TechBrief

The Asphalt Pavement Technology Program is an integrated national effort to improve the long-term performance and cost effectiveness of asphalt pavements. Managed by the Federal Highway Administration through partnerships with state highway agencies, industry and academia, the program's primary goals are to reduce congestion, improve safety, and foster technology innovation. The program was established to develop and implement guidelines, methods, procedures and other tools for use in asphalt pavement materials selection, mixture design, testing, construction and quality control.

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State of the Knowledge for the Use of Asphalt Mixtures with Reclaimed Binder Content

This Technical Brief provides 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 reclaimed asphalt pavement (RAP) and/or reclaimed asphalt shingles (RAS).

Introduction

The purpose of this TechBrief is to provide a state of the knowledge for designing asphalt mixtures containing percentages of recycled binder from reclaimed asphalt pavement (RAP) and/or reclaimed asphalt shingles (RAS). Additionally, it illustrates how reclaimed binder ratio (RBR) is used in current standards for specifying the use of RAP and RAS in asphalt mixtures. FHWA's recycled materials policy (Wright Jr., 2002) is that recycled materials should get first consideration in materials selection within the context of engineering, economic, and environmental benefits and suitability.

The use of RAP and RAS in asphalt mixtures can provide cost savings through the replacement of a portion of the aggregate and virgin asphalt binder in a mixture for use in highways and trails. This keeps the reclaimed material from being discarded in landfills. Improvements in mixture design and materials processing and handling have increased the amount of RAP and RAS that can be used in asphalt mixtures today.

The performance history of RAP mixtures over the past 40 years and RAS over the past 20 years, **when properly engineered, produced, and constructed**, can provide comparable levels of service as asphalt mixtures with no reclaimed materials, referred to as virgin asphalt mixtures (Copeland, 2011). However, care must be taken during design, production, and construction to ensure proper performance.

Explaining Reclaimed Binder Ratio

Historically, agency specifications set limits for RAP and RAS in asphalt mixtures according to their percentage by dry weight of the mixture or dry weight of the aggregate in the mixture, with the limits set to account for the stiffening effect of the reclaimed asphalt binder. However, this approach does not account for the actual binder content in the RAP and RAS or the effective binder and properties which may impact binder grade. *Reclaimed binder ratio* (RBR), a concept recommended in NCHRP Report 752 (West et al., 2013) for RAP mixtures, is now being used by agencies, researchers, and engineering consultants to specify the amount of reclaimed binder from RAP and RAS to total binder in the mixture. Previously, the term *binder replacement* had been used to describe the amount of reclaimed binder in the new mixtures; however, the term RBR is more appropriate as reclaimed binder may not actually be replacing virgin binder in the mixture if it is not being activated and incorporated in the mixture as a binding agent. The following equation explains the binder ratio concept:

$$RBR = \frac{Reclaimed\ Binder\ from\ RAP\ and\ RAS}{Total\ Percent\ of\ Binder\ in\ Mixture}$$

Because the RBR concept accounts for the varying binder content and properties in the RAP and RAS sources used which impact the binder grade, it is a better method for specifying allowable amounts of RAP and RAS rather than the total combined RAP plus RAS content. 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.

There is no widely accepted method to determine the blending of new and reclaimed binder. The amount of blending among RAP and virgin binders is often assumed to be 100 percent, but for RAS mixtures, it is assumed that only partial blending occurs. To maintain similar or better performance, the virgin binder content of the mixture may need to be increased to account for this lack of blending and ensure mixture durability. The RBR method is used to specify a minimum amount of virgin asphalt binder relative to reclaimed asphalt binder.

Determining RBR

AASHTO M 323-17 *Standard Specification for Superpave Volumetric Mix Design* provides guidance for calculating the RAP Binder Ratio using the following equation:

$$RAPBR = \frac{(Pb_{(RAP)} \times P_{RAP})}{100 \times Pb_{(Total)}} \qquad [1]$$

Where:

$RAPBR$ = Reclaimed asphalt pavement binder ratio
$Pb_{(RAP)}$ = Binder content of the RAP
P_{RAP} = RAP percentage by weight of mixture
$Pb_{(Total)}$ = Total binder content in the mixtures

While no equations are given in the previously mentioned AASHTO Standard, the RAS Binder Ratio is calculated using a similar methodology as shown in Equation 2.

$$RASBR = \frac{(Pb_{(RAS)} \times P_{RAS})}{100 \times Pb_{(Total)}} \quad [2]$$

Where:

RASBR	=	Reclaimed asphalt shingles binder ratio
$Pb_{(RAS)}$	=	Binder content of the RAS
P_{RAS}	=	RAS percentage by weight of mixture
$Pb_{(Total)}$	=	Total binder content in the new mixture

The total Reclaimed Binder Ratio is calculated by adding the RAPBR and RASBR as shown in Equation 3.

$$RBR = RAPBR + RASBR = \frac{(Pb_{(RAP)} \times P_{RAP}) + (Pb_{(RAS)} \times P_{RAS})}{100 \times Pb_{(Total)}} \quad [3]$$

Where:

RBR	=	Total Reclaimed binder ratio
RAPBR	=	Reclaimed asphalt pavement binder ratio
$Pb_{(RAP)}$	=	Binder content of the RAP
P_{RAP}	=	RAP percentage buy weight of mixture
RASBR	=	Reclaimed asphalt shingles binder ratio
$Pb_{(RAS)}$	=	*Binder content of the RAS*
P_{RAS}	=	RAS percentage by weight of mixture
$Pb_{(Total)}$	=	Total binder content in the mixtures

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 (2017) *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.

Determining the Binder Content on RAP and RAS

According to research conducted, West (2015) provides two acceptable procedures for determining the binder content of RAP ($Pb_{(RAP)}$). AASHTO T 308-16 uses an ignition furnace to burn the asphalt off the mineral aggregate in a recycled mixture. When using the ignition furnace to determine the asphalt content of RAP it is important to use an appropriate binder-correction factor to account for degradation of aggregates. Alternatives to this approach require the use of solvents and are found in AASHTO T 164-14. Using a solvent extraction is advisable when there are significant variations in aggregate-correction factors from the ignition furnace or when the RAP binder properties need to be determined. Either method provides a suitable answer for determining the RAP binder content.

West (2015) and Willis (2013) recommend determining the RAS binder content by a solvent method (AASHTO T 164-14) because of the presence of backing material and fibers that ignite ahead of the asphalt binder in the ignition furnace yielding unreliable results. Using AASHTO T 164-14 may be unnecessary if comparisons between solvent extraction and the ignition oven show a definitive correlation. Some states have either determined correction factors so that RAS asphalt content can be determined in the ignition oven or determined that there is little quantifiable difference between the asphalt contents returned from solvent extraction and the ignition oven (Willis, 2013).

One should exercise caution if determining asphalt content of RAS in the ignition oven. Instances of combustion or incomplete binder burning have been noted if the sample size is too large. It is recommended that when determining the asphalt content of RAS in the ignition oven, sample sizes should not exceed 500 to 700 grams. Other state agencies recommend using 200 grams (Rodezno et al., 2017).

Differences in RAP and RAS Binder Properties and Determining Binder Grade Adjustments

Binders reclaimed from RAP are generally stiffer than virgin binders due to undergoing oxidative aging and binder from RAS are much stiffer than RAP due to the asphalt binder properties desired in shingle production. RAS binders can come from two different sources. Manufacturing waste asphalt shingles (MWAS) are shingles discarded by manufacturers because they did not meet production standards. Post-consumer asphalt shingles (PCAS) were previously used for roofing and discarded after being in service. PCAS is more prevalent than MWAS in asphalt mixtures due to having more than 10 times the tonnage availability.

Due to the oxidation from years in service on rooftops, recovered PCAS binders are considerably stiffer. This stiffness makes performance grading (PG) for recovered RAS binders very challenging, particularly at critical low temperatures (Bonaquist, 2011; Willis & Turner, 2016). This difficulty stems from the binder having poor relaxation properties when cold and the inability to test the binder using conventional equipment and methods at critical low temperatures greater than about 4°C.

The high temperature grading of recovered RAS binder is also difficult, requiring a research grade dynamic shear rheometer (DSR). DSRs using water baths cannot test RAS binders at the appropriate temperature the phase changes at these temperatures greatly exceed 100°C. Willis & Turner (2016) developed extrapolation procedures for determining high temperature grades using standard equipment. Table 2 illustrates the difference in performance grades noted in the literature between RAS and RAP binders.

Table 1. RAS Binder Performance Grade

Reference	Material	High Temperature Grade	Low Temperature Grade
Standard	Virgin Binder	52°C to 76°C	−28°C to −16°C
NCAT (2014)	RAP	85°C to 95°C	−20°C to −5°C
	MWAS	125°C to 135°C	
	PCAS	150°C to 170°C	
Willis (2013)	MWAS	132°C to 154°C	−18°C to > 0°C
	PCAS	121°C to 175°C	−6.9°C to 41°C
Zhou et al. (2013)	MWAS	124°C to 138°C	
	PCAS	159°C to 214°C	
Bonaquist (2011)	RAS	110°C to 126°C	−10.1°C to 4.5°C
Willis & Turner (2016)	MWAS	126.6°C to 144.7°C	
	PCAS	144.4°C to 170.3°C	

Because RAS binders from MWAS or PCAS are much stiffer and more brittle than RAP binders, RBR for RAP and RAS are addressed separately in this TechBrief. As previously noted, RAPBR and RASBR should be treated individually within the same specifications and standards. The differences between the properties of binder coming from MWAS and PCAS should also make one consider further separating these materials. If RAP is combined with PCAS or MWAS, the limits should state what portion of the total RBR is derived from each material.

RAP Fractionation and Impact on Asphalt Content and Binder Properties

Separating the RAP into two or more stockpiles of different particle sizes, often referred to as fractionating, allows contractors more flexibility in increasing RAP contents while still meeting mixture design requirements. Depending on the amount of each fraction of RAP used, the reclaimed binder ratio will vary. When separated, the coarser fractions of RAP typically have less asphalt than the finer fractions; a 2 percent or greater difference has been observed between coarse and fine fractions (Lee et al., 2012). This is because finer aggregate has a greater surface area coated with binder than coarser aggregate.

RAS Type Impact on Asphalt Content and Binder Properties

Because RAS binders are stiffer than RAP binders, RAS increases the stiffness and brittleness of mixtures to a greater degree than RAP at an equivalent RBR. Asphalt shingles also contain significantly more asphalt binder than RAP. MWAS have binder contents of 19–20 percent and

PCAS have binder contents of 30–36 percent. The higher binder content of PCAS materials is primarily due to the loss of the aggregate coating the shingles during service (Willis, 2013).

Virgin Binder Grade, Recycling Agents, and Binder Content

The use of high percentages of reclaimed binder, without consideration of the virgin binder grade and content, may result in a brittle mixture that is prone to cracking. Current research projects are evaluating the effectiveness of using recycling agents (NCHRP 09-58), softer binders, or additional binder to improve high recycled content mixture performance (Tran et al., 2012; Willis et al., 2012; 2013). Currently, recycling agents are used to some extent; however, their effectiveness is still being evaluated and considered on a project-specific basis.

In developing a mixture design with RAP or RAS, it may be desirable to consider adjusting the binder used to accommodate the stiffer reclaimed binder. AASHTO PP 78-14 (2016) previously recommended a tiered approach to choosing the virgin binder grade; however, this approach is no longer advised, and more rigorous binder testing is now encouraged for the use of high percentages of RAP and RAS.

Many states use different percentages of RAP and RAS based on the total RAP and/or RAS and on local experience instead of using the AASHTO guidelines. Because the RBR concept accounts for the varying binder content and properties in reclaimed sources, it is a better method for specifying allowable amounts of RAP and RAS rather than the total combined RAP plus RAS content. However, it should be used with caution, as the RBRs of different materials may not be equivalent in the way they impact the binder.

Using a normal PG virgin binder in conjunction with the reclaimed binder from RAP or RAS has proven effective in instances where a relatively low reclaimed binder ratio (less than 0.15–0.25) is the target. However, as RAP and/or RAS percentages in a mixture increase, it may be necessary to use a softer binder, more binder, or a recycling agent (if proven to be effective with recycled material source) to take full advantage of the reclaimed binder (Tran et al., 2012). NCHRP Project 09-58 The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios is currently investigating the use of recycling agents on reclaimed asphalt binder. A 2014 National Asphalt Pavement Association scanning tour on high RAP asphalt pavements in Japan, where the average RAP content in mixtures is 47 percent, concluded, “The asphalt industry should also consider [recycling agents] [sic], softening binders, or another agent to facilitate high RAP amounts in asphalt mixtures” (West & Copeland, 2015).

Because it is problematic to extract and grade RAS recovered asphalt binders, a performance-engineered mixture design, which uses mixture performance tests (including rutting, cracking, stripping, durability, and other performance requirements), is beneficial for developing recommendations on binder grade adjustments or designing mixtures with recycled materials. Alternatively, extracted and recovered binders can be blended with virgin binders and/or recycling agents and tested in accordance with the recently published AASHTO PP 78-17 guidance discussed below; however, this method assumes 100 percent blending, which is unlikely with RAS.

Methods for Increasing Binder Content/Durability in Asphalt Mixtures with High Binder Replacement Ratios

In August 2017, AASHTO published significant changes to PP 78-14 (2016). The revised PP 78-17 has binder quantity and binder quality requirements. For binder quantity, the minimum voids in mineral aggregate (VMA) requirement as identified in M 323 should be increased by 0.1 percent for every 1 percent RAS by weight of total aggregate. For binder and mixture quality, there are three options:

1. Evaluate the binder embrittlement using the critical low-temperature differential ($\Delta T_{c.}$) of greater than or equal to −5°C
2. Test the asphalt mixture with performance test as an alternative to binder quality testing
3. Recommend a default value for a maximum RASBR ≤ 0.10

Embrittlement of the composite blended binder is qualitatively captured through measurement of ΔT_c, the difference (Δ) in critical cracking temperature (T_c) based on the stiffness value (S), and the relaxation value (m) as determined by the bending beam rheometer (BBR). More information on this testing parameter is also found in ASTM D7643, *Standard Practice for Determining Continuous Grading Temperature Grades for PG Graded Asphalt Binders*.

ΔT_c provides a method for evaluating the effect of RAS binder on the cracking behavior of asphalt mixtures. This can be used to control the amount of RAS asphalt binder entering a mixture design rather than trying to determine which portion of the RAS binder is effective. The critical temperature difference quantifies the embrittlement and impact of binder aging on performance associated with adding RAS or recycling agents to a mixture. This testing is conducted on virgin material that has undergone long-term aging in the pressure aging vessel. If the final blended binder includes both RAP and RAS or recycling agents, all should be considered in the total blended binder for evaluation.

Testing to determine ΔT_c is conducted on the total blended binder, which is considered a conservative condition, and research is currently being conducted to assess acceptable ΔT_c values and further refine this property's relationship with field performance. Disagreements about the amount of blending that occurs between virgin and reclaimed binder are reduced as the maximum impact of the RAS binder will occur when complete blending occurs. If blending is less than complete, the impact of the RAS binder on the total blended binder's stiffening and relaxation properties is less than what the laboratory would predict. However, not having enough effective binder effective due to incomplete blending in the mixture may also impact the ultimate mixture performance. This would be the case if the binder content from the non-blended RAS is included as total binder content.

To account for the unblended portion of the RAS binder, the revised PP 78-17 recommends increasing the amount of asphalt binder in the mixture by increasing the VMA by 0.1 percent for every 1 percent of RAS by weight of aggregate. It further cautions that this may result in over-asphalting mixtures if a state has increased its effective asphalt content by either increasing VMA or reducing air voids in its mixture designs. While the revised PP 78-17 does not include tiers specifying different grades of virgin asphalt binder at different RASBRs, it does include guidance for agencies to develop these sorts of tiers.

The standard also allows agencies to evaluate the mixture using performance tests in lieu of extracted binder testing. Many agencies use tests such as the Hamburg Wheel Tracking Test and Asphalt Pavement Analyzer to assess rutting (Mohammad et al., 2015) and further work is being conducted to evaluate which cracking test(s) are most appropriate (refer to NCHRP 09-57 and NCHRP 09-57A). Further information on all current cracking tests is provided by Zhou et al. (2016). In addition to these performance tests, the FHWA continues to advance the Asphalt Mixture Performance Tester (AMPT), which may be used to conduct both index-based and performance prediction-based tests (FHWA, 2013a; FHWA 2013b; FHWA 2016). Additionally, moisture sensitivity should be considered using methods such as the Hamburg Wheel Tracking Test, AASHTO T 324, or the Moisture Induced Sensitivity Test (Htet, 2015; Solaimanian et al., 2003).

Performance

Numerous projects or test sections containing RAS and up to 50 percent RAP have been constructed and monitored across the United States over the past several decades. Mixtures where RAP and RAS are both combined tended to exhibit more cracking than virgin mixtures, but the extent of cracking, in most cases, was determined acceptable by the owners (Newcomb et al., 2016). Good performance with RAP and RAS mixtures is reported in different climates and traffic conditions when appropriate design, production, and construction are applied. Proper material processing, design, and construction practices are critical for mixtures having higher RBRs so that premature failures do not occur. The National Asphalt Pavement Association (NAPA) offers guidance on processing RAP and RAS, mixture design with RAP and RAS, and construction practices (West, 2015; West & Copeland, 2015; Hansen, 2009; Newcomb et al., 2007).

In addition, two important observations were made based on the performance of the field test sections cited:

1. The use of a high-quality virgin binder improves the durability and cracking resistance of RAP and RAS asphalt mixtures.
2. High RAP and RAS mixtures can be designed to have better performance than virgin mixtures when an engineered mixture design approach is employed with proper engineering and performance testing (Newcomb et al., 2016).

Summary

Quality asphalt mixtures can be produced and constructed using RAP and RAS given careful consideration of climate, traffic, pavement type, and component materials.

To gain the maximum engineering and performance benefits and reduce life cycle costs from the use of reclaimed asphalt binder, the following recommendations are given:

- Recognize that different sources of RAP and RAS have widely varying binder quantity and material property characteristics. The limits for each should be addressed separately.
- Contractors may fractionate RAP sources to have more flexibility and control in meeting mixture design standards. When fractionating, it is important to consider the RBR due to the different binder contents of the fractionated material.
- RAP binders are stiffer than virgin binders, and RAS binders are much stiffer and, in many cases, have less desirable relaxation properties than RAP binders. Without proper attention to these embrittlement properties, the use of high quantities of RAP and RAS combined may lead to pavement projects with premature cracking. Premature cracking can also be caused by a combination of low total asphalt contents due to the incorrect quantification of available binder in recycled materials plus the impact of the recycled binder on new mixture aging.
- Use the reclaimed binder ratio (RBR) as opposed to using the total amount of reclaimed material (binder plus aggregate) when setting responsible use limits for recycled materials. Given the differences in binder quantities and binder embrittlement (stiffness and relaxation) between RAP and RAS, and the effect of reclaimed binder properties on both binder and mixture performance, RBR offers an improved method for specifying the use of these recycled materials.
- Consider different levels of maximum binder ratios for each material (RAP, MWAS, PCAS, and combinations) by quantifying the properties of blended recycled and virgin binder directly due to differences in the binder properties from each material.
- The revised PP 78-17 has binder quantity and binder quality requirements. For binder quantity, and the minimum VMA requirement in M 323-17 should be increased by 0.1 percent for every 1 percent RAS by weight of total aggregate. For binder and mixture quality, there are three options:
    - Evaluate the binder embrittlement using the critical low-temperature differential (ΔT_c) of greater than or equal to −5°C
    - Test the asphalt mixture with a performance test as an alternative to binder quality testing.
    - Recommend a default value for a maximum RASBR ≤ 0.10.

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State of the Knowledge for Use of Asphalt Mixtures with Reclaimed Binder Content

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