Successful Use of Reclaimed Asphalt Pavement in Asphalt Mixtures

Image: University of Nevada Reno

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Abstract

Over 99 percent of reclaimed asphalt pavement (RAP) is put back to use, with most of it in asphalt pavements. Using RAP in asphalt mixtures can provide initial cost savings by replacing a portion of the aggregate and virgin asphalt binder in the asphalt mixture. It is important to consider the engineering performance of mixture containing RAP, as well as sustainable benefits and recognize that long RAP transportation distances can offset the environmental benefits. This keeps the RAP from being discarded in landfills. Improvements in mixture design and materials processing and handling have increased the amount of RAP that can be used in asphalt mixtures. The performance history of RAP mixtures over the past 50 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. The participating State DOTs indicated that optimizing RAP for good pavement performance can be accomplished through: 1) regular review of DOT specifications and mixture design procedures; 2) monitoring pavement performance; 3) working with asphalt producers, and 4) performing research as a basis for changes. However, in some cases, the durability of asphalt mixtures containing RAP has been poor. Additionally, State DOT rationale for using RAP can be for very different reasons with different goals. Virtual field visits of State DOTs regularly using RAP in asphalt mixtures revealed that DOTs with detailed policy and specifications on RAP use had obtained good control and pavement performance. A wide range of techniques and criteria used by State DOTs specifying and designing mixtures and pavements incorporating RAP were identified and summarized. All of the participating State DOTs indicated the desire to use mixture performance tests. Some wanted to use them for mixture designs in a BMD approach, for test strips (startup evaluations) and production or acceptance. Common themes with this were the need to get adequate virgin asphalt binder in mixtures, the need for appropriately setting performance test criteria and recognition of the benefit of long-term aging cracking test specimens. Another common theme was recognition that the resources required to implement BMD or use of performance tests on a regular basis are significant and may not be available in the short-term.

Key Words: RAP, RBR, RAS, pavement recycling, pavement performance, balanced mix design implementation, specifications

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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Abbreviations

AASHTO – American Association of State Highway and Transportation Officials
a.k.a. – also known as
APA - Asphalt Pavement Analyzer
AV – Air Voids
BOL – Bill of Lading
COC - Certificates of Compliance
DOT – Department of Transportation
DP – Dust proportion (a.k.a. dust to asphalt ratio (D/A))
EPA – Environmental Protection Area
FDOT- Florida Department of Transportation
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 - AASHTO T 324, Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures
IDEAL-CT – ASTM D8225 – 19, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature
IDT – ASTM D6931 - 17, Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures,
I-FIT – Illinois Flexibility Index Test
LTA – Long Term Aging
LTPP – Long Term Pavement Performance
MWAS – Manufactured Waste Asphalt Shingles
NAPA - National Asphalt Pavement Association
NCHRP - National Cooperative Highway Research Program
N_{des} – design number of gyrations
NDOT- Nebraska Department of Transportation
N_{ini} – initial number of gyrations
NJDOT – New Jersey Department of Transportation
NMAS – Nominal Maximum Aggregate Size
N_{max} – maximum number of gyrations
OGFC – Open Graded Friction Course
PCAS – Post-Consumer Asphalt Shingles (a.k.a., tear-offs)
PCCP – Portland Cement Concrete Pavement
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
SCDOT – South Carolina Department of Transportation
SMA – Stone Matrix Asphalt
TDF – Tire Derived Fuel
TFHRC – Turner-Fairbank Highway Research Center
TxOL - Texas Overlay Test
TWM – Total Weight of Mixture
VMA – Voids in Mineral Aggregate
WisDOT – Wisconsin Department of Transportation
WSDOT – Washington State Department of Transportation
WMA – Warm Mix Asphalt

Symbols

V_{be} effective binder volume

Introduction

Reclaimed asphalt pavement (RAP) has been used in asphalt rehabilitation and reconstruction for decades. However, since the 2008 peak in asphalt binder price, the desire to increase the use of RAP 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 RAP has created challenges for some State Departments of Transportation (DOTs) to specify, design, and control the quality of asphalt mixtures containing RAP to assure good long-term pavement performance. Other State DOTs have had success with varying RAP dosages. The primary concern with mixtures containing RAP is assuring that the high stiffness RAP 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, reclaimed asphalt shingles (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 Recycled Materials.

Annual Tons (1,000's)	RAP	RTR	RAS
Generated	97,000	4,464	13,200 to 17,000
Landfilled	100	680	12,000 to 16,000
Recycled into Asphalt Binder and/or Mixtures	89,200	185	921
Recycled Elsewhere[1]	5,500	3,373	50
Stockpiled	138,000	N/A	N/A
No. of State DOTs Allowing (including D.C. and Puerto Rico)	52	12	28

[1]Includes RAP used as aggregate, used in cold mix asphalt and used in other type of recycling.

According to the National Asphalt Pavement Association (NAPA), the amount of RAP accepted in 2019 was 97.01 million tons, and the RAP used in asphalt mixtures increased to 89.2 million tons (1). The average percent RAP used in asphalt mixtures was 21.1 percent by weight. More than 97 percent of asphalt mixture reclaimed from old asphalt pavements was put back to use in new pavement. According to the U.S. Tire Manufacturers Association (USTMA), the amount of scrap tires generated in 2019 was 4.464 million tons (2). The scrap tire market, ground tire rubber accounted for 1.089 million tons, of which 17 percent (0.185 million tons) was used in asphalt mixtures (1). 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 years, between 9 and 14 State DOTs reported using 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 of (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) 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 of (about 16 percent).
- Other applications (about 5 percent).

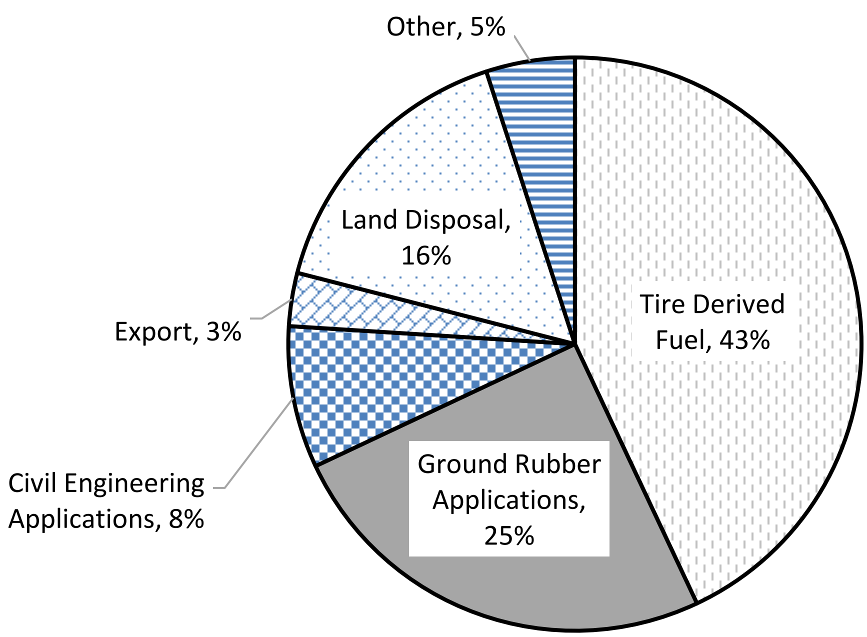

Image: University of Nevada Reno

Figure 1. Scrap tire market distribution (2).

According to the Asphalt Roofing Manufacturers Association, about 13.2 million tons of waste shingles are generated each year in the United States, with 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 asphalt industry recycles more than 99 percent of reclaimed asphalt pavement (1). Since 2009 the average percentage of RAP used in asphalt mixtures has increased from 15.6 percent to 21.1 percent. It is estimated that over 89 million tons of RAP was used in asphalt mixture in 2019. The 89 million tons of RAP represents 4.5 million tons (24 million barrels) of asphalt binder conserved and the replacement of over 84 million tons of virgin aggregate. All State DOTs allow the use of RAP at some dosages depending on an array of conditions.

Background

Benefits and Risks of Using Reclaimed Asphalt Pavement

The usage of RAP offers both benefits and risks. The positive, sustainable benefits (cost, environmental and societal) of using RAP in asphalt mixture have been well document by NAPA, and State DOTs have likely embraced the use of RAP based on them (1). It is important to consider the engineering performance of mixture containing RAP as well as sustainable benefits. When considering sustainable benefits of RAP use it is important to recognize that long transportation distances of RAP can offset the environmental benefits. Tools that can be used to determine when transportation is offsetting the savings realized from RAP use include life cycle assessment (LCA) and environment product declarations (EPD). Based on a review of a national literature summary that included individual State DOT and Long-Term Pavement Performance (LTPP) program data summaries compiled for the 2011 FHWA Report No. FHWA-HRT-11-021 titled, "Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*,"* Copeland stated, "*RAP has successfully been used for more than 30 years. Based on documented past experience, recycled asphalt mixtures designed under established mixture design procedures and produced under appropriate QC/quality assurance measures perform comparably to conventional asphalt mixtures*."

Similarly, the 2013 NCHRP Report 752 titled, *"*Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content," stated "*In-service performance of asphalt pavements containing up to 50 percent RAP in projects with diverse climates and traffic has been very positive…studies have shown that the overlays containing 30 percent RAP have been performing equal to, or better than, virgin mixes for most measures of pavement performance (7). Overall, the overlays containing RAP had more wheel path cracking, but the extent of cracking was acceptable."* The report also stated, "*…there are also engineering risks related to binder quantity requirements for effective asphalt content and binder quality requirements for binder embrittlement*. *As might be expected, compared to control mixtures without RAP, the high RAP content mixtures generally had lower fracture energies at test temperatures used to evaluate susceptibility to fatigue and low-temperature cracking. This finding suggests that careful attention should be given to the selection of the performance grade of the virgin binder used in high RAP content mixtures to minimize any long-term risk of cracking distress.*" Finally, other more recent work has highlighted the potential influence of combinations of RAP asphalt binder source, virgin binder source, and recycling agents on mixture performance test results (8, 9, 10).

On October 20, 2014, the Federal Highway Administration (FHWA) issued a memorandum (HIAP-1) regarding Recycled Materials in Asphalt Pavements (11). The memorandum indicated that several State DOTs were reporting premature cracking in relatively new asphalt pavements, and similarity in many of the pavements was a high percentage of recycled asphalt binder. The issue identified was the high levels of RAP, sometimes in combination with RAS, could lead to very stiff mixtures and cracking. The challenge associated with pinpointing specific drivers of cracking in in-service pavements was described along with ongoing research efforts. The memorandum concluded with recommendations to consider that included following existing AASHTO standards and past performance when establishing standards for RAP and RAS use. 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" (12). It summarized the findings from the completed survey that identified quantities, trends, requirements, and performance of RAS usage along with opinions on FHWA Division Offices and State DOTs that identified knowledge, engineering, and guidance gaps associated with RAS usage.

In September 2018, FHWA published FHWA-HIF-18-059, "State of the Knowledge for the Use of Asphalt Mixtures with Reclaimed Binder Content," providing an overview of current practices and guidance on the design and use of asphalt pavement mixtures that incorporate high levels of reclaimed asphalt binder in the form of RAP and/or RAS (13). The concept of using a reclaimed binder ratio (RBR) rather than percent RAP and/or RAS is to account for differences in fractionated RAP and RAS binder properly. It was introduced along with other practices to consider when designing mixtures with RAP and/or RAS. The other practices included considering virgin binder grade bumping, binder availability of RAP and RAS, virgin binder aging susceptibility, and means of increasing virgin binder content to improve performance. In addition, mixture design is more complicated and more time-consuming, particularly with large quantities of recycled materials identified by high RBRs between 0.3 and 0.5.

Collectively these documents and other recent activities have identified a need to 1) learn more regarding the details of practice recommendations implemented by State DOTs; 2) collect and communicate experiences, lessons learned, and performance information; and 3) identify gaps for the 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.

Scope and Objective

The primary objective of this overall effort is to identify and put forth practices implemented by State DOTs for responsible use of RAP in asphalt mixtures. This will complement the National Asphalt Pavement Association (NAPA) publications QIP-129E, QIP-124, and SR-213, which provide contractors with best management practices and guidelines for the use of high RAP and RAS mixtures (14, 15, 16). To accomplish this objective, the information was collected through virtual site visits and other means with six key State DOTs. With the COVID-19 Pandemic ongoing, it was impossible to have the initially planned State DOT field visits, so virtual visits were proposed.

Site Visits

The following State Departments of Transportation graciously agreed to host a virtual field visit between June and September 2020: South Carolina DOT (SCDOT), Florida DOT (FDOT), Wisconsin DOT (WisDOT), Nebraska DOT (NDOT), and New Jersey (NJDOT). Figure 2 illustrates the State DOTs locations dispersed across the U.S.

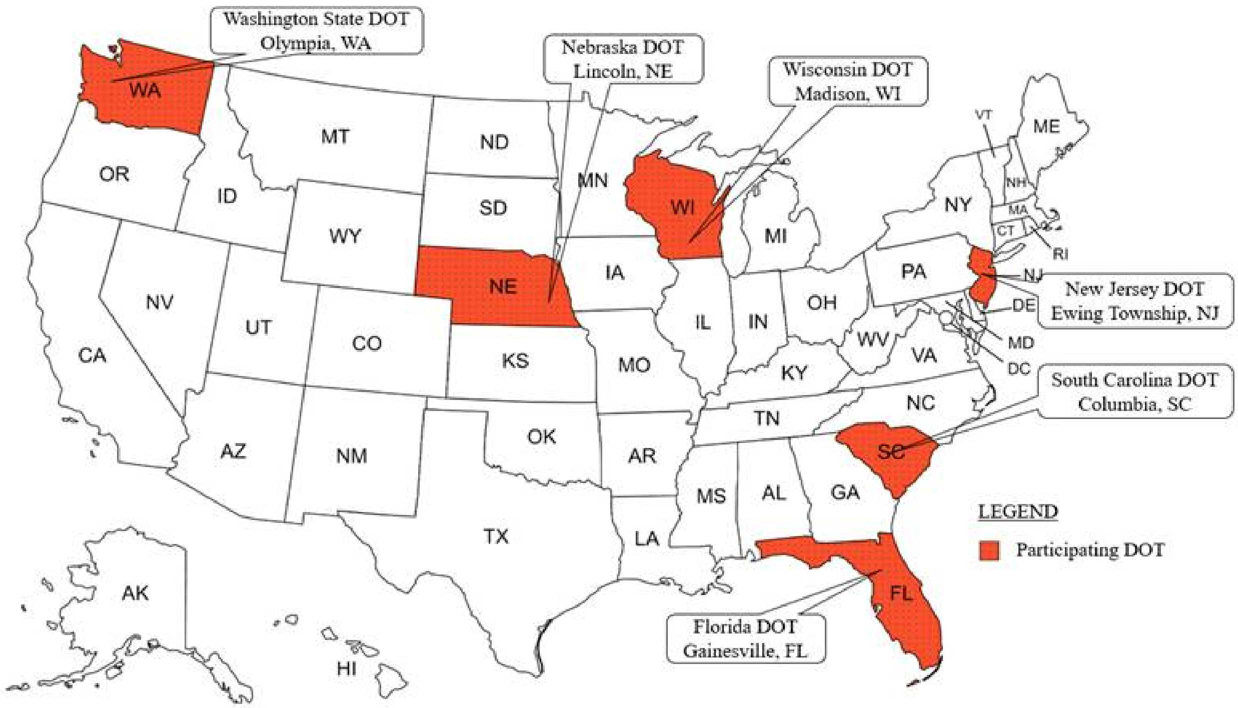

Image: University of Nevada Reno

Figure 2. Map of Participating State DOTs.

The scope of each virtual visit included: a pre-visit kickoff web meeting and review of agency documents (policy, specifications, research reports, etc.) and two or three-day virtual visits to obtain a detailed understanding of agency processes, positive practices, lessons learned, and pavement performance. The virtual visits may have included RAP processing and asphalt mixture plants that illustrated positive practices if possible.

The outcomes of each visit included a brief report to each FHWA Division Office and State DOT visited on the observations, practices, and lessons learned identified. The reports summarized the information collected through interactions with the agency and any industry personnel included in the visits. A summary of each State DOT visit highlights RAP use, key materials, mixture design and acceptance specification items, pavement performance, and, if applicable, production facility virtual visits. This is followed by a summary of key observations from all of the State DOT visits. Finally, important considerations for specifying RAP, designing mixtures containing RAP, producing RAP, producing asphalt mixture containing RAP, and controlling the quality of mixtures containing RAP are provided along with research needs identified.

Additionally, the information in this report will be compiled into a summary document of positive practices and considerations for using High RAP mixtures in the form of an FHWA Technical Brief with an accompanying PowerPoint presentation; and depending on observations, draft standard practices in AASHTO format may be developed along with research need statements for considerations

Reclaimed Binder Ratio

Reclaimed binder ratio (RBR) is now being used by State DOTs, researchers, and engineering consultants to specify the amount of reclaimed binder from RAP and RAS to the total binder in the mixture. The following equation explains the reclaimed binder ratio concept (17):

$$RBR = \frac{Reclaimed\ Binder\ from\ RAP\ or\ RAS}{Total\ Percent\ of\ Binder\ in\ Mixture} \quad \text{Eq. 1}$$

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 specifies 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 (18).

South Carolina Department of Transportation (SCDOT)

General Information on RAP Use, Materials, and Specifications

In 2019 SCDOT used approximately 2.9 million tons of asphalt mixture, integrating about 600 thousand tons of RAP. SCDOT has been using RAP since 1997, and 20 to 22 percent is typically used in asphalt mixtures. RAP use has been consistently in this range for the past four years. Nearly all mix produced in the State includes RAP. It is forecasting that the budget will increase from $450 million to $800 million by 2024.

RAP usage and amount in asphalt mix aren't consistent across the state, with urban areas having more available supply and thus using more. The use of RAP and RAS are at the contractor's option. RAS use has declined and may be sporadic, though a few contractors in the state still use it. Both manufactured waste and post-consumer RAS are allowed, though only post-consumer RAS has been used in the past five years. The maximum amount allowed is 5 percent only in Surface C and D, Intermediate C, and Base mixtures, as shown in Table 2 (19).

Recycled asphalt materials (RAM) include RAP and RAS, and the allowable amount used is specified as the maximum percent of aged binder (MPAB), which is equivalent to reclaimed binder ratio (RBR).

Table 2. Maximum Percent Aged Binder (MPAB) from RAP and RAS Allowed (19).

Type of Mix	Allowable RAS (%)	Non-Fractionated RAP	Fractionated RAP
Surface A	-	-	15
Surface B	-	15	25
Surface C	5	20	30
Surface D	5	20	30
Surface E	5	-	30[1]
PMTLSC	5	15	30[1]
Intermediate A	-	-	15
Intermediate B	-	20	30
Intermediate C	5	25	35
Base A	5	30	35
Base B	5	30	35
Base C	5	-	35[1]
Base D	5	-	35[1]
Shoulder Widening	5	-	45

[1]Fractionated Fine RAP only.

The SCDOT roadway system includes Interstate, Primary (U.S.), and Secondary (lower volume) routes. It is comprised of about 41,000 centerline miles, with about 70 percent of the traffic on Primary and Secondary routes. Table 3 is the SCDOT Guidelines for Asphalt Mixture Selection mix type selection, illustrating which mix types to use for different routes, traffic levels, and locations (surface, intermediate, or base) in a pavement structure (20). The SCDOT workhorse mix type is Surface B. When an overlay is planned on routes other than Interstates and will require patching in excess of 20 to 25 percent, Cement Modified Recycled Base (CMRB) is commonly used, which is also referred to as full-depth reclamation (FDR). SCDOT is the leader in this particular method of in-place recycling with portland cement, with over 25 million square yards having been constructed since 2013. CMRB is currently planned for an Interstate project in 2020 that includes a shoulder widening with some RAP milled off and aggregate base added. This is another excellent form of recycling existing asphalt pavement in rural areas.

RAP fractionation is a contractor option. If fractionation is performed, then the allowable amount of RAP is increased because SCDOT considers the fractionated RAP to be more consistent (better quality). With the RAP fractionated, blend proportions can be adjusted during design and production as needed. This incentivized contractors to fractionate RAP. The increase is about 10 percent more MPAB, as shown in Table 2. The majority of contractors elect to fractionate, even if they do not use the maximum amount of RAP allowed. It is typically fractionated into coarse and fine RAP stockpiles with the fractions being passing ¾ inch and retained on ¼ inch sieves (¾ x ¼) and passing the ¼ inch sieve (minus ¼). This typically results in about 35 to 40 percent coarse RAP and 60 to 65 percent fine RAP.

Table 3. SCDOT Guidelines for Asphalt Mixture Selection (20).

Course	Type Facility	Type	Est. % Binder	Binder Grade	Recom. Rate (Lbs/Sq.yd)	Comments
Surface	Interstate Problem intersections and areas (severe rutting and shoving potential)	A	5.0	PG 76-22	200	Consult with OMR Pavement Design Unit when other facilities are being considered
	High volume primary &secondary ADT ≥ 5000	B	5.3	PG 64-22	175 - 200	Use only on high volume and/ or high % Truck traffic roads FDP – less than 6"
	Low volume primary &secondary ADT 1500 - 5000	C	6.0	PG 64-22	150 - 175	Truck traffic ≥ 20%, use Surface type B FDP – less than 6"
	Low volume secondary routes ADT < 1500	D	6.3	PG 64-22	125 - 150	Truck traffic ≥ 20%, use Surface type C Use in lieu of PMTLSC on roads with rutting or other surface imperfections
	Multiple facility usage Consult with OMR Pavement Design Unit	E	6.5	PG 64-22	45 - 80	Used for ride correction and seal course Leveling between 0.5 - 2.0 inches
Intermediate	Interstate & High-Volume primary (New Construction)	A	4.6	PG 64-22	250 - 300	Use when no drop off restrictions Use Intermediate B when there are drop off restrictions
	High Volume Primary & Secondary ADT ≥ 5000	B	5.1	PG 64-22	200	Old Surface Type B Mixture
	Interstate & High Volume primary ADT ≥ 5000	B Special	5.4	PG 64-22	200 - 500	Special warm mix - only used on high volume routes for partial- full depth rehabilitation and FDP (2 Lifts) Mixture must be placed in confined area
	primary to low volume secondary	C	4.8	PG 64-22	200 - 300	Use for build-up and non-mainline paving and FDP
Base	Intersection & problem areas Interstate Primary and secondary routes with ADT ≥ 5000	A	4.5	PG 64-22	300 - 450	
	Primary and secondary routes with ADT < 5000	B	4.5	PG 64-22	300 - 450	
	Special - Consultant with OMR Pavement Design Unit	C	5.5	PG 64-22	200 - 300	Screening asphalt base - high stability
	Special - Consultant with OMR Pavement Design Unit	D	5.0	PG 64-22	200 - 300	Sand asphalt base - low stability
Specialty Mixes	Interstate	OGFC	6.5	PG 76-22	125	Open graded friction course
	Primary & secondary	PMTLSC	6.0	PG 64-22	0.75" Uncompacted	Preventive maintenance thin lift seal course- select only for good roads
	Primary & secondary	Shoulder widening	5.0	PG 64-22	400 - 600	Non-structural mix Use on outer edge of pavement that does not carry continuous traffic loads

Revised 01-01-18

SCDOT uses a risk-based approach to establish allowable levels of RAM that is a function of several criteria. They include mix type, whether or not RAP is fractionated, and whether or not RAS is allowed, as shown in Table 1 (9). RAM is not allowed in specialty mixes like open-graded friction courses (OGFC) and limited in others like stone matrix asphalt (SMA) to 15 percent.

All SCDOT mix types incorporate PG64-22 binder, except Surface A, SMA, and OGFC, which incorporate PG76-22. What is specified is the maximum percent of aged binder (MPAB), which is equivalent to the reclaimed binder ratio (RBR). The MPAB includes contributions from both RAP and RAS. It is determined with Eq. 2.

$$\%\ Aged\ Binder\ from\ RAP\ and\ RAS\ =\ ((A*B)+(C*D))/((E*100\%)) \qquad \text{E}$$

Where: A = RAP, % Binder Content

B = RAP, % in Mixture (by weight of total mixture)

C = RAS, % Binder Content

D = RAS, % in Mixture (by weight of total mixture)

E = New Mixture Design, % Binder Content*

Up to 5 percent, RAS may be used in some mix types, but MPAB in a mix cannot exceed the limits in Table 2. This, coupled with the SCDOT Guidelines for Asphalt Mixture Selection (Figure 1), makes allowable RAM level(s) a function of mix type, route, traffic level, RAM type, and location of the mix in a pavement structure. As traffic level decreases and depth into the pavement structure increases, allowable MPAB increases. Allowable MPAB increases by 5 to 15 percent with fractionated RAP depending on the mix type.

Mix durability is a primary concern for SCDOT, and it has gone to finer graded mixtures, 9.5mm fine-graded surface mixes, and increased asphalt binder through a combination of several techniques used to increase the amount of virgin asphalt binder in the mix. Several of these are summarized below:

- Design Gyrations. One is reducing the number of gyrations compared to AASHTO M323, Standard Specification for Superpave Volumetric Mix Design (17). Seventy-five gyrations are used for interstate and primary routes, while 50 gyrations are used for secondary routes.
- Design Air Voids. This is combined with the selection of optimum asphalt content at 96 to 97 percent of theoretical maximum specific gravity (Gmm) at the mix designer's discretion, which is normally at 96.0 percent of Gmm (4.0 percent air voids) for RAM mixtures and 96.5 percent of Gmm (3.5 percent air voids) for virgin mixtures.
- Asphalt Binder Availability. For surface and intermediate mix types, a Corrective Optimum Asphalt Content (COAC) is used to adjust the optimum asphalt content up to account for binder availability of RAM. RAM binder availability is fixed at 75 percent. The other 25 percent is "black rock." The COAC is used to add virgin binder to account for the black rock. The COAC is determined by multiplying the asphalt

content of the aged binder by 25 percent and adding it to the optimum asphalt content determined from the volumetric mix design. For example, if the optimum asphalt content from volumetric mixture design were 5.0 percent and the asphalt content from the aged binder was 1.56 percent, then the COAC would be 5.0 + 0.25 x 1.56 = 5.0 + 0.39 = 5.4 percent. In other words, the optimum asphalt contents would be increased by 0.39 percent to account for reduced binder availability (i.e., black rock) of the RAM.

- Voids in the Mineral Aggregate. The aggregates used in South Carolina are primarily low absorption (less than 0.5 percent asphalt absorption) granites. Although there is a minimal amount of limestone (about 1 percent), it is not used on the surface due to friction concerns. SCDOT requires that voids in mineral aggregate (VMA) be 0.5 percent higher than the levels in AASHTO M323 during mixture design and production. However, aggregate absorption is not accounted for when VMA is calculated. Rather than using the bulk dry specific gravity (Gsb) of virgin and RAM aggregates in the calculation, effective specific gravity (Gse) is used. It is estimated that the combination of increased VMA specification, low absorption aggregates, and use of Gse results in 0.3 to 0.5 percent more asphalt content than would be observed per AASHTO M323.
- Dust Proportion (DP). DP ratio requirements for surface and intermediate courses in the mixture design are 0.60 to 1.20 using washed gradations. There is a field requirement using dry gradations of 0.40 to 1.00.
- Softer Binder. Grade bumping down is not done. SCDOT only uses the base grades (PG 64-22 and PG 76-22). PG 64-22 is the neat grade that is naturally produced. Using this minimizes the chance of other additives being introduced.
- Pay for Asphalt Binder Separately. Finally, asphalt binder is a separate pay item, which incentivizes contractors to design and produce durable mixtures rather than minimize asphalt content to reduce mix cost.

To ensure increased durability by increasing the optimum binder content (OBC) is not taken so far that rutting resistance is compromised; three checks are made. First, an allowable range of OBC is specified based on NMAS. Second, regardless of mix type, the combination of selecting an OBC at up to 97.0 percent Gmm and applying the COAC may not lead to design air voids of less than 2.5 percent (more than 97.5 percent Gmm). Finally, and third, the Asphalt Pavement Analyzer (APA) rutting test is used as an index-based performance test during mixture design and at the start of production.

In SCDOT mixtures, about 90 percent of the asphalt binder used is PG64-22, and the remainder is PG76-22. PG64-22 is specified per AASHTO M320, Standard Specification for Performance-Graded Asphalt Binder (21). PG76-22 is specified per AASHTO M332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test (22). It is a V-Grade. Neither grade bumping up nor down is used. This discourages the use of re-refined engine oil bottoms (REOB), which is permissible up to 0.5 percent but has not been used. SCDOT randomly performs x-ray fluorescence testing of asphalt binders, and REOB is not currently being observed in the supply. Recycling agents are not allowed. Asphalt modification of the PG76-22 is normally performed with SBS. Modification type is a contractor option with either SBS polymer or wet process GTR allowed. GTR has been successfully used, but most asphalt is supplied from terminals, and the contractors view GTR as being higher risk, so it is not currently being used. Aramid fibers have been used on selected trial projects to determine if they will reduce reflective cracking.

Chemical warm mix asphalt (WMA) can be used with any mix that contains PG64-22 (23). Recall that PG64-22 is used in about 90 percent of all SCDOT mixes. WMA has been used exclusively in OGFC for five years, and a 2019 supplemental specification for an open-graded friction course requires that it be used (24). With lower production temperatures, fibers are not required, and drain down is not a construction issue. Foam WMA is not used in South Carolina. Chemical WMA is often used with other mix types as a compaction aid, though often for mix produced at higher than WMA temperatures.

In addition to volumetric mixture design with COAC and room for engineering judgment, the SCDOT mixture design requirements include APA rut testing, and moisture sensitivity testing per AASHTO T-283, Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage, that also has to be verified at the start of mix production (25). The APA performance must be re-verified anytime a failing asphalt content or gradation test occurs, and AASHTO T-283 has to be performed every 30 days of production. The dry tensile strength ratio requirement is a minimum of 85 percent during mixture design and 80 percent during production. There is also a minimum dry tensile strength requirement of 65 psi during mixture design and 60 psi during production. SCDOT has arranged procurement of IDEAL-CT equipment based on observations from the National Center for Asphalt Technology (NCAT) work to use it for mixture design and acceptance in the future. Due to staffing limitations, SCDOT is not likely to develop a full, balanced mixture design process but will use performance tests as an additional check on the volumetric properties.

Lime was the primary type of anti-strip historically used by SCDOT, though it has transitioned to allowing the use of liquid anti-strip (LAS) additives that are terminally blended with a virgin binder. Lime has been added to the aggregates with a pugmill on a collector belt prior to introduction into the drum. Recently SCDOT started allowing lime to be injected into the mixing drum also. LAS can be used instead of lime as long as mixtures pass moisture sensitivity test requirements. LAS quality is controlled through the SCDOT qualified product list (QPL) requirements and a fixed required dose of 0.7 percent.

SCDOT suggests that part of the reason for the successful use of high RAP is due to stringent RAP processing and handling requirements. A RAP quality control (QC) plan is required of the contractor, and it has to include one ignition furnace asphalt content and gradation test per 1000 tons of production, along with two moisture content tests per day. Data has to be logged and available to SCDOT staff. Non-fractionated stockpiles have to be dedicated, so they cannot be replenished. This has led to fractionated piles, which can be replenished, becoming the contractor's preference.

To improve the overall durability of all mixtures, SCDOT has gradually moved away from most of the Superpave gradation used for nearly 20 years. They have gone to much finer mixes, especially on the surface. 9.5mm mixtures are predominately used on the surface, which contains more fines, more binder, which results in an easier to compact mix that SCDOT believes will be more durable over the long term. The coarser mixes are used for intermediate mixtures, some of which were surface mixtures previously used under the Superpave gradation limits. These mixes have also been improved with the COAC and lower gyration count to add more binder for durability. So far, the SCDOT and most of the asphalt Contractor community have been pleased with the amount of RAP being utilized.

Standards used by SCDOT include:

- SCDOT Standard Specifications.
- SCDOT Supplemental Technical Specification for Material Properties for Asphalt Mixtures, SCDOT Designation: SC-M-402.
- SCDOT Supplemental Technical Specification for Recycled Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS), SCDOT Designation: SC-M-407.
- AASHTO M320 and M332 binder specifications.
- AASHTO M323 mixture design specification.
- A combination of SCDOT and AASHTO test methods are used.
- Recommendations from SCDOT funded research reports including:
    - Report SPR-720 - AMPT characterization of a mix for local calibration was accomplished. Variables were identified that led to higher |E*| and lower δ values. Variables were also identified that led to higher Flow Number (F.N.) values. Tables were developed for every material combination tested such that data could be input into the Mechanistic-Empirical Pavement Design Guide (MEPDG) software program.
    - Report SPR-705 – The estimated percent savings to SCDOT (expressed as a percent of the total mix cost paid) increased steadily from 9% in 2008 to 16% in 2013. The total savings to SCDOT by utilizing RAP mixtures between 2008 and 2013 was estimated to be $90.7 million.
    - Report SPR-726 – The results indicated that both LAS and hydrated lime could improve the moisture sensitivity of HMA.
    - Report SPR-709 – The low-temperature properties of RAP were estimated without extraction. The minimum low temperatures could be determined based on the simple regression analysis. It was found that the RAP source affected the minimum low temperatures of the various modified binders.
    - Performed research (E*) to assess the ranges of E* for typical mix types with ranges of RAP to determine typical E*.

SCDOT is considering removing RAS in all surface mixes based on NCAT (Lee Road Route 159, test section 24) observations and requiring RAS to be ground to a finer size (from 3/8" to ¼") because the percent cracking is very poor within a few years of service for the thin lift with 5 percent RAS.

Contractor Interviews and Virtual Plant Observations

With the COVID-19 Pandemic leading to virtual site visits, it was impossible to visit contractor RAP processing and asphalt plants. So, just prior to the virtual visit SCDOT and South Carolina Asphalt Pavement Association staff partnered with two asphalt contractors. They visited the contractors' facilities to obtain pictures and videos of typical operations. During the virtual site visit, separate virtual meetings were held with each contractor, during which the pictures and videos were viewed, and the contractor's staff were interviewed using a set of eight open-ended questions. A brief summary of observations based on these activities for each contractor follows.

One contractor's plant near Charleston, South Carolina, was viewed. The site included RAP processing, an asphalt plant, and a QC laboratory. RAP processing was performed with a small portable plant with a crusher and two-deck screen. The asphalt plant was an Astec Double Barrel plant with an external pugmill mixer. The plant included three RAM bins and six silos indicated to be capable of running up to 60 percent RAM. The certified lab had all the equipment necessary for performing the required production QC and verification testing.

Key observations included:

- Both RAP QC and Project QC Plans were being implemented.
- In-coming RAP is pre-screened to sort the best quality supply for SCDOT work.
- RAP is fractionated into ¾" x #4 and minus #4 stockpiles.
- RAP is stored in a shed with a sloped pad to minimize moisture and clumping.
- Three RAP feed bins are used to accommodate running 50 to 60 percent RAP.
- K-rail is used for separating stockpiles, and signage is used.
- Aggregates must be imported to this site at a premium, so a conscious effort is made to balance RAM use and aggregate import to control costs.
- The contractor has an internal QC plan on imported aggregates, which is beyond State DOT requirements. Weekly QC meetings between the contractor and aggregate producer are held where data and observations are discussed to maintain or improve quality.
- The use of an external mixer (post drum discharge) can improve the coating of high RAP mixtures.
- All material collected in the baghouse is returned in dense-graded mixes with a screw auger system, as shown in Figure 3. A storage silo and metering system is not used.
- The company is receptive to the SCDOT use of COAC because it helps with density and mix quality, and the asphalt binder is a separate pay item.

Image: Adam Hand

Figure 3. Baghouse fines Screw Auger Return System.

A contractor with a plant near Columbia, South Carolina, was also interviewed. The site included an aggregate quarry operation, RAP processing, an asphalt plant, and a QC laboratory. A subcontract crusher performed RAP processing with a small portable plant with a crusher and two-deck screen. The asphalt plant was a CMI counterflow drum with a RAP collar. The plant included two RAM bins and three silos indicated to be capable of running up to 50 percent RAM. The certified QC lab was reported to have all the equipment necessary for performing the required production QC and verification testing. The company mixture design lab is located across the street from the plant. Key observations included:

- Both RAP QC and Project QC Plans were being implemented.
- In-coming RAP is pre-screened to sort for consistency and quality.
- RAP processing is performed by a subcontractor.
- RAP is fractionated into ¾" x #4 and minus #4 stockpiles.
- Monitoring RAP moisture content closely, such as two moisture contents per day with one before the start of production daily.
- RAP is not stored under cover since RAP Gators are effective in eliminating clumping.
- All RAM feed bins were equipped with RAP gators (clump breakers).
- All RAM feed bins were equipped with air cannons.
- The plant is equipped to use lime (silo and metering system) as an anti-strip additive.

Pavement Performance Observations

Statements of references to pavement performance observations were not made on this site visit.

Summary of Positive DOT Practices

Throughout the visit, SCDOT identified several practices that were important for their successful use of RAP. They included the following:

Pavement Performance and Quantifying and Communicating Recycling Benefits

1. The estimated percent savings to SCDOT (expressed as a percent of the total mix cost paid) increased steadily from 9% in 2008 to 16% in 2013. The total savings to SCDOT by utilizing RAP mixtures between 2008 and 2013 was estimated to be $90.7 million.

Specifications

1. A well-referenced combination of SCDOT standard specifications, SCDOT supplemental technical specifications, SCDOT test methods, AASHTO standards, and AASHTO test methods make it very clear what the requirements of using RAP are in the state.
2. Other public agencies in the state use SCDOT specifications, reducing work for contractors and agencies.

RAP Criteria

1. Use of MPAB, which is equivalent to RBR, for defining allowable levels. Average RAP use is about 20 percent but can go up to 35 percent.
2. 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 PG for the environment.
3. SCDOT requires plant control software printouts with mixture proportions used reported. Although this is printed every 15 minutes, data is saved such that it can be retrieved for any past period.

Rationale and Location for Using RAP

1. A risk-based approach to establishing allowable levels of recycled materials is a function of route type, traffic, location in the pavement structure, and mix type.
2. Having a published guideline for mix type selection illustrating which mix types to use for different routes, traffic levels, and location (surface, intermediate, or base) in a pavement structure.

Use of Softer Binder and Additives

1. If recycled materials (RAS, RAP, or RAS and RAP) are used, standards exist to assure the binder in a mixture containing recycled materials is not too brittle for the environment.
2. Regression analysis is used to estimate low temperature asphalt binder properties without extraction. It addresses the fact that RAP source can affect the minimum low temperatures of the various modified binders.

Additional Asphalt Content and Mixture Performance Tests

1. Use of a combination of techniques to improve mix durability by increasing the amount of asphalt in mixes which include:

a. Reducing the number of gyrations below the levels in AASHTO M323 to 75 (Interstate) and 50 (Primary and Secondary) routes.
b. Selecting the optimum binder content at 96 to 97 percent G_{mm} (typically 96.5 percent or 3.5 percent air voids) with the mix designer is allowed to exercise engineering judgment in the process.
c. Assuming 75 percent binder availability from RAM and adding virgin binder by applying a COAC that increases the amount of virgin binder by the RAM availability lost.
d. Asphalt binder is a separate pay item, so contractors are not incentivized to develop mix low binder content mixes.

2. Mixture design requirements include APA rutting and moisture sensitivity testing that have to be verified on production start-up.
3. Research is planned for evaluating the IDEAL-CT test for mixture design and production. A question that is desired to answer is if the higher allowable RAP levels for Type C and D mixes lead to top-down cracking.

RAP Processing, Handling, and QC

1. There is a RAM QC plan requirement, and projects require QC plans.
2. SCDOT has a technician certification program that includes QC, mixture design, and roadway technician certifications. SCDOT also has a required laboratory certification program.
3. The allowable amount of RAP that can be used increases if RAP stockpiles are fractionated.
4. Contractors are incentivized to fractionate RAP because allowable RBR is then increased by about 10 percent.

Contractor Input on Successful High RAP Use

1. Both RAP QC and Project QC Plans were being implemented.
2. In-coming RAP is pre-screened to sort the best quality supply for SCDOT work.
3. RAP is fractionated into ¾" x #4 and minus #4 stockpiles.
4. RAP is stored in a shed with a sloped pad to minimize moisture and clumping.
5. Three RAP feed bins are used to accommodate running 50 to 60 percent RAP.
6. K-rail is used for separating stockpiles, and signage is used.
7. Aggregates must be imported to this site at a premium, so a conscious effort is made to balance RAM use and aggregate import to control costs.
8. The contractor has an internal QC plan on imported aggregates, which is beyond State DOT requirements. Weekly QC meetings between the contractor and aggregate producer are held where data and observations are discussed to maintain or improve quality.
9. The use of an external mixer (post drum discharge) can improve the coating of high RAP mixtures.

10. All material collected in the baghouse is returned in dense-graded mixes with a screw auger system, as shown in Figure 3. A storage silo and metering system is not used.
11. The company is receptive to the SCDOT use of COAC because it helps with density and mix quality, and asphalt binder is a separate pay item
12. Monitoring RAP moisture content closely, such as two moisture contents per day with one before the start of production daily.
13. RAP is not stored under cover since RAP Gators are effective in eliminating clumping.
14. All RAM feed bins were equipped with RAP gators (clump breakers).
15. All RAM feed bins were equipped with air cannons.
16. The plant is equipped to use lime (silo and metering system) as an anti-strip additive.

Alternative Uses of RAP and Research Needs

The most common alternative use of RAP in South Carolina is in CMRB (a.k.a., FDR). This is logical since SCDOT is a leader in the use of this in-place recycling technique in the U.S. Cold in-place recycling (CIR) foaming method was successfully used on a US123 project, so it will likely be used more in the future, and there is an interest in cold central plant recycling (CCPR).

Florida Department of Transportation (FDOT)

General Information on RAP Use, Materials, and Specifications

In fiscal year (FY) 2019 (July 1, 2019, to June 30, 2020), FDOT used approximately 4.5 million tons of asphalt mixture, integrating about 765,000 tons of RAP. That would suggest that 17 percent RAP was used in FDOT mixtures on a statewide average, but this percentage is misleading. Some mix types allow no RAP, while others allow an unlimited amount of RAP. When RAP is unlimited, several producers used about 40 percent RAP, with the highest being 50 percent. The total asphalt mixture tonnage includes 502,000 tons of open-graded friction course (OGFC). RAP is not allowed in OGFC mixtures in Florida. It is not allowed in dense-graded friction course (DGFC) mixtures containing south Florida limestone or any High Polymer (HP) mixtures. FDOT High Polymer (HP) mixtures are what some refer to as highly modified asphalt mixtures (HiMA). FDOT limits the amount of RAP in mixtures containing PG 76-22 binder to 20 percent. On average, contractors used 19 percent RAP in these mixtures in FY 2019. There is not a RAP limit on mixtures that do not incorporate modified binders. Contractors used 25 percent RAP in these mixtures on average in FY 2019. Several producers used about 40 percent RAP. The highest amount of RAP used in a mixture design was 50 percent, and that was by only one contractor. Table 4 summarizes mix types, PG binder grade requirements, and allowable RAP use in Florida. The FDOT Flexible Pavement Design Manual provides some direction on binder grade requirements based on traffic classifications consistent with the information in Table 4 (26).

Table 4. FDOT Mix Types, PG Binder Requirements.

Region of State	Aggregate Type	Layer in Structure	Mix Type	PG Binder	Allowable Percent RAP	Notes
Northern	Granite	Surface	All	HP	0	High traffic
Northern	Granite	Surface	OGFC	PG 76-22 Modified	0	
Northern	Granite	Surface	DGFC	PG 76-22 Modified	20	
Northern	Granite	Intermediate	All	HP	0	High traffic
Northern	Granite	Intermediate	Intermediate	PG 76-22 Modified	20	High traffic
Northern	Granite	Intermediate or Base	All	Unmodified	Unlimited	Never surface mix
Southern	Limestone	Surface	All	HP	0	High traffic
Southern	Limestone	Surface	OGFC	PG 76-22 Modified	0	
Southern	Limestone	Surface	DGFC	PG 76-22 Modified	0	
Southern	Limestone	Intermediate	All	HP	0	High traffic
Southern	Limestone	Intermediate	Intermediate	PG 76-22 Modified	20	High traffic
Southern	Limestone	Intermediate or Base	All	Unmodified	Unlimited	Never surface mix

FDOT has been using RAP since the late 1970's, though it does not allow the use of RAS. The use of RAP in Florida has been fairly consistent in the past four years (1). RAP usage and amount in the asphalt mix aren't consistent across the state. The primary reason for this is virgin aggregate supply is different in the southern third of the state and the remaining northern two-thirds of the state. Low absorption, polish resistance granite aggregate is used in the northern portion, while high absorption limestone is used in the southern portion, as shown in Figure 4.

RAP is specified by the weight of the total aggregate. However, for mixtures with a maximum 20 percent RAP by weight of total aggregate, the contractor has the option to choose instead to use the amount of RAP which results in no more than 0.20 RBR. FDOT staff indicate this option is not often exercised by contractors even though it may allow them to increase the amount of RAP used by a couple of percent.

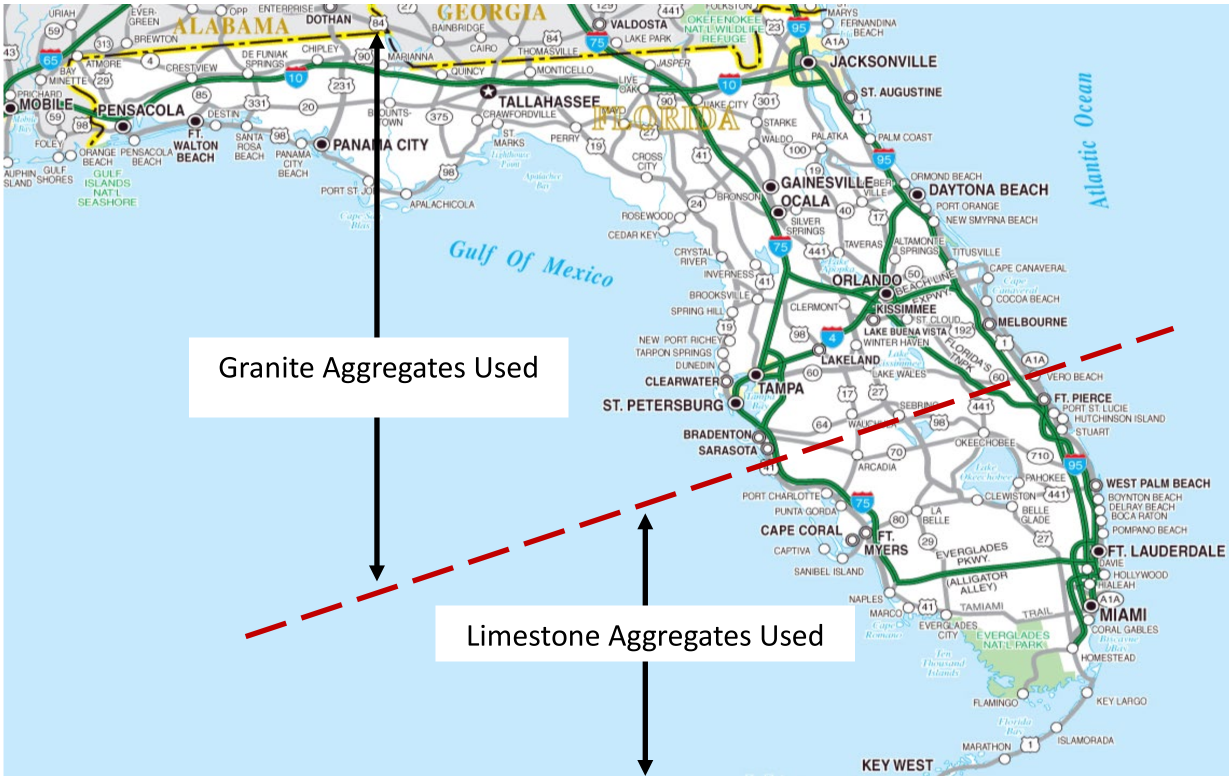

Figure 4. Florida Map Illustrating Granite and Limestone Aggregate Typical Use.

RAP is sometimes fractionated into separate stockpiles. In states where contractors do fractionate RAP, it is common that the RAP will be fractionated into ¾ or ½ inch by #4 (coarse) and minus #4 (fine) stockpiles (14). It is the contractor's option to fractionate RAP into coarse and fine stockpiles. Allowable RAP usage could increase if PG 76-22 were specified; the contractor chose to use RBR, and RAP is fractionated. Not many contractors fractionate RAP in Florida. It has been reported that the clumping of fine RAP stockpiles can be problematic in the Florida climate.

Mixture designs are performed in accordance with AASHTO M 323, Standard Specification for Superpave Volumetric Mixture Design and AASHTO R 35, Standard Practice for Superpave Volumetric Design for Asphalt Mixtures, with a few exceptions (17, 27). The one exception specifically targeted on increasing the amount of virgin binder is the number of gyrations used by FDOT that are lower than those in AASHTO M 323. FDOT used the following three gyration levels:

- Less than 3 million ESALs: Ndes = 65 gyrations
- 3 to 10 million ESALs: Ndes = 75 gyrations
- Greater than 10 million ESALs: Ndes = 100 gyrations

Other volumetric requirements, including design air voids, voids in mineral aggregate (VMA), and Dust Proportion (DP), are consistent with the AASHTO M323. Mix acceptance at the asphalt plant is based on binder content, gradation, and air voids. All RAP binder is assumed to be available to contribute to the total binder content of the mixture. During the mixture design process, FDOT performs a Gmm test and a solvent extraction on RAP to determine estimated asphalt absorption based on a visual assessment of the recovered aggregate type. An automatic extraction device has been ordered by FDOT. The FDOT Mixture Design Manual has asphalt absorption values for aggregate sources shown in Table 5.

Table 5. FDOT Aggregate Formations, Pit Numbers and Asphalt Absorption Values.

Formation	Pit Number	Asphalt Absorption
Gravel	50-120	0.30
Granite Seams Schist	GA-383	0.33
Newalas Limestone	AL-149	0.36
Limestone	AL-485	0.36
Granite Gneiss	GA-177, GA-178, GA-181, GA-182, GA-183	0.43
Limestone	KY-309	0.43
Granite	GA-185	0.47
Limestone	IL-353	0.56
Limestone	KY-329	0.66
Oolitic	87-339	1.77
Ft. Thompson Formation & Caloosahatchee	93-406	1.84
Miami Oolite & Ft. Thompson Formation	86-139, 87-089, 87-145	2.21
Suwannee Limestone	08-004, 08-005, 08-012	2.58
Miami Oolite	87-049, 87-090	2.54
Ft. Thompson Formation & Tamiami	03-017, 03-340, 12-008, 12-260	2.54
Caloosahatchee	01-011	2.69
Avon Park	34-106	3.30
Ocala Formation	38-268, 38-036, 29-023, 29-361	3.28
Ocala Formation & Marianna Limestone	53-311, 53-390	4.62

For calculating VMA, estimated aggregate bulk specific gravity (Gsb) and asphalt absorption are used. Mine targets are used for aggregate bulk specific gravity (Gsb). RAP Gsb is calculated by measuring the RAP Gmm and using an estimated asphalt absorption for the RAP. FDOT sets the asphalt absorption for RAP used in VMA calculations. Asphalt absorption values range from as low as 0.3 percent for gravel up to 4.6 percent for limestone aggregates.

All mix bid unit prices are for mixture and include the cost of the asphalt binder. Because FDOT selects the design asphalt content for OGFC mixtures, if a contractor's approved OGFC mixture design at the time of a bid is renewed or altered due to a component(s) change after the project is bid and the asphalt content is increased, then an adjustment in unit price is provided to the contractor.

FDOT does specify PG based on RAP usage for mixes containing neat asphalt with softer binders specified as RAP dose increases. The three RAP levels and required binder grades used are:

- 0-15 percent RAP: PG 67-22
- 16-30 percent RAP: PG 58-22
- Greater than 30 percent RAP: PG 52-28

These levels and binder grades were established based on a statewide in-house FDOT research effort. FDOT used blending charts for many years, and with the data collection over time, the levels above were established. This eliminated the need for FDOT and contractors to have to perform extractions and blending chart analyses for each mixture design. FDOT uses three safeguards along with this.

One safeguard is for mixes using PG 76-22 or High Polymer (HP) binder; during production, two times per year per project, a mix sample and corresponding virgin binder tank sample are taken. For mixes using all other PG binders unmodified PG binders, during production one time per year per project, a mix sample and corresponding virgin binder tank sample are taken. The binder is extracted from the mix sample, and the high-temperature PG grade is determined per AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder, and AASHTO M 323, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test (17, 21). The virgin binder's high-temperature PG grade is also determined. The test results from these project-level samples are used to determine if contract requirements are being met and to assure that adequate binder stiffness is present to prevent rutting. This latter part is typically only a concern for mixtures containing PG 52-28 or PG 58-22 unmodified binders and RAP. If the RAP binder is softer than normal, then the resulting mix binder stiffness may be too soft, and the virgin binder grade would be “bumped” one grade higher. Fourier Transform Infrared Spectroscopy (FTIR) analysis is also performed to verify the presence of polymer for PG76 all binder and mixture project samples, as well as samples obtained during inspections of the asphalt binder terminals.

A second safeguard is the virgin binder quality, in particular aging characteristics, is important to FDOT. FDOT employs a full-time chemist in the asphalt binder lab. A combination of ΔT_c, a waste oil provision, and an 8 percent maximum allowable re-refined engine oil bottoms (REOBs) are used to manage the use of REOB and other blending stock that may be susceptible to aging and be blended by suppliers that provide virgin binders (both modified and unmodified virgin binders) in Florida.

The final safeguard is the FDOT standard specifications require a 3-year warranty on pavement performance after final acceptance. Because the warranty is not bonded by the contractor, it is called a Value Added Asphalt Pavement. The pavement performance criteria and required repairs, if distress thresholds are exceeded, are shown in Table 6, an excerpt of the FDOT Standard Specifications Section 338 (28). It is often associated with small quantities of localized distress. It is most often associated with raveling and slippage failures. It has been used for rutting, potholes, depressions, and bleeding.

Table 6. Excerpt of FDOT Specification Section 338 with Value Added Asphalt Pavement (i.e., Warranty) Performance Criteria.

Type of Distress	Threshold values	Remedial Work
Rutting (1)	Depth > 0.25 inch	Remove and replace the distressed LOT(s) to full depth of all layers and to the full lane width (2)
Ride (3)	RN < 3.5	Remove and replace the friction course layer for the full length and the full lane width of the distressed LOT(s) (4)
Settlement/Depression (5)	Depth ≥ 1/2 inch	Propose the method of correction to the Engineer for approval prior to beginning remedial work
Cracking (6)	Cumulative length of cracking > 30 feet for cracks > 1/8 inch	Remove and replace the distressed area(s) to the full depth of all layers, and to the full lane width (7)
Raveling and/ or Delamination affecting the Friction Course (8)	Any length	Remove and replace the distressed area(s) to the full distressed depth and the full lane width for the distressed length plus 50' on each end
Potholes and slippage area(s) (8)	Observation by Engineer	Remove and replace the distressed area(s) to the full distressed depth and the full lane width for the full distressed length plus 50' on each end
Bleeding (9)	Loss of surface texture due to excess asphalt, individual area ≥ 10 sf.	Remove and replace the distressed area(s) to the full distressed depth and the full lane width for the full distressed length plus 50' on each end

(1) Rutting: Rut depth to be determined by Laser Profiler in accordance with the Flexible Pavement Condition Survey handbook. For any LOT that cannot be surveyed by Laser Profiler, the rut depth will be determined manually in accordance with the Flexible Pavement Condition Survey Handbook, with the exception the number of readings per LOT will be one every 20 feet. For a partial LOT, a minimum of three measurements not exceeding 20 feet apart will be made. When the average of the measurements obtained manually exceeds 0.30 inch or if any individual measurement exceeds 0.6-inch, remedial work will be required.
(2) Remedial work for Rutting: The Contractor may propose removal and replacement of less than the full depth of all layers by preparation and submittal of a signed sealed engineering analysis report, demonstrating the actual extent of the distressed area(s). Remedial work must be performed in accordance with Table 338-1 unless approved otherwise by the Engineer.
(3) Ride: Ride Number (RN) to be established by Laser Profiler in accordance with FM 5-549.
(4) If the deficient ride is due to underlying asphalt layers; base, subgrade, or embankment which were constructed by the Responsible Party, propose the method of correction to the Engineer for the approval prior to beginning the remedial work.
(5) Settlement/Depression: Depth of the settlement/depression to be determined by a 6-foot manual straightedge.

(6) Cracking: Beginning and ending of 1/8-inch cracking will be determined as the average of three measurements taken at one-foot intervals. The longitudinal construction joint at the lane line will not be considered as a crack.
(7) Remedial work for Cracking: The Contractor may propose removal and replacement of less than the full depth of all layers by preparation and submittal of a signed and sealed engineering analysis report, demonstrating the actual extent of the distressed area(s). Remedial work must be performed in accordance with Table 338-1 unless approved otherwise by the Engineer.
(8) Raveling, Delamination, Potholes, Slippage: As defined and determined by the Engineer in accordance with the examples displayed at the following URL:
http:/www.fdot.gov/programanagement/Implemented/URLinSpecs/Pavement.shtm
Bleeding: Bleeding to be defined and determined by the Engineer in accordance with the examples displayed at the following URL:
http:/www.fdot.gov/programanagement/Implemented/URLinSpecs/Pavement.shtm

FDOT does not allow the use of recycling agents in PG 76-22 to soften RAP binder. However, FDOT does allow binder suppliers to use softening agents to soften stiffer virgin binder grades to obtain softer grades other than PG 76-22. PG 76-22 binder has to be modified with SBS, SB, or ground tire rubber (GTR) at the contractor's option. GTR is available from one south Florida binder supplier, but it is not used anymore. Recent research conducted at the University of Florida has been completed to re-evaluate the current RAP dose limits on mixes using PG 76-22 binder, and a specification revision to increase it is under review. The dose is based on two parameters: 1) the gradation of the RAP passing the #16 sieve and contains three levels, and 2) the RAP high-temperature PG grade and contains two levels. As the proportion of RAP passing the #16 sieve decreases and the RAP high-temperature PG grade decreases, then the allowable RAP dose increases.

Warm mix asphalt (WMA) is never required by specification but is always allowed if an approved warm mix additive or process is used. WMA is defined as using an approved process or additive having the following maximum mixture design production temperatures by specification:

- Unmodified mixtures: below 285°F.
- Modified mixtures - below 305°F.

Chemical additives can be used as a compaction aid and, for some products, as a LAS agent at the same time. WMA additives, which also function as a LAS, must be approved for use as a LAS and included on the FDOT LAS approved products list.

Mix cracking performance is a primary concern for FDOT, and it is seeking the identification of a practical cracking performance test. Rutting was a primary concern in the past, though it is not currently, as Superpave mixture design and a significant use of polymer-modified PG 76-22 binder has resulted in a statewide system of less than 0.5 percent of lane miles that have rutting values that exceed the pavement condition survey allowable maximum of 0.5 inches. The asphalt pavement analyzer (APA) has been successfully used in the past for mixture design purposes, though it is not a current requirement. A Florida version of AASHTO T 283, "Standard

Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," is used for assessing moisture sensitivity (25). The lab mixture aging protocol used is consistent with AASHTO M 323. For mix sampled at the mix asphalt plant, one hour of oven aging at the compaction temperature is used to simulate haul time to the paving location.

RAP requirements are clearly defined in the FDOT specifications. In most cases, the contractor takes possession of RAP when it is generated on a project. On occasion, Maintenance will request a certain tonnage of millings to be delivered to the regional maintenance facility. This quantity is identified in the plans prior to bidding. Generally, when the following conditions are met, the use of recycled material is encouraged, and RAP meets all of these conditions:

- The mix performs as well or better compared to a mix without the recycled material,
- The recycled material reduces the impact on limited resources,
- And/or the recycled material results in cost savings in the specifications.

RAP stockpiles can be designated as "continuous" at the contractor's option. This is an option in which a contractor occasionally adds to the stockpile while performing material property tests with each addition. Stockpiles may be fractionated, but it is not required or common in Florida. Each project requires a QC plan, which must include RAP processing, handling, and testing. Some contractors self-perform RAP crushing, while others use subcontract crushing services. Before a stockpile of RAP can be used, it has to be tested, visually inspected, and approved by FDOT. Millings directly from an FDOT project are also acceptable for use. RAP gradation must be measured once per 1000 tons during production, and Gmm must be measured once per 5000 tons of production. RAP stockpiles must have a minimum binder content of 4.0 percent. If RAP is fractionated into coarse and fine stockpiles, the coarse stockpile must have a minimum binder content of 2.5 percent. RAP cold feed bins must have scalping screens to prevent clumps from being introduced into the bins. The FDOT specifications don't directly include any RAP moisture management requirements. However, mix discharge temperature has to be recorded every 100 tons of production.

FDOT believes that its QC plan requirements and having a full-time plant inspector present during production are effective in helping contractors successfully use high RAP because of stringent RAP processing and handling requirements and continuous inspection. Things that assure FDOT that the proper amount of RAP is being used include the RAP percentage being listed on the mixture design that can be compared with the hot mix plant control settings by the inspector; FDOT specifications do not allow the contractor to alter any component blend percentage by more than 5 percent, and mix volumetric properties, asphalt content and gradation are checked at a minimum of once per 1000 tons. Recovered binder samples are also obtained from the mix on every project that can be used for forensic purposes if needed.

FDOT uses both FDOT and AASHTO specifications and test methods. Those relevant to this effort include:

- FDOT Standard Specifications, Sections 320, 334, 337, and 916.

- FDOT Test Methods for Gmb, Gmb, Gmm, Ignition Furnace Asphalt Content and Moisture Sensitivity tests that are similar to the AASHTO Standard but contain precision statements derived by FDOT work which can be found at: https://www.fdot.gov/materials/administration/resources/library/publications/fstm/bytesttype.shtm.
- AASHTO M 320 and M 332 binder specifications.
- AASHTO M 323 mixture design specification.
- AASHTO R 35 standard practice for mixture design
- AASHTO test methods.
- Recommendations from FDOT funded research reports.

Contractor Interviews and Virtual Plant Observations

With the COVID-19 Pandemic leading to virtual site visits, it was impossible to visit contractor RAP processing and asphalt plants. During the virtual site visit, separate virtual meetings were held with two contractors using a set of eight open-ended questions. A brief summary of observations based on these activities for each contractor follows.

A contractor with asphalt plants near Jacksonville, Florida, was interviewed. The contractor uses up to 40 percent RAP in mixture designs for commercial customers and 20 percent on most FDOT projects. The average is about 30 percent across all mixes produced. RAP demand is beginning to exceed supply in the Jacksonville area. All virgin aggregates are granite imported by rail from Georgia or Nova Scotia. A second contractor located in the Miami, Florida area, was also interviewed. About 75 percent of the mixture produced at this plant meets FDOT requirements, and the remainder is for airports and commercial customers. FDOT mixes incorporate 15 to 25 percent RAP. The FAA does not allow RAP in the asphalt mix. Up to 40 percent RAP is used in commercial mixes. One plant is a Cedarapids parallel flow drum mix plant. The other is a hybrid drum mix plant with Stansteel components. Both plants have two cold feed bins. RAP processing is self-performed

Key observations included:

- FDOT does not require crushing RAP, but it is helpful to maintain good control. RAP is sorted for asphalt mix and environmental base purposes. One contractor follows the FDOT RAP testing requirements but doubles the testing frequency specified by FDOT. Gradation is measured even 500 tons and G_{mm} every 2500 tons. RAP is crushed to minus 3/8 inch. RAP is not fractionated.
- Plant modifications are needed to successfully produce high RAP mixtures. Plants are flighted for appropriate heat transfer and have the ability to accurately meter baghouse fines and waste them if necessary. Plants used included a double barrel drum plant and a counterflow drum with an external mixer. Plants are equipped with two RAP cold feed bins.
- Contractors indicated that having a full-time FDOT plant inspector is helpful.
- Having to control the amount of dust prevents the contractor from using more RAP in mixtures.

- Using video cameras to monitor RAP bins during production to watch for clumping and consistent material flow is helpful.
- Measure volumetric properties, asphalt content, and gradation during mixture production are important because the FDOT percent within limits (PWL) specification requires consistency.

During the contractor interviews, the advantages and disadvantages of fractionating RAP into multiple stockpiles were discussed. Fractionation does not commonly occur in Florida. In states where contractors do fractionate, it is fairly common that RAP will be fractionated into ¾ or ½ inch by #4 (coarse) and minus #4 (fine) stockpiles (14). Reported advantages of fractionating are:

- Having flexibility for meeting mixture design requirements with:
    - Different nominal maximum aggregate sizes
    - Limited virgin aggregate stockpile sizes
    - Rigorous volumetric requirements
- Having better ability to control RAP consistency.
- Having the ability to increase RBR when RAP is specified by percent RAP by maximizing the use of fine RAP, which contains a higher asphalt content than coarse RAP.

Commonly referred to disadvantages of fractionating are:

- Increased processing cost since:
    - More equipment is needed.
    - Two stockpiles have to be built.
    - Greater crushing and screening energy consumption, thus cost.
- Increased handling and feeding costs because:
    - Maintaining separate stockpiles takes more ground area, which is particularly important in urban areas where RAP supply is normally greatest.
    - The loader has to make more trips to feed two stockpiles versus one stockpile.
    - Multiple feed bins and controls are required.
- Increased QC costs since two materials have to be tested rather than one.
- Fine RAP will more readily clump than coarse RAP in some environments.
- Fine RAP has a high percentage of material passing the #200 sieve, which could limit its use.
- If moisture is controlled using a paved stockpile area and/or covered structures, more paved area/structure space will increase the cost.

Regardless of whether or not RAP stockpiles are fractionated, good processing, handling, storage, and QC practices are required to successfully use RAP in high percentages. If they are not followed, fractionated RAP may not provide the benefits desired.

Pavement Performance Observations

An assessment of the impact of RAP on pavement performance in Florida was performed by FDOT and published in 2012 (29). The mixtures were designed by the Marshall Method and placed below the surface course mix in the structure. The performance period considered was 1991-1998. The conclusions indicated the importance of including traffic volume when analyzing performance life, rather than just age when resurfacing is performed. When accounting for traffic volume, as shown in Figure 5, there is a trend suggesting that as percent RAP increases, performance decreases. However, in the range of percent RAP analyzed (30-50), all mixtures containing RAP performed better than the mixtures without RAP. At the time, the authors suggested a similar analysis of Superpave design mixtures be performed in the future.

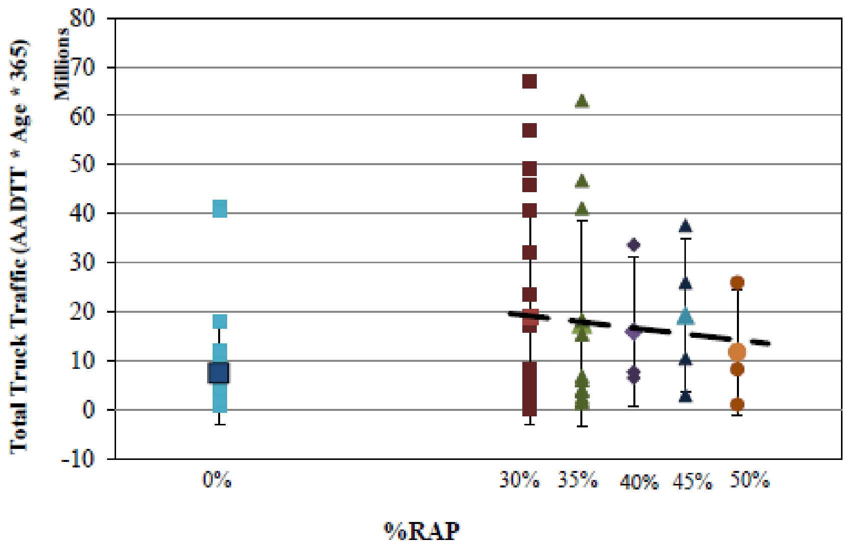

Figure 5. Pavement Performance versus Percent RAP in Intermediate Course Mixes (29).

Recently completed research focused on evaluating the effect of RAP binder stiffness and RAP gradation on cracking resistance and on determining whether the current maximum RAP usage in modified and HP mixes may be increased with or without the need for RAP characterization (30). It was determined that finer and stiffer RAP was more detrimental to cracking performance than coarser and less stiff RAP. Ultimately a proposed guideline for determining maximum RAP usage in modified mixes based on RAP gradation and stiffness characteristics was developed. It would potentially allow for up to 30 percent RAP to be used with PG 76-22 modified mixtures. The research also concluded that incorporating 20 percent RAP would compromise the cracking performance expected for HP mixes. Similar to the FDOT research in 2012, this research also indicated that in some cases, increasing RAP could lead to better performance. FDOT currently has a specification revision under review that will increase the amount of RAP allowed in mixes with PG 76-22 binder.

Summary of Positive DOT Practices

Throughout the visit, FDOT identified several practices that were important for their successful use of RAP. They included the following:

Pavement Performance and Quantifying and Communicating Recycling Benefits

1. Pavement performance with RAP has been researched. Conclusions indicate that the use of RAP has provided acceptable pavement performance.

Specifications

1. FDOT specifications are very clear on RAP use.
2. The partnership between FDOT and contractors appears to be beneficial to both.
3. FDOT specifications clearly address absorptive aggregates and have unique requirements for the two types of aggregate used in the state.
4. Other public agencies in the state use FDOT specifications, reducing work for contractors and agencies.

RAP Criteria

1. Some mix types allow no RAP, while others allow an unlimited amount of RAP. When RAP is unlimited, several producers used about 40 percent RAP, with the highest being 50 percent.
2. RAP is specified by the weight of the total aggregate. However, for mixtures with a maximum 20 percent RAP by weight of total aggregate, the contractor has the option to choose to use the amount of RAP which results in no more than 0.20 RBR.
3. The quantity of RAP allowed is based on many factors: surface vs. intermediate layers, modified vs. unmodified binders, traffic, and friction characteristics of virgin aggregates.

Rationale and Location for Using RAP

1. The quantity of RAP allowed is based on many factors: surface vs. intermediate layers, modified vs. unmodified binders, traffic, and friction characteristics of virgin aggregates.

Use of Softer Binder and Additives

1. FDOT specifies PG based on RAP usage for mixes containing neat asphalt with softer binders specified as RAP dose increases. The three RAP levels and required binder grades used are:
    a. 0-15 percent RAP: PG 67-22
    b. 16-30 percent RAP: PG 58-22
    c. Greater than 30 percent RAP: PG 52-28
2. These levels and binder grades were established based on a statewide in-house FDOT research effort. FDOT used blending charts for many years, and with the data collection over time, the levels were established, eliminating the need for FDOT and contractors to have to perform extractions and blending chart analyses for each mixture design.
3. A statewide RAP dose PG requirement for softer binder based on statewide FDOT research eliminating the need for FDOT and contractors to perform extraction and blending chart analyses for each mixture design.
4. Use of ΔT_c, a waste oil provision, and maximum allowable REOB percentage (8.0%) to control the use of REOB and other blending stocks in virgin binders that are susceptible to aging.
5. Having a full-time chemist in the asphalt binder lab.

Additional Asphalt Content and Mixture Performance Tests

1. Use of a combination of techniques to improve mix durability by increasing the amount of asphalt in mixes which include:
    a. Reducing the number of gyrations
    b. Keeping volumetric requirements including design air voids, voids in mineral aggregate (VMA), and Dust Proportion (DP) consistent with AASHTO M 323
    c. Determining RAP asphalt absorption during mix design.
2. Having research performed by others to support optimized use of RAP. This includes contracted laboratory-based University research and sponsored test sections at the National Center for Asphalt Technology (NCAT), focusing on increased RAP usage
3. Performing ongoing internal research to fundamentally understand virgin binder quality and RAP mix composition.

RAP Processing, Handling, and QC

1. RAP stockpiles can be designated as “continuous” at the contractor’s option, with the contractor occasionally adding to the stockpile while performing material property tests with each addition.
2. Stockpiles may be fractionated, but it is not required or common.
3. Before a stockpile of RAP can be used, it has to be tested, visually inspected, and approved by FDOT.
4. Millings directly from an FDOT project are also acceptable for use.

Contractor Input on Successful High RAP Use

1. FDOT does not require crushing RAP, but it is helpful to maintain good control. RAP is sorted for asphalt mix and environmental base purposes. One contractor follows the FDOT RAP testing requirements but doubles the testing frequency specified by FDOT. Gradation is measured even 500 tons and Gmm every 2500 tons. RAP is crushed to minus 3/8 inch. RAP is not fractionated.
2. Plant modifications are needed to successfully produce high RAP mixtures. Plants are flighted for appropriate heat transfer and have the ability to accurately meter baghouse fines and waste them if necessary. Plants used included a double barrel drum plant and a counterflow drum with an external mixer. Plants are equipped with two RAP cold feed bins.
3. Contractors indicated that having a full-time FDOT plant inspector is helpful.
4. The use of PWL specifications for acceptance has been important in maintaining consistency in the RAP and ensuring the approved amount of RAP is actually used.
5. The requirement that each asphalt plant has an on-site QC lab.
6. Having to control the amount of dust prevents the contractor from using more RAP in mixtures.
7. Using video cameras to monitor RAP bins during production to watch for clumping and consistent material flow is helpful.

8. Measure volumetric properties, asphalt content, and gradation during mixture production are important because the FDOT percent within limits (PWL) specification requires consistency.
9. Contractors focusing on QC, with management support for resources, are able to successfully optimize RAP use while providing FDOT with a high-quality mix and earn a bonus for the quality delivered under the FDOT PWL specification.

Alternative Uses of RAP and Research Needs

FDOT currently allows the use of RAP in asphalt mixtures, soil stabilization, and embankment. One of the contractors interviewed indicated that they made a recycled-based course material from poor quality or contaminated RAP and other materials, including crushed portland cement concrete. One also indicated that excess RAP processed to meet FDOT project specification requirements is used for agricultural applications and port facilities in thickness up to 18 inches unstabilized with heavy cranes operated on it.

Other uses of RAP that could be considered by FDOT include:

- Cold recycling techniques: cold central plant recycling (CCPR), cold in-place recycling (CIR), full-depth reclamation (FDR) techniques, and a stabilized RAP base course.
- Development of high RAP mixture design methodology for very low volume roads.

FDOT has used hot in-place recycling in the past, but the performance of the projects was not as good as other rehabilitation techniques.

Wisconsin Department of Transportation (WisDOT)

General Information on RAP Use, Materials, and Specifications

WisDOT uses approximately 2.8 million tons of asphalt mix annually, integrating about 500,000 tons of RAP. The overall average RAP used in WisDOT mixes has been approximately 18 to 21 percent in the past several years and will likely remain similar in the future (31). Over 95 percent of the 2.8 million tons of asphalt used by WisDOT contains RAP. The exception is a specialty “interlayer” mix that is fine graded with a high percentage of polymer that may not contain any recycled asphalt materials (RAM). Though allowed, it is estimated that only about 20,000 to 30,000 tons of RAS is used in WisDOT mixes annually, which is 0.7 percent statewide. When used, it is most often at 3 to 5 percent. It is important to note that some WisDOT approved mixture designs do not get used on WisDOT projects, including many that include RAS. RAS use is more common in urban areas (e.g., southeast WI) where post-consumer RAS is available. WisDOT has been using RAP for decades, though its use increased significantly when WisDOT transitioned to the Superpave mixture design method in the late 1990’s. It has been the contractor’s option to use RAM, which includes RAP and RAS. In 2011 significant specification changes were made on RBR based on research and performance observations that have been effective.

WisDOT standard specifications include seven asphalt mixtures, five dense-graded, and two stone matrix asphalt (SMA) (32). They are identified by the number associated with nominal maximum aggregate size (NMAS) as mix type shown in Table 7. The WisDOT workhorse surface course mixtures are No. 4 and No. 5, dense-graded 12.5mm and 9.5mm mixes, respectively. WisDOT also uses three traffic categories when selecting mixes for use: low traffic (LT), medium traffic (MT), and high traffic (HT). Mixture designs are developed per the WisDOT Construction and Materials Manual (CMM) Section 8-66, which refers to AASHTO M 323, Standard Specification for Superpave Volumetric Mixture Design, with some modifications (17, 33). Mixture designs are to be performed by technicians certified per the Highway Technician Certification Program (HTCP) in labs conforming to the WisDOT qualified laboratory program. Most other agencies (cities and counties) in the state specify WisDOT approved mixture designs, and WisDOT will review and approve mixture designs that may not be used on WisDOT projects. This benefits the other agencies and contractors since contractors don't have to have separate mixture designs, and agencies don't have asphalt mixture specifications and an approval process. The benefit for WisDOT is that when city and county projects tie into WisDOT facilities, all the work is done under WisDOT specifications. Mixture designs are valid for three years, and there are provisions for updating them during that period, if necessary, to account for changes in RAM materials and minor changes in feed bin percentages to account for this.

Table 7. Table 460-1 Excerpt from WisDOT Standard Specifications.

Sieve	Percent Passing Designated Sieves						
	Nominal Size						
	No.1 (37.5 mm)	**No.12 (25.0 mm)**	**No.3 (19.0 mm)**	**No.4 (12.5 mm)**	**No.5 (9.5 mm)**	**SMA No.4 (12.5 mm)**	**SMA No.5 (9.5 mm)**
50.0-mm	100						
37.5-mm	90 - 100	100					
25.0-mm	90 max	90 - 100	100				
19.0-mm	-	90 max	90 - 100	100		100	
12.5-mm	-	-	90 max	90 - 100	100	90 - 97	100
9.5-mm	-	-	-	90 max	90 - 100	58 - 80 *	90 - 100
4.75-mm	-	-	-	-	90 max	25 - 35	35 - 45
2.36-mm	15 - 41	19 - 45	23 - 49			15 - 25	18 - 28
0.60-mm *	-	-	-	-	-	18 max *	18 max *
75-µm	0 - 6.0	1.0 - 7.0	2.0 - 8.0	2.0 - 10.0	2.0 - 10.0	8.0 - 11.0 *	10.0 - 12.0 *
% Minimum VMA	11.0	12.0	13.0	14.0[1]	15.0[2]	16.0	17.0

[1] 14.5 for LT and MT mixes.
[2] 15.5 for LT and MT mixes.
*

The use of recycled materials in WisDOT mixtures is a contractor's option. Allowable RAP and RAS is specified by RBR and location in the pavement structure, as shown in Table 8 (11). Note that RAS cannot exceed 5 percent of the total weight of aggregate blend when combined with RAP. Also, that the maximum RBR in SMA mixtures is 15 percent. When used in dense-graded mixes, RAS is normally used with RAP also. Exceptions to the RBR in Table 8 will be approved if blending chart analysis or physical blending of virgin and RAM binder demonstrates that at higher RBR, the blended binder meets the specified performance grade (PG) for the project per AASHTO M332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test (22). However, WisDOT indicates that this exception is extremely rare, being exercised once or twice per construction season. RBR criteria related to traffic is not explicit in the specifications, but it is indirectly incorporated in the PG binder requirements and mixture design methods. Recycled material dose criteria related to RAP fractionation is shown in Table 8. Still, WisDOT indicates that contractors do not fractionate RAP unless they supply mix in a neighboring state that requires RAP fractionation.

Table 8. Maximum Allowable Percent Binder Replacement.

Recycled Asphaltic Material	**Location in Pavement Structure and Allowable RBR**	
	Lower Layers (RBR %)	**Upper Layers (RBR %)**
RAS if used alone	25	20
RAP and FRAP in any combination	40	25
RAS, RAP, and FRAP in combination *[1] [2]*	35	25

WisDOT specifies PG binders meeting the requirements of AASHTO M 332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test (22). Because this grading system integrates criteria specifically for traffic categories, the WisDOT specifications include criteria for different traffic categories, but it is not tied to RAM dose.

Mixture designs are performed per AASHTO M 323 and AASHTO R 35, Standard Practice for Superpave Volumetric Design for Asphalt Mixtures, with a few exceptions noted in the WisDOT standard specifications section 460 (17, 27, 32). Noted exceptions used specifically to increase the amount of virgin binder in mixes include

- Regressed design air voids – optimum asphalt content (OBC) is selected at 97 percent of Gmm rather than 96 percent of Gmm, typically leading to a 0.3 percent increase in asphalt content.
- For workhorse dense-graded surface course mixes #4 and #5 used for LT or MT Traffic Levels, the minimum voids in mineral aggregate (VMA) is increased 0.5 percent above the AASHTO M 323 criteria. See Table 9.
- The number of gyrations in AASHTO M 323 are used for design; except for the lowest traffic category (LT), they are reduced from 50 to 40, and for SMA, 65 gyrations are used. See Table 9.

The decision to regress air voids was made based on research and collaboration with industry (34). Per the WisDOT Construction and Materials Manual, the contractor must submit mixture designs that meet the VMA requirements in Table 9, and bulk specific gravity (Gsb) of virgin and RAM aggregates is used for calculating VMA. All RAM binder is assumed to be available when performing the mixture designs also.

Table 9. Table 460-2 Excerpt from WisDOT Standard Specifications.

Mixture Type	LT	MT	HT	SMA
LA Wear (AASHTO T96) 100 revolutions (max % loss) 500 revolutions (max % loss)	 13 50	 13 45	 13 45	 13 35
Soundness (AASHTO T104) (Sodium sulphate, mass % loss)	12	12	12	12
Freeze/Thaw (AASHTO T103) (specified countries, max % loss)	18	18	18	18
Fractured Faces (ASTM D5821 as modified in CMM 8-60) (one face/2 face, % by count)	65	75 / 60	98 /90	100 / 90
Flat & Elongated (ASTM D4791) (max %, by weight)	5 (5:1 ratio)	5 (5:1 ratio)	5 (5:1 ratio)	20 (3:1 ratio)
Fine Aggregate Angularity (AASHTO T304, method A, min)	40 [1]	43[1]	45	45
Sand Equivalency (AASHTO T176, min)	40	40[2]	45	50
Clay Lamps and Friable Particle in Aggregate * (AASHTO T112)	<= 1%	<= 1%	<= 1%	<= 1%
Plasticity Index of Material Added to Mix Design as Mineral Filler * (AASHTO T89/90)	<= 4	<= 4	<= 4	<= 4
Gyratory Compaction Gyrations for N_{ini} Gyrations for N_{des} Gyrations for N_{max}	 6 40 60	 7 75 115	 8 100 160	 7 65 100
Air Voids, % Va (%G_{mm} N_{des})	4.0 (96.0)	4.0 (96.0)	4.0 (96.0)	4.5 (95.5)
% G_{mm} N_{ini}	<= 91.5 [3]	<= 89.0 [3]	<= 89.0	-
% G_{mm} N_{max}	<= 98.0	<= 98.0	<= 98.0	<= 98.0
Dust to Binder Ratio [4] (% passing 0.075/Pbe)	0.6 - 1.2[5]	0.6 - 1.2[5]	0.6 - 1.2[5]	1.2 - 2.0
Voids filled with Binder (VFB or VFA, %)	68 - 80[6,8]	65 - 75[6,7,9]	65 - 75[6,7,9]	70 - 80
Tensile Strength Ratio (TSR) (AASHTO T283) [10,11] no antistripping additive with antistripping additive	 0.75 min 0.80 min	 0.75 min 0.80 min	 0.75 min 0.80 min	 0.80 min * 0.80 min
Drain down (AASHTO T305) (%)	-	-	-	<= 0.30
Minimum Effective Asphalt Content, Pbe (%)	-	-	-	5.5

[1] For No 6 (4.75 mm) nominal maximum size mixes, the specified fine aggregate angularity is 43 for LT and 45 MT mixes.
[2] For No 6 (4.75 mm) nominal maximum size mixes, the specified sand equivalency is 43 for MT mixes.
[3] The percent maximum density at initial compaction is only a guideline.
[4] For a gradation that passes below the boundaries of the caution zone (ref. AASHTO M323), the dust to binder ratio limits are 0.6 - 1.6.
[5] For No 6 (4.75 mm) nominal maximum size mixes, the specified dust to binder ratio limits are 1.0 - 2.0 for LT mixes and 1.5 - 2.0 for MT and HT mixes.
[6] For No. 6 (4.75mm) nominal maximum size mixes, the specified VFB is 67 - 79 percent for LT mixes and 66 - 77 percent for MT and HT mixes.

[7] For No. 5 (9.5mm) and No. 4 (12.5 mm) nominal maximum size mixtures, the specified VFB range is 70 – 76 percent.
[8] For No. 2 (25.0mm) nominal maximum size mixes, the specified VFB lower limit is 67 percent.
[9] For No. 1 (37.5mm) nominal maximum size mixes, the specified VFB lower limit is 67 percent.
[10] WisDOT eliminates freeze-thaw conditioning cycles from the TSR test procedure.
[11] Run TSR at asphalt content corresponding to 3.0% air void regressed design, or 4.5% air void design for SMA, using distilled water for testing.

The contractor is required to determine RAM properties, including asphalt content, gradation, and aggregate bulk specific gravity (Gsb), and provide them along with RAM samples to WisDOT for mixture designs requiring comparison level submission. RAM Gsb can be measured on aggregates obtained with an ignition furnace or solvent extraction. The mixture design process doesn't currently include performance tests though there are tensile strength ratio (TSR) requirements per AASHTO T 283 Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage (25). Design TSR requirements are 0.75 and 0.80 without and with an antistrip additive, respectively. It was noted that during the mixture design process if a TSR of less than 0.86 is observed for #4, #5, or any mix containing WMA, TSR testing of plant-produced material is performed, and a value of at least 0.80 must be observed. WisDOT reviews and approves contractor mixture designs that are good for three years.

It is very important to note that when a mixture design is reviewed, the volumetrics at 96 percent of Gmm are compared with the criteria in AASHTO M 323. After the gradation is selected at 96 percent of Gmm, the OBC is selected at 97 percent of Gmm by adding virgin asphalt to the mix. Also, in production, the lower specification limit on VMA is 0.5 percent less than the design VMA requirements shown in Table 9. Additionally, an ignition furnace correction factor must be established prior to the mix being used on a WisDOT project by the contractor. The contractor also supplies WisDOT with asphalt mix samples for establishing an ignition furnace correction factor. Importantly, during production, if an individual virgin aggregate or RAM percentage changes more than 5 percent, a new ignition furnace correction factor must be established. There is also a provision for making job mix formula (JMF) changes to account for RAM asphalt content changes. Essentially if RAM QC is performed during a season or while doing annual RAM processing, the contractor can submit RAM property changes (asphalt content and gradation) and related JMF changes, as long as the RBR in Table 8 is not exceeded. There is also language recommending that RAM stockpile samples are taken and tested when applicable.

On projects using greater than 5000 tons of mix, the contractor is required to perform QC testing at a frequency that is a function of total daily plant production, which includes asphalt content, gradation, bulk, and maximum specific gravity of mixture (Gmb and Gmm), and report percent air voids (AV) and VMA. QC and WisDOT quality verification (QV) testing frequencies are shown in Table 10. The RAM aggregate Gsb provided by the contractor as part of the mixture design submittal is used during production for calculating VMA. Mix acceptance is based on quality verification (QV) tests performed by WisDOT for Gmb, Gmm, and reported AV, VMA, and in-place density. These quality characteristics were used with PWL for over half of WisDOT's total asphalt tonnage in 2019.

WisDOT does not specify polymer type or loading; instead, it relies on AASHTO M 332 to assure polymer is present. The WisDOT specifications do not include a provision for the use of recycling agents. WMA additives may be used at the contractor's option in accordance with the manufacture's recommendations if the product is on the WisDOT approved products list (APL). Testing for approval of WMA additives on the APL is conducted by AASHTO's National Transportation Product Evaluation Program (NTPEP). If WMA is used, a "Sister Mixture Design" is submitted with a standard design, with the only change being made is mixing and compaction temperatures. If specified, a WMA mix must be produced at WMA temperatures. Chemical WMA additives may be used, at the contractor's option, as a compaction aid with mix produced at hot mix temperatures without submitting a new mixture design. For anti-strip additives, either hydrated lime or LAS are allowed. The are no ties between additive use and RAM use.

WisDOT does not currently have performance tests and criteria as part of the mixture design or acceptance process. However, it has previously had external balanced mix design (BMD) research performed, currently has external BMD research ongoing, and is performing related internal research (25, 34, 35). There is a primary interest in implementing rutting (Hamburg Wheel Track) and cracking (IDEAL-CT) tests for both mixture design and production, though the production testing would likely be at a low frequency like one test per 50,000 tons due to available resources. It is worth noting that the current research assessing IDEAL-CT includes long-term aging of test specimens and potential minimum IDEAL-CT criteria of 40. The only binder performance testing being used is MSCR. During production, binder samples are obtained from the supply line between the asphalt storage tank and drum introduction.

Table 10. Contractor QC and WisDOT QV Testing Frequencies.

Test Type	Total Daily Plant Production tons (QC) or Contract tonnage (QV)	Samples Per Day (QC) or Contract tonnage (QV)	Tests Required
QC	50 to 600	1	%AC, gradation, Gmb, Gmm, AV, VMA
	601 to 1500	2	%AC, gradation, Gmb, Gmm, AV, VMA
	1501 to 2700	3	%AC, gradation, Gmb, Gmm, AV, VMA
	2701 to 4200	4	%AC, gradation, Gmb, Gmm, AV, VMA
	Greater than 4200	Add 1 test per 1500 tons	%AC, gradation, Gmb, Gmm, AV, VMA
		1/50,000 tons	TSR[1]
QV	Less than 501	0	%AC, Gmb, Gmm, AV, VMA
	501 to 5000	1	%AC, Gmb, Gmm, AV, VMA
	Greater than 5000	Add 1 test per 5000 tons	%AC, Gmb, Gmm, AV, VMA

[1] *Conduct TSR tests during mixture production according to CMM 8-36.6.14. Test each full 50,000-ton production increment, or fraction of an increment, after the first 5000 tons of production. Perform required increment testing in the first week of production of that increment. If production TSR values are below the limit specified in CMM 8-36.6.14, notify the engineer. The engineer and contractor will jointly determine corrective action.*

Agencies are often faced with knowing if the RAP addition rate at the asphalt plant is consistent, especially with high RAP mixes. WisDOT doesn't have full-time plant inspectors or require plant production reports. It relies on several items to answer this question. They include:

- Trained inspectors visit plants, and at the completion of projects, contractors are required to submit a report of material quantities supplied.
- Contractors conduct RAM QC testing during stockpile production at their discretion.
- Provisions for RAM asphalt content, gradation, and Gsb changes based on stockpile QC and related JMF changes with updated ignition furnace correction factor determinations also during the life of a mixture design.
- Use of a PWL acceptance specification that encourages consistency and results in reward or penalty based on it.
- Virgin binder is randomly sampled every 15,000 tons of mixture and tested every per AASHTO M 332 during production.

WisDOT specifications are not prescriptive in terms of RAM QC plans, processing, fractionation, storage, the dedication of stockpiles, moisture management, or feeding at plants. Contractors can decide on these operational items that lead to the optimal use of RAM for them while meeting WisDOT specifications.

Mix durability (cracking and raveling) performance is a primary concern for WisDOT. In 2017 two significant specification changes were made by WisDOT, which included regressed design air voids and a one and a half percent increase to lower traffic level in-place density specifications. These changes were made based on external research. WisDOT has a very active research program, and many research projects related to flexible pavement, recycled materials, BMD, and performance tests have been completed or are ongoing (35). These research projects have provided the rationale for specification changes to optimize the use of recycled materials. On-going BMD research by the National Center for Asphalt Technology (NCAT) coupled with WisDOT QV and performance testing on projects using PWL to quantify quality will be used to further optimize the use of recycled materials in asphalt pavements for WisDOT.

WisDOT uses both WisDOT and AASHTO specifications and WisDOT, AASHTO and ASTM test methods. It also relies heavily on the WisDOT CMM. Those relevant to this effort include:

- WisDOT Standard Specifications, Section 460 Hot Mix Asphalt Pavement
- WisDOT CMM Section 8.
- AASHTO M 332 binder specifications.
- AASHTO M 323 mixture design specification.
- AASHTO R 35 standard practice for mixture design.
- Recommendations from WisDOT funded research reports.

The WisDOT asphalt mixture specification is reviewed regularly and was last updated in 2019 and effective with 2020 bid lettings. During the visit, some relevant planned future changes were identified that include:

- Implementation of a BMD method based on ongoing internal and external research that will include a rutting and a cracking test.
- Including the BMD performance tests on test strips and/or within the first 50,000 tons of production.

Contractor Interviews and Virtual Plant Observations

With the COVID-19 Pandemic leading to virtual site visits, it was impossible to visit contractor RAP processing and asphalt plants. During the virtual site visit, a separate virtual meeting was held with WisDOT, contractors, and Wisconsin Asphalt Pavement Association (WAPA) staff using a set of eight open-ended questions.

Key observations included:

- RAP stockpile construction is important to get consistent material with minimized segregation.
- Ample QC sampling and testing are important.
- Using two cold feed bins for feeding RAP at hot plants is a good practice since RAM percentage may be over 30 percent.
- One contractor has been using the Troxler MMS system for three years, but they are not used on all plants because of cost and the fact that technicians are on-site performing other tests and can perform conventional moisture content measurement.
- Covered stockpiles and tarps are also used to control moisture.
- Having a good understanding of the RAP and RAS properties is critical, including asphalt content, gradation, and aggregate specific gravity.
- Contractors have internal standard operating procedures (SOP) that are based on the QC requirements that were used when WisDOT high RAP pilot projects were historically performed.
- It is important to have representative RAP samples, so some contractors use full-size milling machines to obtain 300 to 400-ton mixture design samples.
- If materials are variable (e.g., mainline versus shoulder), millings may be separated into individual stockpiles.
- An important consideration is that there is adequate time for millings to be obtained and mixture designs performed.
- Having asphalt plant feed belts with equipment on them used to scalp oversize and crush it on the fly (closed-circuit system) and return it to the feed to address clumping.
- Baghouse fines are returned to the mix as often as possible.
- Almost all fine aggregates are washed to allow for high RAM use without having to reject baghouse fines.
- Return of fines and type of metering is handled differently at different asphalt plants.
- Using chemical WMA additives to assist with high RAM material flow and mix coating was reported by one contractor. Less plant wear is being observed, and the amount of maintenance (chipping and cleaning) required is reduced while improving the mix coating.
- Tight QC is required, and the WisDOT PWL acceptance specifications force maintaining consistency and tight control on feeds resulting in consistent asphalt mixtures.

Pavement Performance Observations

Pavement performance observations were not made during the virtual visit.

Summary of Positive DOT Practices

Throughout the visit, WisDOT identified several practices that were important for their successful use of RAP. They included the following:

Specifications

1. WisDOT specifications are clear and easily understood, with emphasis placed on performance rather than being very prescriptive
2. Most other agencies (cities and counties) in the state specify WisDOT approved mixture designs, and WisDOT will review and approve mixture designs that may not be used on WisDOT projects. This benefits the other agencies and contractors since they don't have to have separate mixture designs.
3. Mixture designs are to be performed by technicians certified per the Highway Technician Certification Program (HTCP) in labs conforming to the WisDOT qualified laboratory program.
4. WisDOT requires all technicians (DOT and industry) working on WisDOT projects to be certified, and the WisDOT Central Lab is AASHTO resource accredited. WisDOT Regional Labs and industry labs must conform to the WisDOT laboratory qualification requirements.
5. The partnership between WisDOT and the industry appears to be positive and beneficial to both.
6. Regularly performing ongoing internal research and research by academia to understand and optimize the use of recycled materials in the state.

RAP Criteria

1. Allowable recycled material doses are specified by RBR and include criteria for:
    a. RAS alone
    b. RAP or FRAP
    c. Combinations of RAS, RAP, and FRAP
2. RAS cannot exceed 5 percent by the total weight of aggregate.
3. Exceptions to the RBR criteria will be approved if blending chart analysis or physical blending of virgin and RAM binder demonstrates that at higher RBR, the blended binder meets the specified performance grade (PG) for the project per AASHTO M 332.

Rationale and Location for Using RAP

1. Allowable levels of recycled materials are a function of location in the pavement structure and mix type.
2. It is also indirectly a function of traffic level because AASHTO M 332 is used to specify asphalt binders

3. WisDOT standard specifications and special standard specifications 325, 327, and 330 include provisions for in-place pulverizing, partial and full-depth milling with and without active filler and stabilizers and these techniques lead to the use of RAM in cost-effective and sound engineering applications, which help balance the supply and demand of RAM in the state.

Use of Softer Binder and Additives

1. Exceptions to the RBR criteria will be approved if blending chart analysis or physical blending of virgin and RAM binder demonstrates that at higher RBR, the blended binder meets the specified performance grade (PG) for the project per AASHTO M 332.
2. Use of MSCR to control virgin binder quality and integration of polymer in virgin binders coupled with randomly sampling virgin binder and testing it per AASHTO M 332 during production.

Additional Asphalt Content and Mixture Performance Tests

1. Use of a combination of techniques to improve mix durability by increasing the amount of asphalt in mixes which include:
    a. Regressed design air voids – optimum asphalt content (OBC) is selected at 97 percent of Gmm rather than 96 percent of Gmm, typically leading to a 0.3 percent increase in asphalt content.
    b. For workhorse dense-graded surface course mixes #4 and #5 used for LT or MT Traffic Levels, the minimum voids in mineral aggregate (VMA) is increased 0.5 percent above the AASHTO M 323 criteria.
    c. Using virgin and RAM materials Gsb for calculating VMA.
    d. The number of gyrations in AASHTO M 323 are used for design; except for the lowest traffic category (LT), they are reduced from 50 to 40, and for SMA, 65 gyrations is used.
2. The decision to regress air voids was made based on research and collaboration with the industry.
3. WisDOT does not currently have performance tests and criteria as part of the mix mixture design or acceptance process. However, it has previously had external balanced mix design (BMD) research performed, currently has external BMD research ongoing, and is performing related internal research.

RAP Processing, Handling, and QC

1. WisDOT specifications are not prescriptive in terms of RAM QC plans, processing, fractionation, storage, the dedication of stockpiles, moisture management, or feeding at plants.
2. Contractors can decide on these operational items that lead to the optimal use of RAM for them while meeting WisDOT specifications.

3. Some contractors on some projects are taking conventional cold milling machines to projects and generating 300 to 400 tons of millings to use for mixture design purposes when the project schedules allow for this

Contractor Input on Successful High RAP Use

1. WisDOT does not require crushing RAP, but it is helpful to maintain good control. RAP is sorted for asphalt
2. RAP stockpile construction is important to get consistent material with minimized segregation.
3. Ample QC sampling and testing are important.
4. Using two cold feed bins for feeding RAP at hot plants is a good practice since RAM percentage may be over 30 percent.
5. One contractor has been using the Troxler MMS system for three years, but they are not used on all plants because of cost and the fact that technicians are on-site performing other tests and can perform conventional moisture content measurement.
6. Covered stockpiles and tarps are also used to control moisture.
7. Having a good understanding of the RAP and RAS properties is critical, including asphalt content, gradation, and aggregate specific gravity.
8. Contractors have internal standard operating procedures (SOP) that are based on the QC requirements that were used when WisDOT high RAP pilot projects were historically performed.
9. It is important to have representative RAP samples, so some contractors use full-size milling machines to obtain 300 to 400-ton mixture design samples.
10. If materials are variable (e.g., mainline versus shoulder), millings may be separated into individual stockpiles.
11. An important consideration is that there is adequate time for millings to be obtained and mixture designs performed.
12. Having asphalt plant feed belts with equipment on them used to scalp oversize and crush it on the fly (closed-circuit system) and return it to the feed to address clumping.
13. Baghouse fines are returned to the mix as often as possible.
14. Almost all fine aggregates are washed to allow for high RAM use without having to reject baghouse fines.
15. Return of fines and type of metering is handled differently at different asphalt plants.
16. Using chemical WMA additives to assist with high RAM material flow and mix coating was reported by one contractor. Less plant wear is being observed, and the amount of maintenance (chipping and cleaning) required is reduced while improving the mix coating.
17. Tight QC is required, and the WisDOT PWL acceptance specifications force maintaining consistency and tight control on feeds resulting in consistent asphalt mixtures.

Alternative Uses of RAP and Research Needs

WisDOT currently allows the use of RAM per WisDOT standard specifications and standard special provisions 325, 327, and 330 for in-place pulverizing, partial and full-depth milling with and without active filler and stabilizers. The use of in-place recycling techniques may be decreasing with fewer reconstruction projects in recent years. However, when used, these techniques lead to RAM use in cost-effective and sound engineering applications.

Nebraska Department of Transportation (NDOT)

General Information on RAP Use, Materials, and Specifications

The typical annual tonnage of asphalt mix used by NDOT hovers around two million tons and integrates about 800,000 tons of RAP. The overall average RAP used in NDOT mixtures has been 39 percent for the past six years and is likely to remain near this level in the short term. NDOT does not use RAS in asphalt mixes. NDOT has successfully been using high RAP for over 25 years with 50 percent RAP in shoulder mixes. However, RAP use in mainline workhorse mixes was significantly lower until 2008. With standard specification changes in 2008, including a "RAP Incentive," RAP use increased from less the 10 percent in 2007 to 27 percent in 2009 and continued to rise to 39 percent in 2013, and it has held steady from 2013 through 2019, as shown in Figure 6.

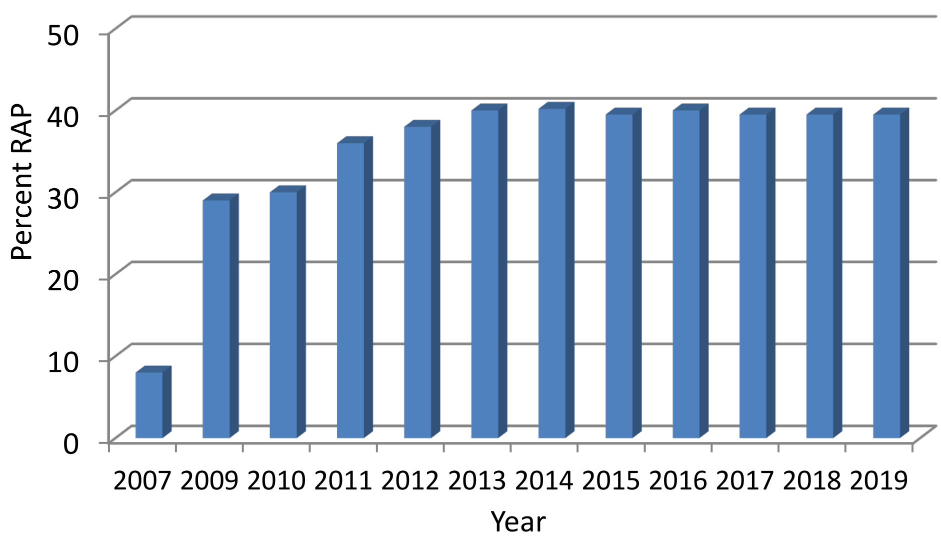

Figure 6. NDOT RAP Use Since 2008 Specification Changes.

From 2008 to 2020, approximately 9.2 million tons of aggregates have been recycled, and 498,000 tons of asphalt binder have been recycled or replaced with an estimated cost saving realized of $408 million in binder and aggregate. The average annual saving over this period has been $34 million. Prior to 2008, there were as many as 75 large RAP millings stockpiles around the state, referred to as "Mountains of Millings," and there was not adequate room to store more RAP.

NDOT has an annual goal of 33 percent overall replacement of virgin materials with post-consumer recycled materials. The goal includes all pavement materials with the primary contributions from RAP, recycled Portland cement concrete, and fly ash. NDOT communicates its goal and the success of its commitment to recycling and environmental stewardship in its NDOT

Annual Report and through Post-Consumer Labeling on plan sets (37). The annual report can be found on the NDOT website at the following URL https://dot.nebraska.gov/media/3493/annual-report.pdf. The annual report includes materials recycled, tons of raw materials used, recycle content of raw materials used, and the estimated value of the recycled materials.

NDOT staff indicated that a key driver leading to the success of its recycling efforts is NDOT Special Provision 10-7-1217, *Incentive Payment for the Use of Recycled Asphaltic Pavement (RAP) for Asphalt Mixtures* (38). This special provision provides a financial incentive to contractors to use RAP. Depending on the RAP source, saving associated with RAP is shared between NDOT and the contractor. Cost savings that go to the contractor as an incentive to use RAP range from 15 to 50 percent of the total cost saving. The use of the RAP incentive special provision coupled with the fact that NDOT pays for asphalt binder as a separate item encourages the development and production of mixtures with adequate asphalt binder. The RAP Incentive Factor is calculated per Eq. 3.

$$RAP\ Incentive\ Factor = \frac{(A-B)}{100}\ x\ C\ xD \qquad \text{Eq. 3}$$

where: *A* = State's Estimated Percent Binder Value based on mix type as shown in Table 11
B = Actual percentage of binder added to asphalt mixture
C = Unit price of binder
D = RAP Pay Factor shown in Table 12

Table 11. State's Estimated Percent Binder Values ("A" Values).

Asphaltic Mixture Type	**"A" Value**
SPH having 0.500-inch grading band	5.2% Binder
SPS, SPL, SPR and SPR (Fine)	5.2% Binder
SLX	5.5% Binder
SPH having 0.375-inch grading band	5.8% Binder
LC	6.2% Binder
SRM	4.8% Binder

Table 12. RAP Pay Factor ("D" Values).

RAP Source	**"D" Value**
State Supplied RAP coming from an ON-project source[1]	0.15
State Supplied RAP coming from an OFF-project source	0.35
Contractor Supplied RAP	0.50

[1]*RAP coming from an ON-project source shall be completely utilized before allowing RAP from any other source to be used in the asphalt production. An ON-project source shall be considered any asphaltic material removed from the project.*

NDOT staff indicate that about 95 percent of projects use milling from the project (State supplied RAP coming from an ON-project source) and that typical milling depths range from 1 to 5 inches with an average of 3 inches. It was further indicated that it is common for milling depths to be about 50 percent of the planned overlay thickness, which would produce about 50 percent RAP for a project.

Table 13 is a summary of NDOT mix types and several related parameters (39). NDOT primarily uses dense-graded mixtures with surface coarse mix nominal maximum aggregate size (NMAS) mostly being ½ or 3/8 inch. Specialty mixes, such as stone matrix asphalt (SMA) and open-graded friction course (OGFC), are not used by NDOT as aggregate must be imported to produce them.

Table 13. NDOT Mix Types and Related Parameters.

Asphaltic Concrete Type	NMAS	Ndes Gyrations	Minimum Binder Content (%, twm)	Design Air Voids	Traffic Level or Route Class	Location (surface, binder, or base course)	Allowable Percent RAP by Weight of Mix	Typical Percent RAP by Weight of Mix
SPS	¾”, ½”, 3/8” or #4	40	4.8	1.5 to 5.0	TBD	Shoulders	0 to 65	50
SPR	½”	65	5.0	3.0	TBD	Surface and Intermediate	0 to 55	50
SPH	3/8”	95	5.1	4.0	TBD	Surface Classic Superpave	0 to 35	35
SLX	3/8”	50	5.3	2.5 to 3.5	TBD	Surface (thin lift and up to 4 inches)	20 to 35	35
SRM	3/8” or ½”	65	4.5	2.5	TBD	Base	35 to 65	50 to 65

The criteria for using RAP in mixes is dependent on location in the pavement structure. Premium surface course mixes (SPH and SLX) can contain up to 35 percent RAP, and the SPR “workhorse” mixes (about 70 percent of asphalt mix used by NDOT) can contain up to 55 percent RAP, while base and shoulder mixes can contain up to 65 percent RAP. NDOT reports that most mixes produced by contractors are at 50 percent or near the maximum allowable RAP percentage, as shown in the last column of Table 13. Criteria related to traffic is not explicit in the specifications, but it is indirectly incorporated in the PG binder and mixture design method. There is not recycled material dose criteria related to RAP fractionation. RAP has to be pre-processed by *fractionating, screening, and/or crushing* prior to use to a size such that the combined hot mix meets the required gradation (39). However, it does not have to be fractionated.

The contractor performed mixture designs are developed per AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design* and AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures* (17, 27). The NDOT standard specifications include the following modifications when applying AASHTO M 323 and R 35: minor changes to aggregate coarse and fine aggregate angularity consensus property requirements, a statewide average aggregate specific gravity is used for virgin and RAP aggregates (2.585) for VMA determination that is only used for mixture design, modifications to the dust to binder ratio to 0.7 to 1.70 for all mixes except SRM which has criteria of 0.7 to 1.90, and design air void level criteria which range from 1.5 to 5.0 percent depending on mix type. Target binder content is determined by ignition furnace results. A correction factor of 0.1% will be added to the ignition furnace results for mixes containing WMA.

Mixture designs incorporate PG binders specified per AASHTO M 332, *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test Table 1,* and the grades specified in individual project contracts have to be used for the production of HMA (16). Polymer-modified binders are subject to a PG+ specification which is AASHTO M 332 with the specific MSCR percent recovery criteria shown in Table 14 and may be modified with SB, SBS, SBR, PPA, or GTR (39).

Table 14. NDOT Specific Polymer Modified Asphalt Requirements for AASHTO M 332.

AASHTO M 332 MSCR Average Percent Recovery @ 3.2kPa Requirements for Modified PG Binders	
AASHTO M 332 Performance Grade	**Test Temperature of 58ºC**
58S – 34	-
58H – 34	30 Minimum
58V – 34	55 Minimum
58E – 34	75 Minimum

The type of PG Binder will be shown in the contract, except for the following:

- SLX mixes shall be 58V-34 with 0.7 percent of an approved *WMA* additive.
- SRM mixes shall be 58H-34 with 0.9% of an approved *WMA* additive.
- All other mix types are required to have 0.7% of an approved *WMA* additive except for shoulder mixes.

It is important to note that the low temperature of the virgin binder was bumped down from a “-28” based on the climate in Nebraska to a “-34.” NDOT has also been researching using a “-40” PG binder to improve low-temperature performance with high recycled content mixtures.

NDOT has several requirements in its mixture design specifications to encourage the use of high RAP while maintaining the durability of asphalt mixtures by getting adequate virgin binder in them that include:

1. A minimum asphalt content for each mix type.
2. Reduced number of Gyrations.
3. Reduced design air voids, as low as 1.5 percent for shoulder mix, 2.5 percent for base mix, and 3.0 percent for a premium surface mix.
4. Softer polymer modified asphalt binders per a PG+ specification.
5. Asphalt binder is a separate pay item.
6. Incentive and disincentive on mainline and joint density.

Details of items 1 through 3 are shown in Table 13. A discount rate to account for black rock is not used by NDOT.

Contractors are required to have QC plans. An acceptance lot is 5000 tons. QC requirements are 1 sample per 1000 tons of production, and tests include CAA and FAA on cold feed samples; ignition asphalt content, ignition gradation, ignition CAA and FAA; compacted mix bulk specific gravity (Gmb) and theoretical maximum specific gravity (Gmm). Reported results include all of the items plus percent air voids at Ndes, VMA, and dust to binder ratio. Department verification testing is on a split of 1 sublot per lot, and verification tolerances in Table 15 and Table 16 are applied. If a tolerance is exceeded, an Independent Assurance review occurs.

Table 15. Asphaltic Concrete Testing Tolerances.

Test	Tolerance
Asphalt Content by Ignition Oven	0.5%
Gyratory Density	0.020
Maximum Specific Gravity	0.015
Bulk Dry Specific Gravity (Gsb)	0.020
FAA	0.7%
CAA	10%
Field Core Density	0.020
Air Voids	1.0%

Table 16. Blended Aggregate Gradation Testing Tolerances.

Sieve Size	Tolerance
3/4 inch (19 mm), 1/2 inch (12.5 mm), 3/8 inch (9.5 mm), No. 4 (12.5 mm), No. 8 (2.36 mm)	6%
No. 16 (1.18 mm), No. 30 (600 µm), No. 50 (300 µm)	5%
NO. 200 (75 µm)	3%

Production tolerances are presented in Table 17, and disincentives are applied if the deviation from the target value exceeds the allowable deviations in Table 17. Pay factors are assigned to air void measurements with acceptance schedules that are unique to each mix type. As an example, Table 18 is the acceptance schedule for the SPR mix type.

Table 17. Production Tolerances[1].

Test	Allowable Deviation from Specification
Dust to Asphalt Ratio	None
Coarse Aggregate Angularity	5% below Min.
Fine Aggregate Angularity for SPR, SLX and SRM	0.2% below Min. for cold feed or 0.5% below Min. for ignition oven
Fine Aggregate Angularity for all other Mixes	0.5% below Min. for cold feed or 1.0% below Min. for ignition oven
Minimum Binder Content	None

[1] These tolerances are applied to the mix design specification values, not the submitted mix design targets.

Table 18. Acceptance Schedule Air Voids – Ndes.

Air voids test results for Asphaltic Concrete Type SPR	Pay Factor	
	Moving average of four	**Single test**
Less than 0.5%	50% or Reject	50% or Reject
0.5% to 0.9%	50% or Reject	50%
1.0% to 1.4%	50% or Reject	95%
1.5% to 1.9%	90%	95%
2.0% to 2.4%	100%	100%
2.5% to 3.5%	102%	104%
3.6% to 4.0%	100%	100%
4.1% to 4.5%	95%	95%
4.6% to 5.0%	90%	95%
5.1% to 5.5%	50% or Reject	90%
5.6% to 6.0%	50% or Reject	50%
6.1% and over	50% or Reject	50% or Reject

All test results must be entered in an NDOT supplied Superpave Software (Excel spreadsheet).

The only mix performance test currently used by NDOT is the moisture sensitivity test associated with the Superpave mixture design method. However, NDOT has purchased a Hamburg Wheel Track Tester and has plans to further evaluate the semicircular bend test (SCB) with other nationally recognized performance tests. No asphalt binder performance tests are used beyond AASHTO M332 MSCR.

A project QC plan is required, but a RAP QC plan is not required. The QC plan includes lab equipment calibration and qualified technicians. The only specified RAP processing requirements are that RAP must be pre-processed by fractionating, screening, and or crushing prior to use to a size such that the combined hot mix meets the required gradation. Dedicated stockpiles are not required, and there are no requirements around RAP moisture management. NDOT staff indicated that contractors diligently monitor RAP properties, although not required by specifications because RAP is such a large proportion of asphalt mixtures. With batch plants, it is typically impossible to run more than about 25 to 35 percent RAP, so in Nebraska, contractors have transitioned to entirely all continuous flow drum plants, both parallel and counterflow to run at higher RAP contents.

Agencies are often faced with knowing if the RAP addition rate at the asphalt plant is consistent, especially with high RAP mixes. NDOT does have plant inspectors that visit plants throughout production and require plant production reports. It relies on several items to answer this question. They include:

- A 600-ton asphalt mix control strip with three mix samples is required but can be waived at the contractor's option. Testing includes air voids, asphalt content ignition, gradation, dust to binder ratio, and consensus aggregate properties.
- Plant calibration is required, and each time a portable plant is moved, it is re-calibrated.
- Use of an acceptance specification that encourages consistency by the use of incentives or disincentives on required and validated quality control testing.
- A material tracking system is implemented daily by NDOT Project Construction Technicians that involves recording asphalt tank stabs at the beginning and end of each day, binder quantities from delivery truck weight tickets, acceptance asphalt content ignition test results, and monitoring plant control outputs.
- One virgin binder sample per 200-ton binder lot is taken at the plant from the line between the storage tank and the mixer, or from the tank supplying material to the line, at a location from which material sampled is representative of the material in the line to the mixer and tested per AASHTO M 332 during production.

NDOT uses both NDOT and AASHTO specifications and AASHTO test methods. Those relevant to this effort include:

- NDOT Standard Specifications (2017), Section 501 General Requirements, Section 503 Asphalt Concrete, Section 1028 Superpave Asphaltic Material, Section 1029 Performance Graded Binder, and Section 1080 Warm Mix Asphalt.
- NDOT Special Provision 10-7-1217, Incentive Payment for the Use of Recycled Asphaltic Pavement (RAP) for Asphalt Mixtures.
- AASHTO M 332 binder specifications.
- AASHTO M 323 mixture design specification.
- AASHTO R 35 standard practice for mixture design.
- AASHTO test methods.
- Recommendations from NDOT sponsored research reports.

Contractor Interviews and Virtual Plant Observations

With the COVID-19 Pandemic leading to virtual site visits, it was impossible to visit contractor RAP processing and asphalt plants. During the virtual site visit, a virtual meeting was held with the contractor's staff with three companies using a set of eight open-ended questions. A brief summary of observations based on this activity follows. Prior to the meeting, NDOT staff took videos of two asphalt plants in the state. One was a relatively new fixed plant located in Lincoln, and the other was a typical portable plant used in the state.

Key observations included:

- Obtaining representative RAP samples for mixture design can be a challenge.
- If able to crush RAP, a more uniform product is obtained and preferred.
- If oversize is crushed rather than scalped, variability is reduced.
- A small closed-circuit crusher and screening system is very helpful.
- Flighting has to be changed sometimes on portable plants as the RAP percentage changes.
- Lengthened drums (10 feet) and use of counterflow drums have been typical, as well as adding external mixers.
- The use of variable frequency drives (VFDs) on drums to optimize performance under different RAP doses, moisture contents, and planned production rates has been helpful.
- Being able to meter baghouse dust is critical to successful production, with one downside being excess dust that has to be wasted is a challenge sometimes.

Pavement Performance Observations

Reflective cracking performance is a primary concern for NDOT regardless of whether or not the mix contains RAP. Historically, rutting had been a concern, but it no longer is with the use of high RAP mixtures. The NDOT Annual Report 2019 contains a section on Asset Management highlighting performance measures developed to monitor the condition of Nebraska's roadways, bridges, and fleet (37). Figure 7 is an excerpt from the report on the pavement condition of Nebraska highways. It is a plot of the Nebraska Serviceability Index (NSI) over time. NSI is a composite index that incorporates automated and visual inspection data with a scale of 0 to 100. An NSI rating of 70 or above is considered "Good" performance, and NDOT's goal is to have 80 to 85 percent of the highway system in the "Good" category. Figure 7 shows that 92 percent of the Interstate routes are in good condition, and 83 percent of the total highway system is in good condition. Interestingly the overall condition of the highway system has improved since the implementation of high RAP asphalt mixtures.

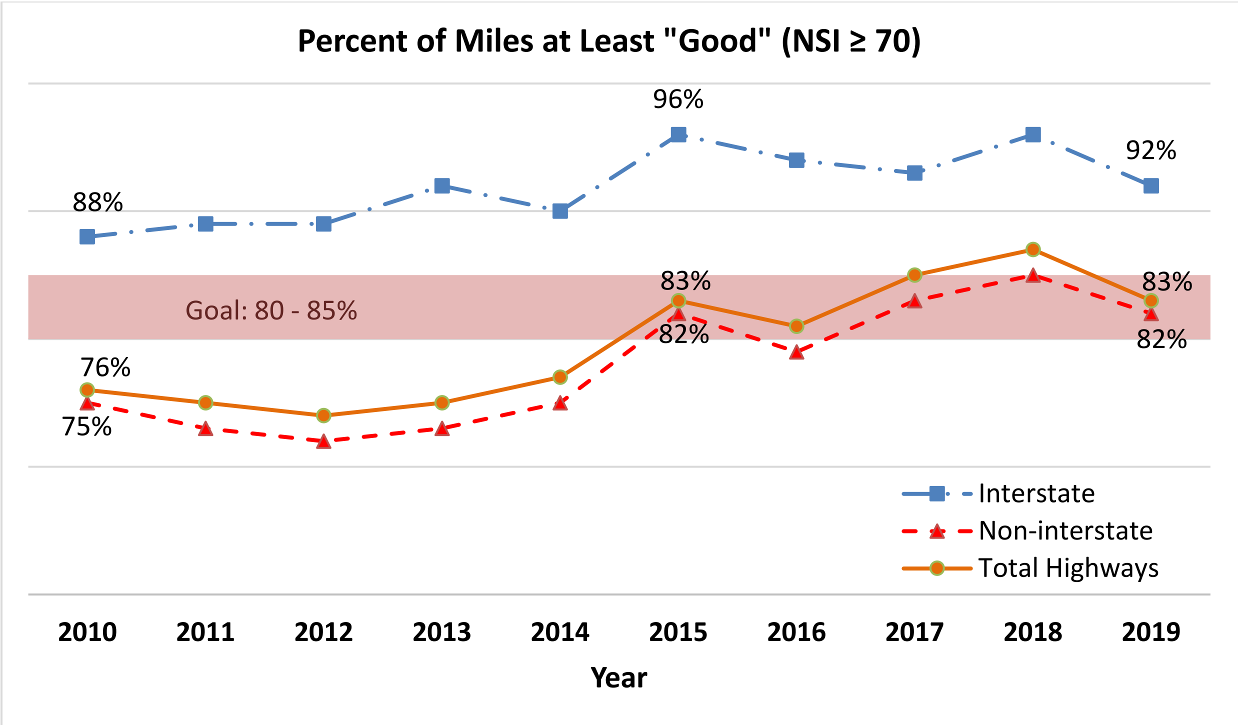

Figure 7. Nebraska Highways NSI Scores.

NDOT currently has research underway at the University of Nebraska Lincoln (UNL) comparing the performance of 5 to 10-year old pavements constructed with low and high RAP mixes, which is scheduled for completion in 2020. Ride quality (IRI), rutting, cracking, and life cycle cost analysis (LCCA) are the parameters being analyzed. The LCCA analyses are ongoing, but IRI, rutting, and cracking analyses have been completed. summaries of statistical analyses and data analyses to date given below (41).

Summary of Mann-Whitney U-Test Results

- Results showed insignificant difference when comparing the 45% RAP sections with 0% RAP sections regarding IRI, rut depth and severity.
- Cracking and severity showed statistical difference between 45% RAP and 0% RAP in northern NE sections.
- No significant difference was observed between the 40% RAP sections and 0% RAP sections.

Summary of Data Analysis

- Sections with high RAP content (up to 45%) showed no significant difference regarding IRI and rut depth when they are compared with other RAP sections.
- IRI and rutting were generally within the acceptable limits for all sections examined.
- Projects constructed with 45% RAP in northern NE reached the cracking limit (40%) and severity limit (0.4) after around 5-6 years in service.
- Projects constructed with 25-45% RAP southern NE showed satisfactory performance in both cracking and severity up to 8 years in service.
- It should be noted that data collected and analyzed are for projects with ADT<1600 and ADT<200.

NDOT staff indicated that initial findings are similar in performance and being observed for both low and high RAP pavements in terms of IRI and rutting performance. Additionally, that differences in thermal cracking performance appear may, in part to be due to differences in climate (north vs. south).

NDOT has sponsored several pavement and materials research projects at UNL. A web meeting was held with Hamzeh Haghshenas Fatmehsari of UNL, during which he shared information on past, current, and planned research relative to high RAP mixtures. The work has included asphalt binder, recycling agent, antioxidants, with binder and mixture evaluations using multiple asphalt binder and mixture test and analysis methods. The work with antioxidants is particularly promising as it has shown that plant-based recycling agents and antioxidants can significantly reduce the aging susceptibility of asphalt binder (42). The goal of the research is to allow for the design of good performing asphalt mixtures containing up to 65 percent RAP. In addition to the laboratory work described, a full-scale field test containing 52 percent RAP, a recycling agent, an antioxidant, and an antistrip additive was constructed in 2019. Additional laboratory work is in progress, and a larger-scale effort is in the planning phase. Additional work is being done analyzing the long-term aging performance of binder and mixtures.

Summary of Positive DOT Practices

Throughout the visit, NDOT identified several practices that were important for their successful use of RAP. They included the following:

Pavement Performance and Quantifying and Communicating Recycling Benefits

1. The NDOT Annual Report 2019 contains a section on Asset Management highlighting performance measures developed to monitor the condition of Nebraska’s roadways, bridges, and fleet (37). The latest report indicated that 92 percent of the Interstate routes are in good condition, and 83 percent of the total highway system is in good condition. Interesting, the overall condition of the highway system has improved since the implementation of high RAP asphalt mixtures
2. NDOT publicly communicates the success of its recycling goals in an NDOT Annual Report.

3. Post-consumer labeling content is included in project plan sets, and quantities have been reported with cost savings in the NDOT Annual Report since 2014. These efforts illustrate NDOT's commitment to recycling and environmental stewardship.
4. The estimated dollar value of the post-consumer recycled content is also reported on the labeling.
5. From 2008 to 2020, approximately 9.2 million tons of aggregates have been recycled, and 498,000 tons of asphalt binder have been recycled or replaced with an estimated cost saving realized of $408 million in binder and aggregate. The average annual saving over this period has been $34 million

Specifications

1. NDOT staff indicate that a key driver leading to the success of its recycling efforts is NDOT Special Provision 10-7-1217, Incentive Payment for the Use of Recycled Asphaltic Pavement (RAP) for Asphalt Mixtures (38). This special provision provides a financial incentive to contractors to use RAP. Cost savings that go to the contractor as an incentive to use RAP range from 15 to 50 percent of the total cost saving.
2. NDOT pays for asphalt binder as a separate item which encourages the development and production of mixtures with adequate asphalt binder.
3. All asphalt plants be equipped with systems to meter the return of baghouse fines to the mix.
4. Cold feed bins have vibratory screening units for removing oversize material from both virgin and RAP material.
5. Plants shall be equipped with a system that provides a continuous electronic readout and collection of all setting data, and it is made available to the Engineer.
6. QC plans are required, along with laboratory equipment calibration and technician qualifications.
7. Other public agencies in the state use NDOT specifications, reducing work for contractors and agencies.
8. The partnership between NDOT and the industry appears to be positive and beneficial to both.

RAP Criteria

1. Allowable RAP dosage is specified as percent RAP by weight of mix. The average RAP use has been 39 percent since 2013.

Rationale and Location for Using RAP

1. Allowable RAP percentage is a function of location in the pavement structure and mix type.
2. Criteria related to traffic is not explicit in the specifications, but it is indirectly incorporated in the PG binder and mixture design method.

Use of Softer Binder and Additives

1. PG binders specified per AASHTO M 332 with PG58(S, H, V, or E)-34 used with NDOT specific MSCR percent recovery criteria
2. The low temperature of the virgin binder was bumped down from a "-28" based on the climate in Nebraska to a "-34." NDOT has also been researching using a "-40" PG binder to improve low-temperature performance with high recycled content mixtures.
3. All mixtures have to incorporate a minimum WMA additive dose of 0.7 to 0.9 percent, except shoulder mixes.

Additional Asphalt Content and Mixture Performance Tests

1. NDOT has several requirements in its mixture design specifications to encourage the use of high RAP while improving the durability of asphalt mixtures that include:
    a. A minimum asphalt content for each mix type.
    b. Reduced number of Gyrations.
    c. Reduced design air voids, as low as 1.5 percent for shoulder mix, 2.5 percent for base mix, and 3.0 percent for a premium surface mix.
    d. Softer polymer modified asphalt binders per a PG+ specification.
    e. Asphalt binder is a separate pay item.
    f. Incentive and disincentive on mainline and joint density.
2. Regularly performing ongoing internal research and research by academia to understand and optimize the use of recycled materials in the state.
3. Methodically evaluating pavement performance over time to assess the impact of RAP on mix durability.

RAP Processing, Handling, and QC

1. NDOT specifications are not prescriptive in terms of RAP QC plans, processing, or fractionation.
2. A project QC plan is required, but a RAP QC plan is not required.
3. RAP has to be pre-processed by fractionating, screening, and/or crushing prior to use to a size such that the combined hot mix meets the required gradation.
4. Dedicated stockpiles are not required, and there are no requirements around RAP moisture management.
5. NDOT staff indicated that contractors diligently monitor RAP properties, although not required by specifications because RAP is such a large proportion of asphalt mixtures.

Contractor Input on Successful High RAP Use

1. If able to crush RAP, a more uniform product is obtained and preferred.
2. If oversize is crushed rather than scalped, variability is reduced.
3. A small closed-circuit crusher and screening system is very helpful.
4. Flighting has to be changed sometimes on portable plants as the RAP percentage changes.
5. Lengthened drums (10 feet) and use of counterflow drums have been typical, as well as adding external mixers.

6. The use of variable frequency drives (VFDs) on drums to optimize performance under different RAP doses, moisture contents, and planned production rates has been helpful.
7. Being able to meter baghouse dust is critical to successful production, with one downside being excess dust that has to be wasted is a challenge sometimes.

Alternative Uses of RAP and Research Needs

The primary use of RAP in Nebraska is in asphalt mixture, and this is strongly encouraged by NDOT specifications. The primary alternative use of RAP is for bituminous base course material for the reconstruction of asphalt and portland cement concrete pavements. Since transitioning to a high RAP asphalt mix specification, the use of cold in-place recycling (CIR) and full-depth reclamation (FDR) has decreased significantly. NDOT maintenance forces also use portable small batch asphalt recycling machines with binder pods containing a plant-based recycling agent to produce 100 percent recycled high-performance hot mix patch material that includes millings, binder, and special additives. The new binder pods resulted from the department's efforts to find a cost-effective way to produce high-performance hot mix patch material year-round.

New Jersey Department of Transportation (NJDOT)

General Information on RAP Use, Materials, and Specifications

Estimates of the NJDOT annual asphalt mixture use, percent of mix tons with RAP, and approximate tons of RAP used per year are summarized in Table 19 for 2015-2019.

Table 19. Estimated NJDOT Tonnage and RAP Use by Year.

Year	2015	2016	2017	2018	2019
Tons of asphalt mixture	1,600,000	2,900,000	1,300,000	1,600,000	1,800,000
Average percent in asphalt mixture	14.8	14.0	10.7	10.3	11.5
Tons of RAP	237,000	402,000	135,000	165,000	206,000

RAP is primarily allowed in dense-graded mixtures. NJDOT has implemented a High RAP mixture specification that integrates performance tests in a balanced mixture design approach. The specification calls for minimum percentages of RAP, as shown in Table 20 (43). Some small amounts of other recycled materials are allowed in some NJDOT mix types also. The materials include Ground Bituminous Post-Manufacturer Shingle Material (GBSM), Remediated Petroleum Contaminated Soil Aggregate (RPCSA), or Crushed Recycled Container Glass (CRCG). The allowable amounts of recycled materials in mix types are summarized in Table 20 (43).

Table 20. Comparison of Standard and High RAP Mix Types and Related Properties.

Properties	Mix Type					
	Standard Mix Types (902.02.02)			High RAP Mix Type (902.13.02)		
Location	Surface	Intermediate	Base	Surface	Intermediate	Base
RAP (%)	0-15	0-25	0-25	≥20	≥30	≥30
Other RAM (%)	0	0-10	0-10	0	0-10	0-10
Total RAM%	0-15	0-35	0-35	≥20	≥30	≥30
Binders	PG64-22, Engineer may Direct Softer Grade			As required to meet Performance Tests		
Performance Tests	N/A			APA and Tx Overlay		

Recycled materials are not allowed in specialty mixtures, including OGFC, Modified OGFC, Ultra-Thin HMA, SMA, AR-OGFC, HPTO, BRIC, BRBC, and AR-GG, except AR-GG may contain up to 10 percent RAP in intermediate layers. This is one reason for the reduction in the percentage of asphalt mix tons with RAP in the past five years because the use of specialty mixes has increased (1). Another reason is that NJDOT is generating less RAP because it embraces more pavement preservation treatments that create little or no RAP that are providing performance equal to or better than milling and resurfacing with HMA containing RAP. Examples include:

- 1” HPTO = no milling and longer life than mill 2” pave 2” with HMA including % RAP.
- Mill X Pave X with SMA = longer life (2x!) than mill X Pave X with HMA including % RAP.
- Mill 3” Pave 3” with 2” SMA+1” BRIC = longer life than mill 3” Pave 3” with HMA including % RAP.
- Slurry seal/chip seal/micro-surfacing/cape seal/UTFC = no milling and equal life of mill 2” pave 2” with HMA including % RAP.

NJDOT has been using RAP since 1977, starting with 50 percent RAP in shoulder mix at that time. In the mid-1980’s, 10 percent was allowed in surface mixes, and 15 percent was allowed in intermediate and base mixes. In the late 2000’s, at the urging of the asphalt industry, a series of 25 percent surface mix projects were constructed, and their performance was poor, holding the allowable RAP down at 15 percent. This led to developing a High RAP mixture design method and specifications, with the first project built to them in 2012, which has performed well. The use of High RAP mixes is a contractor option, though the use of them has been limited to date with one primary user in the central region of the state. The limited use is likely market-driven with the relatively low cost of virgin binder today, coupled with a lack of experience and perceived risk of failing performance test requirements during production.

RAP is specified by the total weight of the mixture. RBR is not used, and there are aggregate property requirements in the standard specifications for RAP (43). The criteria for RAP dose include the location of the mix in the pavement structure, as shown in Table 20. RAP fractionation is not required, and the allowable amount of RAP is not related to fractionation, although some contractors do fractionate RAP. RAP must be processed through a screening and crushing operations to ensure that it is 100 percent passing the maximum aggregate size for the mixture.

NJDOT has implemented a High RAP mixture specification that integrates performance tests in a balanced mixture design approach. High RAP mixture designs are generally performed in accordance with AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design,* and AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures*, with a few exceptions (17, 27). Table 21 is an excerpt from the NJDOT High RAP specifications showing gradation, gyratory compaction effort, and volumetric requirements.

Exceptions to AASHTO M 323 and R 35 that are specifically targeted on increasing the amount of virgin binder to improve durability and prevent rutting include:

1. Reduced N_{des} gyrations.
2. Minimum VMA requirement in mixture design and during production that is 1.0 percent higher than the AASHTO M 323 requirements.
3. No change in dust proportion (DP) criteria in production from AASHTO M 323.
4. Maximum allowable aggregate absorption.
5. Required rutting and cracking performance tests.
6. Moisture susceptibility is evaluated during mixture design also.

Table 21. Excerpt for NJDOT High RAP Specification

Sieve Size	**Nominal Maximum Aggregate Size - Control Point (Percent Passing)**											
	37.5 mm		**25 mm**		**19 mm**		**12.5 mm**		**9.5 mm**		**4.75 mm**	
	Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
2"	100	-	-	-	-	-	-	-	-	-	-	-
1 - 1/2"	90	100	100	-	-	-	-	-	-	-	-	-
1"	-	90	90	100	100	-	-	-	-	-	-	-
3/4"	-	-	-	90	90	100	100	-	-	-	-	-
1/2"	-	-	-	-	-	90	90	100	100	-	100	-
3/8"	-	-	-	-	-	-	-	90	90	100	95	100
No. 4	-	-	-	-	-	-	-	-	-	90	90	100
No. 8	15	41	19	45	23	49	28	58	32	67	-	-
No. 16	-	-	-	-	-	-	-	-	-	-	30	60
No. 200	0	6	1	7	2	8	2	10	2	10	6	12

Compaction Level	**ESAL's (millions)**	**N_{des}**	**N_{max}**
L	< 0.3	50	75
M	≥ 0.3	75	115

1. Design ESALs (Equivalent (80 kN) Single-Axle Loads) refer to the anticipated traffic level expected on the design lane over a 20- year period.

Compaction Levels	**Required Density (% of Theoretical Max. Specific Gravity)**		**Voids in Mineral Aggregate (VMA)[2], % (minimum)**					**Voids Filled with Asphalt (VFA) %**	**Dust-to-Binder Ratio**
			Nominal Max. Aggregate Size, mm						
	N_{des}[1]	**N_{max}**	**25.0**	**19.0**	**12.5**	**9.5**	**4.75**		
L	96.0	≤ 98.0	13.0	14.0	15.0	16.0	17.0	70 - 85	0.6 - 1.2
M	96.0	≤ 98.0	13.0	14.0	15.0	16.0	17.0	65 - 85	0.6 - 1.2

The rutting performance test is AASHTO T 340, *Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)*" and the cracking performance test is NJDOT B-10, *Overlay test for Determining Crack Resistance of HMA* (44, 45). AASHTO T 283, *"Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage"* (25).

Virgin aggregate bulk dry specific gravities are measured. RAP aggregate specific gravities are assumed to be equal to the virgin aggregate specific gravities when calculating VMA. A "discount rate" is not used to add additional asphalt binder.

For High RAP mixtures, virgin binder grade is not specified, and the contractor selects a grade that provides the required rutting and cracking performance. It can be a softer grade than would be required based on the climate, and recycling agents, polymers, WMA additives, and anti-strip additives can be used. Binder performance tests like ΔTc are not used. AASHTO M 320, "*Standard Specification for Performance-Graded Asphalt Binder,"* and AASHTO M 332, *"Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test,"* are both used for binder testing when performed during mixture design and production (21, 22). Blending charts are not used. High RAP mixture designs must be submitted 45 days prior to planned production.

As previously mentioned, mixture performance test requirements are imposed during mix, startup (test strip), and during production. Table 22 is an excerpt from the NJDOT High RAP specification showing performance test requirements. All performance test specimens are conditioned with short-term oven aging (STOA) per AASHTO R 30, *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)* (46). It is important to note the:

1. Rutting and cracking performance test criteria in Table 22 were established based on virgin mixtures, so High RAP mixtures must provide similar performance to virgin mixtures
2. Samples are conditioned at test temperature for a minimum of 2 hours.
3. Performance test requirements apply during mixture design, test strip construction, and production.

Table 22. NJDOT High RAP Specification Excerpt Showing Performance Test Criteria

Test	**Requirement**			
	Surface Course		**Intermediate and base Coarse**	
	PG 64 - 22	**PG 64E - 22**	**PG 64 - 22**	**PG 64E - 22**
APA @ 8,000 loading cycles (AASHTO T340)	≤ 7 mm	≤ 4 mm	≤ 7 mm	≤ 4 mm
Overlay Tester (NJDOT B - 10)	≥ 200 cycles	≥ 275 cycles	≥ 100 cycles	≥ 150 cycles

There are volumetric controls used in production, which are summarized in Table 23. The contractor must perform QC per a QC plan to monitor and control mix composition. Acceptance is based on performance test results with the criteria and related payment schedule in Table 24.

A lot is defined as 3500 tons of mix, and there are five 700-ton sublots per lot. All performance testing is performed by NJDOT.

Table 23. NJDOT High RAP Specification Excerpt Showing Volumetric Control Criteria.

Compaction Levels	Required Density (% of Theoretical Max. Specific Gravity) @N_{des}[1]	Voids in Mineral Aggregate (VMA), % (minimum)					Dust-to-Binder Ratio
		Nominal Max. Aggregate Size, mm					
		25.0	**19.0**	**12.5**	**9.5**	**4.75**	
L, M	95.0 - 98.5	13.0	14.0	15.0	16.0	17.0	0.6 - 1.3

1. As determined from the values for the maximum specific gravity of the mix and the bulk specific gravity of the compacted mixture. Maximum specific gravity of the mix is determined according to AASHTO T 209. Bulk specific gravity of the compacted mixture is determined according to AASHTO T 166.

A couple of safeguards used during production include virgin binder is sampled from the asphalt plant facility during production each lot to assure that it has properties similar to the virgin binder used in the mixture design based on a set of tolerances. Additionally, a tester/inspector is on-site during production, and plant production reports showing mix composition are generated for NJDOT by the contractor every 15-30 minutes.

Table 24. NJDOT High RAP Specification Excerpt Showing High RAP Pay Adjustment Criteria.

Test	Surface Course		PPA
	PG 64 - 22	**PG 64E - 22**	
APA @ 8,000 loading cycles, mm (AASHTO T 340)	t ≥ 7	t ≤ 4	0
	7 < t ≤ 10	4 < t ≤ 7	PG 64 - 22: - 50(t-7)/3 PG 64E - 22: - 50(t-4)/3
	t > 10	t > 7	-100 or Remove & Replace
Overlay Tester, cycles (NJDOT B - 10)	t ≥ 200	t ≥ 275	0
	200 > t ≥ 150	275 > t ≥ 200	Surface PG 64 - 22: -(200-t) Surface PG 64E - 22: -(275-t)/1.5
	t < 150	t < 200	-100 or Remove & Replace
Test	**Intermediate and Base Course**		**PPA**
	PG 64 - 22	**PG 64E - 22**	
APA @ 8,000 loading cycles, mm (AASHTO T 340)	t ≥ 7	t ≤ 4	0
	7 < t ≤ 10	4 < t ≤ 7	PG 64 - 22: -50(t-7)/3 PG 64E - 22: - 50(t-4)/3
	t > 10	t > 7	-100 or Remove & Replace
Overlay Tester, cycles (NJDOT B - 10)	t ≥ 100	t ≥ 150	0
	100 > t ≥ 75	150 > t ≥ 110	Intermediate PG 64 - 22: -(2t-200) Intermediate PG 64E - 22: -1.25(150-t)
	t < 75	t < 110	-100 or Remove & Replace

NJDOT relies on several documents/standards for its High RAP specification. They include:

- New Jersey Public Law 2017, CHAPTER 325, approved January 16, 2018.

- NJDEP Recycled Asphalt Pavement (RAP) Reuse Guidance, Version 2.0, October 2018.
- NJDOT Bureau of Research Technical Brief FHWA-NJ-2017-008, May 2017.
- NJDOT standard specifications.
- NJDOT B-10 test method.
- AASHTO M 323 mixture design specification.
- AASHTO R 35 standard practice for mixture design
- AASHTO M 320 and M 332 binder specifications.
- AASHTO test methods.
- Recommendations from NJDOT funded research reports.

NJDOT has relied on research recommendations in developing and refining its High RAP specifications. This has formed a rational basis for the specifications and criteria in them. References 47, 48, and 49 are examples of the research efforts.

Contractor Interviews and Virtual Plant Observations

Contractor interviews or virtual plant observations were not performed.

Pavement Performance Observations

Pavement performance observations were not made.

Summary of Positive DOT Practices

Throughout the visit, NJDOT identified several practices that were important for their successful use of RAP. They included the following:

Specifications

1. There is policy and guidance on the use of RAP in New Jersey that includes:
    a. State Statute P.L. Chapter 325,
    b. New Jersey Department of Environmental Protection (NJDEP) Guidelines,
    c. An NJDOT Bureau of Materials Technical Brief, and
    d. An NJDOT High RAP Specification
2. The NJDOT High RAP specification includes rutting and cracking performance tests in a balanced mix design approach during mixture design, at project start-up, and during production for acceptance which had led to good initial pavement performance.
3. The rutting and cracking performance test criteria were established based on virgin mixtures, so High RAP mixtures must provide similar performance to virgin mixtures.
4. For High RAP mixes, a test strip must be completed 14 days in advance of planned production to allow for mix verification, including rutting and cracking performance tests before production begins.
5. The partnership between NJDOT and contractors appears to be beneficial to both.

RAP Criteria

1. RAP is specified by the total weight of the mixture.

2. For most dense-graded mixtures, there is not a maximum percent RAP specified.
3. There are minimum RAP requirements of 20 to 30 percent.
4. Some small amounts of other recycled materials (shingles, glass, and remediated soils) are allowed in some NJDOT mix types.
5. NJDOT is generating less RAP because it embraces more pavement preservation treatments that create little or no RAP that are providing performance equal to or better than milling and resurfacing with HMA containing RAP.
6. Recycled materials are generally not allowed in specialty mixtures.

Rationale and Location for Using RAP

1. Allowable RAP percentage is a function of location in the pavement structure and mix type.

Use of Softer Binder and Additives

1. PG binder grades are not specified with high RAP mixtures, and the contractor selects a grade that provides the required rutting and cracking performance.
2. Contractor-selected virgin binders can be a softer grade than would be required based on the climate, and recycling agents, polymers, WMA additives, and anti-strip additives can be used.
3. AASHTO M 320 and AASHTO M 332 are both used for binder testing when performed during mix mixture design and production. Acceptance requirements include sampling and testing of the virgin binder during the production of each lot to assure that it has properties similar to the virgin binder used in the mixture design based on a set of tolerances.

Additional Asphalt Content and Mixture Performance Tests

1. Exceptions to AASHTO M 323 and R 35 that are specifically targeted on increasing the amount of virgin binder to improve durability and prevent rutting include:
    a. Reduced Ndes gyrations.
    b. Minimum VMA requirement in mixture design and during production that is 1.0 percent higher than the AASHTO M 323 requirements.
    c. No change in dust proportion (DP) criteria in production from AASHTO M 323.
    d. Maximum allowable aggregate absorption.
    e. Required rutting and cracking performance tests.
    f. Moisture susceptibility is evaluated during mixture design also.
2. Having research performed by others to support optimized use of RAP.

RAP Processing, Handling, and QC

1. There is a contractor QC plan requirement with RAP included in it, as well as QC technicians must hold certifications

2. RAP fractionation is not required, and allowable RAP percentage is not related to fractionation, although some contractors fractionate RAP.
3. RAP must be processed through a screening and crushing operations to ensure that it is 100 percent passing the maximum aggregate size for the mixture.

Alternative Uses of RAP and Research Needs

NJDOT currently allows the use of RAP in asphalt mixtures and in a 50/50 aggregate/RAP blend for the base course. Additionally, RAP millings may be used in the lower portion of I-14 soil aggregates. NJDOT has had limited but positive experiences using RAP for cold in-place recycling (CIR) and full-depth reclamation (FDR) with cement. CIR and FDR with foamed asphalt and emulsified asphalt were identified by NJDOT as techniques that could be used more frequently in the future.

Washington State Department of Transportation (WSDOT)

General Information on RAP Use, Materials, and Specifications

In 2020 WSDOT planned to use approximately 800,000 tons of asphalt mix, integrating about 200,000 tons of RAP. The planned tonnage is down slightly from previous years. The overall average RAP used in WSDOT mixtures is approximately 20 percent and will likely remain constant (1). Although the average RAP use is 20 percent some high RAP mixture contains up to 40 percent. Though allowed, very little RAS is used in WSDOT mixes, with only 0.2 percent being used only in western Washington. WSDOT has successfully been using RAP since the mid-1980's. It has been the contractor's option to use zero to 20 percent RAP in dense-graded mixes without the need to adjust binder properties or limit RAP to meet project-specific PG requirements. In 2008, WSDOT specifications were revised to allow up to 40 percent recycled binder in mixes, with no more than 20 percent of it being from RAS. WSDOT primarily uses dense-graded mixtures with surface coarse mix nominal maximum aggregate size (NMAS) being ½ or 3/8 inch. Specialty mixes, such as stone matrix asphalt (SMA), are not permitted to be produced with RAP; however, this type of mix is rarely used.

Typical WSDOT mixes are accepted based on statistical evaluation and referred to as "Low RAP/No RAS or High RAP/Any RAS HMA." WSDOT also using visual evaluation for "Commercial HMA" (50). This review was limited to Statistical mixes since they represent the bulk of materials used on WSDOT pavements. Washington is blessed with very good-quality aggregates consisting of basalt and gravel sources. Mixture designs are developed per the WSDOT standard operating procedure WSDOT SOP 732, *Volumetric Design for Hot-Mix Asphalt (HMA)"* (51). The WSDOT SOP 732 mixture design requirements are essentially per AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design,* with minor modifications to aggregate requirements and the addition of the Hamburg Wheel Track (HWT) and indirect tensile strength (IDT) index-based performance tests (52, 53). The WSDOT standard specifications were developed with input from the Washington State Chapter of the American Public Works Association (APWA), making it possible for WSDOT approved mixture designs to be used by some other public agencies. Contractors develop mixture designs and submit materials to WSDOT for mixture design evaluation and approval. Once a mixture design is approved by WSDOT, it goes on the WSDOT qualified products list (QPL). An approved mixture design is valid for one year and can be extended to two years. Having all approved mixture designs publicly posted on the WSDOT QPL creates transparency and efficiency for WSDOT, contractors, and other public agencies.

WSDOT uses a mixture design classification system based on RAP/RAS content, as shown in Table 17 (51). It then actually controls the maximum amount of RAP and/or RAS in the mixture by RBR, as shown in Table 26. The percent RAP in Table 25 may be exceeded as long the RBR in Table 26 is not exceeded.

Table 25. WSDOT Mixture Design Classification Based on RAP and RAS Content.

RAP / RAS Classification	**RAP / RAS Content (% by total weight of HMA)**
Low RAP / No RAS	0% ≤ RAP% ≤ 20% and RAS% = 0%
High RAP/Any RAS	20% < RAP% ≤ Maximum Allowable RAP[1] and/or 0% < RAS% ≤ Maximum Allowable RAS[1]

[1]See Table 26 limits on the maximum amount RAP and/or RAS.

Table 26. WSDOT Maximum Amount of RAP and/or RAS in HMA.

RAP (% by the ratio of the weight of binder from RAP to total weight of binder in the mix)	**RAS (% by the ratio of the weight of binder from RAS to total weight of binder in the mix)**
40% minus contribution of binder from RAS	20%

The criteria for using recycled materials is the same for all dense-graded mixes regardless of location in the pavement structure. As previously mentioned, RAP and RAS are not allowed SMA. Criteria related to traffic is not explicit in the specifications, but it is indirectly incorporated in the PG binder and mixture design methods. There are no recycled material dose criteria related to RAP fractionation either. WSDOT does not require RAP fractionation.

PG binder meeting the requirements of AASHTO M 332, *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Recovery (MSCR) Test,* Table 1 in the grades specified in the Contract has to be used for the production of HMA (22). For HMA with greater than 20 percent RAP by total weight of HMA or any amount of RAS, the new asphalt binder, recycling agent, and recovered asphalt (RAP and/or RAS) when blended in the proportions of the mixture design have to meet the PG asphalt binder requirements of AASHTO M 332 Table 1 for the grade of asphalt binder specified by the Contract. In addition to AASHTO M 332 Table 1 specification requirements, PG asphalt binders also have to meet the requirements in Table 27. However, they do not have to meet RTFO Jnr_{diff} nor the PAV direct tension specifications in AASHTO M 332. WSDOT typically specifies PG H and V grades. All binder used in eastern Washington is polymer modified, and about 25 percent of binder used in western Washington is polymer modified.

Table 27. WSDOT Additional Requirements to AASHTO M332 Table 1.

Property	**Test Method**	**PG58S-22**	**PG58H-22**	**PG58V-22**	**PG64S-28**	**PG64H-28**	**PG64V-28**
RTFO Residue: Average percent recovery at 3.2kPa	AASHTO T350	n/a	n/a	30% min	20% min	25% min	30% min

Mixture designs are performed per the WSDOT standard operating procedure WSDOT SOP 732, which is similar to AASHTO M 323 and AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures*, with a few exceptions (51, 17, 27). The one exception that is specifically targeted on increasing the amount of virgin binder is the number of gyrations used by WSDOT is lower than those in AASHTO M 323.

WSDOT only uses three levels of gyrations as shown in Table 28 and design air voids of 96 percent of G_{mm}. The design number of gyrations is 100 for mixes expected to experience greater than or equal to 3 million ESALs. Note that the table also includes index-based performance test criteria.

Other volumetric requirements, including design air voids, voids in mineral aggregate (VMA), and Dust Proportion (DP), are consistent with the AASHTO M323, except the DP criteria is 0.6 to 1.6 according to AASHTO M 323 Note 7. The contractor must submit a mixture design that meets the VMA requirements in AASHTO M 323. In 2021, WSDOT's verification of the mixture design allows 0.5 percent lower VMA. VMA will be used as a pay factor, with the lower limit being 0.5 percent lower than the AASHTO M 323 requirement. All RAP binder is assumed to be available. The mixture design process consists of the contractor performing a mixture design and WSDOT evaluating and approving or rejecting the mixture design. The WSDOT evaluation is essentially performing a complete mixture design per AASHTO M 323 with the addition of index-based performance tests. The *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures,* AASHTO T 324 is used to evaluate rutting and moisture susceptibility, while the *Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures*, ASTM D6931 is used for cracking evaluation per the criteria shown in Table 28 (52, 53).

Table 28. WSDOT Mixture Design Gyrations and Performance Test Requirements Based on Traffic Level.

Design ESALs (millions)	N_{ini} gyrations	N_{des} gyrations	N_{max} gyrations	HWT number of passes with no stripping and maximum rut depth of 10mm	Indirect tensile strength max. (psi)
Less than 0.3	6	50	75	10,000	175
0.3 to less than 3.0	7	75	115	12,500	175
Greater than 3.0	8	100	160	15,000	175

For high RAP/Any RAS mixes, WSDOT requires that the contractor determine RAP properties, including asphalt content, gradation, aggregate bulk specific gravity (Gsb), and provide RAP and recovered RAP and RAS asphalt binder to WSDOT as part of the mix evaluation and approval process. RAP Gsb is obtained by contractors using an ignition furnace or solvent extraction. The contractor also provides virgin aggregates. WSDOT obtains the recycling agent (if used) from the supplier, then physically blends the virgin binder, RAP binder, and recycling agent to verify the specified grade is met. WSDOT and contractor determined Gsb values are currently compared during the mixture design evaluation process.
Mix acceptance is based on binder content, gradation, air voids, VMA, and in-place density. These quality characteristics are used with percent within limits (PWL). VMA was included in the past and removed but was added back in the 2018 specification update. WSDOT will physically test the virgin aggregate Gsb during production. In addition to using the RAP aggregate Gsb provided by the contractor as part of the mixture design evaluation process, it is used during production also.

For High RAP/Any RAS mixes, WSDOT requires a 600 to 1000-ton test section to be constructed prior to starting full production. The mix in the test section is evaluated over 4 days considering asphalt content, gradation, laboratory air voids, VMA, HWT, and IDT. HWT and IDT are pass/fail properties. If either one fails, the mix is rejected.

Some agencies use grade bumping down based on percent recycled materials, while others might use blending charts. WSDOT uses a more rigorous process of requiring physical blending the testing of virgin binder, RAP and RAS, if used, binder, and recycling agent if used coupled with AASHTO M 332 requirements. Recycling agents are not required to be on the WSDOT QPL. They can be evaluated and approved as just described. When used, recycling agents must be added to the virgin binder prior to being delivered to the contractor's plant. WSDOT does not specify polymer type or loading, instead, it relies on AASHTO M 332 and their percent recovery specification to assure polymer is present. WMA may not be used with High RAP/Any RAS mixes. The specification is permissive if used with Low RAP/No RAS mix as long as the WMA technology is recognized by WSDOT. Organic, chemical and foaming are all included. The HWT is used to evaluate moisture sensitivity. If liquid anti-strip (LAS) is needed to pass the HWT, the contractor selects the product from the WSDOT QPL and selects the dosage prior to mixture design submittal. As with recycling agents, LAS must be added to the virgin binder prior to being delivered to the contractor's plant.

The mix performance tests and criteria used by WSDOT were presented in Table 28. WSDOT is interested in implementing the IDEAL-CT test in place of the IDT test. The only binder performance testing being used is MSCR. WSDOT is currently evaluating the rheological parameters delta Tc (ΔTc) and crossover temperature.

WSDOT does not require fractionation of RAP stockpiles. For High RAP/Any RAS classification, Form 350-042 is required with mixture design submittals. The testing requirements for High RAP/Any RAS classification are: 1/1000 tons of RAP (minimum of 10 per mixture design) ignition furnace asphalt content and washed sieve analysis and 1/100 tons of RAS (minimum of 10 per mixture design) ignition furnace asphalt content and washed sieve analysis. For Low RAP/No RAS, it is the contractor's option whether to include RAP in the mixture design. For a mixture with greater than 20 percent RAP by total weight of HMA, the RAP has to be processed to ensure that 100 percent of the material passes a sieve twice the size of the maximum aggregate size for the class of mix to be produced. When any amount of RAS is used in the production of the asphalt mixture, the RAS shall be milled, crushed, or processed to ensure that 100 percent of the material passes the ½ inch sieve. Extraneous materials in RAS such as metals, glass, rubber, soil, brick, tars, paper, wood, and plastic shall not exceed 2.0 percent by mass as determined on material retained on the No. 4 sieve. A separate RAP QC plan is not required. Still, the Form 350-042 required with mixture design submittal includes the following testing requirements: for High RAP/Any RAS classification 1/1000 tons of RAP (minimum of 10 per mixture design) ignition furnace asphalt content and washed sieve analysis and 1/100 tons of RAS (minimum of 10 per mixture design) ignition furnace asphalt content and washed sieve analysis. The WSDOT specifications don't dictate the number of cold feed bins that have to be used. For High RAP/Any RAS mixes, stockpiles must be dedicated and cannot be supplemented once sequestered. For Low RAP/No RAS mixes, dedicated stockpiles are not required, and they may be supplemented. WSDOT specifications are silent on RAP/RAS moisture management, other than having a maximum mixture moisture content of 2 percent of plant discharge.

Agencies are often faced with knowing verify if the RAP addition rate at the asphalt plant is consistent, especially with high RAP mixes. WSDOT does not have full-time plant inspectors or require plant production reports. It relies on several items to answer this question. They include:

- The requirement for dedicated RAP stockpiles with production testing.
- The test section requirement includes mix evaluation relative to the mixture design, including HWT and IDT tests with pass/fail criteria.
- Use of a PWL acceptance specification that encourages consistency and results in reward or penalty based on it.
- Virgin binder is randomly sampled with every other mixture quality assurance sample and tested every per AASHTO M 332 during production.
- In addition to regular quality assurance sampling and testing, 1/10,000 tons mix is randomly sampled during construction for confirmation testing using the same suite

of tests used during the test section. Though these conformation tests are for information only, they can be used to focus attention on potential issues.

WSDOT uses both WSDOT and AASHTO specifications and WSDOT, AASHTO, and ASTM test methods. Those relevant to this effort include:

- WSDOT Standard Specifications, Section 5-04 Hot Mix Asphalt
- WSDOT SOPs and FOPs.
- AASHTO M 320 and M 332 binder specifications.
- AASHTO M 323 mixture design specification.
- AASHTO R 35 standard practice for mixture design.
- AASHTO test methods including AASHTO PP 78.
- ASTM D6931 test method.
- Recommendations from WSDOT funded research reports.

The WSDOT asphalt mixture specification is reviewed regularly and updated as needed. During the visit, several relevant planned changes were identified by WSDOT that might be implemented as early as 2021. They included:

- Increasing production VMA by reducing the lower limit 0.5 percent below AASHTO M 323 and increasing the weight (f factor) to 10 percent in the composite pay factor calculation.
- Increasing in-place density lower specification limit 0.5 percent.
- Developing a new specification for high RAP stockpiles that would allow supplementing them as long as a given set of RAP processing and QC requirements are met.
- Raising the limit on the amount of material passing the #200 sieve from 7 to 8 percent in production without making changes to dust to asphalt criteria of 0.6 to 1.6.

Contractor Interviews and Virtual Plant Observations

With the COVID-19 Pandemic leading to virtual site visits, it was impossible to visit contractor RAP processing and asphalt plants. During the virtual site visit, a separate virtual meeting was held with one contractor's staff using a set of eight open-ended questions. A brief summary of observations based on this activity follows. The reason only one contractor was interviewed is that this contractor has many plants in the state that produce high RAP mixes.

The contractor indicated that in eastern Washington, about 20 percent RAP is used, and in western Washington, up to 40 percent RAP is used. RAS is used in WSDOT and commercial mixes at two plants. Two to three percent RAS is blended with RAP. With 3/8-inch surface mixes, it is necessary to reject baghouse fines, while with larger size mixes, washing aggregates can prevent the need to reject fines. Use is market-driven, and in some markets with aggregate shortages, RAP is maximized. The sales are about 40 percent to public customers and 60 percent to private customers. You have to use RAP supply, and demand is pretty well balanced in the state of Washington.

Key observations included:

- When trying to get to a 40 percent binder replacement, knowing exactly what is in your stockpiles matters.
- The WSDOT requirements for high RAP stockpile testing in production are a must. Fractionation is not used, but experience with it has been positive and negative in the past. With more 3/8 inch mixtures being specified in Washington, RAP is crushed to ½ inch minus.
- Baghouse fines control is very important. Having two RAP feed bins is helpful for control and producing different size mixes.
- The WSDOT PWL acceptance specifications force maintaining the consistency of raw materials and mixture produced.

Pavement Performance Observations

Mix durability (cracking and raveling) performance is a primary concern for WSDOT. WSDOT performed an analysis of the performance of mix with and without recycled materials in the mid 1980's and again recently (54). In January of 1985, 24 recycled mix projects were thoroughly evaluated in the field and laboratory. At the beginning of the study, there were 16 completed projects that were examined. Evaluation of the laboratory and pavement performance data showed that the first two WSDOT RAP project constructed, Renslow to Ryegrass (1977) and Yakima River to West Ellensburg Interchange (1978), were 7 and 8 years old and still performing very well. Although the other 14 projects had only been constructed within the previous two and a half years, the early data indicates equally promising results. Because of the impressive pavement performance exhibited by the recycled pavements, together with mix recycle benefits such as conservation of natural resources, the feasibility of construction, and its cost advantage of over virgin mix, hot-mix recycling became an attractive addition to the WSDOT paving program. In 2017, University of Washington (UW) researchers analyzed the WSDOT PMS database considering individual distress types and composite factors, such as cracking index, to compare the performance of high and low RAP mixes (55). There was no statistical evidence to suggest a difference in performance between high-RAP (> 20%) and up-to-20%-RAP mixtures. They indicated that the in-service pavement data approach is a repeatable framework that can be used to understand better the relationship between actual in-service performance and mixture design, structural design, and construction variables.

Another recently published work by UW and WSDOT indicated that RAP is generally advertised as the most recycled material in the U.S., and it comprises, on average, about 20% of the nationwide asphalt mixture production by weight (56). The study described an economical method to estimate the volume and weight of RAP stockpiles using Google Earth Pro software and publicly available information on a case study of Washington State. Aggregating the information over a geographic area can provide accurate RAP locations and quantity information for entire regions or states and within a range of years. The findings of the study contrasted partially with aggregated estimates on receipt/use survey data from National Asphalt Pavement Association (NAPA) for Washington State during the past decade. Discussions on data reliability, inconsistencies with NAPA survey results, and alternative approaches to utilizing the oversupply of RAP identified were presented.

WSDOT is also currently supporting research on RAP mixture design materials selection, the impact of RAP levels on binder and mixture properties, and evaluation of the IDEAL-CT test for RAP mix cracking performance. The project includes the evaluation of long-term in-service pavements and virgin plus plant-produced materials from recently constructed pavements. The project will be completed in 2020.

Summary of Positive DOT Practices

Throughout the visit, WSDOT identified several practices that were important for their successful use of RAP. They included the following:

Pavement Performance and Quantifying and Communicating Recycling Benefits

1. WSDOT conducted a detailed performance review of pavements, including 24 pavement sections constructed with RAP mixtures in the mid 1980's, not finding a difference in observed performance.
2. In 2017, University of Washington (UW) researchers analyzed the WSDOT PMS database considering individual distress types and composite factors, such as cracking index, to compare the performance of high and low RAP mixes, and there was no statistical evidence to suggest a difference in performance between high-RAP (> 20%) and up-to-20%-RAP mixtures.

Specifications

1. For High RAP/Any RAS mixtures, HWT rutting and IDT cracking performance tests are used in a balanced mix design approach, which also requires volumetric requirements of AASHTO M 323 are met, and a test section is required with mixture evaluation relative to the mixture design including HWT and IDT tests with pass/fail criteria.
2. In addition to regular quality assurance sampling and testing, 1/10,000 tons mix is randomly sampled during construction for confirmation testing using the same suite of tests used during the test section. Though these conformation tests are for information only, they can be used to focus attention on potential issues.
3. WSDOT specifications are very clear and easily understood with just two recycled mix classifications, Low RAP/No RAS and High RAP/Any RAS.
4. WSDOT standard specifications were developed with input from the Washington State Chapter of the APWA, making it possible for WSDOT approved mixture designs to be used by other public agencies in the state. Once a mix design is approved by WSDOT, it goes on the WSDOT qualified products list (QPL).
5. The relationship between WSDOT and the industry appears to be positive and beneficial to both parties.

RAP Criteria

1. The WSDOT Low RAP/No RAS and High RAP/Any RAS mixture classifications are defined by percent RAP and/or RAS by weight of the mixture. Still, the High RAP/Any RAS classification has maximum contributions of RAP and RAS binder based on RBR.

2. The maximum RBR of High RAP/Any RAS mixture is 40 percent, with a maximum contribution from RAS of 20 percent.
3. WSDOT regularly performs internal research and sponsors research by academia to understand and optimize the use of recycled materials in the state.

Rationale and Location for Using RAP

1. Criteria for using recycled materials is the same for all dense-graded mixes regardless of location in the pavement structure.
2. Criteria related to traffic is not explicit in the specifications, but it is indirectly incorporated in the PG binder specifications using AASHTO M 332.

Use of Softer Binder and Additives

1. For High RAP/Any RAS mixtures, the physical blend of virgin binder, RAM binder, and recycling agent (if used) must meet the grade specified for the project location.
2. AASHTO M 332 is used for binder testing when performed during mix design and production. Acceptance requirements include sampling and testing of the virgin binder during the production of each lot to assure that it has properties similar to the virgin binder used in the mixture design based on a set of tolerances.
3. Recycling agents are allowed for High RAP/Any RAS mixtures. When used, recycling agents must be added at to the virgin binder prior to being delivered to the contractor's plant.
4. WMA may not be used with High RAP/Any RAS mixtures.

Additional Asphalt Content and Mixture Performance Tests

1. Exceptions to AASHTO M 323 and R 35 that are specifically targeted on increasing the amount of virgin binder to improve durability and prevent rutting include:
    a. Reduced number of gyrations.
    b. Use of Gsb for virgin and RAP aggregates.
2. Use of a PWL acceptance specification that encourages consistency and results in reward or penalty based on it.

RAP Processing, Handling, and QC

1. WSDOT does not require fractionation of RAP stockpiles, and allowable RAP percentage is not related to fractionation, although contractors can fractionate if desired.
2. RAP has to be processed to ensure that 100 percent of the material passes a sieve twice the size of the maximum aggregate size for the class of mix to be produced.
3. A separate RAP QC plan is not required but Form 350-042 required with mixture design submittal includes the following testing requirements: for High RAP/Any RAS classification 1/1000 tons of RAP (minimum of 10 per mixture design) ignition furnace asphalt content and washed sieve analysis.
4. For High RAP/Any RAS mixes, stockpiles must be dedicated and cannot be supplemented once sequestered.

Contractor Input on Successful High RAP Use

1. When trying to get to a 40 percent binder replacement, knowing exactly what is in your stockpiles matters.
2. The WSDOT requirements for high RAP stockpile testing in production are a must.
3. Fractionation is not used, but experience with it has been positive and negative in the past.
4. With more 3/8-inch NMAS mixtures specified in Washington, RAP is being crushed to ½ inch minus.
5. Having two RAP feed bins is helpful for control and producing different size mixes.
6. Baghouse fines control is very important.
7. The WSDOT PWL acceptance specifications forces maintaining the consistency of raw materials and mixture produced.

Alternative Uses of RAP and Research Needs

WSDOT currently allows the use of RAP per WSDOT standard specifications include it as up to 25 percent of the blend in: ballast, permeable ballast, crushed surfacing, aggregate for gravel base, class A and B gravel backfill for foundations, gravel borrow, select borrow and common borrow. It can be 100 percent of select and common borrow that is at least 3 feet below the subgrade. Although these options exist, RAP is not commonly used for these applications due to its value in asphalt mix and, in some cases, challenges with density determinations.

Summary of Document Reviews and State DOT Interviews

State DOT's experience using RAP 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 ten years. Integration of RAP into asphalt mixtures is somewhat market-driven and influenced by cost, availability, DOT allowance for use, and sustainability ambition.

Pavement Design and Performance Strategy Considerations

Each state has a strategy that relates the quality of its 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. Both can result in good pavement performance while using the different philosophies. These are considerations when reviewing the information in this report, whether comparing the information between State DOTs in this report.

Pavement Performance Observations

Monitoring pavement performance over time is a method some DOTs use to assess how specifications and changes to them influence performance. Three of the participating DOTs had relatively recently performed analyses of pavements containing RAP.

- FDOT assessment of the impact of RAP on pavement performance in Florida and published the findings in 2012 (29). The mixtures were designed by the Marshall Method and placed below the surface course mix in the structure. The performance period considered was 1991-1998. The conclusions indicated the importance of including traffic volume when analyzing performance life. When accounting for traffic volume, as shown in Figure 8, there is a trend suggesting that as percent RAP increases, performance decreases. However, in the range of percent RAP analyzed (30-50), all mixtures containing RAP performed better than the mixtures without RAP. At the time, the authors suggested a similar analysis of Superpave design mixtures be performed in the future. FDOT standard specifications require a 3-year warranty on pavement performance after final acceptance. Because the warranty is not bonded by the contractor, it is called a "Value Added Asphalt Pavement." The pavement performance criteria and required repairs, if distress thresholds are in the FDOT Standard Specifications Section 338 (28). It is most often associated with raveling and slippage failures. It has been used for rutting, potholes, depressions, and bleeding.

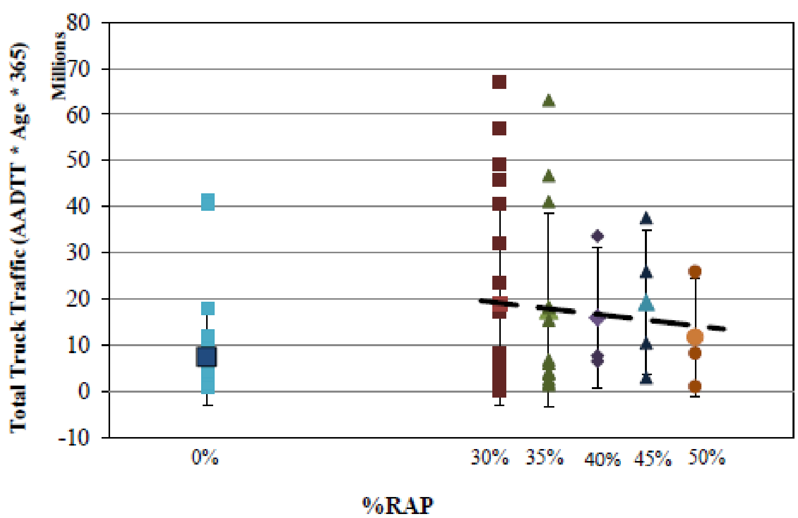

Figure 8. Pavement Performance versus Percent RAP in Intermediate Course Mixes.

- The NDOT Annual Report 2019 contains a section on Asset Management highlighting performance measures developed to monitor the condition of Nebraska's roadways, bridges, and fleet (37). Figure 9 is an excerpt from the report on the pavement condition of Nebraska highways. It is a plot of the Nebraska Serviceability Index (NSI) over time. NSI is a composite index that incorporates automated and visual inspection data with a scale of 0 to 100. An NSI rating of 70 or above is considered "Good" performance, and NDOT's goal is to have 80 to 85 percent of the highway system in the "Good" category. Figure 9 shows that 92 percent of the Interstate routes are in good condition, and 83 percent of the total highway system is in good condition. Interestingly the overall condition of the highway system has improved since the implementation of high RAP asphalt mixtures.

- NDOT currently has research underway at the University of Nebraska Lincoln (UNL) comparing the performance of 5 to 10-year-old pavements constructed with low and high RAP mixes, which was scheduled for completion in 2020. Ride quality (IRI), rutting, cracking, and life cycle cost analysis (LCCA) are the parameters being analyzed. The LCCA analyses are ongoing, but IRI, rutting, and cracking analyses have been completed. Summaries of preliminary statistical analyses and data analyses are also given below. NDOT staff indicated that initial findings are similar in terms of performance for both low and high RAP pavements in terms of IRI and rutting performance. Additionally, that differences in thermal cracking performance appear may, in part to be due to differences in climate (north vs. south).

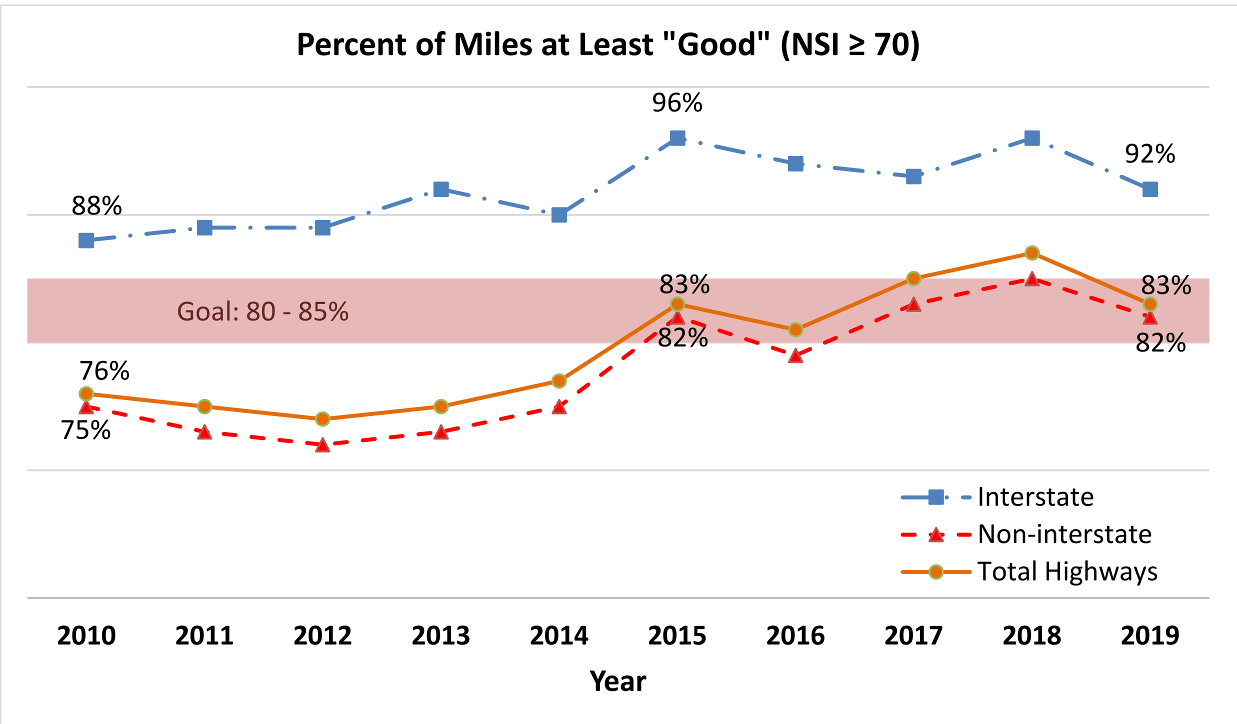

Figure 9. Nebraska Highways NSI Scores.

- WSDOT performed an analysis of the performance of mix with and without recycled materials in the mid 1980's and again recently (54). In January of 1985, 24 recycled mix projects were thoroughly evaluated in the field and laboratory. At the beginning of the study, there were 16 completed projects examined. Evaluation of the laboratory and pavement performance data showed that the first two WSDOT RAP project constructed were 7 and 8 years old and still performing very well. Although the other 14 projects had only been constructed within the previous two and a half years, the early data indicates equally promising results. Because of the impressive pavement performance exhibited by the recycled pavements, together with mix recycle benefits such as conservation of natural resources, the feasibility of construction, and its cost advantage of over virgin mix, hot-mix recycling became an attractive addition to the WSDOT paving program. In 2017, University of Washington (UW) researchers analyzed the WSDOT pavement management system database considering individual distress types and composite factors, such as cracking index, to compare the performance of high and low RAP mixes (55). There was no statistical evidence to suggest a difference in performance between high-RAP (greater than 20 percent) and up to 20 percent RAP mixtures. They indicated that the in-service pavement data approach is a repeatable framework that can be used to understand better the relationship between actual in-service performance and mixture design.

NDOT Summary of Mann-Whitney U-Test Results

- Results showed insignificant difference when comparing the 45% RAP sections with 0% RAP sections regarding IRI, rut depth and severity.
- Cracking and severity showed statistical difference between 45% RAP and 0% RAP in northern NE sections.
- No significant difference was observed between the 40% RAP sections and 0% RAP sections.

NDOT Summary of Data Analysis

- Sections with high RAP content (up to 45%) showed no significant difference regarding IRI and rut depth when they are compared with other RAP sections.
- IRI and rutting were generally within the acceptable limits for all sections examined.
- Projects constructed with 45% RAP in northern NE reached the cracking limit (40%) and severity limit (0.4) after around 5-6 years in service.
- Projects constructed with 25-45% RAP southern NE showed satisfactory performance in both cracking and severity up to 8 years in service.
- It should be noted that data collected and analyzed are for projects with ADT<1600 and TADT<200.

Quantifying and Communicating Recycling Benefits

Two participating State DOTs have quantified the financial benefits of recycling, NDOT, and SCDOT.

- NDOT publicly communicates the success of its recycling goals in an NDOT Annual Report illustrating its commitment to recycling and environmental stewardship (37). Table 29 is an example of post-consumer labeling content from a project plan set. Post-consumer labeling content is included in project plan sets and NDOT has reporting the quantities and cost savings in its annual report since 2014 (37). These efforts illustrate NDOT's commitment to recycling and environmental stewardship. The reported information is based on quantities of asphalt and concrete and calculated recycled contents. The estimated dollar value of the post-consumer recycled content is also reported on the labeling. NDOT staff indicated that a key driver leading to the success of its recycling efforts is NDOT Special Provision 10-7-1217, Incentive Payment for the Use of Recycled Asphaltic Pavement (RAP) for Asphalt Mixtures (38). This special provision provides a financial incentive to contractors to use RAP. Depending on the RAP source, saving associated with RAP is shared between NDOT and the contractor. Cost savings that go to the contractor as an incentive to use RAP range from 15 to 50 percent of the total cost saving. The use of the RAP incentive special provision coupled with the fact that NDOT pays for asphalt binder as a separate item encourages the development and production of mixtures with adequate asphalt binder. From 2008 to 2020, approximately 9.2 million tons of aggregates have been recycled, and 498,000 tons of asphalt binder have been recycled or replaced with an estimated cost saving realized of $408 million in binder and aggregate. The average annual saving over this period has been $34 million.

Table 29. NDOT Summary of Data Analysis.

	Project Raw Materials (Tons)	4,394,568
	Post-Consumer Recycle Content in Project Raw Materials (Tons)	1,537,389
	Post-Consumer Recycle Content	35%
	Estimated Value of Post-Consumer Content Recycled	$60,623,102

SCDOT has estimated the percent cost savings it realizes through allowing the use of RAP. It is expressed as a percent of the total mix cost paid. The savings increased steadily from 9 percent in 2008 to 16 percent in 2013. The total savings to SCDOT from utilizing RAP mixtures between 2008 and 2013 was estimated to be $90.7 million.

Specification Reviews and Improvements

A common observation during multiple State DOT visits was DOTs regularly review specifications, mixture design requirements, test methods, and consider pavement performance. This information was used to make changes to improve performance based on those observations while working with industry and researchers. Some states have unique conditions that are reflected in their design standards and specifications also.

For example, FDOT sees RAP usage and amount in asphalt mix vary across the state because virgin aggregate supply is different in the southern third of the state and the remaining northern two-thirds of the state. Low absorption, polish resistance granite aggregate is used in the northern portion, while high absorption limestone is used in the southern portion.

Many State DOTs have been revising specifications to increase the amount of virgin binder in asphalt mixture containing RAP. SCDOT assumes 75 percent binder availability from the RAP and adds virgin binder by applying a COAC that increases the amount of virgin binder by the RAP availability lost. The increase is typically 0.3 to 0.4 percent virgin binder.

NDOT had been using up to 50 percent RAP in shoulders for many years, but the overall percentage of RAP in asphalt mixture was well below 10 percent. With standard specification changes in 2008, including a "RAP Incentive," RAP use increased to 27 percent in 2009 and continued to rise to 39 percent in 2013, and it has held steady from 2013 through 2019, as shown in Figure 10.

From 2008 to 2020, approximately 9.2 million tons of aggregates have been recycled, and 498,000 tons of asphalt binder have been recycled or replaced with an estimated cost saving realized of $408 million in binder and aggregate. The average annual savings over this period has been $34 million. Prior to 2008, there were as many as 75 large RAP millings stockpiles around the state, referred to as "Mountains of Millings," and there was not adequate room to store more RAP.

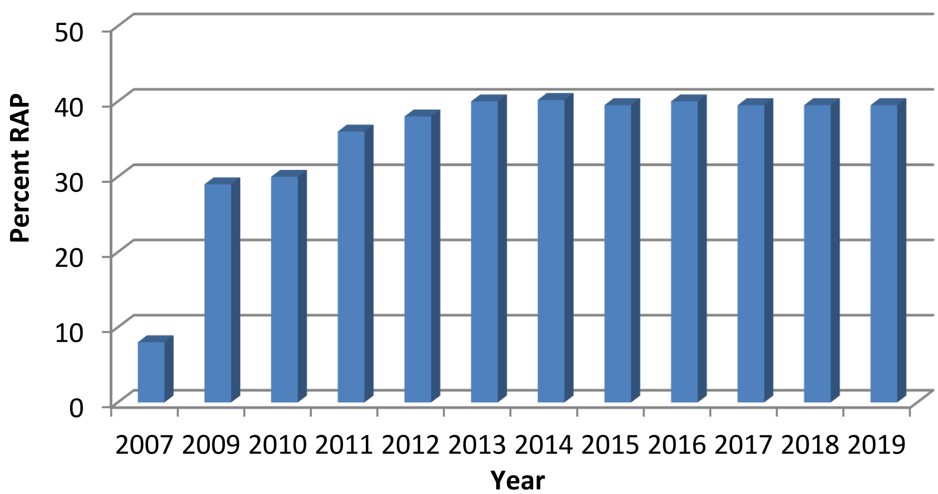

Figure 10. NDOT RAP Use Since 2008 Specification Changes.

NJDOT has implemented a High RAP mixture specification that integrates performance tests in a balanced mixture design approach. The specification calls for minimum percentages of RAP. Interestingly, it has seen a slight decline in the amount of RAP used statewide because it has increased its use of specialty mixtures for surface designs, like OGFC, Ultra-Thin HMA, SMA, and AR-GG, that RAP cannot be used.

Over 95 percent of the asphalt mixture used by WisDOT contains RAP. WisDOT has been using RAP for decades, though its use increased significantly when WisDOT transitioned to the Superpave mixture design method in the late 1990's. It has been the contractor's option to use RAM, which includes RAP and RAS. In 2011 significant specification changes were made on RBR based on research and performance observations indicate that it has been effective.

In 2008, WSDOT specifications were revised to allow up to 40 percent recycled binder in mixes, with no more than 20 percent of it being from RAS. Currently, the average RAP used in WSDOT mixtures is approximately 20 percent annually. With very different climatic conditions from the Pacific coast to Eastern Washington, the asphalt producers don't exercise the option to use high RAP mixes in the eastern part of the state.

Ranges of Allowable RAP and RAS

There was a wide range in quantities of recycled materials used among the participating States. The quantities of RAP and RAS allowed in each State are shown in Table 30. In many cases, the table's ranges were associated with where the mixture was placed in the pavement structure (e.g., surface, intermediate of base layer), roadway functional classification, or mix type.

Table 30. RAM Ranges Among Participating State DOTs.

State DOT	**RAM Content Allowed (% by Weight)**		**RAM Content Allowed (RBR)**	
	RAS	**RAP**	**RAS**	**RAP**
FDOT	0%	0% or 0-20% or Unlimited	NA	NA
NDOT	0%	0-35% or 20-35% or 0-55% or 35-65%	NA	NA
NJDOT	0%	≥20%[1]or ≥30%[1]	NA	NA
SCDOT	NA	NA	0.05	0.00-0.30 or 0.15-0.45 FRAP
WisDOT	NA	NA	0.20-0.25	0.25-0.40 RAP+FRAP or 0.25-0.35 RAS+RAP+FRAP
WSDOT	NA	NA	0.20	0.40 or 0.20 RAS+0.20RAP (0.40 total)

[1]*With passing asphalt mixture performance tests.*

It is important to note that it is difficult to directly compare RAP or RAP and RAS quantities from DOT to DOT. Each State DOT has a different process for designing its asphalt mixtures, designing its pavement overlay program, and writing its specifications when using recycled materials. The information provided is intended to provide an overview of existing practices.

Summary of Observations by Category

Each State DOT has its own methodology to accommodate the use of RAP. Over time standard mixture design requirements and specifications have been modified to accommodate recycled materials. Mixture design requirements, specifications, and other methodologies can be categorized and contrasted to allow for a better understanding of them. The following categories were used:

- RAP Criteria by weight and/or RBR.
- Rationale and location for using RAP.
- Use of a softer binder
- and additives.
- Obtaining additional asphalt content
- and performance testing.
- RAP processing, handling, and QC

Table 31 contains a list of requirements of DOTs for RAP use associated with each category. Not every DOT has requirements in each category, and requirements for a DOT can apply from multiple categories in combination.

Table 31. Requirements of State DOTs for RAP Use.

Requirements of DOTs for RAP Use	**FDOT**	**NDOT**	**NJDOT**	**SCDOT**	**WisDOT**	**WSDOT**
% RAP Criteria	X	X	X			X[7]
RBR Criteria	X[1]			X	X	X
%RAS Criteria			X	X	X	X
Specifications Used by Others	X	X		X	X	X
Lift Location Criteria	X	X	X	X	X	
Traffic Criteria	X			X	X	X
Specialty Mixture Criteria	X		X	X	X	X
Binder Type Criteria	X	X		X		X
Softer Binder by Grade Bump	X	X	X[5]			
Softer Binder by Blending Chart			X[5]		X	X
Softer Binder by PG of Actual Blend			X[5]		X	X
Recycling Agent Additive		X	X[5]			X
WMA Additive	X	X	X[5]	X	X	X
Additional Asphalt at Design	X	X	X	X	X	
Additional Asphalt at QA			X	X	X	
Gsb for RAP Aggregates					X	X
Mixture Performance Test(s)			X	X[2]		X
Pay for Binder Separately		X		X		
RAP Fractionation	X[2]			X[2]	X[2]	
RAP QC Plan	X		X	X		
Dedicated RAP Stockpiles	X[3]			X[6]		

[1]*Contractor option for RAP over 20 percent, but RBR may not exceed 0.20*
[2]*Contractor option, use may be greater for FRAP than RAP*
[3]*Contractor option*
[4]*APA rutting test only*
[5]*Contractor option to meet performance test criteria*
[6]*If not fractionated*
[7]*RAS percent specified but overruled by RBR.*

RAM Criteria by Weight and RBR

When an agency allows both RAP and RAS, it is important that policy, materials selection, mixture design, and specifications clarify how to integrate both. The criteria (by weight and RBR) used by participating States for RAS and RAP are summarized in Table 32. In many cases, the ranges in the table were associated with where the mixture was placed in the pavement structure (e.g., surface, the intermediate of base layer), roadway functional classification, or mix type.

Table 32. RAM Ranges Among Participating State DOTs.

State DOT	RAM Content Allowed (% by Weight)		RAM Content Allowed (RBR)	
	RAS	**RAP**	**RAS**	**RAP**
FDOT	0%	0% or 0-20% or Unlimited	NA	NA
NDOT	0%	0-35% or 20-35% or 0-55% or 35-65%	NA	NA
NJDOT	0%	≥20%[1]≥30%[1]	NA	NA
SCDOT	NA	NA	0.05	0.00-0.30 or 0.15-0.45 FRAP
WisDOT	NA	NA	0.20-0.25	0.25-0.40 RAP+FRAP or 0.25-0.35 RAS+RAP+FRAP
WSDOT	NA	NA	0.20	0.40 or 0.20 RAS+0.20RAP (0.40 total)

[1]*With passing asphalt mixture performance tests.*

Half of the States (FDOT, NDOT, and NJDOT) use percent by weight, and half (SCDOT, WisDOT, and WSDOT) use RBR. However, when RBR is used, percent by weight is indirectly controlled.

- FDOT and NDOT do not allow any RAS, while NJDOT, SCDOT, WisDOT, and WSDOT allow RAS.
- NJDOT is generating less RAP because it embraces more pavement preservation treatments that create little or no RAP. NJDOT also allows a small amount of other RAM. Other RAM include: Ground Bituminous Post-Manufacturer Shingle Material (GBSM), Remediated Petroleum Contaminated Soil Aggregate (RPCSA), or Crushed Recycled Container Glass (CRCG). The allowable amounts of recycled materials in mix types are summarized in Table 33 (43).

Table 33. Comparison of NJDOT Standard and High RAP Mix Types.

Properties	**Mix Type**					
	Standard Mix Types (902.02.02)			**High RAP Mix Type (902.13.02)**		
Location	Surface	Intermediate	Base	Surface	Intermediate	Base
RAP (%)	0-15	0-25	0-25	20-?	30-?	30-?
Other RAM (%)[1]	0	0-10	0-10	0	0-10	0-10
Total RAM%	0-15	0-35	0-35	20-?	30-?	30-?
Binders	PG64-22, ME may Direct Softer Grade			As required to meet Performance Tests		
Performance Tests	N/A			APA and Tx Overlay		

Rationale and Location for Using RAP

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

- FDOT allowance for RAP is based on mix type, location, binder type, and geographic location. Granite aggregate is used in the northern part of the state, while limestone is used in the southern part of the state. There is no limit on the amount of RAP that can be used in intermediate and base mixes made with Granite aggregate. Twenty percent RAP is allowed in dense-graded friction course (DGFC) and intermediate mixtures containing PG 76-22 binder made with Granite aggregate. FDOT does not allow RAP in OGFC, High Polymer (HP) mixtures, or dense graded friction course (DGFC) mixtures containing south Florida limestone. Figure 11 shows the geographic break in aggregate types.
- NDOT criteria for using RAP in mixes is dependent on location in the pavement structure. Premium surface course mixes (SPH and SLX) can contain up to 35 percent RAP, and the SPR "workhorse" mixes (about 70 percent of asphalt mix used by NDOT) can contain up to 55 percent RAP, while base and shoulder mixes can contain up to 65 percent RAP. NDOT reports that most mixes produced by contractors are at 50 percent or near the maximum allowable RAP percentage.
- NJDOT has minimum RAP contents and uses performance tests in a balanced mix design approach. It primarily allows RAP in dense-graded mixtures. Some small amounts of other recycled materials are allowed in some NJDOT mix types also. The materials include: Ground Bituminous Post-Manufacturer Shingle Material (GBSM), Remediated Petroleum Contaminated Soil Aggregate (RPCSA), or Crushed Recycled Container Glass (CRCG). Recycled materials are not allowed in specialty mixtures, including OGFC, Modified OGFC, Ultra-Thin HMA, SMA, AR-OGFC, HPTO, BRIC, BRBC, and AR-GG, except AR-GG may contain up to 10 percent RAP in intermediate layers. This is one reason for the reduction in the percentage of asphalt mix tons with RAP in the past five years. Another reason is that NJDOT is generating less RAP because it embraces more pavement preservation treatments that create little or no RAP that are providing performance equal to or better than milling and resurfacing with HMA containing RAP.

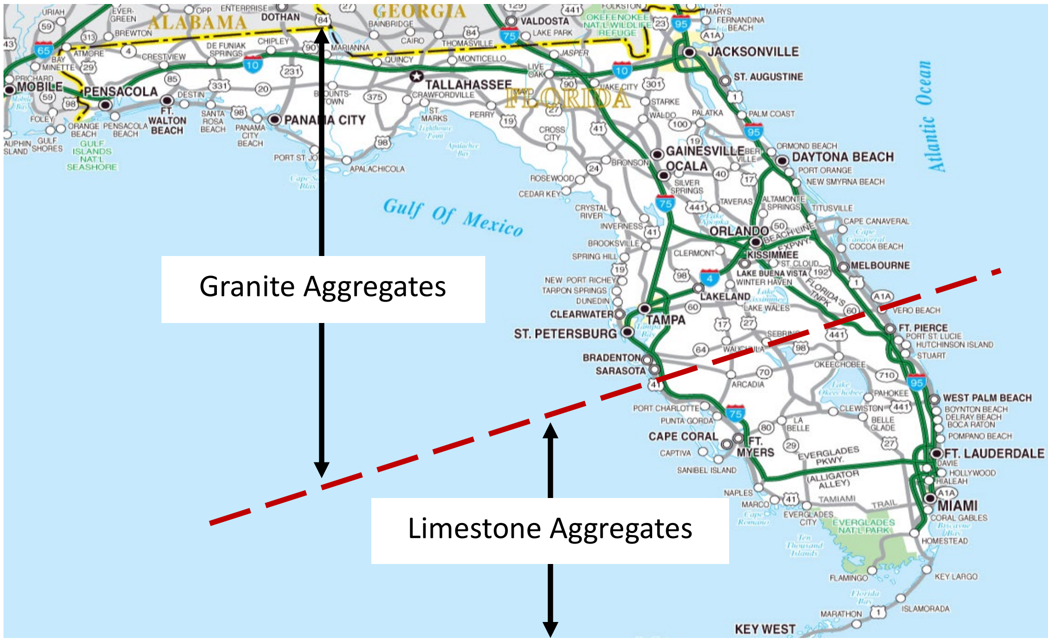

Figure 11. Florida Map Illustrating Granite and Limestone Aggregate Typical Use.

- SCDOT RAP usage and amount in asphalt mix are not consistent across the state, with urban areas having more available supply and thus using more. RAS is also allowed. Table 34 is the SCDOT mixture type selection guide showing that mixture type is based on location and classification/traffic. The allowable amounts of RAP and RAS are a function of mix type and location also. As traffic level decreases and depth into the pavement structure increases, allowable RAP increases. The amount of RAP allowed increases by about 10 percent if the RAP is fractionated, which incentivizes contractors to fractionate.
- WisDOT allows both RAP and RAS in all mix types except for a specialty interlayer mix. The criteria for the amount of RAM are based on location, traffic level, RAM type, and whether or not RAP is fractionated.
- WSDOT allows both RAP and RAS in dense-graded mixture regardless of location in the pavement structure. RAP and RAS are not allowed specialty mixes (SMA and OGFC). Criteria related to traffic is not explicit in the specifications, but it is indirectly incorporated.

Use of Softer Binder

Using a softer binder has been a technique using with RAP by many states. 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 the final mixture. Examples of the criteria used for softer binders are summarized in Table 35 and described below.

Table 34. SCDOT Guidelines for Asphalt Mixture Selection (20)

Course	Type Facility	Type	Est. % Binder	Binder Grade	Recom. Rate (Lbs/Sq.yd)	Comments
Surface	Interstate Problem intersections and areas (severe rutting and shoving potential)	A	5.0	PG 76-22	200	Consult with OMR Pavement Design Unit when other facilities are being considered
	High volume primary &secondary ADT ≥ 5000	B	5.3	PG 64-22	175 - 200	Use only on high volume and/ or high % Truck traffic roads FDP – less than 6"
	Low volume primary &secondary ADT 1500 - 5000	C	6.0	PG 64-22	150 - 175	Truck traffic ≥ 20%, use Surface type B FDP – less than 6"
	Low volume secondary routes ADT < 1500	D	6.3	PG 64-22	125 - 150	Truck traffic ≥ 20%, use Surface type C Use in lieu of PMTLSC on roads with rutting or other surface imperfections
	Multiple facility usage Consult with OMR Pavement Design Unit	E	6.5	PG 64-22	45 - 80	Used for ride correction and seal course Leveling between 0.5 - 2.0 inches
Intermediate	Interstate & High-Volume primary (New Construction)	A	4.6	PG 64-22	250 - 300	Use when no drop off restrictions Use Intermediate B when there are drop off restrictions
	High Volume Primary & Secondary ADT ≥ 5000	B	5.1	PG 64-22	200	Old Surface Type B Mixture
	Interstate & High Volume primary ADT ≥ 5000	B Special	5.4	PG 64-22	200 - 500	Special warm mix - only used on high volume routes for partial- full depth rehabilitation and FDP (2 Lifts) Mixture must be placed in confined area
	primary to low volume secondary	C	4.8	PG 64-22	200 - 300	Use for build-up and non-mainline paving and FDP
Base	Intersection & problem areas Interstate Primary and secondary routes with ADT ≥ 5000	A	4.5	PG 64-22	300 - 450	
	Primary and secondary routes with ADT < 5000	B	4.5	PG 64-22	300 - 450	
	Special - Consultant with OMR Pavement Design Unit	C	5.5	PG 64-22	200 - 300	Screening asphalt base - high stability
	Special - Consultant with OMR Pavement Design Unit	D	5.0	PG 64-22	200 - 300	Sand asphalt base - low stability
Specialty Mixes	Interstate	OGFC	6.5	PG 76-22	125	Open graded friction course
	Primary & secondary	PMTLSC	6.0	PG 64-22	0.75" Uncompacted	Preventive maintenance thin lift seal course- select only for good roads
	Primary & secondary	Shoulder widening	5.0	PG 64-22	400 - 600	Non-structural mix Use on outer edge of pavement that does not carry continuous traffic loads

- FDOT specifies PG based on RAP usage for mixes containing neat asphalt only. Softer binders are specified as the RAP dose increases. The three RAP levels and required binder grades used are:

- 0-15 percent RAP: PG 67-22
- 16-30 percent RAP: PG 58-22
- Greater than 30 percent RAP: PG 52-28

These levels and binder grades were established based on a statewide in-house FDOT research effort. FDOT used blending charts for many years, and with the data collection over time, the levels above were established. This eliminated the need for FDOT and contractors to have to perform extractions and blending chart analyses for each mixture design. FDOT uses three safeguards along with this.

NDOT only specifies MSCR PG, and it is important to note that the low temperature of the virgin binder was bumped down from a "-28" based on the climate in Nebraska to a "-34." NDOT has also been researching using a "-40" PG binder to improve low-temperature

- performance with high recycled content mixtures.
- NJDOT requires PG64-22 for Standard mixtures, though the Materials Engineer may require a one PG drop. For high RAP mixtures, the contractor selects the PG required to meet mixture performance test (APA and TxOL) criteria.

Table 35. Summary of Criteria for using Softer Binder by State.

State	Softer Binder	Blending Chart	Actual PG of Blended Asphalt
FDOT	One to two PG bumps down based on RAP dose.	N/A	N/A
NDOT	Low PG bumped down one grade. Only MSCR grades are specified.	N/A	N/A
NJDOT	PG64-22, ME may Direct Softer Grade.	N/A	N/A
SCDOT	N/A	N/A	N/A
WisDOT	N/A	Only to demonstrate that at higher RBR, the blended binder meets the specified (PG) for the project per AASHTO M 332.	Only to demonstrate that at higher RBR, the blended binder meets the specified (PG) for the project per AASHTO M 332
WSDOT	N/A	N/A	For all mixes containing RAS or > 20% RAP.

- SCDOT mix types incorporate PG64-22 binder, except Surface A, SMA, and OGFC, which incorporate PG76-22. The maximum percent of aged binder (MPAB), which is equivalent to the reclaimed binder ratio (RBR), is specified. Grade bumping is not used. SCDOT uses regression analysis to estimate low temperature asphalt binder properties without extraction and addresses the fact that RAP source can affect the minimum low temperatures of the various modified binders. WisDOT specifies PG binders meeting the requirements of AASHTO M 332. Blending chart analysis or physical blending of virgin and RAM binder may demonstrate that at higher than allowed RBR could be used if the blended binder meets the specified performance grade (PG).WSDOT specifies PG binders meeting the requirements of AASHTO M 332 for each project climate condition. In addition to AASHTO M 332 Table 1 specification requirements, PG asphalt binders also have to meet the requirements in Table 36. However, they do not have to meet RTFO Jnr_{diff} and the PAV direct tension specifications in AASHTO M 332. WSDOT typically specifies PG H and V grades.

Table 36. WSDOT Additional Requirements to AASHTO M 332 Table 1.

Property	Test Method	PG58S-22	PG58H-22	PG58V-22	PG64S-28	PG64H-28	PG64V-28
RTFO Residue: Average percent recovery at 3.2kPa	AASHTO T 350	n/a	n/a	30% min	20% min	25% min	30% min

Use of Additives

Some State DOTs are using additives to support their recycling processes. These include WMA additives, anti-strip additives, and recycling agents. Examples of the requirements for additives used are described below.

- All six State DOTs allow the use of WMA, typically at the contractor’s option. All allow chemical WMA, and four allow foamed WMA. FDOT is the only state the specific maximum WMA production temperatures of 305°F for polymer-modified asphalts and 285°F for neat asphalts. The maximum temperature at mixing is 275°F, and the maximum temperature behind the paver is 215°F. FDOT reported that WMA at lower temperatures was specified to minimize the activation or mobilization of the RAS binder. Consideration is being given to requiring WMA chemical additives.
- Five of the six DOTs allow or require liquid anti-strip and one (WisDOT) includes hydrated lime.
- NDOT, NJDOT and WSDOT allow recycling agents to be used. For NJDOT, they are at the contractor’s option to meet High RAP mixture performance test requirements. Similarly, it is the contractor’s option in Washington as long as the blended binder (virgin, RAP, and recycling agent) meets the PG requirement for the project location.
- FDOT has a virgin binder quality aging characteristic safeguard. A combination of ΔTc, a waste oil provision, and an 8 percent maximum allowable re-refined engine oil bottoms (REOBs) are used to manage the use of REOB and other blending stock that may be susceptible to aging and be blended by suppliers that provide virgin binders (both modified and unmodified virgin binders).

Additional Asphalt Content

It is important that the asphalt mixtures contain an adequate amount of virgin asphalt binder. To emphasize the importance of the virgin binder content, a couple of agencies also emphasized meeting dust to asphalt content ratio requirements. All participating DOTs required mixture designs performed per AASHTO M 323 and AASHTO R 35, with a few exceptions. The exceptions were often specifically to increase the amount of virgin binder. Examples of effective methods to ensure that there is an adequate amount of virgin asphalt are described below.

- FDOT uses:
    - A reduced number of gyrations.
    - Requires all volumetric requirements of AASHTO M 323 are met.
- NDOT uses:
    - A reduced number of gyrations.
    - Design air void ranges that are up to 2.5 percent lower than AASHTO M 323.
    - Minimum asphalt content requirements.
    - Asphalt binder is paid for as a separate item.
- NJDOT uses:
    - Asphalt binder is paid as a separate item.
    - A reduced number of gyrations.
    - Minimum VMA in mixture design and during production that is 1.0 percent higher than the AASHTO M323 requirements.
    - No change in dust proportion (DP) criteria in production from AASHTO M 323.
    - Maximum allowable aggregate absorption.
    - Rutting and cracking performance tests.
- SCDOT uses:
    - Asphalt binder is paid as a separate item.
    - Finer graded mixtures and 9.5mm fine-graded surface mixes.
    - A reduced number of gyrations.
    - Selection of optimum asphalt content at 96 to 97 percent of theoretical maximum specific gravity (Gmm) at the mixture designer's discretion, which is normally at 96.0 percent of Gmm (4.0 percent air voids) for RAM mixtures and 96.5 percent of Gmm (3.5 percent air voids) for virgin mixtures; for surface and intermediate mix types.
    - A Corrective Optimum Asphalt Content (COAC) is used to adjust the optimum asphalt content up to account for binder availability of RAM. RAM binder availability is fixed at 75 percent. The other 25 percent is considered to be "black rock." The COAC is used to add virgin binder to account for the black rock. The COAC is determined by multiplying the asphalt content of the aged binder by 25 percent and adding it to the optimum asphalt content determined from the volumetric mixture design. For example, if the optimum asphalt content from volumetric mixture design were 5.0 percent and the asphalt content from the aged binder was 1.56 percent, then the COAC would be 5.0 + 0.25 x 1.56 = 5.0 + 0.39 = 5.4 percent. In other words, the optimum asphalt content would be

    increased by 0.39 percent to account for reduced binder availability (black rock) of the RAM.
    - Minimum VMA of 0.5 percent higher than AASHTO M 323 during mixture design and production.
    - Low absorption aggregates only in surface mixtures. Aggregate absorption is not accounted for when VMA is calculated. Rather than using the bulk dry specific gravity (Gsb) of virgin and RAM aggregates in the calculation, effective specific gravity (Gse) is used. It is estimated that the combination of increased VMA specification, low absorption aggregates, and use of Gse results in 0.3 to 0.5 percent more asphalt content than would be observed per AASHTO M 323.
    - DP ratio requirements for surface and intermediate courses in the mixture design are 0.60 to 1.20 using washed gradations and a field requirement using dry gradations of 0.40 to 1.00.
    - Asphalt binder is a separate pay item that incentivizes contractors to design and produce durable mixtures rather than minimize asphalt content to reduce mix cost.
- WisDOT uses a combination of several items to increase the amount of virgin binder in mixes, including:
    - Regressed design air voids so optimum asphalt content (OBC) is selected at 97 percent of Gmm, rather than 96 percent of Gmm, typically leading to a 0.3 percent increase in asphalt content.
    - For workhorse dense-graded surface course mixes #4 and #5 used for LT or MT Traffic Levels, the minimum voids in mineral aggregate (VMA) is increased 0.5 percent above the AASHTO M 323 criteria.
    - The number of gyrations for design, except for the lowest traffic category (LT), are reduced from 50 to 40, and for SMA, 65 gyrations is used.
- WSDOT uses:
    - Gsb of aggregates and RAM be when determining VMA.
    - Rutting and cracking performance tests during mixture design, test sections, and 1/10,000 tons of mixture production.

Mixture Performance Tests

Mixture performance tests with results correlating to field performance are desired by contractors and State DOTs. This would allow contractors to be innovative with the selection of various types of materials and proportions of them. Some states are using performance tests, and others are evaluating the use of performance tests. The addition of recycled materials makes an asphalt mixture more susceptible to cracking while using softer binder and recycling agents could make a mixture more susceptible to rutting. Since cracking is related to long-term aging (LTA), it is important that cracking performance tests be conducted on aged materials.

Several State DOTs indicated an interest in using index-based performance tests for mixture design, test strips, and production acceptance. It is important to note, however, they also indicated that they did not have the resources to do so. This was especially clear for product acceptance testing when considering the test turnaround time. Several State DOTs also indicated that they had ongoing performance tests or BMD research or had recently completed some related research. Table 37 is a summary of performance tests use by the participating State DOTs, along with when they are used.

- FDOT has successfully used the asphalt pavement analyzer (APA) during the mixture design process in the past, though it is not a current requirement. Research is planned for evaluating the IDEAL-CT test for mixture design and production.
- NDOT is investigating the potential for the use of HWT and SCB tests in the future.
- NJDOT high RAP specifications include the APA rutting test and NJDOT B-10, Overlay test for Determining Crack Resistance of HMA for mixture design and production acceptance purposes. NJDOT B-10 is very similar to the TxOL test. The performance test criteria used by NJDOT are shown in Table 38, and acceptance and payment information are shown in Table 39.

Table 37. Current State DOT Performance Tests and When Used.

State	FDOT	NDOT	NJDOT	SCDOT	WisDOT	WSDOT
Rutting Test			APA	APA		HWT
Cracking Test			TxOL			IDT
Mixture Design			APA and TxOL	APA		HWT and IDT
Test Strip			APA and TxOL	APA		IDT
Production or Acceptance			APA and TxOL			1/10,000 tons
Recent or On-going Research	RAP Dose and Cracking Tests	Recycling Agents, Value of Recycling	BMD, Performance Tests, Value of Recycling	E*, RAP property estimates without extraction	BMD, Performance Tests	BMD, Performance Tests
Test(s) of Interest	IDEAL-CT	HWT, SCB		HWT, IDEAL-CT	HWT, IDEAL-CT	HWT, IDT, IDEAL-CT

- SCDOT is not likely to develop a full, balanced mixture design process but is likely to use performance tests as an additional check on the volumetric properties in the future.
- WisDOT plans to implement a BMD method and conduct performance tests during test strips or within the first 50,000 tons of production.
- WSDOT standard specifications for high RAP mixtures have included the BMD approach since 2018. The HWT is used for a rutting test, and indirect tensile strength (IDT), per ASTM D6931, is used for a cracking test during mixture design, test section, and optionally 1/10,000 tons of mixture production. The criteria used are shown in Table 40. WSDOT is currently evaluating the IDEAL-CT test and may transition to it.

Table 38. NJDOT High RAP Specification Excerpt Showing Performance Test Criteria.

Test	Requirement			
	Surface Course		Intermediate and Base Course	
	PG 64 - 22	PG 64E - 22	PG 64 - 22	PG 64E - 22
APA @ 8,000 loading cycles, mm (AASHTO T 340)	≤ 4 mm	≤ 4 mm	≤ 7 mm	≤ 4 mm
Overlay Tester, cycles (NJDOT B - 10)	≥ 200 cycles	≥ 275 cycles	≥ 100 cycles	≥ 150 cycles

Table 39. NJDOT High RAP Specification Pay Adjustment Criteria.

Test	Surface Course		PPA
	PG 64 - 22	PG 64E - 22	
APA @ 8,000 loading cycles, mm (AASHTO T 340)	t ≥ 7	t ≤ 4	0
	7 < t ≤ 10	4 < t ≤ 7	PG 64 - 22: - 50(t-7)/3 PG 64E - 22: - 50(t-4)/3
	t > 10	t > 7	-100 or Remove & Replace
Overlay Tester, cycles (NJDOT B - 10)	t ≥ 200	t ≥ 275	0
	200 > t ≥ 150	275 > t ≥ 200	Surface PG 64 - 22: -(200-t) Surface PG 64E - 22: -(275-t)/1.5
	t < 150	t < 200	-100 or Remove & Replace
Test	**Intermediate and Base Course**		**PPA**
	PG 64 - 22	**PG 64E - 22**	
APA @ 8,000 loading cycles, mm (AASHTO T 340)	t ≥ 7	t ≤ 4	0
	7 < t ≤ 10	4 < t ≤ 7	PG 64 - 22: -50(t-7)/3 PG 64E - 22: - 50(t-4)/3
	t > 10	t > 7	-100 or Remove & Replace
Overlay Tester, cycles (NJDOT B - 10)	t ≥ 100	t ≥ 150	0
	100 > t ≥ 75	150 > t ≥ 110	Intermediate PG 64 - 22: -(2t-200) Intermediate PG 64E - 22: -1.25(150-t)
	t < 75	t < 110	-100 or Remove & Replace

Table 40. WSDOT BMD Performance Test Requirements.

Design ESALs (millions)	N_{ini}	N_{des}	N_{max}	Minimum HWT passes with no stripping and maximum rut depth of 10mm	Indirect tensile strength (maximum, psi)
Less than 0.3	6	50	75	10,000	175
0.3 to less than 3.0	7	75	115	12,500	175
Greater than 3.0	8	100	160	15,000	175

RAP Processing, Handling and QC

Highlights of the participating State DOTs RAP processing, QC, or stockpile requirements include the following:

- FDOT allows RAP fractionation at the contractor's option, though it is not common. It has been reported the fine RAP stockpiles can be problematic in the Florida climate. There is an allowance for increasing RAP percent with fractionation. RAP stockpiles have a minimum binder content of 4.0 percent. If RAP is fractionated, the coarse stockpile minimum binder content is 2.5 percent. Stockpiles can be designated as "continuous" at the contractor's option. This is an option in which a contractor occasionally adds to the stockpile while performing material property tests with each addition. Each project requires a QC plan, which includes RAP processing, handling, and testing. Before a stockpile of RAP can be used, it has to be tested, visually inspected, and approved by FDOT. Millings directly from an FDOT project are also acceptable for use. RAP gradation is measured once per 1000 tons during production, and Gmm is measured once per 5000 tons of production. RAP cold feed bins must have scalping screens to prevent clumps from being introduced into the bins.
- NDOT requires a project QC plan. The QC plan includes lab equipment calibration and qualified technicians. A RAP processing requirement is that RAP must be pre-processed by fractionating, screening, and or crushing prior to use to a size such that the combined hot mix meets the required gradation. NDOT staff indicated that contractors diligently monitor RAP properties, although not required by specifications because RAP is such a large proportion of asphalt mixtures. NDOT has other controls in place that include accurate metering of baghouse fines, continuous recording of plant control settings, and vibrating screens are required over RAP cold feed bins.
- NJDOT does not require RAP fractionation and the allowable amount of RAP is not related to fractionation, although some contractors do fractionate RAP. RAP must be processed through a screening and crushing operations to ensure that it is 100 percent passing the maximum aggregate size for the mixture.
- SCDOT suggests that part of the reason for the successful use of high RAP is due to stringent RAP processing and handling requirements. A RAP QC plan is required of the contractor, and it has to include one ignition furnace asphalt content and gradation test per 1000 tons of production, along with two moisture content tests per day. Data has to be logged and available to SCDOT staff. Non-fractionated stockpiles have to be dedicated, so they cannot be replenished. This has led to fractionated piles, which can be replenished, becoming the contractor's preference. Fractionation also increases the allow RAP by 10 percent. SCDOT requires plant control software printouts with mixture proportions used reported. Although this is printed every 15 minutes, data is saved such that it can be retrieved for any past period.

- WisDOT has recycled material dose criteria related to RAP fractionation. Still, WisDOT indicates that contractors do not fractionate RAP unless they supply mix in a neighboring state that requires RAP fractionation.
- WSDOT specifies that for High RAP/Any RAS mixes, stockpiles must be dedicated and cannot be supplemented once sequestered. Fractionation of RAP stockpiles is not required. The testing requirements for High RAP/Any RAS classification are: 1/1000 tons of RAP (minimum of 10 per mix mixture design) ignition furnace asphalt content and washed sieve analysis and 1/100 tons of RAS (minimum of 10 per mix mixture design) ignition furnace asphalt content and washed sieve analysis. For a mix mixture with greater than 20 percent RAP by total weight of HMA, the RAP must be processed to ensure that 100 percent of the material passes a sieve twice the size of the maximum aggregate size for the class of mix to be produced. For Low RAP/No RAS mixes, dedicated stockpiles are not required, and they may be supplemented.

Contractor Input on Successful High RAP Use

During interviews, contractors identified practices used when producing RAP and using RAP in asphalt mixtures, as well as some challenges with it. Table 41 summarizes items multiple contractors indicated focus was placed on. Contractors were not interviewed in New Jersey.

Table 41. Contractor Identified Focus Items by State.

State	FDOT	NDOT	NJDOT	SCDOT	WisDOT	WSDOT
Heat Transfer	X	X		X		
RAM Feed Bins	X	X		X		
Dust Control	X	X			X	X
Moisture Control				X	X	
Quantity Management				X		
Verify RAP Percentage	X	X		X	X	X
Milling in Mix Design		X			X	

The items contractors expressed challenges with included:

- Having representative RAP in a timely fashion to get mixture designs completed on portable projects. For example, not having RAP milling for mixture design purposes.
- Unbalanced RAM supply (shortage or excess) in some markets.
- Meeting or cost-effectively meeting the DP requirement in AASHTO M 323 when producing high RAM mixtures.
- Having to wait after test section construction to get performance test results in order to keep producing on projects.
- Contractors identified several positive practices used to improve the quality of high RAP mixtures. They included: Obtaining representative RAP samples for mix design using full-size cold milling machines to obtain 300 to 400-ton samples.
- Having the appropriate plant equipment to produce high RAP mixes in good working order such as:

- Drum types, drum/collar modifications, and external mixers for adequate heat transfer and mixing. One contractor with a new plant has the necessary equipment to successfully produce using as much as 50 to 60 percent RAP.
- Having an adequate number of and appropriately equipped RAM feed bins. One contractor reported using three feed bins.
- Equipping all RAP feed bins with RAP Gators (clump breakers) or a scalping screen and a small closed-loop crusher circuit were reported to be effective, especially when RAP is not stored undercover.
- Using video cameras to monitor RAP bins during production to watch for clumping and consistent flow of material.
- Having baghouse collection, storage/waste, and return systems to control the amount of material passing the number 200 sieve on plant discharge for dust control.
- Use of variable frequency drives on electric motors to cost-effectively and accurately produce high RAP mixtures.
- Making drum flighting changes to accommodate increased RAP percentages.
- Calibrating a plant at least twice annually and frequently performing self-verifications of feed bins and weighbridges, as well as having plant controls printouts with mixture proportions shown.

- Minimizing and monitoring RAP stockpile moisture, especially in wet climates.
    - Paving under stockpiles and/or covering them.
    - Covering stockpiles with roofs and tarps were identified.
    - g Measuring RAP moisture content at least twice per day with one before the start of production daily.
- Processing and handling RAP to improve consistency.
    - Pre-screening incoming RAP to sort for consistency and quality.
    - If materials are variable (e.g., mainline versus shoulder), separating millings into individual stockpiles.
    - Some contractors relied on fractionation while others did not.
    - Obtaining more uniform RAP by crushing it, including crushing oversize rather than scalping it.
    - Using good stockpiling practices to maximize consistency of RAP.
        - Minimizing contamination by using placing dividers between stockpiles.
        - Minimizing segregation when building stockpiles.
        - Keeping the loader bucket out of the stockpile floor area.
        - Blending the stockpile face when feeding the plant.
- Controlling fines (material passing the #200 sieve, baghouse fines) when producing aggregates and during plant production.
    - Washing virgin aggregates to reduce fines and may prevent the need to reject baghouse fines.

    - Being able to accurately meter baghouse fines was reported to be critical to successful production.
    - Accurate metering was reported with using a silo for baghouse fines and positively weighing the return.
    - Having the ability to waste excess fines was reported necessary by some contractors.
- Contractor process control and QC
    - A contractor reported using an internal QC plan on imported aggregates, which is beyond State DOT requirements. Weekly QC meetings between the contractor and aggregate producer are held where data and observations are discussed to maintain or improve quality.
    - Some State DOTs had RAP QC requirements, while others did not.
    - Multiple contractors indicated the need to monitor RAP gradation and asphalt content during RAP production or stockpiling.
    - Multiple contractors indicated the RAP mixture process control and QC testing were important to meeting State DOT PWL specification requirements.
- A State DOT requirement that each asphalt plant has an on-site QC lab.
- Having a full-time State DOT inspector at the asphalt plant.
- State DOT PWL specifications incentivize contractors to produce consistent RAP and consistent RAP mixtures that lead to adequate contractor process control and QC.

RAP Implementation Considerations

Some High RAP implementation considerations identified by participating State DOTs include:

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

Examples of each implementation consideration follow, and for each example, State DOTs using the consideration are identified in parentheses.

RAP Programmatic Considerations

Programmatic considerations some of the participating State DOTs identified include:

- Use of project selection criteria and or mixture type criteria that define what mixtures may contain RAP and allowable RAP content in mixtures in specific locations in a pavement structure (FDOT, NDOT, NJDOT, SCDOT, WisDOT).
- Having a strong QA program that defines QC responsibilities for contractors and acceptance responsibilities for DOTs (All participating DOTs).
- Tracking and reporting the use of RAP annually (NDOT).
- Providing a financial incentive to contractors for using RAP (NDOT).
- Tracking and reporting the cost savings associated with using RAP (NDOT, SCDOT).

- Monitoring the performance of mixtures containing RAP and making specification changes to optimize performance over time, that is often coupled with research (All participating DOTs).

RAP Mixture Design Considerations

RAP mixture design considerations some of the participating State DOTs identified include:

- Using mixture performance tests in a balanced mix design approach (NJDOT, WSDOT).
- Having criteria for RAP that is the percent by weight and/or RBR (All participating DOTs).
- Separating RBR from the RAP and RAS (NJDOT, SCDOT, WisDOT, WSDOT).
- Specifying softer binders (FDOT, NDOT, SCDOT, WisDOT, WSDOT).
- Using binder performance testing like ΔTc or the Glover-Rowe parameter (FDOT).
- Considering the use of additives such as recycling agents and warm mix technologies (NDOT, NJDOT, WisDOT).
- Characterizing RAP by determining the asphalt content, aggregate gradation (All participating State DOTs).
- Using additional asphalt binder through regressed design air voids, increased minimum VMA or other means (All participating State DOTs).
- Using Gsb of the RAP aggregates, rather than Gse, to assure the most accurate indication of VMA possible (WisDOT, WSDOT).
- Using mixture performance tests, typically rutting and cracking tests, to assess mixture performance and optimize mixture designs (NJDOT, WSDOT).

RAP Mixture Acceptance Considerations

RAP mixture acceptance considerations some of the participating State DOTs identified include:

- Using mixture performance tests during test strips and in the acceptance process (NJDOT, WSDOT).
- Paying for asphalt binder as a separate item.
- Using PWL in acceptance specifications that include volumetrics as producers indicated that this led to consistent production (FDOT, WisDOT, WSDOT).

RAP Production Considerations

RAP production considerations some of the participating State DOTs or contractors in the states identified include:

- Requiring dedicated RAP stockpiles (FDOT, SCDOT, WSDOT).
- Processing by blending, screening, and crushing over-size materials for consistency (FDOT, SCDOT, WisDOT, WSDOT).
- Requiring or allowing fractionation of RAP for consistency (FDOT, SCDOT, WisDOT).

RAP Mixture QC and other Quality-Related Considerations

RAP mixture QC considerations some of the participating State DOTs or contractors in the states identified include:

- Requiring RAP QC plans or having provisions for RAP be included in Project QC plans (FDOT, NDOT, NJDOT, SCDOT).

- Having full-time inspectors at the asphalt plant during production (FDOT).
- Requiring plant control reports indicating proportioning (FDOT, NDOT, SCDOT).

Research and Training Needs Identified

Some participating State DOTs identified research needs related to the use of RAP. Most identified research needs are associated with the use of BMD and index-based performance tests. In addition to this, the following needs were identified.

- FDOT indicated a need to develop a high RAP mixture design methodology for very low volume roads.
- NDOT indicated the need for research to support the use of recycling agents.
- NJDOT indicated a need for identifying alternative RAP uses because thin high-performance surface mixtures are more frequently being successfully used, but they do not contain RAP.
- SCDOT indicated the need to determine if the higher allowable RAP levels are leading to top-down cracking.
- SCDOT interviews identified a need for education on the benefits of RAP to get more buy-in from some agencies beyond SCDOT.
- WisDOT indicated a need for regularly performing internal research and research by academia to understand and optimize the use of recycled materials.
- WisDOT interviews revealed that education is important, and agency staff need the training to understand that high RAM mixes can be very consistent and perform well
- WSDOT indicated the need for research to support the use of recycling agents.
- WSDOT also indicated a need for training and education for local agencies on the successful use of high RAP mixtures.

Alternative Uses of RAP

Several participating State DOTs identified alternative uses of RAP. This is important as the combination of using RAP in asphalt mixtures and the use of RAP for other purposes leads to balancing of available supply and use of it.

- FDOT currently allows the use of RAP in asphalt mixtures, soil stabilization, and embankment. A contractor interviewed indicated that they made a recycled-based course material from poor quality or contaminated RAP and other materials, including crushed portland cement concrete. Another indicated that excess RAP processed to meet FDOT project specification requirements is used for agricultural applications and port facilities in thickness up to 18 inches un-stabilized with heavy cranes operated on it.
- NDOT specifications strongly encourage the use of RAP in asphalt mixtures. The primary alternative use of RAP is for bituminous base course material for the reconstruction of asphalt and portland cement concrete pavements. NDOT maintenance forces also use portable small batch asphalt recycling machines with binder pods containing a plant-based recycling agent to produce 100 percent recycled high-performance hot mix patch material that includes millings, binder, and special additives. The new binder pods resulted from the department's efforts to find a cost-effective way to produce high-performance hot mix patch material year-round.

- NJDOT currently allows the use of RAP in a 50/50 aggregate/RAP blend for the base course. RAP millings can also be used in soil aggregates. NJDOT has had limited but positive experiences using RAP for cold in-place recycling (CIR) and full-depth reclamation (FDR) with cement. CIR and FDR with foamed asphalt and emulsified asphalt were identified by NJDOT as techniques that could be used more frequently in the future.
- SCDOT indicated the most commonly used alternate for RAP is in CMRB (a.k.a., FDR). This is logical since SCDOT is a leader in the use of this in-place recycling technique in the U.S. Cold in-place recycling (CIR) foaming method was successfully used on a US123 project, so it will likely be used more in the future, and there is an interest in cold central plant recycling (CCPR).
- WisDOT currently allows the use of RAM per WisDOT standard specifications and standard special provisions for in-place pulverizing, partial and full-depth milling with and without active filler and stabilizers. The use of in-place recycling techniques may be decreasing with fewer reconstruction projects in recent years. However, when used, these techniques lead to the use of RAM in cost-effective and sound engineering applications.
- WSDOT currently allows the use of up to 25 percent RAP blended in ballast, permeable ballast, crushed surfacing, aggregate for gravel base, gravel backfill for foundations, gravel borrow, select borrow, and common borrow. It can be 100 percent of select and common borrow that is at least 3 feet below the subgrade. Although these options exist, RAP is not commonly used for these applications due to its value in asphalt mix and, in some cases, challenges with density determinations

Summary

Using RAP in asphalt mixtures can provide initial cost savings by replacing a portion of the aggregate and virgin asphalt binder in the asphalt mixture. It also provides other sustainable benefits, as long as haul distance does not offset them. This keeps the RAP from being discarded in landfills. Improvements in mixture design and materials processing and handling have increased the amount of RAP that can be used in asphalt mixtures today. The performance history of RAP mixtures over the past 50 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 (6, 7, 29, 55). The participating State DOTs indicated that optimizing RAP for good pavement performance can be accomplished through: 1) regular review of DOT specifications, mixture design procedures, and performance test methods; 2) monitoring pavement performance; 3) working with asphalt producers for improvement, and 4) performing research as a basis for changes.

A wide range of techniques and criteria used by State DOTs specifying and designing mixtures and pavements incorporating RAP were identified and summarized. Important considerations identified by the State DOTs and contractors for implementing the use of RAP were summarized and described that might be of benefit to other State DOTs wanting to use RAP or increase RAP use. They included programmatic, mixture design, mixture production, mixture acceptance, RAP production, and QC considerations. Collectively this illustrated that care should 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.

All of the participating State DOTs indicated the desire to use mixture performance tests. Some State DOTs indicated to use in mixture design in a BMD approach, and some State DOTs indicated use for test strips and production or acceptance. Common themes with this were the need to get adequate virgin asphalt binder in mixtures, the need for appropriately setting performance test criteria, and recognition of the benefit of long-term aging cracking test specimens. Another common theme was recognition that the resources that would be required to implement BMD or use of performance tests on a regular basis are significant and they may not be available in the short term. Finally, all State DOTs had strong partnerships with academia that they leveraged to evaluate performance and/or refine specifications and test methods directly related to the implementation of recycled mixtures.

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