sections that had been in service for 4 years with mixture containing 4 percent RAS and 25 percent RAP having an RBR of 0.37 were inspected. The inspected sections were all relatively low volume local roads. The surface mixture was all the same, though existing underlying structures varied. Figure 46 shows moderate severity high extent fatigue cracking and moderate severity high extent block and transverse cracking after 4 years of service. Figure 47 shows low severity moderate to high extent block cracking after 4 years of service on another section. The third section exhibited similar performance. Delaware allows RAS from either MWAS or PCAS and has criteria for percent RAS, RBR, softer binder, additional asphalt binder, and specialty mixtures. DelDOT is currently evaluating performance tests including the TxOL and IDEAL-CT for future integration into its specifications.

![Image: University of Nevada Reno](image)

Figure 46. Briarbush, constructed 2015, moderate severity high extent fatigue cracking (likely load related) and moderate severity high extent block and transverse cracking.
Figure 47. Plaindealing Road, constructed 2015, low severity moderate to high extent block cracking.

Two thin overlay pavement sections containing RAS were inspected in Texas that had been in service up to 7 years. A project constructed in 2016 included overlays on jointed plain concrete pavement (JPCP) and asphalt pavement (AP) shown in Figure 48 and Figure 49 with reflective cracking in the portion over JPCP and reflective cracking and some fatigue cracking in the portion over AP. Figure 50 shows a 1.5-inch overlay after 7 years of service placed on JPCP performing well for its intended purpose with limited reflective, longitudinal and block cracking. TxDOT specifications allows RAS from either MWAS or PCAS and have criteria for percent RAS, RBR, softer binder, specialty mixtures and RAP type. TxDOT is currently evaluating performance tests including the TxOL and IDEAL-CT for future integration into its mixture design and acceptance specifications.
Figure 48. US 180 constructed 2016, longitudinal and transverse cracking on JPCP.

Figure 49. US 180 constructed 2016, longitudinal, transverse and fatigue cracking on ACP.
Field performance reviews of in-service pavements up to 9 years old containing RAS or RAP and RAS revealed that with appropriate policy, mixture design and control of quality good performance can be obtained. Two items common to all observed good performing pavements were that they:

1. Contained an adequate amount of virgin asphalt binder.
2. Had virgin binder used in the mixtures that was selected to minimize embrittlement, resulting in bumping the PG binder down one or two temperature grades.

One interesting observation, though it is based on a limited number of pavement sections, was that the relatively stiff mixtures containing RAS appeared to perform better on PCCP than on asphalt pavements.

**Observations Based on RAS Processing and Asphalt Plant Visits**

During the agency visits RAS processing facilities were visited in Pennsylvania, Missouri and Texas. Asphalt plant production facilities were visited in Pennsylvania, Oregon, Missouri, Delaware and Texas. There were common themes with the desire to obtain desired material quality while controlling production costs and different techniques used to achieve it.
RAS Processing Facilities
Three RAS processing facilities were visited. Two were co-located at contractor asphalt plant facilities, while one was a recycling center that processed many other types of materials. The presence of asbestos in the RAS supply was not a concern for processors using only MWAS like the material shown in Figure 51. When PCAS are used, a process for separating and testing lots is necessary. A good example of this is a rigorous QC Plan requirement for RAS sources developed by IDOT in partnership with the Illinois Environmental Protection Agency, which approves and authorizes the RAS suppliers beneficial use determination (BUD) application. The QC Plan and corresponding activities leads to RAS sources being on the IDOT qualified producer list.

All three processors used hand picking and magnets on the feed to conventional shredders to process RAS to 3/8-inch minus like the one shown in Figure 52. Trommels, like the one shown in Figure 53 were used to further process the RAS to ¼-inch or #4-minus at two of the facilities. The processors/contractors reported believing that more RAS binder was mobilized, and thus effective, when processed down to ¼-inch minus. A lot of water was used, particularly in the shredding operations with one processor indicating that it significantly reduced wear costs. The fact that moisture impacts production and fuel consumption at the asphalt plant was discussed and the processor indicated that the RAS/fine-aggregate blend was stored on paved sloped stockpile areas that were covered to reduce moisture prior to use at the contractor’s asphalt plant.

At a recycling center in Missouri about 15,000 tons of PCAS are processed annually. The operator indicated that it costs $50 per ton to send shingles to a landfill, but the tipping fee at this location was only $35 per ton. Additionally, that the cost of processing shingles is about 50 percent higher than the cost of processing other recycled materials due to equipment wear. At that time, processing costs were approximately $20 per ton and they were sold for approximately $12 per ton. MWAS from a nearby manufacturing facility were being sent to a land fill. Shingles are undesirable in landfills as they trap methane gas and create issues. The recycler visited indicated it blended RAP and RAS with emulsion which it sells as base course material and is another beneficial use of RAS.

Concern with clumping of RAS was consistently mentioned by both RAS producers and asphalt plant operators. Clumping can lead to waste and inconsistent feeding, and thus inconsistent asphalt mixture. Several techniques can be used to prevent clumping during RAS production which include: high moisture while shredding; blending with other materials; use of small stockpiles to prevent consolidation; and “just-in-time” production. A drawback to increased moisture is asphalt plant drying costs increase and production rate may need to be reduced. Blending processed RAS with other materials, including fine aggregate or RAP, can reduce clumping. A clean sand was blended 50/50 with RAS is shown in Figure 54. At this facility, significant effort went into getting the blend correct, which resulted in extensive on-site QC of the RAS, sand, and RAS/sand blend. Two coldfeed bins were used to feed the RAS and sand to conveyors equipped with weigh bridges. Once produced and at an asphalt plant site, techniques used to address RAS clumping include: use of small stockpiles or just-in-time delivery, storing RAS on a sloped paved surface with or without a cover, having the loader operator blend the RAS stockpile face prior to loading coldfeed bins; installing small crushers (lump breakers) on feed belts to coldfeed bins; placing scalping screens over coldfeed bins; using coldfeed bins specifically designed for feeding RAS; and using air cannons and/or vibrators on coldfeed bins. Figure 55 shows RAS stored on a paved surface with a tent. Local climate obviously played a role in the decisions to cover or not cover the stockpiles.
Figure 51. MWAS stockpile showing whole shingles and tab punch outs.

Figure 52. PCAS being processed with a shredder.
Figure 53. RAS processing trommel used to produce RAS passing ¼-inch sieve.

Figure 54. Finely ground RAS blended with sand (50/50) to prevent clumping.
Asphalt Plant Visits
Asphalt plant production facilities were visited in Pennsylvania, Oregon, Missouri, Delaware and Texas. There were several things in common at these plants. All of the plants were counterflow continuous mix plants with RAP collars. A typical example is shown in Figure 56. All of the plants produced mixture for public agencies and private customers. All were also equipped with the ability to produce WMA either by foaming or with chemical additive. Two of the plants were equipped to introduce recycling agents on-site.

One of the questions commonly asked by agencies is, “How do we know we are getting the correct amount of RAP, RAS...etc.?” The usual answer is by requiring plant calibrations and assuring all feed system components are interlocked with the plant controls. The reality is specifically for RAS and/or RAP there are several techniques that can be used to answer the question. They include:

- plant calibration (coldfeeds, weigh bridges, asphalt meter, baghouse return system, etc.) and interlocking feed systems with plant controls;
- routine verification of calibrations;
- monitoring RAS and combined feed moisture content;
- having covers over weigh bridges to minimize environmental impacts;
- requiring QC testing that is reported to the agency;
- having strong agency acceptance criteria;
- agency on-site inspection; and reconciliation of quantities from plant control settings with plant production reports and with mixture loadout ticket quantities.
On a gross scale, especially with a dedicated plant, quantities from bills of lading for asphalt binder, aggregates, mineral filler and RAS can be reconciled with loadout tickets. It is important that every ton of mixture produced everyday be inventoried to make this possible, recognizing that some mixture is typically wasted each day (normally it goes to a RAP stockpile). Strong agency acceptance criteria would include:

- review of calibration records and plant job mix formula settings;
- on-site inspection in the control room and of the plant while running;
- having a rigorous asphalt content calibration procedure if using ignition furnaces for asphalt content determinations; and
- using percent within limits (PWL) for acceptance and payment with quality characteristics that are sensitive to changes in RAS or RAP content.

Asphalt content is a critical example. In the near future a stiffness measurement on plant produced mixture may be a reality and would be a good parameter also.

The reality is plant operators ask the same questions wanting to assure in-specification material is being produced. Items observed at the plants that were identified by the plant operators as being important for producing good quality mixture with RAS or RAP and RAS included:

- An emphasis on RAS and RAP moisture managing including storage locations that are sloped, paved, and/or covered at some locations.
- Efforts to minimize, and if necessary, remove RAS clumps.
- Specially configured and equipped recycled material feed bins that allowed for uniform and accurate feed.
- Weigh bridges on the collector belts to the RAP collar.
- Baghouse fines return systems that could accurately meter, and waste if necessary, the fines back to the mixing chamber.
- Thorough mixing capabilities to assure good coating.
- Accurate WMA and recycling agent metering systems when used.
- On-site QC capabilities so quality could be rapidly monitored.

Figure 57 is an example of a cover over RAS and RAP stockpiles in Oregon. In other locations with less inclement weather, such as Texas, small RAS stockpiles (about 1000 tons) were not covered and did not have high moisture contents. An example is shown in Figure 58. The operators also indicated that the small stockpile size minimized clumping.

Though described by some operators, none of the plants visited were equipped with positive weigh RAS coldfeed bins (suspended on loadcells) which are reported to work effectively. One plant visited has recycled material feed bins specifically manufactured for feeding recycled materials shown in Figure 59. Note the inclined configuration as well as the scalping screen over the bin to remove any RAS clumps from the RAS stockpile. Most of the plants used typical aggregate coldfeed bins with modifications made to them. They included feed bins with combinations of flop gates, air cannons, vibrators and limit switches. Figure 60 illustrates air cannons and vibrators on RAS feed bins used to help keep the flow uniform and prevent clumping in the bins. Figure 61 and Figure 62 show flop gates on feed bin discharges close to the conveyor belt under the bins. This is used to control and help make uniform the limited amount of material being fed from the bins. A limit switch is also visible in Figure 62 that will notify the plant operator if the flow is interrupted.
All but one plant visited had weigh bridges on the conveyor feeding to RAP collars and all of them had covers on them to minimize the influence of environmental factors such as wind. Figure 63 illustrates a good example. One plant had a late entry RAP collar and incorporated a post drum external mixing drum which did an excellent job of coating. The baghouse fines were returned to the external mixer along with the asphalt binder supply. The drum and external mixing drum are shown in Figure 64. Figure 65 illustrated the well-coated material on discharge from the external mixing drum.

Since recycled materials typically have high percentages of material passing the #200 sieve it is important to be able to accurately control the introduction of baghouse fines into the mixing chamber of a plant. Several of the plants visited had well-designed systems for this. They included storage silos with weigh pods used to accurately measure the very light baghouse fines material for return to the mixing drum as illustrated in Figure 66. Other materials used at some plants that require very accurate metering because very small quantities are used are recycling agents and WMA additives. Two plants were equipped with good examples. Figure 67 illustrates a good example of a recycling agent pump and metering system for inline blending with asphalt binder at an asphalt plant in Delaware.

![Image: University of Nevada Reno](Image: University of Nevada Reno)

Figure 56. Counterflow drum with RAP collar and covered RAP feed belt with weigh bridge.
Figure 57. Covered RAS and RAP stockpiles.

Figure 58. Finely ground RAS stockpile in Missouri.
Figure 59. Coldfeed bin specifically manufactured to feed recycled materials with scalping screen to remove RAS clumps.

Figure 60. Air cannon and vibrators on RAS coldfeed bins.
Figure 61. Gate installed on the RAS coldfeed bin to allow for consistent low flow.
Figure 62. RAS feed bin with a gate to limit flow and a limit switch.

Figure 63. Cover on belt scale on conveyor to the RAP collar on the drum.
Figure 64. Dryer drum and external mixing drum, a.k.a., “mini-mixer.”
Figure 65. Well coated asphalt mixture with high RBR and recycling agent on discharge from the external mixing drum.
Image: University of Nevada Reno

Figure 66. Mineral filler and baghouse fines silos with weigh pods.
RAS Implementation Considerations

Should an agency decide to implement RAS, there is a greater chance for success if several factors are considered. These factors need to be established by the DOT and include:

- RAS programmatic considerations.
- RAS mixture design considerations.
- RAS mixture acceptance considerations.
- RAS mixture production considerations.
- RAS mixture QC considerations.

**RAS programmatic considerations:**

- An agency should consider having project selection guidelines that define what mixtures may contain RAS, how much RAS is allowed in mixtures in what locations in a pavement structure. This could also include the type of RAS (MWAS/PCAS), inclusion in specialty mixtures, traffic levels, the use of RAS with polymer modified asphalt, and others.
- Providing clear guidance when using both RAP and RAS.
- Have mixture design standards.
- Have a strong QA program that includes clearly defined QC responsibilities for the contractor and acceptance responsibilities for the agency to ensure the desired mixture is provided.
- Address mixture properties to be used for pavement design inputs, even if it is simply to state they are the same as other mixtures.
- Clearly tracking and reporting the use of recycled and reclaimed materials annually.
• Coordinating with the state environmental agency (SEA).
• Monitoring pavement performance of those mixtures with RAS compared to those without RAS. It is important to use the data from the pavement management system as well as making occasional project visits by walking along the pavement. Video logging of the pavement network on a regular basis to capture useful information to compare the existing pavement condition to that prior to overlay. Specifications often need to be adjusted based on pavement performance.

**RAS mixture design considerations**:

- Having criteria for reclaimed materials.
  - Percent by weight and/or RBR.
  - RBR separate from RAP and from RAS.
  - RAS when used alone versus when RAS is used with RAP.
  - RAS types: MWAS or PCAS.

- Specifying softer binders.
  - Accurately characterizing RAS or RAP and RAS by determining the PG of the materials, as well as gradation and specific gravity.
  - Selecting the appropriate virgin binder to assure the blend of RAS or RAP and RAS binder with the virgin binder result in the PG appropriate for the environment. This can be done with grade bumping, blending charts and/or determining the actual PG of the blended binder.

- Using additional asphalt binder.
  - Using Gsb of the RAS and RAP aggregates, rather than Gse, to assure the most accurate indication of VMA possible.
  - Depending on roadway classification, adjusting the asphalt mixture design criteria in AASHTO M 323 and AASHTO R 35. This could include strategically designing at a lower air void content, a higher VMA requirement and/or a lower number of design gyrations.
  - Including multiple binder sources for a mix design and a requirement to evaluate moisture sensitivity when a source change occurs during production in the agency’s specifications to minimize disruption during construction.

- Allowing or specifying the use of additives.
  - Consideration of the recycling agents allowance to address binder embrittlement.
  - Consideration of the use of WMA additives, particularly if the mixture is produced at lower temperature to prevent the combining of the RAS and virgin binders.
  - Consideration of the use of WMA technology at WMA temperatures.

- Using mixture and/or binder performance testing.
  - Using mixture performance tests, typically rutting and cracking tests, to assess mixture performance and optimize mixture designs.
  - Considering both short- and long-term mixture aging in the mix design process.
  - Using binder performance testing such as determining the ΔTc or the Glover-Rowe parameter.

**RAS mixture acceptance considerations**

- Including a minimum VMA in production that is equal to or greater than the minimum VMA in mixture design.
• Requiring minimum design VMA 0.5 percent higher than specified in AASHTO M323 and production VMA no less than the minimum specified in AASHTO M323.
• Including a dust to asphalt ratio requirement in acceptance.
• Using the mixture design RBR as a minimum acceptance criteria.

**RAS mixture production considerations:**
• Considering plant calibrations and all feed systems interlocked with the plant control and recordation system.
• Using plant equipment (bins, weighing systems and controls) specifically designed for use with RAS that can accurately supply and meter the materials.
• Using multiple cold feed bins when blended RAS/RAP exceeds more than 30 percent of a mixture composition.
• Having scalping screens over RAS and RAP bins to prevent feed of clumped material.
• Use air cannons and/or vibrators on RAS and RAP/RAS feed bins.
• Use limit switches to positively identify material flow on RAS and RAP/RAS feed.
• Having a weigh bridge on the conveyor feeding to the RAP collar on continuous mix plants.
• Having covers over weigh bridges on collector belts.
• Using WMA technology to produce mixture at WMA temperatures.
• Having accurate means of metering recycling agents if introduced at the asphalt plant.
• Using plant primary collector and baghouse fines return systems that can accurately meter, and reject if necessary, these materials.
• Minimizing RAS and RAP stockpile moisture by having sloped, paved, and/or covered stockpile areas.
• Considering post dryer drum mixers with high RBR mixtures.
• Having on-site QC.

**RAS production considerations:**
• Having regular inspection of incoming supply.
• Eliminating shingles containing asbestos in the supply stream.
• Minimizing deleterious materials (wood, nails, etc.).
• Keeping MWAS and PCAS separated.
• Shredding to the specified size and at least passing the 3/8-inch sieve.
• Using a trommel to size RAS to ¼-inch minus.
• Minimizing moisture during RAS production as much as possible.
• Metering and verifying accurately the blending of RAS with fine aggregate or RAP when blending is used.
• Using plant equipment (bins, weighing systems and controls) specifically designed for use with RAS.
• Minimizing the moisture in RAS by paving under and/or covering RAS stockpiles.

**RAS mixture QC considerations:**
• Using RAS production QC plans with provisions for identification of asbestos, elimination of deleterious materials, quality and consistency of material blended with RAS (fine aggregate or RAP), consistency of produced RAS or RAS blended with fine aggregate or RAP, and accuracy of the system used to meter the blending of RAS with other materials.
• Keeping RAS consistency and consistency of RAS feed are critical.
• One agency indicated interest in going to a certificate of compliance (COC) program and RAS being on approved product lists.

Research Needs Identified
Through the agency visits and preparation of this report the following research needs were identified:
1. What are suggested practices for measurement, metering and verification of the quantity of recycled materials supplied in mixtures?
2. How to use RAS as “black rock” in asphalt mixture and obtain mixture performance similar to virgin asphalt mixture.
3. How to more accurately determine the availability of binder in RAS and RAP.
4. Could RAS be used in cold in-place and cold central plant recycling.
5. What are other applications for the use of RAS, e.g., asphalt pavement base layers for PCCP, and unprocessed shingles that could be used as soil replacement for expansive soils.
6. How can two common issues be addressed when using RAS in asphalt mixtures: 1) clumping and 2) identifying the actual amount of shingles entering the asphalt mixture. Methods to improve these should be identified. One example could be the use of a screw auger to feed the shingles.
7. Can the ability to accurately measure RAS binder properties and/or create a database of typical properties by region be improved and made available for use DOTs.
8. Are there correlations that could be established between simple performance tests and field performance that can practically be used for mix design and acceptance accounting for the influence of lab versus plant production.

Other RAS Uses
Throughout the visits, agency and contractor personnel were asked if they were aware of other beneficial uses of RAS other than in asphalt mixtures. These could also be the topic of research needs. The following were identified:
1. Could blending RAS with aggregate base for dust suppression on low-volume roads be effective.
2. Could blending RAS with RAP and emulsion be used for patching materials.
3. Could RAS be a component in flowable fill (Controlled Low-Strength Material (CLSM)) for use around utilities.
4. Could RAS be used as a snow/ice removal material, much like cinders/slag.

Closing
The use of RAP and RAS in asphalt mixtures can provide initial cost savings through the replacement of a portion of the aggregate and virgin asphalt binder in a mixture for use in highways and trails. This keeps the reclaimed material from being discarded in landfills. Improvements in mixture design and materials processing and handling have increased the amount of RAP and RAS that can be used in asphalt mixtures today. The performance history of RAP mixtures over the past 40 years and RAS over the past 20 years, when properly engineered, produced, and constructed, can provide comparable levels of service as asphalt mixtures with no reclaimed materials, referred to as virgin asphalt mixtures (20). This was typically obtained through the following comprehensive steps: 1) regular and diligent review of the agency’s specifications and mixture design procedures, 2) monitoring pavement performance, 3) working with industry and 4) performing research as a basis for changes.
This effort showed that agencies with detailed policy and specifications on RAS use had the best control and performance. Field performance reviews of in-service pavements up to 9 years old containing RAS or RAP and RAS revealed that with appropriate policy, mixture design and control of quality, good performance can be obtained. This was typically obtained through regular diligent review of specifications and design procedures and pavement performance while working with industry and performing research as a basis for changes.

A wide range of criteria used by agencies specifying and design mixtures and pavements incorporating RAS were identified and summarized. They were then compared to pavement performance to assess their effectiveness and identify opportunities for improvement. Important considerations for implementing the use of RAS were identified and described or illustrated that could be of benefit to other agencies wanting to use RAS. They included programmatic, mixture design, mixture production, mixture acceptance, RAS production, and QC considerations. Collectively this illustrated that care must be taken during design, production, and construction to ensure desired performance. It also revealed that there are also opportunities for future improvements that can be accomplished through research needs identified.
References


