Final Report

IMPACT OF RECYCLED ASPHALT SHINGLES (RAS) ON ASPHALT BINDER PERFORMANCE

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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 feel	0.093	square meters	m^2
yd^2	square yards	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	Mg
		TEMPERATURE (exact)		
°F	Fahrenheil temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	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	35.71	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	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

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

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16. Abstract

This study evaluated the effect of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) on virgin binder true grade and fracture energy density (FED). A mortar approach, which avoids the need for binder extraction, was adopted to quantify the RAP/RAS effect on virgin binder true grades by using the grade change rate (GCR) parameter. The existing data analysis method was found to yield unreliable RAP/RAS GCR results, and an alternative method was developed to predict the properties of RAP/RAS blended binders for GCR determination. The enhanced mortar approach successfully captured the stiffening effect of RAP/RAS: (1) RAS had greater GCR at high and low temperatures than the RAP; (2) the stiffest RAP had greater GCR than the other two RAPs; and (3) tear-off (TO) shingles exhibited greater high temperature GCR and slightly lower temperature GCR than the manufacture waste shingles. Results also revealed that RAP GCR is independent of RAP binder replacement rate, but RAS GCR increases exponentially with increased RAS binder replacement rate.

Use of soft virgin binders appeared to effectively compensate for the stiffening effect of RAP/RAS, in terms of Superpave binder true grades. The limit of RAS content was found to be approximately half of the allowable RAP content for a given virgin binder. However, whereas RAP binder increased the FED of virgin unmodified binders, the opposite trend was observed for RAS binder, especially for the TO shingles which caused significant reductions in virgin binder FED. This is an important finding because decreased binder FED indicates deteriorated binder fracture tolerance. In addition, great caution should be exercised when polymer-modified asphalt (PMA) binders are used in RAP/RAS mixtures because both RAP and RAS decreased the PMA binder FED, with the RAS effect being much more pronounced. A follow-up study is recommended to extend the research efforts to mixture evaluation since mixture performance is governed by factors other than binder performance, such as RAP/RAS gradation and mixture gradation.

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EXECUTIVE SUMMARY

The use of recycled asphalt shingle (RAS) as a partial replacement for virgin binder and aggregate in asphalt mixtures has increased over the past decade for economic and environmental benefits. However, the current usage of RAS is still low, and tremendous amounts of RAS are used in low-value, non-bituminous applications, or discarded. This is due to several concerns related to the reduction in performance caused by increasing the amount of recycled material incorporated into the pavement mixtures. Soft virgin binder has typically been used to offset the stiffening effects introduced by reclaimed asphalt pavement (RAP) in asphalt mixes. To select the proper virgin binder, it is essential to know the true grade of RAP binder and how much RAP binder blends with the virgin binder. However, it is difficult to characterize the stiff RAS binder through conventional Superpave binder testing, especially for its low temperature properties, which are practically impossible to obtain. Also, it is still unknown how much RAS binder is active for blending with the virgin binder in mixtures.

This study adopted a mortar testing approach, which avoids the need for solvent-based binder extraction and recovery, to assess how RAP/RAS binder affects the performance of virgin binders in terms of Superpave true grade. Mortar characterization was conducted by performing the Superpave binder tests (i.e., dynamic shear rheometer (DSR) and bending beam rheometer (BBR)) on blends of virgin binder and RAP/RAS fine fractions at high, intermediate, and low temperatures. In addition, the binder fracture energy (BFE) tests were conducted on blends of virgin and RAP/RAS binders to determine the RAP/RAS effect on the fracture tolerance of virgin binders at intermediate temperatures. This study employed three RAP sources, two RAS sources, two rejuvenators, and six virgin binders including two unmodified binders, three rejuvenated binders and one polymer-modified asphalt (PMA) binder. Impacts of RAS source, RAP source, virgin binder type, recycled binder replacement rate and the inclusion of rejuvenators on virgin binder performance were evaluated.

Two preliminary sets of tests were conducted on mortars with RAP-alone and RAS-alone, following the AASHTO provisional draft. However, the data analysis procedure in the existing draft failed to provide reliable grade change rate (GCR) results, especially at high and intermediate temperatures. The shift factor in the existing mortar approach was identified as the source of underestimated RAP/RAS effect at high temperatures and possibly overestimated effect at low temperatures. In response, this study developed an alternative data analysis method that eliminates the use of a shift factor. The alternative method was validated by satisfactory comparison between predicted and measured high temperature true grades of RAP binder blends at three RAP binder replacement rates (i.e., 15%, 30%, and 100%). This also indicates that (1) a high level of blending (close to complete) occurred between virgin and RAP binders in blended binders and RAP mortars and (2) RAP GCR was independent of RAP binder replacement rate.

RAS GCR determined from 15% RAS mortars was used to predict the grades of RAS binder blends at three binder replacement rates (i.e., 15%, 30% and 100%). Although accurate grade predictions were made for 15% TO shingle binder blends, predictions for 30% and 100% were notably low. This indicates the RAS GCR or RAS effect increases exponentially with increased RAS binder replacement rate. Predictions based on the GCR obtained from 30% RAS

mortars matched the measured grades of 30% RAS binder blends. This implies that RAS GCR needs to be determined at the RAS binder replacement rate intended for use.

The enhanced mortar approach with the alternative data analysis method was used to capture the stiffening effect of RAP/RAS on virgin binders. For a given virgin binder type, the stiffest RAP (i.e., WHI RAP) had greater GCR values at high and low temperatures than the other two RAP sources. Furthermore, two RAS sources exhibited greater GCR values at high and low temperatures than the three RAP sources. Finally, TO shingles had greater high temperature GCR but smaller low temperature GCR values than the MW shingles.

The assumption that RAP-alone and RAS-alone GCR can be linearly combined to predict the RAP-RAS GCR at any RAP/RAS binder replacement rate was evaluated in this study. Mortar samples simultaneously containing RAP and RAS were prepared and tested to obtain the RAP-RAS GCR. The use of linearly combined RAP-alone and RAS-alone GCR yielded true grades of RAP-RAS blended binders comparable to values as predicted using measured RAP-RAS GCR. The average differences between two predictions were 1.1°C and 0.9°C for the high and low temperature true grades of the RAP-RAS binder blends, respectively. This supports the use of the linear assumption for the contents of RAP-RAS evaluated in this study.

RAP/RAS GCR also allows for accurate determination of RAP/RAS content for use in mixtures. Since there is no target grade of blended binders, those based on a typical RAP (i.e., ATL RAP) in Florida with qualified virgin binders (i.e., PG 52-28 and PG 58-28) at specified contents were used as thresholds for RAS binder blends. The limit of RAS content at each tier was found to be approximately half of the allowable RAP content. Although the use of PG 52-28 binder is recommended for RAS mixtures in the upcoming FDOT Dev334RAS specification (FDOT, 2014), the use of RAS GCR provides a more consistent way of selecting the PG grade of virgin binder for different type and amount of RAS and different type and amount of other inclusions, such as RAP.

Use of soft virgin binders including, those rejuvenated with Aromatic oil and re-fined engine oil bottom (REOB), effectively compensates for the RAP/RAS stiffening effect. However, RAS was found to reduce the fracture energy density (FED) of virgin binders, indicating deteriorated fracture tolerance at intermediate temperatures; whereas an opposite trend was observed for RAP. Great caution should be exercised when PMA binders are used as virgin binders in mixtures containing RAP and/or RAS. The addition of RAP/RAS binder significantly reduced the PMA binder FED, which potentially can be attributed to the dilution of polymer modification in addition to the stiffening effect.

It must be emphasized that neither binder nor mortar evaluation truly represents the actual blending between virgin and RAP/RAS binder in mixtures. Also, mixture performance is governed by factors that the two approaches cannot account for, such as RAP/RAS gradation and resulting mixture gradation. Thus, a follow-up study is strongly recommended to extend the research efforts to mixture evaluation.

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CHAPTER 1 INTRODUCTION

1.1 Background

With increases in the price of asphalt binder, the asphalt industry has been searching and experimenting with sustainable alternatives since the 1970s. This has led to the implementation of various recycling techniques that are aimed at reducing energy consumption, construction waste, and construction cost for highway pavement. The use of reclaimed asphalt pavement (RAP) is commonplace in the United States, and another waste material that has gained increasing interest in the asphalt industry is recycled asphalt shingle (RAS). Compared to RAP, RAS contains a higher content of a more aged asphalt binder. A survey by Hansen and Copeland (2017) showed that the use of RAP and RAS as alternatives to virgin asphalt and aggregate saved 2.6 billion dollars in 2015 alone, in addition to the environmental benefit of resource preservation. However, the same survey also reported that the average RAP content used in asphalt mixtures is still low (20.3% as of 2015), and only 15% of the total available supply of waste shingle is recycled into asphalt pavements.

The main reason that hinders the use of higher RAP and RAS contents is the concern over excessively stiff and brittle mixtures with potentially diminished cracking performance. The effect of highly aged RAP and RAS binder on virgin binder performance has been commonly evaluated by means of binder tests conducted on blends of virgin and recovered RAP/RAS binders. However, binder extraction and recovery is notably time-consuming (it takes approximately 8 hours to complete) and may also affect binder properties due to the use of solvents. Furthermore, recycled binder may only partially blend with virgin binder in real mixtures. Despite extensive research efforts, there is still no well-accepted methodology to reliably determine the degree of blending between virgin and RAP/RAS binders in a mixture (Huang et al., 2005; Al-Qadi et al., 2009; Shirodkar et al. 2011). Typically, a full blending scenario is assumed for RAP (e.g., blending chart approach) while a contribution factor (between 0.5−1 according to AASHTO PP 78) is estimated for RAS. Still, neither full blending nor an estimated degree of blending represents how aged binder differentially distributes in a real mixture. Most importantly, even if it was possible to accurately determine the degree of blending, its meaning with respect to mixture performance would require further investigation.

For these reasons, the asphalt community seeks a method to determine RAP and RAS binder properties without the need for binder extraction and to predict the effect of RAP and RAS on virgin binder properties in a manner that more closely simulates the real blending scenario in a mixture. One promising approach is to test mortar samples composed of fine fractions of RAP/RAS and virgin binder. Ma et al. (2010a, 2011) developed a testing procedure to estimate the low temperature properties of RAP binder based on Superpave bending beam rheometer tests on a series of mortar and binder specimens. Additionally, Ma et al. (2010b) applied that mortar testing approach to determine the allowable RAP content to meet low temperature grade requirements when combined with a given virgin binder. After extensive data verification, Swiertz et al. (2011) modified the testing procedure to evaluate the effect of RAP/RAS on binder low temperature true grade. A major simplification of the modified procedure was the need to test only two mortar specimens and a virgin binder specimen. Also, the concept of grade change rate (GCR) was introduced to predict binder true grade at any RAP/RAS binder replacement rate. Later, Swiertz and Bahia *(2011)* extended the mortar testing approach to intermediate and high temperatures. Finally, a provisional standard draft, entitled *"Standard Method of Test for Estimating Effect of RAP and RAS on Blended Binder Performance Grade without Binder Extraction"* was put forward for consideration by the American Association of State Highway and Transportation Officials (AASHTO).

1.2 Objectives

The major objective of this research is to determine the effect of recycled shingles on asphalt binder performance. The study included RAS binder, RAP binder and virgin binder combined at different binder replacement rates. Detailed objectives of this project are:

- Assess how the addition of RAS binder affects the performance of combined binders in terms of Superpave continuous performance grade and fracture energy density.
- Evaluate how important factors such as RAS source, virgin binder type, RAP source, recycled binder replacement rate and inclusion of rejuvenators impact binder performance in the above assessment.

It was anticipated that the findings of this research would lead to conclusions on whether RAS can be introduced with minimal impact to binder performance. If appropriate, recommendations and guidelines would be developed on how to effectively incorporate RAS for optimized binder performance.

1.3 Scope

Two RAS sources, three RAP sources which are typically used together with RAS, and six virgin binder types including one heavily polymer-modified, two unmodified and three rejuvenated binders were employed in this study. Assessments of RAP/RAS effect on virgin binder true grades were made based on a mortar testing approach, which applies the Superpave binder tests (dynamic shear rheometer (DSR) and bending beam rheometer (BBR)) on blends of virgin binder and RAP/RAS fine fractions. Mortar tests were conducted on samples containing: 1) RAP-alone; 2) RAS-alone; and 3) combinations of RAP and RAS; at high, intermediate and low temperatures. Effect of RAP/RAS on fracture tolerance of virgin binders were evaluated by using the binder fracture energy (BFE) tests on blends of virgin and extracted RAP/RAS binders at intermediate temperatures.

1.4 Research Approach

To meet the objectives of the project, the research was categorized into tasks, summarized below:

Task 1—Literature review: A comprehensive literature review was conducted to identify primary factors and constraints associated with the use of RAS, including RAS binder replacement rate, type of virgin binder, combined use of RAP and RAS, binder characterization and existing sources of RAS in Florida. The literature review focused on obtaining the understanding necessary to help identify the impact of RAS on laboratory measured material properties and potential field performance.

Task 2—Material Acquisition and Characterization: Based on information and results identified in Task 1, factors deemed to be most important for immediate study were shown in Figure 1-1 and briefly described below:

- Two shingle sources: (i) one tear-off (TO) shingle source and (ii) one manufacture waste (MW) shingle source.
- Three RAP source stockpiles: (i) RAP from Atlantic Coast (fine aggregate gradation, Georgia granite); (ii) RAP from Whitehurst (coarse aggregate gradation, FL oolitic limestone); and (iii) RAP from Anderson Columbia (coarse aggregate gradation, Georgia granite).
- Two rejuvenators were selected: (i) aromatic oil and (ii) re-fined engine oil bottoms (REOB).
- Six virgin asphalt binder types were employed, including (i) two unmodified binder; (ii) one heavily polymer-modified binder; and (iii) three rejuvenated binders.[1]

Solvent methods were used to determine RAP and RAS binder contents and to collect RAP and RAS binders for characterization. The true grades of virgin binders and extracted RAP/RAS binders were determined following the standard Superpave binder grading procedures. In addition, the binder fracture energy (BFE) tests were performed to determine the fracture energy density (FED) of virgin binders at intermediate temperatures (0–25°C).

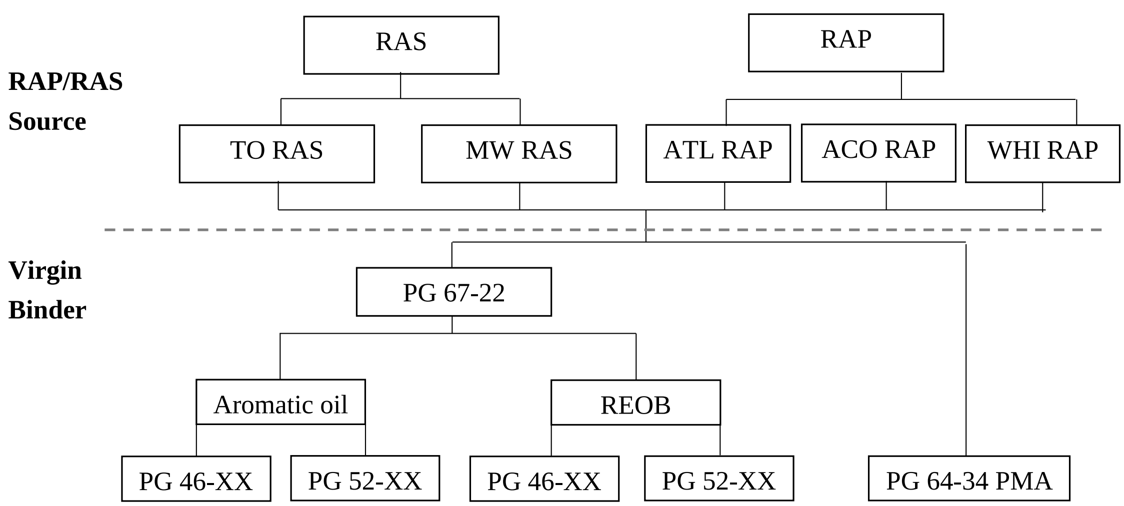

Figure 1-1. Materials selected for evaluation

[1] Virgin binder types were later changed based on testing results. Details can be found in section 3.3.2.

Task 3—Experimental Design: Assessment of the effect of RAP/RAS binder were made based on the Superpave binder testing (bending beam rheometer (BBR) and dynamic shear rheometer (DSR)) and the binder fracture energy (BFE) tests.

Two preliminary sets of tests on mortar specimens were conducted before selecting the final eight combinations of RAP and RAS. Mortar testing were performed according to the procedure proposed by Swiertz et al. (2011), which has been implemented into a draft AASHTO method, titled "Standard Method of Test for Estimating Effect of RAP and RAS on Blended Binder Performance Grade without Binder Extraction".

One preliminary set included virgin binder and RAP-alone. The purpose of this set is to quantify the change in true grade caused by introduction of RAP binder for a given virgin binder and RAP source. This parameter is called RAP grade change rate and is defined in ºC/%RAP. Assuming a linear relationship, the RAP grade change rate provides a prediction of the change in true grade for any RAP binder replacement rate. Similarly, a second set included virgin binder and RAS-alone. The purpose of this set is to determine the RAS grade change rate (ºC/%RAS). The RAS grade change rate provides a prediction of the change in true grade for any RAS binder replacement rate.

It is also assumed in the AASHTO draft that any combination of RAP and RAS binder percentages followed a linear combination of the RAP-alone and RAS-alone blends. Thus, RAP-alone GCR and RAS-alone GCR results can be used to predict the true grade of a virgin binder blended with any RAP and RAS binder replacement rates (Figure 1-2). This key assumption was evaluated by comparing the grades of RAP and RAS blended binders predicted using 1) linearly combined RAP-RAS GCR and 2) RAP-RAS GCR measured from mortars simultaneously containing RAP and RAS. A total of eight combinations of RAP-RAS mortars were prepared for testing at high, intermediate and low temperatures.

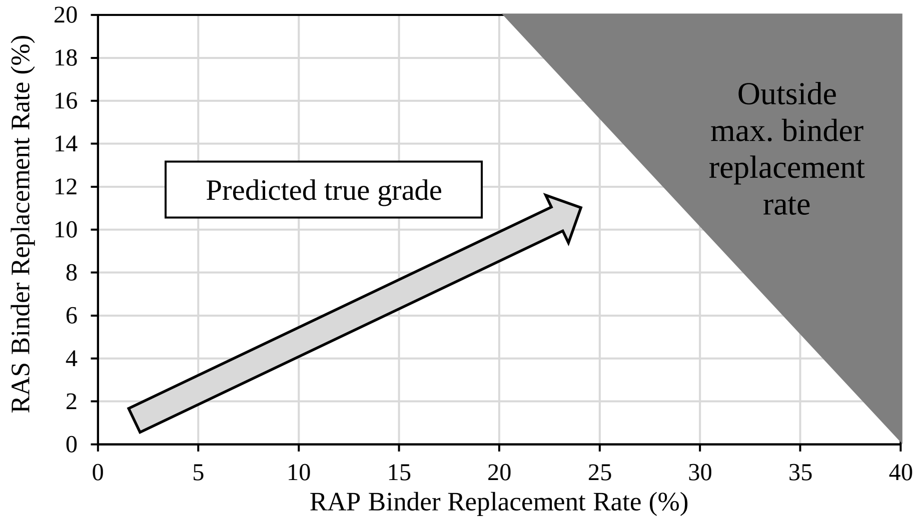

Figure 1-2. Chart of continuous PG grade of combined binder for different RAP-RAS replacement rates (for illustration purposes)

In addition, the binder fracture energy (BFE) tests were performed to evaluate the RAS effect on fracture tolerance of virgin binders at intermediate temperatures. Since the primary focus of this study was on RAS effect, limited BFE tests were also conducted on selected RAP binder blends. Nine combinations of the WHI RAP binder (the stiffest RAP in this study) and three virgin binders at three RAP binder replacement rates were evaluated. Then, a total of twenty-four RAS binder blends including two RAS sources, two RAS binder replacement rates and six virgin binders were prepared and tested.

Task 4—Testing and Analysis of Results: Laboratory tests were conducted in accordance with the experimental plan developed in Task 3 which included 1) determine and evaluate the RAP-alone GCR and RAS-alone GCR; 2) evaluate the assumption made in the draft that RAP-alone and RAS-alone GCR can be linearly combined to predict the RAP-RAS GCR; and 3) evaluate the RAP/RAS effect on the virgin binder fracture energy density (FED) at intermediate temperatures.

Task 5—Findings and Conclusions: All binder and mortar results were thoroughly evaluated for consistency and to evaluate the effects of RAS source, virgin binder type, RAP source, recycled binder replacement rate and inclusion of rejuvenators on binder performance.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

With increases in the price of asphalt binder, the asphalt industry has been searching and experimenting with sustainable alternatives since the 1970s. This has led to the implementation of various recycling techniques that are aimed at reducing energy consumption, construction waste and construction costs for highway pavements. The use of reclaimed asphalt pavement (RAP) is commonplace around the country; many states are comfortable with using RAP because the asphalt binder in the RAP blends appreciably with the virgin binder and contributes to the properties of the blend (Zhou et al., 2012). Recycled asphalt shingles (RAS) is another source of material which can be used as a partial replacement for virgin asphalt and aggregate in asphalt mixtures. As an extensive literature review had been conducted on the use of RAP in hot mix asphalt (HMA) mixes (Roque et al., 2015), this study mainly focused on the primary factors and constraints associated with the use of RAS and combinations of RAP and RAS in HMA mixes.

There are generally two sources of RAS materials for paving applications: manufacturing waste (MW) shingles and tear-off (TO) shingles. MW shingles are post-industrial scraps which have not been used as roofing material. TO shingles are composed of scraps that were removed from roofs in service, which are often called post-consumer (PC) shingle scraps. MW shingles tend to be more consistent and less stiff than TO shingles because they have not been exposed to the environment and further oxidation. In the US, roof installation generates an estimated 7 to 10 million tons of shingle tear-off waste and installation scraps annually, while more than 60 manufacturing plants generate another 750,000 to 1 million tons of manufacturing shingle scraps (Grzybowski, 1993).

The use of RAS in HMA production has been increasing over the past decade for technical, economical, and environmental reasons. A survey by the National Asphalt Pavement Association (NAPA) showed that the amount of RAS used in asphalt mixtures increased significantly from 0.7 million tons in 2009 to 1.65 million tons in 2013 (Hansen et al. 2014). Assuming a conservative asphalt binder content of 20% for shingles, this represents approximately 0.3 million tons (1.9 million barrels) of asphalt binder conserved in 2013. The survey also showed that 36 states used RAS in new asphalt mixes in 2013. However, the use of RAS in HMA production only consumes approximately 15% of the total amount of RAS produced, which indicates that a tremendous amount of RAS, especially TO shingles, are accumulated, and then used in either low-value, non-bituminous applications, or are being wasted. Therefore, more effort is needed for the evaluation and use of TO shingles.

Similar to RAP, it is common practice to dry blend RAS with the aggregates before the asphalt binder is added to the mixes. AASHTO PP 78, *Standard Practice for Design Consideration When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures*, provides a procedure for incorporating RAS in HMA. Unlike RAP binder, the asphalt binder in RAS is a very stiff, highly oxidized material that was not originally manufactured for paving application. Also, RAS has much higher asphalt binder content (20% -35%) than RAP (~5%), and therefore most states allow high amounts of RAP mixtures (>25% RAP by weight) but only up to 5% RAS by weight in new pavements. The maximum allowable amount of RAS was selected based on the observations that mixes which contained up to 5% RAS by weight performed equally well as traditional HMA pavements in the field (Krivit., 2007).

In addition to the dry processing method, Elseifi et al. (2012) proposed another strategy in which RAS is ground via a wet process to ultrafine particles (more than 80% passing sieve No. 200-0.075 mm) and then blended with virgin asphalt binder at high temperature prior to mixing with the virgin aggregate. Elseifi et al. (2012) concluded that the wet process offers the potential to use more RAS in mixes and may allow for better control of the chemical and physical reactions taking place in the blend.

While the recycling of RAS brings economic and environmental benefits, it should not compromise pavement performance. It is general knowledge that the inclusion of RAS could reduce the mixture susceptibility to permanent deformation; however, the oxidized/aged binder could also adversely affect the mixture's cracking performance, especially with excessive amounts of RAS without pretreatment and modification. There are several reasons for the lack of desirable performance and consistency in using RAS, such as the variability in the properties of RAS, uncertainty of how RAS binder interacts with virgin binder and how this interaction affects mixture performance.

2.2 RAS Characterization

2.2.1 RAS Processing

In general, there are five steps to process RAS: collecting, sorting, grinding, screening and storing the processed RAS, plus asbestos testing for the TO shingles (Zhou et al., 2012). As shown in Figure 2-1, RAS must be processed, or ground to a uniform size, before being used in asphalt paving mixtures (Willis., 2013).

Figure 2-1. RAS stockpile before (left) and after (right) grinding

Debris such as metal, plastic and wood should be removed prior to grinding. These deleterious materials are more often present in TO than MW shingles. To avoid agglomerating during grinding, it is recommended to pass the RAS material through the grinding equipment only once to reduce heating (Chesner et al., 1997). RAS sizing is a key characteristic which determines the product's suitability for various applications. The current specification (AASHTO MP 23) states that RAS should be ground such that 100 percent passes the 12.5 mm sieve. However, a finer grind of RAS has been found to be more beneficial. For example, McGraw et al. (2007) stated that RAS ground to a finer size passing the 4.75 mm sieve can be expected to effectively utilize as much as 95% of the total available asphalt.

The ground shingles need to be screened to remove the oversized pieces which may not be able to release the recycled binder in asphalt mixtures and behave like aggregate particles (Chesner et al., 1997). Processed RAS tends to agglomerate during static storage in a stockpile, especially in a high temperature environment. To prevent the processed RAS from clumping together, it is recommended that contractors blend the processed RAS with a small amount of less sticky material, such as sand or RAP (Im and Zhou, 2014). Also, it is important to store the TO shingles and MW shingles separately because they normally have different recycled asphalt binder content and properties as described in Sections 2.2.2 and 2.2.3.

2.2.2 RAS Asphalt Content and Aggregate Gradation

Asphalt shingles typically consist of felt, asphalt, mineral filler, and mineral granules. Most felts used today are made of glass fibers, but some shingle felts recycled from old roofs are based on wood or cellulous fibers. Typically, glass fiber-based shingles have AC content in the rage of 15% to 20% whereas the AC content for organic shingles is in the range of 30% to 35%. Normally, TO shingles have higher AC content than MW shingles, as TO shingles tend to lose part of the surface granules during service due to weathering (Davis, 2009).

Similar to RAP, there are two types of RAS gradations. One is the gradation of RAS particles (without removing the coating binder) which depends on the grinding technique applied. Figure 2-2 compares a regular ground RAS to a finer ground RAS. It should be noted that finer grinding may result in excessive dust (minus No.200 sieve). Table 2-1 illustrates the requirements on RAS particle gradation for different state transportation agencies. The second gradation type is the distribution of RAS aggregate after removing the coating binder, which is always finer than the RAS particle gradation. Either solvent-based binder extraction or the ignition oven test can be performed to remove the RAS binder and obtain the RAS aggregate for gradation analysis.

Table 2-1 Requirements for RAS gradation

States in the U.S.	1/2"	3/8"	#4	No.100	No.200
Georgia	100%	--	--	--	--
Iowa	100%	98%	90%	--	--
South Carolina	100%	--	70-95%	15%Max	7%Max
Minnesota	100%	--	90%	--	--
Texas	100%	95%	--	--	--
Virginia	100%	--	--	--	--
AAHSTO PP78	100%	100%	--	--	--

Figure 2-2 Normal grind RAS (left) and finer grind RAS (right)

Zhou et al. (2012) performed the ignition oven tests on seven different types of processed RAS which were sampled from stockpiles around the state of Texas. All seven processed RAS sources met the TxDOT's specification which requires 100 percent passing 1/2 inch and a minimum of 95 percent passing the 3/8-inch sieve. As shown in Table 2-2, TO shingles not only had higher asphalt binder contents but also higher variability in asphalt content than MW shingles. Figure 2-3 indicates that MW shingles had a slightly finer aggregate gradation than the TO shingles. Since the asphalt content for RAS is very high (more than 20%), the researchers recommended a reduction of the sample size for the ignition oven test from 1300 g to approximately 600 g to ensure complete burning of the asphalt binder and to obtain accurate measurements.

Table 2-2 RAS asphalt content determined by using the Ignition oven test

Asphalt Content (%) (Ignition Test)	Blended (MW +TO Shingles)	MW Shingle 1	MW Shingle 2	MW Shingle 3	TO Shingle 1	TO Shingle 2	TO Shingle 3
Replicate 1	20	21	20	21	25	33	22
Replicate 2	22	29	20	21	24	29	24
Replicate 3	20	21	20	21	28	28	22
Replicate 4	20	19	23	20	28	28	23
Replicate 5	19	20	19	19	28	27	23
Replicate 6	20	20	24	20	28	27	23
Replicate 7	20	19	24	20	28	27	24
Average	20	20	22	20	27	28	23

Hassan et al. (2014) evaluated a wide range of RAS materials collected from recycling plants across the US, including nine TO shingle sources and one MW shingle source. Based on ignition oven test results, the asphalt binder content for TO shingles ranged from 24% to 31% and MW shingle source (from Minnesota) had lowest value of 20.4% (Figure 2-4). Interestingly, the

RAS aggregate gradation obtained in this study was much coarser than the one recommended in AASHTO PP 78, as shown in Figure 2-5.

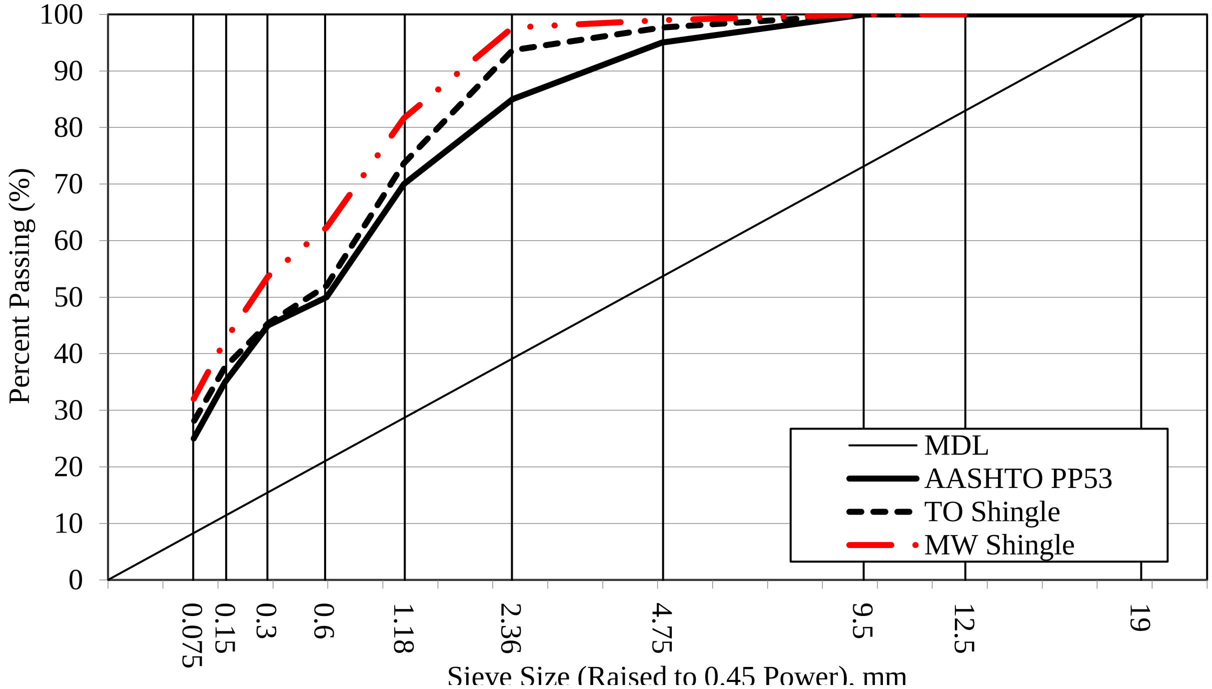

Figure 2-3. RAS aggregate gradations

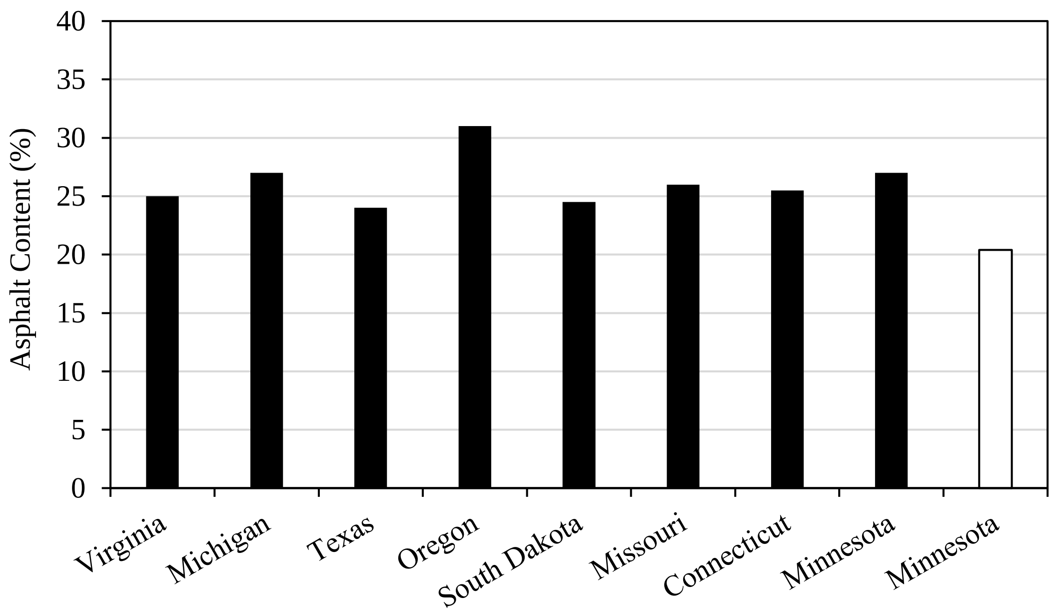

Figure 2-4. Asphalt content for various RAS sources (Hassan et al. 2014)

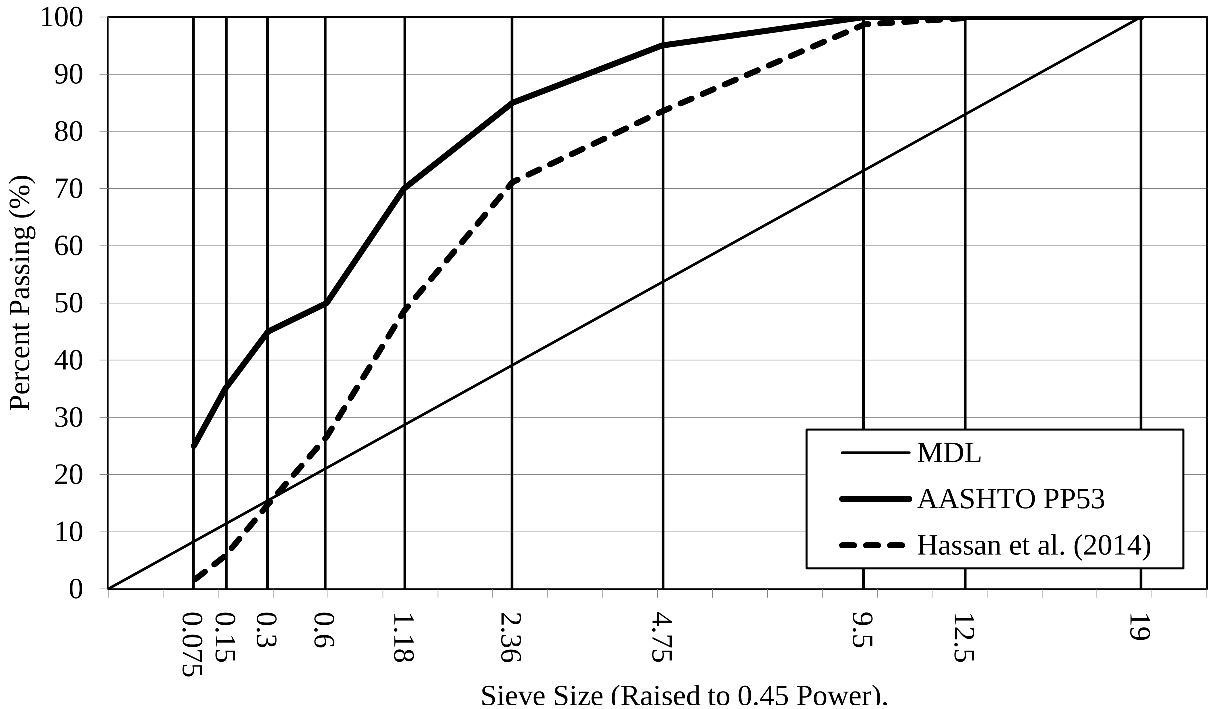

Figure 2-5. RAS gradation curve recommended by Hassan et al. (2014) and AASHTO PP 78-14

2.2.3 RAS Binder

AASHTO PP 78-14 suggests that the performance grade of binders in mixes containing RAS be determined based on a linear blending analysis, similar to that used for high RAP content mixes. This requires the RAS binder be extracted, recovered, and tested using standard asphalt binder performance grading procedures. However, this process is very challenging for RAS binders. RAS binders are stiffer and have different rheological properties than virgin or modified binders since they are air-blown during shingle production. In addition, further aging in the rolling thin film oven (RTFO) test and pressure aging vessel (PAV) test makes the material difficult to mold and characterize.

Zhou et al. (2013) characterized ten processed RAS binders obtained in Texas, including both MW and TO shingles. The BBR test was unable to provide reliable low temperature grade results due to the inability of the PAV-aged shingle binders to relax under force. An alternative test, such as a binder cracking test, was thus recommended for further study. The researchers also found that regular DSR testing cannot be used for RAS PG grading since most RAS binders have a critical high temperature greater than the boiling point of water. A DSR with high-temperature model was successfully used to measure high grades of these stiff binders. The TO shingle binders with an average high temperature grade of 178°C were found to be much stiffer than MW shingle binders having an average high temperature grade of 131°C. It appears that the RAS binders are very stiff with a low ability to relax; therefore, it is critical to understand the impact of RAS binders on the rheological properties of the combined binder after blending with virgin binders.

Hassan et al. (2014) measured the rheological properties of recovered binder from five processed RAS stockpiles obtained across the US, including one MW and four TO shingles. Similar to what Zhou et al. (2013) observed, they found that the RAS binder could not be graded by using the BBR test at low temperatures, even when tested at 0 °C. All RAS binders were graded as PG 118 +/- XX using the Superpave binder specification system, indicating the high temperature properties of the binders from RAS sources sampled from different recycling plants around the country did not substantially change. In addition to the Superpave binder tests, high-pressure gel permeation chromatography (HP-GPC) analysis was conducted on the same five processed RAS binders. Except for one TO RAS, the content of high molecular weight (HMW) and low molecular weight (LMW) in three RAS sources did not vary substantially. Three TO shingles were reported to have higher content of HMW than the MW shingle, and Hassan et al. (2014) explained that increased content of HMW could result in more brittle and stiffer RAS binder.

2.3 Blending between Virgin and Aged Binders

AASHTO PP 78 recommends that the blending chart analysis from AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design*, be used with RAS binders. NCHRP Project 9-12 concluded that performance graded properties of the binder in mixtures containing RAP could be reasonably estimated from the properties of the virgin binder and the properties of recovered RAP binder using a linear blending analysis.

However, it is difficult to apply this procedure in practice with RAS because unlike RAP, the true grade of recovered RAS binder cannot be determined using conventional Superpave binder test equipment. In addition, RAS binder is often air-blown and consequently has extremely high stiffness and less capability to relax under force. When investigating the full blending chart of virgin binder and RAS binder, Zhou et al. (2013) found the linearly blending approach was only applicable when RAS binder was less than 30% of the total binder. When RAS binder is limited to 30% of the total binder, conventional DSR and BBR can be used to evaluate the high and low PG temperature of the blended binders. If the properties of the virgin binder and blended binders are known and linear blending applies, then the properties of the RAS binder can be extrapolated. Details on determining the continuous PG grade of recovered RAS binder can be found in Appendix A.

The blending chart approach in AASHTO M323 assumes that RAP binder completely blends with virgin binder. However, only a certain portion of the aged RAS binder is assumed to blend with virgin binder. Initially, a shingle binder availability factor (SAF) value of 0.7 was recommended in AASHTO PP 78, while the most current version specifies a procedure to estimate SAF, which typically ranges from 0.7 to 0.85. The detailed procedure to determine SAF can be found in Appendix B.

Several researchers (Huang et al., 2005; D' Angelo et al., 2011; Shirodkar et al., 2011) have conducted blending studies to evaluate the blending efficiency of RAP mixtures. The RAP aggregate and virgin aggregate were designed to be visually detected and manually separated after mixing with virgin binder in the laboratory. Significant differences in binder properties, as well as binder content, were observed between binders from virgin aggregate and RAP aggregate. Huang et al. (2005) conducted staged extraction and recovery tests on the RAP aggregate after being separated from the virgin aggregate after mixing. Binder viscosity was found to increase from outside to inside with around 60% of the inner portion of the binder (nearest the RAP aggregate) close to pure RAP binder. Their conclusion was that the major portion of RAP binder did not fully melt to blend with virgin binder, but formed a stiff layer which coated the RAP aggregate. Later, Bowers et al. (2014) applied Gel Permeation Chromatography (GPC) and Fourier Transform Infrared Spectroscopy (FTIR) to quantitatively evaluate the staged extracted and recovered RAP binders. Blending between virgin binder and RAP binder was found to occur within all staged extracted and recovered binder, however, blending was not completely uniform.

Zhao et al. (2014) conducted blending studies as well as evaluation of the blending between virgin binder and RAS binder. RAS was pre-blended with small size virgin aggregate and then blended with virgin binder and medium and large size virgin aggregate. After manual separation, the GPC test was conducted to measure the percentage of large molecules (LMS) within binder extracted from each size of aggregate. Binder coating small virgin aggregate carried higher LMS than the ones coating medium and large size virgin aggregate indicating that partial blending occurred between virgin binder and RAS binder.

It should be noted that how recycled binders, including RAP and RAS binders, blend with virgin binder and to what extent blending occurs during the mixing and construction processes are unknown. Research by Nahar et al. (2013) observed for the first time the blending zone morphology at the interface between virgin binder and RAP binder. Atomic force microscopy (AFM) was applied to probe the change of microstructural properties from a RAP binder and virgin binder to the blending zone of these two. The following observations were made based on the domain phases of the microstructure shown in Figure 2-7: 1) RAP binder was smaller in size and had less surface coverage than virgin binder, 2) RAP binder had round shape but virgin binder had elliptical shape and 3) the fully blended binder in the blending zone had microstructural properties between virgin binder and RAP binder and consequently was treated as a completely blended new material. The same methodology was later applied to evaluate the blending between virgin binder and RAS binder. Nahar et al. (2014) concluded that RAS binder simply mixed with virgin binder because highly aged RAS binder matrix hinders the mobility and therefore domains stabilizes locally, while the RAP binder blended with virgin binder resulting in fully blended new material (Figure 2-7).

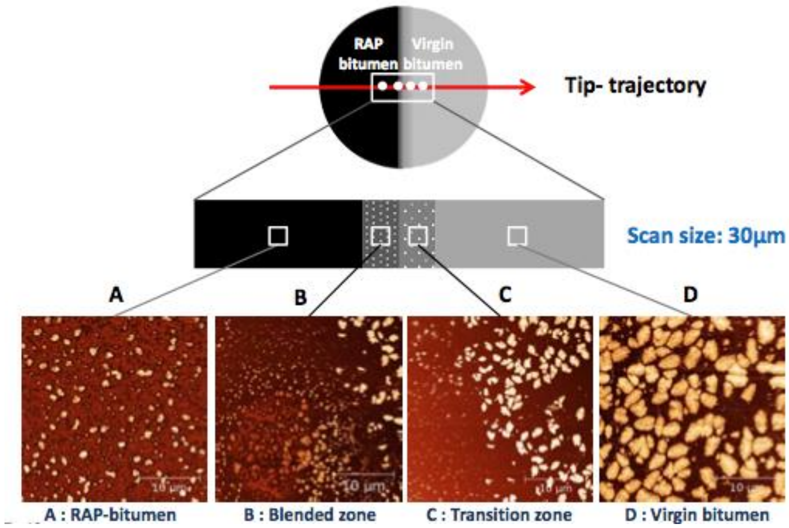

Figure 2-6. Measurement scheme and results at a glance (Nahar et al. 2013)

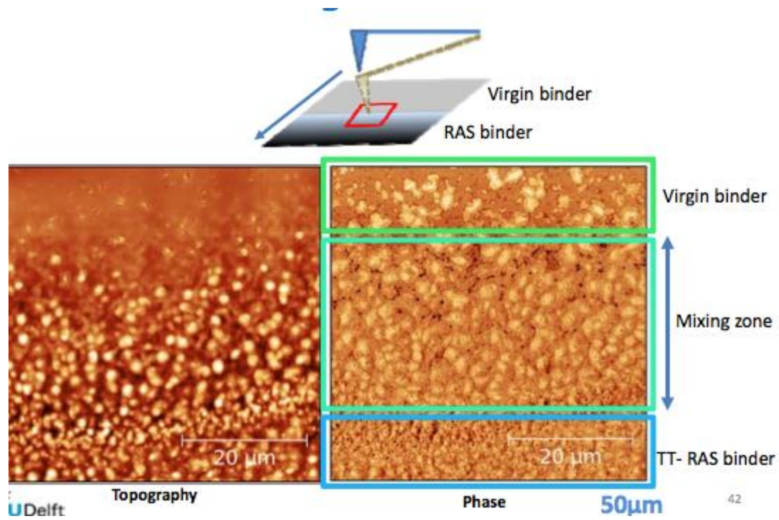

Figure 2-7 RAS and virgin binder interface (right) (Nahar et al. 2014).

Based on the evaluation of binder rheological properties and binder chemical components, the aforementioned research approaches proved that partial blending occurred between virgin binder and RAP/RAS binder, but did not provide a procedure to accurately determine the blending level. In addition, it is worth noting that all approaches required extraction and recovery of binder from specimens that are not representative of actual Superpave HMA mixes. Bonaquist et al. (2007) proposed an approach to evaluate binder blending in plant-produced RAP mixes. The general steps of this approach include: 1) prepare and test mix specimen for unconfined dynamic modulus, E*; 2) extract and recover the binder from the same specimen for binder shear modulus measurement, G*; 3) predict E* based on measured G* and specimen volumetric properties using Hirsh model; and 4) compare the measured E* and predicted E*. Comparison results indicate that good blending between virgin binder and RAP binder occurs during mixing.

Although many researchers have adopted this approach to evaluate blending, contradictory results have been obtained. Mogawer et al. (2012) and McDaniel et al. (2000) used Bonaquist's technique to evaluate plant-produced mixtures containing various RAP contents and they found significant blending was evident for most of mixtures containing RAP. However, Copeland et al. (2010) compared the E* of a regularly prepared RAP mix and a zero blending RAP mix and surprisingly no difference was observed. The same conclusion was made by Zhou et al. (2013) when comparing the measured E* from regularly prepared RAS mix and zero blending RAS mix. When comparing the measured and predicted E* for WMA mixes, Copeland et al. (2010) even found the measured E* was higher than the predicted E* which was calculated based on fully blended binder properties.

2.4 Effect of RAS Binder on Blended Binder

When high RAS and/or RAP content is used in HMA mixes, adjustments to the mix design are required to accommodate for stiffer binder. It is also necessary to quantify the effect of the aged binder on the virgin binder used in the mixture.

2.4.1 Solvent-based Binder Characterization

One way to assess the impact of RAS binders on the rheological properties of the combined binder is to characterize the combined binder extracted and recovered from mixtures containing RAS. It is important to note that the process of extracting and recovering the asphalt binder will result in complete blending of the recycled and virgin binders, which does not necessarily represent the true level of blending achieved in the mix. However, results of characterizing fully-blended materials provide valuable information on the differences in rheological properties due to varying RAP content, mixture components and proportions, and mixture conditioning levels that are related to aging.

McGraw et al. (2007) studied combined binders recovered from three mixtures containing recycled materials, including a 20% RAP (control) mix, 15% RAP + 5% TO shingles mix, and 15% RAP + 5% MW shingles mix. All three mixtures contain the same PG 58-28 virgin asphalt binder. Although detailed information on mix design was not included, results of extracted gradation and recovered binder showed that all three mixtures had similar gradations and the same asphalt content of 6.2%. It was found that compared to the control mix (graded as PG 64.2-29.2), the mix with MW shingles was one PG grade higher (PG 70.9-26.2) on the high temperature property, while the mix with TO shingles was 1.5 PG grade higher (PG 73.2-28.8). The BBR results showed that the addition of shingles slightly increases the stiffness but significantly lowered the m-value, indicating a significant reduction in relaxation properties.

Foxlow et al. (2011) designed four mixtures using the same target gradation to allow a more direct evaluation of the different RAP/RAS contents on the material properties, including a 18.5% RAP mix, a 4.5% RAP + 2.5% RAS (Normal Ground) mix, a 4.5% RAP + 5.0% RAS (+50 Mesh) mix, and a 4.5% RAP + 2.0% RAS (-50 Mesh) mix. Superpave mixture designs resulted in higher asphalt contents for the RAS mixtures (6.0-6.5%) than the RAP mixture (5.7%). The same virgin binder PG 64-28 was used. Results of the DSR test showed that the three recovered RAS mixture binders had very similar stiffness. The recovered binder from the RAP mixture was softer than the RAS mixture at low frequencies (high temperatures), but it was comparable to the RAS mixture binders at the higher frequencies. The recovered binder from the RAP mixture had a higher phase angle than the RAS mixture binders. The BBR results showed that mixtures containing RAS were comparable to the mix containing RAP at -12ºC, but were less stiff at -18 ºC. The RAS mixtures generally had lower m-values than the RAP mixture, so the low temperature PG grade of the RAP mixture would tend to be limited by the S value whereas the m-values would tend to control the low PG grade of the RAS mixtures.

2.4.2 Nonsolvent-based Binder Characterization

Characterization of blends between a virgin binder and a highly oxidized binder from RAP and/or RAS sources has been extensively conducted on the basis of chemical extraction and recovery of the binder. However, there always has been the legitimate question of whether the use of solvents through the extraction/recovery process affects the properties of the binder. Previous research indicated that even 0.5% residual solvent can cause a 50% decrease in viscosity (Peterson et al. 1999). In addition, the binder extraction and recovery test is a time-consuming process which can take approximately eight hours to complete.

For these reasons, a new characterization method without need for binder extraction and recovery has been put forward by Ma et al. (2010a) to estimate the effects of RAP on low-temperature properties of virgin binders. Instead of conducting laboratory tests on binder, mortar specimens are prepared by mixing asphalt binder and the RAP fraction that passes a #8 sieve (2.38 mm). The standard BBR mold was modified such that the new thickness is more than four times the maximum aggregate size (2.38 mm). The idea behind this approach is that the properties of a blend between a virgin binder of known properties and a RAP binder can be predicted from tests performed on two mortar specimens (Figure 2-8). Total binder content and R_8 gradation are fixed for both mortar specimens; hence the presence of RAP binder in one of the specimens is the only difference between both mortars. Therefore, any difference between mortar properties can only be attributed to the presence of RAP binder. The difference in properties between mortars is quantified in terms of a shift factor, which is applied to the properties of the virgin binder to estimate the properties of the combined binder.

Swiertz et al. (2011) modified this existing procedure and applied it to RAS and combinations of RAP and RAS. Mortar specimens are prepared by mixing asphalt binder and the RAP/RAS fraction that passes a #50 sieve (0.30 mm) and is retained on a #100 sieve (0.15 mm), denoted as R_{100}. Testing results showed that a linear combination existed between the RAS-alone and RAP-alone blends, which allowed the effect on low-temperature PG of any RAP-RAS blend to be estimated.

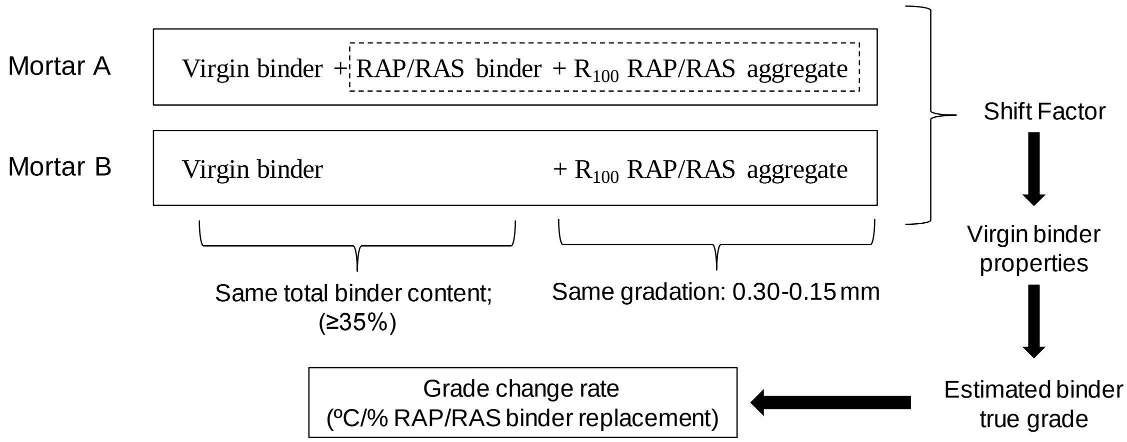

Figure 2-8. Procedure to estimate combined binder PG grade from mortar specimens without need for binder extraction/recovery

Later, a procedure was proposed which has been implemented into an AASHTO draft titled "Standard Method of Test for Estimating Effect of RAP and RAS on Blended Binder Performance Grade without Binder Extraction". It should be noted that the shift factor, which is related to the difference between two mortar properties, has to be determined at low, intermediate and high temperatures for the complete characterization of the combined binder according to Superpave binder grading system (Swiertz et al. 2011). According to this procedure, for a given virgin binder and RAP source, the change in PG grade caused by RAP is quantified and designated as °C/%RAP. Similarly, the change in PG grade caused by RAS was quantified and designated as °C/%RAS. By assuming a linear relationship, the continuous PG grade of binders combined of any RAP/RAS replacement can be predicted, Equation 1.

$$PG_{combined} = PG_{virgin} + BRR_{RAP} \cdot GCR_{RAP} + BRR_{RAS} \cdot GCR_{RAS} \quad (1)$$

where:

$PG_{combined}$ is the predicted continuous PG grade of the combined binder
PG_{virgin} is the continuous PG grade of the virgin binder
BRR_{RAP} is the binder replacement rate for RAP
GCR_{RAP} is the grade change rate for RAP
BRR_{RAS} is the binder replacement rate for RAS
GCR_{RAS} is the grade change rate for RAS

2.5 Effect of RAS on Mixture Performance

McGraw et al. (2007) conducted IDT tests on three Minnesota mixtures to evaluate the effect of RAS on low temperature properties. The results showed that TO shingles reduced creep compliance of the mixture at all test temperatures (0, -10, -20ºC). The highest drop in creep compliance was observed at the lowest temperature. MW shingles caused a decrease in creep compliance only at -10ºC, while at 0 and -20ºC it exhibited values similar to the control mixture. Strength tests indicated that the tensile strength was not sensitive to the addition of shingles, regardless of shingle type. This same study also included IDT results of four Missouri mixtures: 20%RAP (PG 64-22), 15%RAP+5%RAS (PG 64-22), 20%RAP (PG 58-28), 15%RAP+5%RAS (PG 58-28). Only TO shingles were used in this part of the study. The results showed RAS reduced creep compliance at the two lower test temperatures, -20 and -30ºC. Compared to the mixtures with PG -28, the mixtures with the stiffer binder (PG -22) exhibited a much higher drop in creep compliance. Again, tensile strength was not significantly changed with the addition of shingles.

Foxlow et al. (2011) performed the dynamic modulus test, thermal stress restrained specimen test (TSRST), and push-pull fatigue test on four mixtures. The results indicated that the RAP-only mixture had a higher dynamic modulus than the RAS mixtures at higher frequencies (or lower temperatures), while the RAS mixtures appeared to be similar. The lower asphalt content in the RAP-only mixture may explain the higher stiffness of the mixture. The TSRST results indicated that the load and temperature at failure were not significantly different among all mixtures, indicating similar low temperature performance. The fatigue tests and S-VECD analysis showed the +50-mesh shingle mixture performed better than the RAP mixture, however, the improvement in performance was likely due to the higher total asphalt content and presence of fibers in the +50 mesh shingle mixture.

Zhou et al. (2013) designed six mixtures including two RAS types (TO shingles and MW shingles) and three RAS contents (0%, 3%, and 5%). The same virgin binder PG 64-22 was used in all six mixtures. The 0% RAS/PG 64-22 mix served as the control mix. When RAS was included, the virgin aggregate percentage was adjusted to maintain similar gradations among all mixtures. In addition, for each RAS type, a 0% RAS/PG 70-22 mix was added to compare with the 5% RAS/PG 64-22 mix. Mix design results showed that RAS generally increased the design asphalt content (DAC) of the HMA mixes by 0.2% and 0.5% for 3% and 5% RAS, respectively. Dynamic modulus data indicated that RAS had no significant influence on the stiffness of HMA mixtures. In general, RAS resulted in worse performance (lower overlay tester (OT) cycles) than control HMA mixtures. It appeared that TO shingles caused a more significant reduction in OT cycles than the MW shingles. Further investigation led to the discovery that using softer binders on the low-temperature grade (PG XX-28 and PG XX-34) can significantly improve cracking resistance.

Wu et al. (2016) investigated the effects of RAS on performance of HMA with RAP/RAS based on the evaluation of field cores drilled from four experimental pavement sections. All mixes were designed to have same blend gradation with varied contents of reclaimed materials including 15% RAP, 3% RAS+15%RAP (two sections with different asphalt content), and 15% RAP. PG 64-22 was used as virgin binder for all mixes. As presented in Table 2-3, the addition of reclaimed materials was found to increase the true grades (both high and low temperature) of all recovered binders from the four sections. Both multiple stress creep recovery (MSCR) test and Hamburg wheel tracking device (HWTD) test results indicated that the incorporation of RAS improved rutting performance. However, the mixtures with RAS exhibited similar thermal cracking performance as the mixtures without RAS, which was not consistent with the thermal cracking binder test results. The researchers believed that the fibers in the RAS may make asphalt mastic that is beneficial to mix performance.

Table 2-3 Performance grades of recovered binders

Section	Material	Virgin Binder	AC (%)	Recovered	
				True Grade	PG Grade
1	15% RAP	64-22	5.6	73.4-17.0	70-16
2	3% RAS +15% RAP		5.6	79.7-19.6	76-16
3	3% RAS +15% RAP		6.4	73.6-17.4	70-16
4	15% RAP		5.4	74.4-14.4	70-10

Im and Zhou (2014) evaluated the performance of a series of field test sections with varying contents of RAP and/or RAS. The same mixes with higher design density (higher virgin binder content) and softer virgin binders resulted in enhanced field cracking performance. In terms of reflective cracking, poor relationships were established between OT cycles and the field performance. For example, RAP/RAS mixes on SH 146 in the Houston area had OT cycles of 3, but exhibited no cracking after three years traffic. Also, two RAS mixes on US 87 had relatively higher OT cycles (96 and 48) than others, but displayed reflective cracking very early. The researchers concluded that it is extremely difficult to evaluate cracking performance of asphalt mixes based on a single parameter or requirement, therefore the RAP/RAS mix design and performance evaluation system should be developed based on project-specific service conditions including traffic, climate, existing pavement conditions, etc.

2.6 Effect of Rejuvenators on RAS Mixture Performance

Rejuvenators have been extensively used for cold in-place recycling and pavement preservation to help re-balance the maltenes to asphaltenes ratio of the aged binder (Brownridge, 2010). Several studies found that the use of rejuvenators may eliminate the need for a softer binder typically used with HMA mixes with high RAP/RAS contents, and allows for more RAP/RAS to be incorporated (Al-Qadi et al. 2007, Shen et al. 2007, Mogawer et al. 2013). However, most state agencies in the USA do not encourage the use of rejuvenators in HMA containing high reclaimed materials because of the uncertain effectiveness of rejuvenators. There are several factors that determine the effectiveness of a rejuvenator, such as the amount of rejuvenator to be added, the performance grade of the virgin and recycled binder, the dispersion of the rejuvenator within the recycled mixture, and the diffusion of the rejuvenator into the aged binder coating the outside of the aggregate (Tran et al. 2012).

Mogawer et al. (2013) evaluated the effects of rejuvenators on the rutting and cracking performance of HMA mixes with varying contents of reclaimed materials (0%, 40% RAP, 35% RAP +5% RAS and 5% RAS). All mixtures had the same blend gradation, virgin binder (PG 58-28) and total binder content (6%). It should be noted that rejuvenators were added directly into the virgin binder, and the dosage used for each rejuvenator was recommended by the manufacturers. The HWTD test results indicated that incorporation of rejuvenators increased mixture susceptibility to rutting and moisture damage, especially for 5% RAS mixture. Based on the OT results, the RAP, RAS, and RAP+RAS mixtures exhibited a clear drop in the number of cycles to failure relative to the control mixture, suggesting poor reflective cracking performance. The use of rejuvenators increased the OT cycle numbers, but the improvement was relatively lower for the rejuvenator used in conjunction with warm mix technology. TSRST results suggest that incorporation of rejuvenators improved the low temperature cracking, relative to the control mixture by almost 2 °C.

Tran et al. (2012) concluded that rejuvenators, when properly used, could improve the cracking performance of HMA mixtures without relinquishing their resistance to permanent deformation and moisture damage. Five mixes were designed and evaluated, including: the control, 50% RAP mixture, 50% RAP mixture with rejuvenator, 20% RAP +5% RAS mixture, and 20% RAP +5% RAS mixture with rejuvenator. The dosage of the rejuvenators was determined based on a linear relationship between the rejuvenator content and performance properties of the blend of rejuvenators and recycled binder. The resistance to top-down cracking was evaluated using the HMA-FM approach developed at the University of Florida. The use of rejuvenator improved the mixture fracture properties and all mixtures, except 50% RAP mix without rejuvenator, met the proposed requirements for acceptable cracking performance. The rutting resistance of five mixtures was evaluated using the asphalt pavement analyzer (APA). Although the use of rejuvenator increased the rutting depths, all mixtures exhibited a rutting depth less than 5.5 mm, which is the maximum depth proposed by the NCAT to ensure acceptable rutting performance.

Im and Zhou (2014) investigated the impact of various rejuvenators on engineering properties of asphalt mixtures with reclaimed materials. Three control mixtures with 5% RAS, 13% RAP + 5% RAS and 19% RAP, were produced to compare the mixture performance and engineering properties to those of rejuvenated mixtures. All mixtures had similar gradation and PG 64-22 was used as virgin binder. Based on limited HWTD test results, the incorporation of rejuvenators with RAP and/or RAS improved the rutting resistance and moisture susceptibility of HMA and WMA mixtures. However, dynamic modulus test results showed that rejuvenators reduced the stiffness of mixtures at lower loading frequency levels (or higher temperature ranges). In addition, no definitive conclusion was made based on the repeated load test results, as some mixtures with rejuvenators exhibited similar rutting resistance characteristics, while others showed less or better resistance characteristics compared to the control mixtures. In terms of reflective cracking, rejuvenated mixtures exhibited higher OT cycles than the control mixtures, indicating the rejuvenators reduced the stiffness of the aged binder from the reclaimed materials and consequently improved the cracking resistance of mixtures.

2.7 Summary

The use of RAS as a partial replacement for virgin binder and aggregate in HMA mixes has increased in the last several years for economic and environmental reasons. Yet, tremendous amounts of RAS are still accumulating in stockpiles, used in low-value, non-bituminous applications, or being wasted. This is due to several concerns related to the reduction in performance caused by increasing the amount of recycled material incorporated into the pavement mixtures. One of the major concerns with the use of high RAS or RAP and RAS contents in asphalt mixes is the increased susceptibility to cracking due to the presence of extremely aged recycled binder.

Softer virgin binder has been used to offset the stiffening effects introduced by the recycled materials in asphalt mixes. To select the proper virgin binder, it is essential to know the true PG grade of recycled binder and how much recycled binder blends with the virgin binder. However, it is difficult to characterize the RAS binder, especially the low temperature properties, and it is still unknown how much recycled binder is available for blending with the virgin binder. Significant efforts have been made to address these concerns, and great progress has been made in terms of characterizing the RAS binder. However, there is currently no available method to accurately measure or predict the blending between recycled binder and virgin binder in mixtures.

Rejuvenators have been used to improve the engineering properties of asphalt mixtures with high contents of recycled materials. However, the effectiveness of rejuvenators is difficult to guarantee, as improved results depend on many factors, such as the rejuvenator dosage, the virgin binder selected, mixing time and temperature, and reaction time for diffusion to occur. Several studies determined that although the use of rejuvenators may improve the cracking performance of RAS mixtures, it could also raise rutting-related concerns (Shen et al., 2007; Im and Zhou., 2014; Tran et al., 2012).

CHAPTER 3 MATERIAL ACQUISITION AND CHARACTERIZATION

This chapter presents laboratory characterization of two recycled asphalt shingle (RAS) sources, three reclaimed asphalt pavement (RAP) sources, two virgin binders including a PG 67-22 unmodified and PG 58-28 polymer-modified asphalt (PMA) binder, and two levels of softer virgin binder by mixing PG 67-22 with rejuvenators at different proportions. Properties of RAS/RAP obtained include asphalt content, aggregate gradation, and the true or true grade of the recovered binder. A blending chart was used to determine the amount of rejuvenator needed to result in target softer binders (PG 52-xx and PG 46-xx). In addition, the binder fracture energy (BFE) test developed at the University of Florida (UF) was used to measure the fracture tolerance of virgin binders and the rejuvenated softer binders at intermediate temperature ranges (0–25°C).

3.1 Recycled Asphalt Shingle (RAS)

Two types of RAS material were selected and evaluated, including one Tear Off (TO) shingle (Figure 3-1 left) and one Manufactured Waste (MW) shingle (Figure 3-1 right). The TO shingle had a darker color than the MW shingle, because it had higher asphalt content due to the loss of surface granules during service. The RAS binder, regardless of TO or MW shingle type, was much stiffer than any conventional virgin binder used for pavement construction, because it was highly oxidized during its production. The TO shingles became even stiffer and more oxidized through their service life.

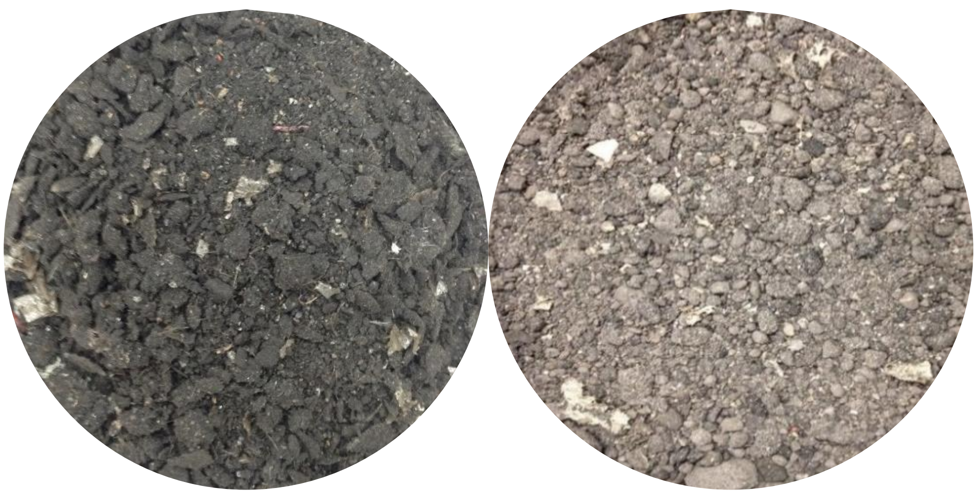

Figure 3-1. TO shingles (left) and MW shingles (right)

3.1.1 RAS Particle Gradation

The RAS material was first dried in a forced-draft oven at 122°F for 36 to 48 hours to a constant weight. This approach was taken to fully dry the material without further aging it. Gradation analysis was conducted in accordance to AASHTO T 27, *Sieve Analysis of Fine and Coarse Aggregates*. The RAS materials were separated into various sizes and stored in flat pans. Table 3-1 presents the TO and MW shingle particle which were used to batch specimens to determine the RAS aggregate gradation and asphalt content. The MW shingles were coarser than the TO shingles and it was noticed that the MW shingles failed to meet the gradation requirements by the AASHTO MP 23 *Reclaimed Asphalt Shingles for Use in Asphalt Mixtures*. However, this study only involved the evaluation of RAS/RAP binder properties.

Table 3-1. TO and MW shingle particle gradations

Sieve Size	TO shingle	MW shingle	AASHTO MP 23
	%Passing		
3/4"	100%	100%	100%
1/2"	100%	95%	100%
3/8"	100%	90%	100%
#4	92%	68%	-
#8	80%	49%	-
#16	60%	34%	-
#30	37%	22%	-
#50	23%	13%	-
#100	11%	4%	-
#200	3.6%	0.9%	-

3.1.2 Extraction and Recovery of RAS Binder

The RAS binder was extracted using the reflux method in accordance with Florida Method of Test (FM) 5-524, *Reflux Extraction of Bitumen from Bituminous Paving Mixtures*, and recovered following FM 3-D 5404, *Recovery of Asphalt from Solution Using the Rotavapor Apparatus*. Figure 3-2 shows the extraction and recovery process, which takes approximately 8 hours to complete. The researchers were aware of the general concerns of this solvent method, however, a recent study by Zhou et al. (2013) clearly showed that trichloroethylene (TCE) as a solvent had negligible effect on the RAS binder as the rheological and chemical components between the original shingle binder and the extracted/recovered binder were identical.

Three RAS specimens (400 grams each) were prepared for extraction and recovery. As shown in Figure 3-3, the TO shingle binder was so stiff that it did not drain down from the flask (after sitting in an oil bath). The same observation was made for the MW shingle binder. Also, the TO shingle binder cooled down so fast as it kept the air entrapped during the recovery process and looked like foamed binder. To collect sufficient shingle binder (both TO and MW shingle) for characterization, the researchers put the flasks (with the shingle binder inside) in an oven at 163°C for 20 minutes.

Figure 3-2. Asphalt binder extraction and recovery

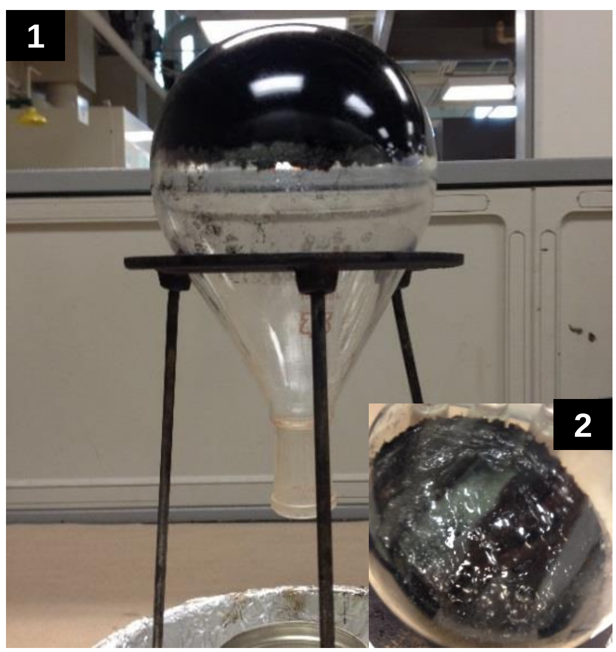

Figure 3-3. RAS binder that failed to drain down from the flask and entrapped air

3.1.3 RAS Asphalt Content and Aggregate Gradation

The RAS asphalt binder content and RAS aggregate gradation were determined based on results from the AASHTO T 308, *Standard Method for Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method*. For each RAS, three specimens were tested and a small variance in asphalt content was observed which was consistent with the information provided by the local contractor. Table 3-2 shows the asphalt content for both RAS sources. As expected, the TO shingle had a much higher asphalt content than the MW shingle, however, it should be noted that the asphalt content of the MW shingles was much lower than values reported by other studies, which were typically around 20% (McGraw et al. 2007, Zhou et al. 2012).

Table 3-2. Asphalt content of TO and MW shingle from the ignition method

Asphalt Content	Sample I	Sample II	Sample III	Average
TO shingle	24.9%	24.1%	24.7%	24.5%
MW shingle	10.5%	10.6%	10.1%	10.4%

In general, most agencies allow no more than 5% RAS in asphalt mixes, which results in an almost negligible effect in the overall mixture gradation. For convenience, the older AASHTO specification (PP 53-09), *Design Considerations When Using reclaimed Asphalt Shingles (RAS) in New Hot Mix Asphalt (HMA)*, provided a standard RAS aggregate gradation for use in a mix design. However, work by Willis (2013) found the standard RAS gradation may be inappropriate for a RAS mix design. The most recent AASHTO specification (PP 78-14) specifies that the RAS aggregate gradation should be determined, not assumed, following AASHTO T 27. In this study, the recovered RAS aggregate gradation was determined following T 27 and the average result of three specimens was reported, as shown in Figure 3-4 for TO shingles and Figure 3-5 for MW shingles.

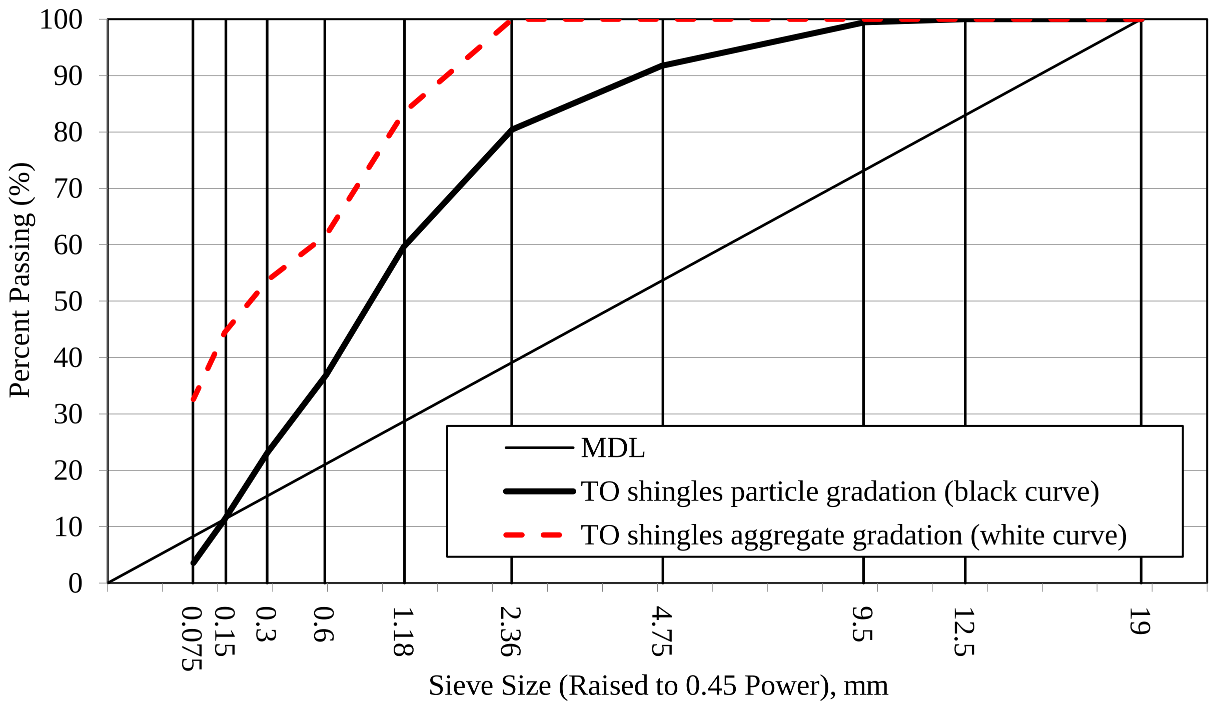

Figure 3-4. TO shingles particle gradation and aggregate gradation: Ignition method

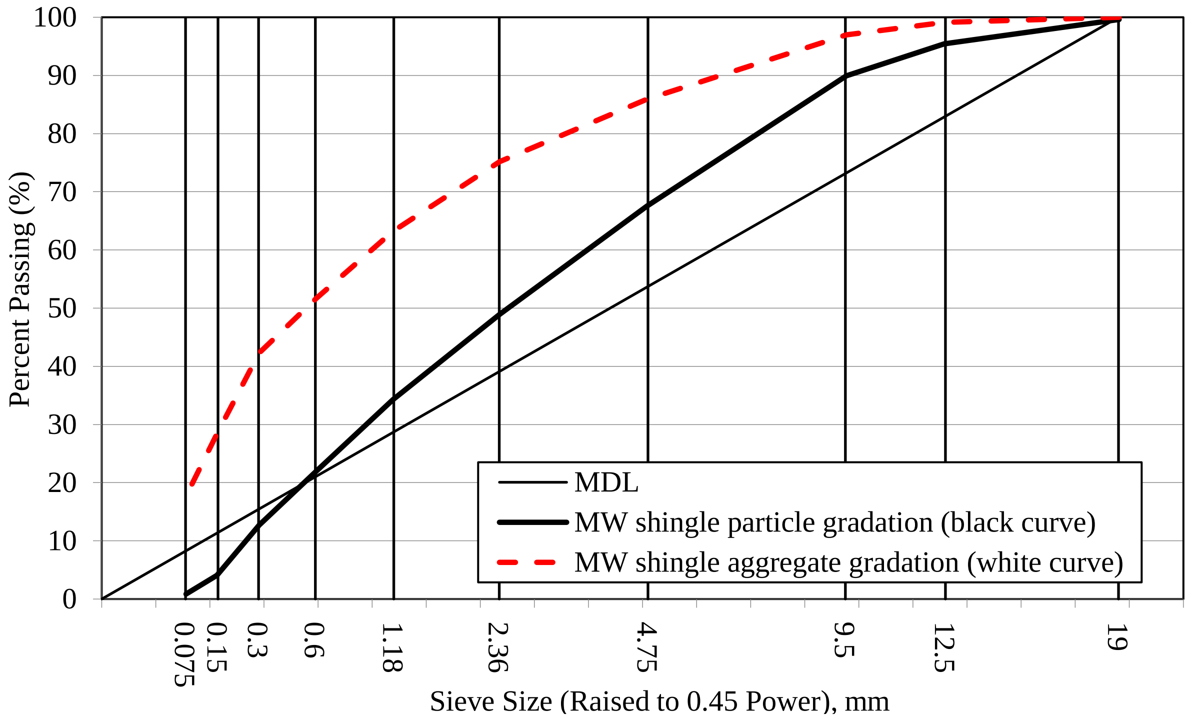

Figure 3-5. MW shingles particle gradation and aggregate gradation: Ignition method

3.1.4 Glass Fiber in RAS

Glass fiber is an integral part of RAS and its content generally ranges from 2% to 15% by weight (Foxlow et al. 2011). Although very little work has been done to quantify the effect of glass fiber in asphalt mixtures, there is some speculation that glass fiber may improve mixture performance by acting like filler and stiffening the asphalt mastic (Foxlow et al. 2011). Typically, glass fiber content has been determined by collecting glass fibers in extracted aggregate on a larger sieve (No. 4). However, this may lead to inaccurate measurements since a considerable amount of glass fiber was found to be present on smaller sieves (e.g., No.30 sieve) as well, as shown in Figure 3-6.

Figure 3-6. Glass fiber (left) and retained on the No. 30 Sieve (right)

3.1.5 True Grade of RAS Binder

AASHTO PP 78-14 adapted the virgin binder grade adjustment guidelines (Table 3-3) from AASHTO M 323, *Superpave Volumetric Mix Design*. According to this method, when more than 25% RAS or RAS plus RAP binder is used, a soft virgin binder should be selected by using the blending chart. The blending chart approach requires the determination of the true grade of the extracted/recovered RAS binder. However, it is difficult to obtain a direct measurement of the high temperature true grade of the RAS binder due to equipment limitations of typical Dynamic Shear Rheometers (DSR). Also, it is practically impossible to determine the low temperature true grade of RAS binders as the Bending Beam Rheometer (BBR) specimens failed to meet the *m-value* (≥0.300) criteria even at temperatures above 0°C. Bonaquist (2011) proposed an approach to extrapolate the PG grades of RAS binder from a blend of known virgin binder with RAS binder at a known proportion. A study by Zhou et al. (2013) also found that when RAS binder was limited to 30% of the total binder, conventional DSR and BBR equipment can be used to evaluate the high and low PG temperature of the blended binders. If the properties of the virgin binder and blended binders are known and linear blending applies, then the properties of RAS binder can be extrapolated.

In this study, the high temperature true grade of the RAS binder was measured by using a special DSR with a temperature control device that allows measurements at up to 200°C. The TO shingle binder was graded as PG 173°C and the MW shingle binder was graded as PG 127°C. As expected, the low temperature true grade of the RAS binder could not be determined as it failed to meet the BBR *m-value* requirement (≥ 0.300) at 0°C. Attempts were made to extrapolate the true grade of RAS binder following the method proposed by Bonaquist (2011). Great difficulty was encountered in blending the RAS binder with virgin binder because the former did not melt at typical mixing temperatures (approximately 163 °C), as shown in Figure 3-7. Zhou et al. (2013) heated the RAS binder to 200°C and then blended it with a virgin binder. However, the effect of the high heating temperature on the virgin and RAS binders was unclear. In addition, the degree of blending between the RAS and virgin binders could not be guaranteed. Therefore, for the work presented herein, the RAS binder was first dissolved in a solvent (TCE) and then added in PG 67-22 at known proportions. Finally, the fully blended virgin and RAS binder was recovered by evaporating the TCE.

Table 3-4 presents the proportions of virgin and RAS binder and the true grade of the blended binders. The DSR test was conducted on original and RTFO aged specimens and the lower grade between the two was reported as the high temperature true grade. BBR tests were performed on PAV-aged specimens and the lower temperature value between the ones obtained from failing *m*-value (≥0.300) and S (≤300 MPa) was selected as the low temperature true grade. It was observed that the BBR specimens failed the *m-value* first which indicated the reduced capability of the blended binders to relax stress. The critical temperature difference (ΔT_c) between the low temperatures where the binders reached their respective limits of 0.300 *m-value* and 300 MPa stiffness (S) was also reported for each blended binder. Anderson (2011) indicated there is a significant loss of cracking resistance when the ΔT_c exceeds -5°C. Although the blends were not created to evaluate cracking performance, it is interesting to see that blends with TO shingle binder failed to meet the requirement of -5°C.

Table 3-3. Binder grade guidelines for mixtures with RAS (PP 78-14)

Recommended Virgin Asphalt Binder Grade	RAS or RAS + RAP Binder (By weight of total binder)
No change in binder selection	<15%
Select virgin binder on grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used) or blending chart recommendations	15 to 25%
Follow blending chart recommendations	>25%

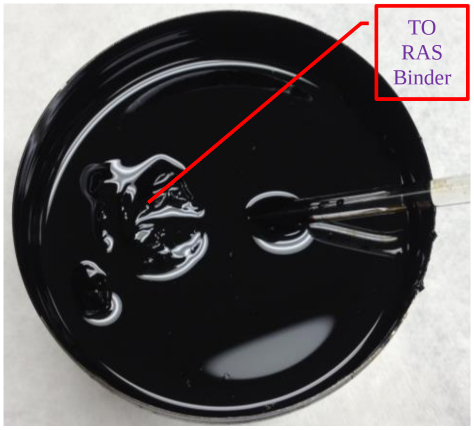

Figure 3-7. TO shingle binder and virgin binder blended at 163°C

Table 3-4. Determination of true grade for blended virgin and RAS binder

	Binder replacement rate (%)		DSR	BBR	
	TO Shingles	MW Shingles	High PG(°C)	Low PG(°C)	ΔTc (°C)
Blend 1	20	-	88.0	-19.6	-7.7
Blend 2	17	-	83.2	-21.9	-5.8
Blend 3	-	20	76.4	-20.4	-4.6
Blend 4	-	17	74.0	-21.5	-3.7

Figure 3-8 plots the high temperature true grade of the blends as a function of RAS binder content in the blends. Linear relationship fit the limited dataset well. However, the extrapolated high temperature true grades of RAS binders were much lower than the measured values, indicating that the relationship is generally non-linear at higher RAS binder content. Zhou et al. (2013) observed the same trend and concluded that non-linear behavior would occur when more than 30% RAS binder was added in the blends. Figure 3-9 shows the effect of increasing RAS content for the low temperature true grade of the blends based on the *m-value*. The extrapolated low temperature true grade for TO shingle binder was 5.7°C and 3.5°C for MW shingle binder. However, the low temperature true grade of RAS binder could not be directly measured.

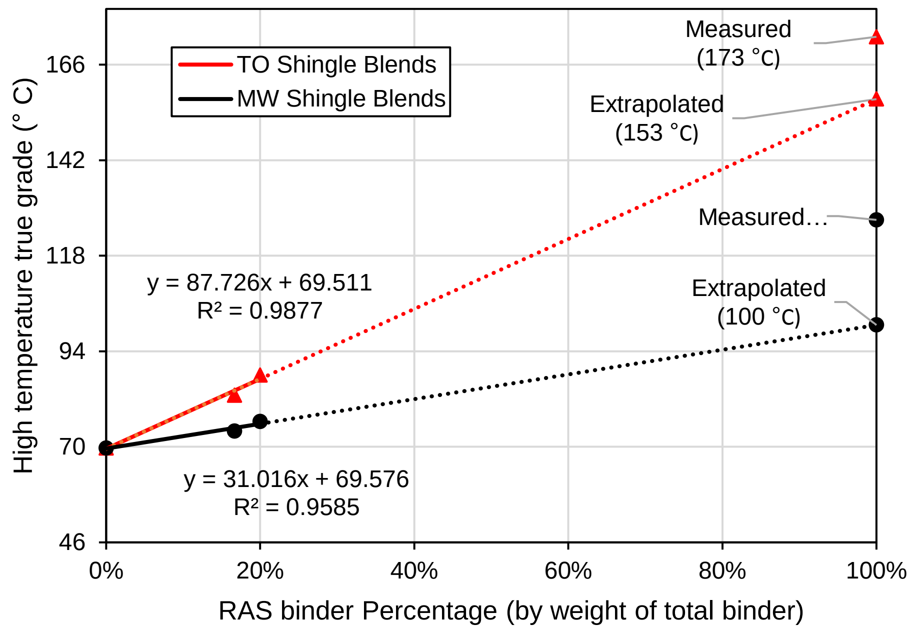

Figure 3-8. High PG determination of blended virgin and RAS binders

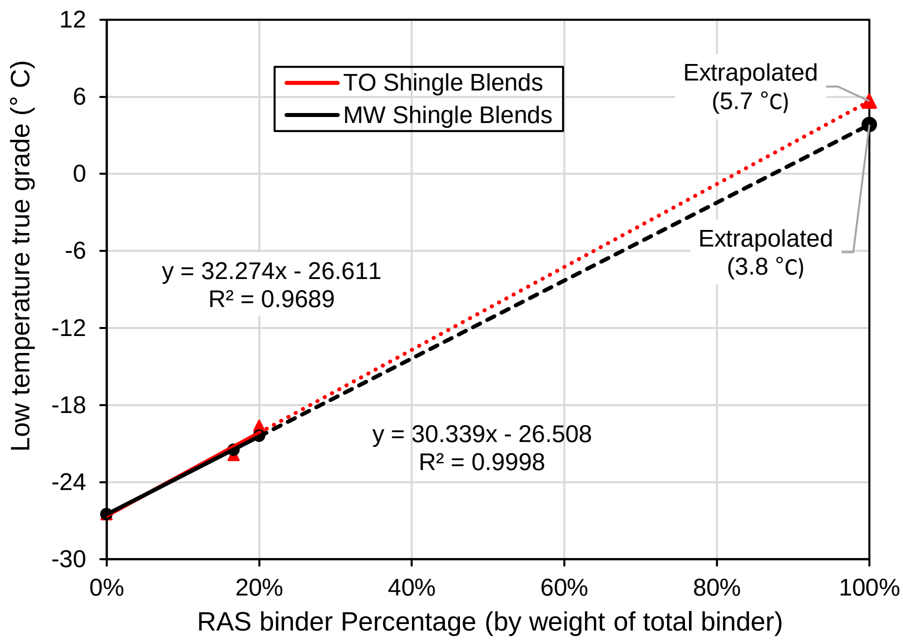

Figure 3-9. Low PG determination of blended virgin and RAS binders

3.2 Reclaimed Asphalt Pavement (RAP)

Three RAP sources were selected and characterized. RAP was first dried and sieved, and three representative samples were prepared for RAP binder collection (solvent method), and another three for asphalt content and aggregate gradation determination (ignition method). Based on a visual inspection of the extracted aggregate, ATL RAP was mainly composed of granite aggregate whereas ACO and WHI RAP were mainly composed of FL limestone, as shown in Figure 3-10. As shown in Figure 3-11, Figure 3-12 and Figure 3-13, the ATL RAP had a finer aggregate gradation than the ACO and WHI RAP. Table 3-5 presents the high and low temperature true grade (failed the *m-value*) for both RAP binders. In terms of binder rheological properties, ATL and ACO RAP were close to a RAP source typically encountered in Florida (approximately PG 90-20) whereas the WHI RAP was an extremely stiff RAP.

Figure 3-10. Aggregate components of ATL RAP (left), ACO RAP (middle) and WHI RAP (right)

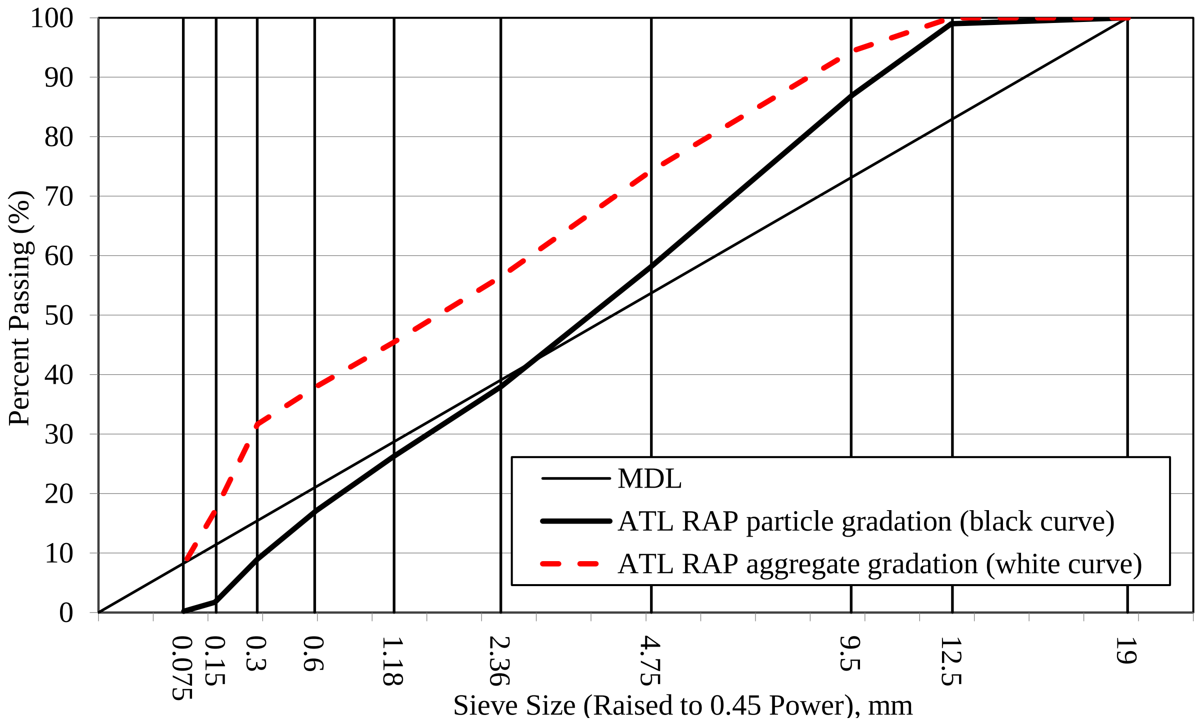

Figure 3-11. ATL RAP particle gradation and aggregate gradation: Ignition method

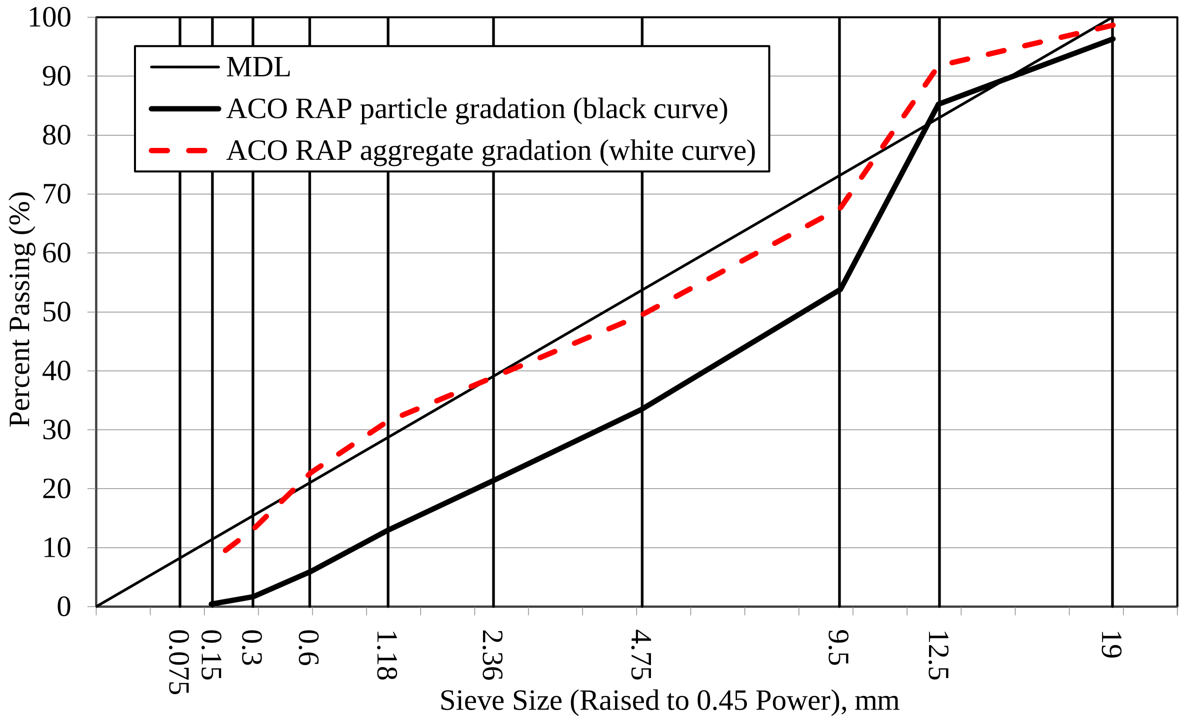

Figure 3-12. ACO RAP particle gradation and aggregate gradation: Ignition method

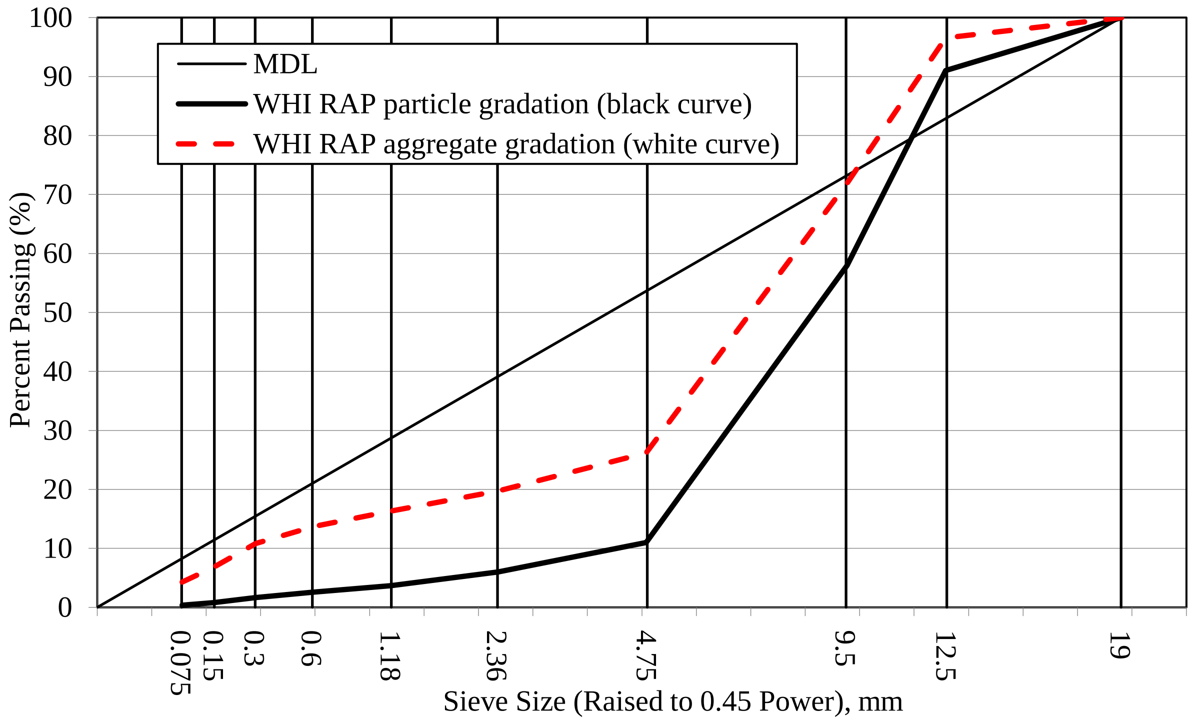

Figure 3-13. ACO RAP particle gradation and aggregate gradation: Ignition method

Table 3-5. Determination of true grade of recovered RAP binder

RAP type	High temp. true grade (°C)	Low temp. true grade (°C)		
		m	s	ΔTc
ATL RAP	88	-22.6	-24.9	-2.3
ACO RAP	93	-23.5	-25.4	-1.9
WHI RAP	104	-17.1	-23.6	-6.4

3.3 Virgin Binder Characterization

3.3.1 Conventional binders

The two conventional binders assessed in this study were a PG 67-22 unmodified binder, which is commonly used in Florida and a PG 58-28 SBS polymer-modified asphalt (PMA) binder. PMA binders have become increasingly popular because of their proven effect in mitigating rutting as well as in enhancing cracking performance of asphalt mixtures. The FDOT fully adopted the PG 76-22 SBS PMA binder in the early 2000s (considering it their "Gold Standard" binder), specifying its use in surface courses for high-traffic volume facilities. Considering the stiff nature of RAS binder and the advantages of adding polymer, it is of great interest to include a soft virgin binder modified with SBS polymer.

Table 3-6 presents the true grades of virgin binders. It should be noted that the true grade of the PG 58-28 PMA was PG 64-34. The multiple stress creep recovery (MSCR) test, which is currently specified by FDOT for modified binders, was conducted on the PG 58-28 PMA binder. Two RTFO-aged specimens were tested at 52°C and the two parameters obtained from this test were non-recoverable creep compliance at 3.2 kPa (Jnr-3.2) and % Recovery at 3.2 kPa (Rec-3.2). Table 3-7 presents the averaged Jnr-3.2 and Rec-3.2 results and corresponding requirements.

In addition to binder rheological tests, the binder fracture energy (BFE) tests were conducted to evaluate the fracture tolerance of virgin binders. As shown in Figure 3-14, the PG 58-28 PMA binder had much higher peak stress and larger peak strain than the PG 67-22 unmodified binder. As expected, the fracture energy density (FED), which is the area under the true stress-true strain curve up to the peak stress, was significantly higher for the PMA binder (11,600 kJ/m^3) than for the unmodified binder (3,000 kJ/m^3).

Table 3-6. True grade determination of virgin binders

True grade determination	High temp. true grade (°C)		Low temp. true grade (°C)	
	Original	RTFO	m	S
PG 58-28 PMA	68.4	66.6	-35.1	-36.2
PG 67-22 Unmodified	70.1	69.8	-26.5	-27.0

Table 3-7. MSCR testing results of PG 58-28 PMA binder

MSCR @52 °C	Jnr-3.2 (kPa^{-1})	V Grade Maximum (kPa^{-1})	Jnr, diff (%)	Jnr, diff Maximum (%)	Rec-3.2 (%)	Minimum (%) (29.37× Jnr-3.2^- 0.263)
Specimen I	0.11	1.0	50.4	75	76.3	52
Specimen II	0.11		44.7		76.1	

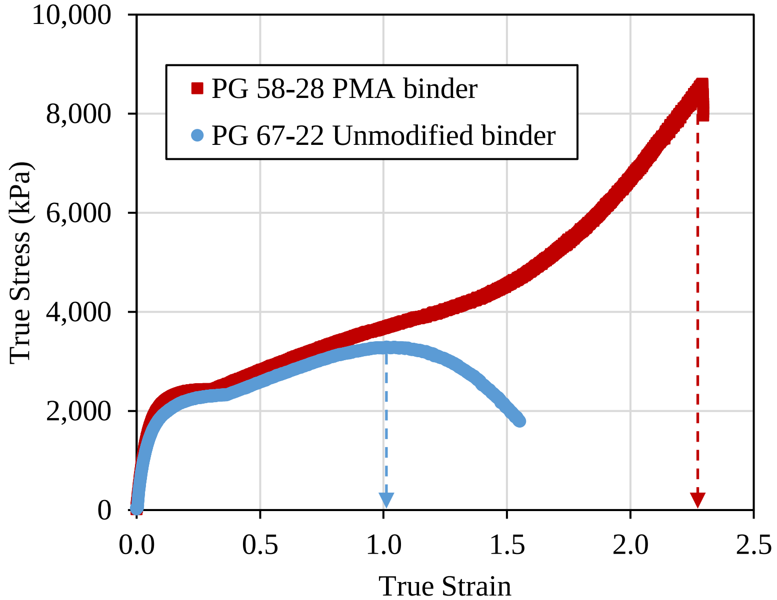

Figure 3-14. True stress-true strain curves for virgin binders

3.3.2 Rejuvenated Binders

It is common practice to introduce a softer virgin binder or rejuvenator to reduce the stiffness of RAS/RAP mixtures. Two types of rejuvenators were selected for this study: an aromatic oil extract and re-fined engine oil bottoms (REOB). The goal was to soften the PG 67-22 unmodified binder by mixing it with rejuvenators to two target levels: PG 52-xx and PG 46-xx. Figure 3-15 shows the softening curves of a PG 67-22 mixed with the two rejuvenators at various proportions. Compared to Aromatic oil, a larger amount of REOB was required to obtain the same target binder.

Although the target PG grades were fixed, there were two different scenarios in terms of binder true or true grades: the lower limit and the upper limit of the desired PG grades. A first attempt was made to target the lower limit of desired PG grades. Table 3-8 presents the rejuvenator dosage used and the true grade of the resulting binders. To obtain the same target virgin binder, (PG 52-xx and PG 46-xx), larger amount of REOB rejuvenator was required than Aromatic oil rejuvenator. It appears that excessive amounts of both rejuvenators were needed to meet the low limit of target binder grades. Note the low PG grade for the PG 46-40 REOB could not be accurately determined as it was out of the low limit (-40°C) of the BBR.

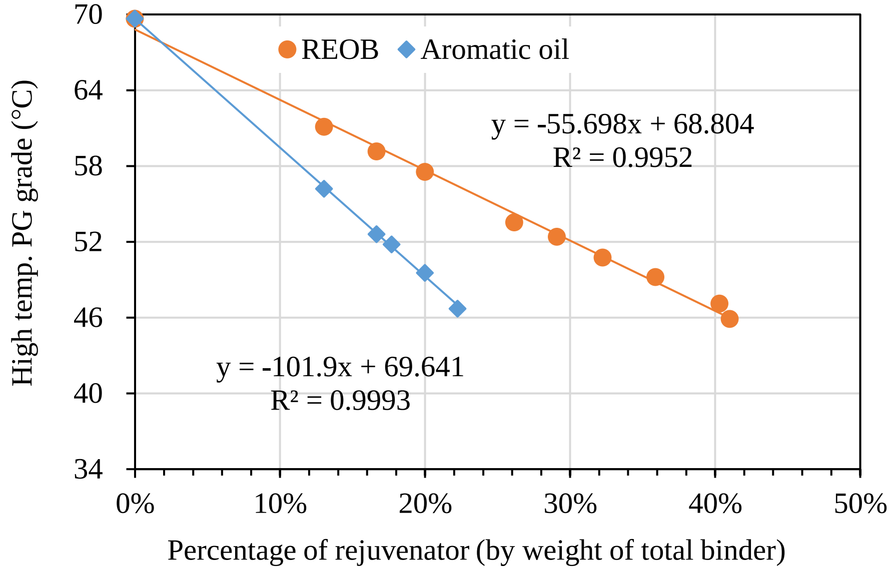

Figure 3-15. Softening curves for PG 67-22 with two rejuvenators at various proportions

Table 3-8. Rejuvenator application rates used for two levels of softer virgin binder

Base binder	Rejuvenator	Dosage (%)	True grade (°C)	PG grade (°C)
PG 67-22	Aromatic oil	17.2	52.1-35.9	PG 52-34
		22.2	46.7-37.1	PG 46-34
	REOB	29.1	52.4-39.1	PG 52-34
		41.0	46.0-40.0	PG 46-40

The BFE tests were conducted on the rejuvenated binders. For each binder, two RTFO plus PAV-aged specimens were tested at 5°C and the averaged FED value was reported. Figure 3-16 shows the true stress-true strain curve and the FED values for two PG 52-xx binders. The PG 52-26 Aromatic oil had a FED value of 2500 kJ/m^3, close to a PG 52-28 binder evaluated in a separate study. However, the FED value of the PG 52-39 REOB was 1200 kJ/m^3, much lower than the PG 52-26 Aromatic oil. Attempts were made to perform BFE tests on the PG 46-xx binders, however, the PG 46-40 REOB was too soft to fracture properly, even at 0°C. Two successful tests were conducted for the PG 46-27 Aromatic oil and the average FED value was 2800 kJ/m^3, slightly higher than the PG 52-26 Aromatic oil (2500 kJ/m^3).

To reduce the dosage of rejuvenator, the target binder true grade was adjusted to meet the upper limit of the high temperature grade. For example, 17.2% Hydrolene was initially needed to obtain a PG 52-xx binder with a high true grade of 52.1°C; however, only 12.8% Hydrolene was required for a high true grade of 57.2°C. According to the Superpave binder grading system, both binders can still be designated as PG 52-xx. In addition to requiring a greater rejuvenator dosage, binders with REOB exhibited lower FED than those with Hydrolene. Therefore, the base binder for REOB was changed from a PG 67-22 to a PG 52-28 binder. Figure 3-17 show the softening curve of PG 52-28 mixed with REOB at various proportions for high temperature true grade and Figure 3-18 for low temperature true grade. As depicted in Table 3-9, the rejuvenator dosages based on modified target binder grade were significantly reduced.

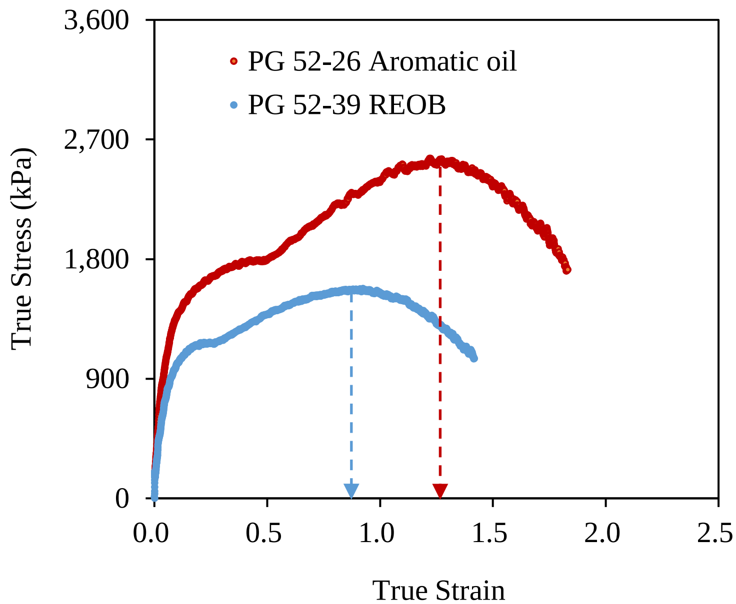

Figure 3-16. True stress-true strain curves and FED values for PG 52-xx binders

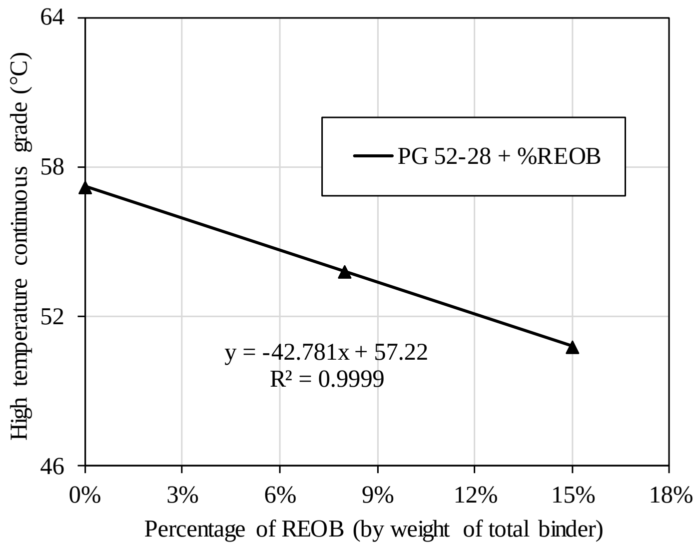

Figure 3-17. High temperature softening curve for PG 52-28 with REOB

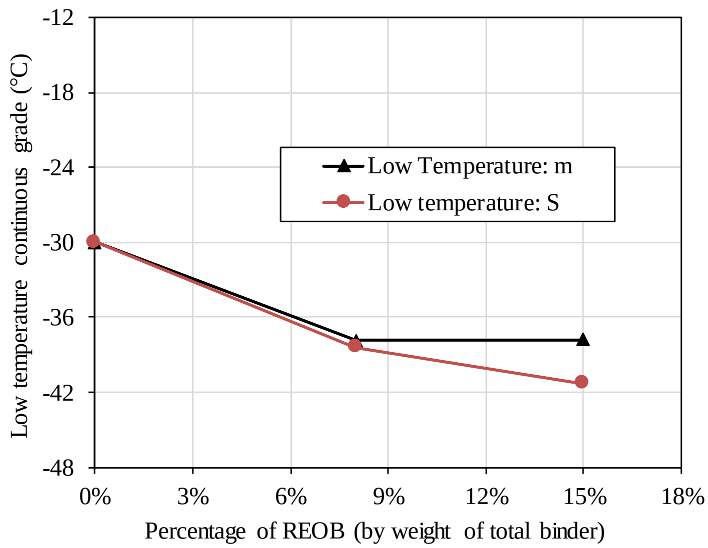

Figure 3-18. Low temperature softening curve for PG 52-28 with REOB

Table 3-9. Rejuvenator dosage (%) determined based on modified targets

Base binder	Rejuvenator	Dosage (%)	True grade (°C)	PG grade (°C)
PG 67-22	Hydrolene	12.8	57.2-32.2	PG 52-28
		18.5	51.5-35.8	PG 46-34
PG 52-28	REOB	15.0	50.9-37.8	PG 46-34

Table 3-10 summarizes the performance and true grade of the six virgin binders finally selected. Additionally, the ΔTc parameter, which refers to the difference between the failure grade for stiffness (temperature at which the stiffness reaches 300 MPa) and for relaxation (temperature at which m-value reaches 0.300) was also calculated for all binders. PG 52-28 base binder had almost identical failure grade for stiffness and relaxation. However, Hydrolene and REOB induced distinctive effects: binders with Hydrolene failed the stiffness requirement first whereas those with REOB failed the m-value requirement first. Research done by Anderson (2011) and Bennert (2015) showed that ΔTc values equal or lower than -5°C are associated with a significant loss in cracking resistance. All virgin binders met this requirement although the PG 46-34 REOB was marginal.

Table 3-10. Performance grade (PG) and true grade of virgin binders

Virgin binder type	High temp. true grade (°C)		Low temp. true grade (°C)			True grade (°C)	Performance grade (°C)
	Original	RTFO	Stiffness	m	ΔTc (min -5°C)		
PG 58-28	62.8	61.3	-30.1	-30.0	-0.1	61.3-30.0	58-28
PG 52-28	57.2	58.0	-33.6	-33.7	0.1	57.2-33.6	52-28
PG 64-34 PMA	68.4	66.6	-36.2	-35.1	-1.1	66.6-35.1	64-34
PG 46-34 (Hydrolene)	52.8	51.6	-35.1	-38.2	3.1	51.6-35.1	46-34
PG 52-28 (Hydrolene)	57.9	57.2	-32.2	-35.4	3.2	57.2-32.2	52-28
PG 46-34 (REOB)	50.8	50.9	-41.3	-36.8	-4.5	50.8-36.8	46-34

Figure 3-19 shows the FED values of six virgin binders. Binders with higher PG designation exhibited greater binder FED values and the heavily polymer modified binder (i.e., PG 64-34 PMA) had the greatest value. The PG 46-36 REOB which was an extremely soft binder had the lowest FED of all virgin binders.

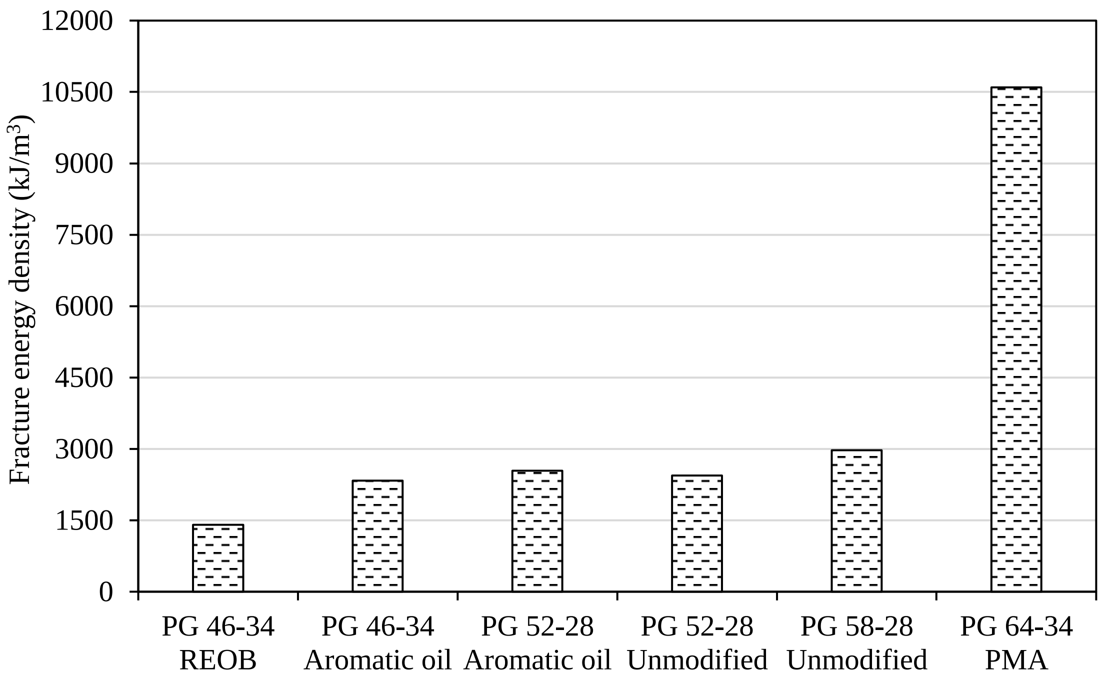

Figure 3-19. Fracture energy density of six virgin binders

3.4 Summary

Based on the data presented previously, findings may be summarized as follows:

- The TO shingles had a higher asphalt content and much stiffer binder than the MW shingles, so it is necessary to differentiate the two when specifying the maximum allowable amount of RAS in asphalt mixes.

- Whereas the high temperature true grade of the RAS binder could be measured by using a special DSR with high temperature upper limit (up to 200 °C), it was practically impossible to determine its low temperature true grade using a BBR as the RAS binder beam failed the BBR *m-value* requirement even at 0 °C.

- Blends of virgin and RAS binders were created and their true grades were successfully determined using conventional DSR and BBR equipment. However, the extrapolated high temperature true grades for RAS binders were much lower than the measured values, indicating that non-linear blending occurred between virgin and RAS binder and this non-linearity increased with RAS content.

- To obtain same target virgin binder (PG 52-xx and PG 46-xx), larger amount of REOB rejuvenator was required than Aromatic oil rejuvenator. In addition, the use of REOB rejuvenator resulted in binders with much lower fracture tolerance (higher fracture energy density) than Aromatic oil, which raised concern on its usage. To avoid an excessive use of rejuvenators, the decision was made to meet the upper limit of desired PG grades to reduce the usage of rejuvenators. Also, the base binder for REOB was changed from a PG 67-22 to a PG 52-28 binder

CHAPTER 4 EXPERIMENTAL DESIGN

Based on the literature review (Chapter 2), factors deemed to be the most important for immediate study were RAS source, RAP source (as typically used together with RAS), virgin binder type (grade), rejuvenator type and recycled binder replacement rate. Chapter 3 presented the laboratory characterization of two RAS sources, three RAP sources, three virgin binders and two rejuvenators. Assessment of RAP/RAS effect on virgin binder performance was made based on the mortar characterization approach which avoids the needs for binder extraction and recovery by testing on blends of virgin binder and RAP/RAS fine fractions.

Two preliminary sets of tests on mortar samples (one set of RAP-alone and another set with RAS-alone) were conducted in this task to obtain the RAP-alone GCR and RAS-alone GCR before selecting the final eight combinations of RAP and RAS. The sensitivity of the mortar testing methodology to RAP/RAS source and virgin binder source was also investigated. Based on testing results, a full laboratory experimental design was developed at the end of this chapter.

4.1 Mortar Characterization Approach

The effect of highly oxidized RAP and/or RAS binder on virgin binder performance has been commonly evaluated by means of tests conducted on blends of virgin and recovered binders. However, the question of whether the use of solvents through the extraction/recovery process affects the properties of the binder still remains. In addition, binder extraction and recovery is a time-consuming process. More importantly, virgin binder only partially blends with recycled binder in real mixtures and the degree of blending cannot be accurately determined. In the case of RAS, it was not even possible to create a blend of virgin and recovered RAS binder at a typical mixing temperature (e.g., 165°C). For these reasons, a new characterization method without the need for binder extraction and recovery has been put forward by researchers at the University of Wisconsin-Madison (Swiertz et al., 2011) and adopted in this study.

As previously shown in Figure 2-8, mortar samples were prepared by mixing asphalt binder and the RAP/RAS fraction that passed a #50 sieve (0.30 mm) and was retained on a #100 sieve (0.15 mm), denoted as R_{100}. Two types of mortar samples were prepared with identical gradation and identical total asphalt content. Mortar A sample was composed of RAP/RAS R_{100} and virgin binder whereas mortar B contained recovered RAP/RAS R_{100} aggregate and virgin binder. In other words, the percentage of RAP/RAS binder in mortar A was replaced by an identical percentage of virgin binder in mortar B. Therefore, any difference in properties between mortar A and mortar B was attributed to the presence of RAP/RAS binder. The difference between mortar properties was quantified in terms of a shift factor (δ), which was applied to the properties of the virgin binder to estimate the properties of the blended virgin and RAP/RAS binder. The shift factor (δ) had to be determined at low, intermediate and high temperature for a complete characterization of the true grade of a blended binder. Ultimately, the impact of RAP/RAS on virgin binder performance will be evaluated by using the grade change rate (GCR, °C/% replacement), which stands for the rate of virgin binder grade increment per percent binder replaced.

4.1.1 Preliminary Tests

Two preliminary sets of tests on mortar specimens were conducted before selecting the final four RAP/RAS binder combinations at two binder replacement rates. Mortar testing was performed according to the procedure proposed by Swiertz et al. (2011), which has been implemented into a draft AASHTO method. One preliminary set included virgin binder and RAP at a binder replacement rate of 15%. The purpose of this set was to quantify the change in true grade caused by introduction of RAP binder for a given binder and RAP source. This parameter is called RAP GCR and is defined in °C/%RAP. Assuming a linear relationship, the RAP GCR provides a prediction of the change in true grade at any RAP binder replacement rate. Similarly, a second preliminary set included virgin binder and RAS at a binder replacement rate of 15%. The purpose of this set was to determine the RAS GCR (°C/%RAS). The RAS grade change rate provides a prediction of the change in true grade at any RAS binder replacement rate for a given binder and RAS source. Figure 4-1 illustrates the testing plan for preliminary evaluation.

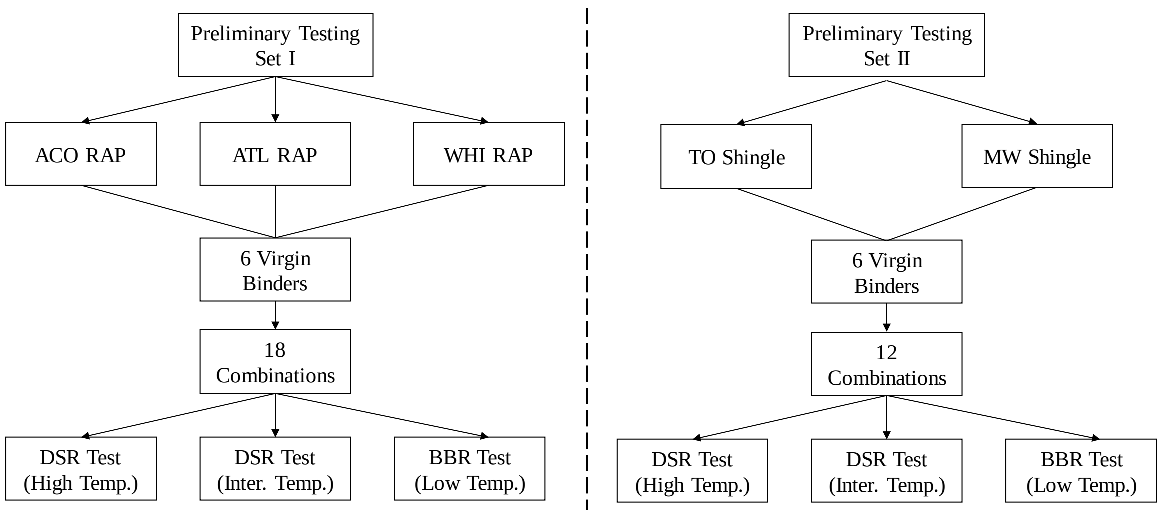

Figure 4-1. Preliminary tests on mortars with RAP-alone and RAS-alone

4.1.2 Specimen Preparation

RAP and RAS material was dried and sieved. Material passing sieve #50 and retained on #100 sieve was collected and denoted as R_{100}. Following FM 5-563, ignition oven tests were conducted to determine the RAP/RAS binder content of the R_{100} material and to procure the RAP/RAS R_{100} aggregate. Since the asphalt content of R_{100} is relatively high, the sample weight was reduced to 300 grams to ensure a complete burning of recycled binder. For each RAP and RAS source, three samples were tested and the average value was reported, as listed in Table 4-1.

Table 4-1. Asphalt content for R_{100} fraction of RAP and RAS

Recycled Material	Asphalt content of R_{100} material (%)
ACO RAP	8.0
ATL RAP	5.5
WHI RAP	9.5
TO Shingle	26.5
MW Shingle	7.4

As previously explained, there are two types of mortar sample. Mortar A is composed of virgin binder and R_{100} material whereas mortar B contains virgin binder and recovered R_{100} aggregate. Table 4-2 illustrates the composition of mortar A samples based on 100 grams of R_{100} material. The total asphalt content of mortar samples must provide enough workability to cast BBR and DSR samples with no air voids. Swiertz et al. (2011) recommended a total asphalt content of 30 percent by weight as a starting point. However, this study found the minimum total asphalt content had to be approximately 35 percent so the pre-heated mortar could be poured into a BBR mold. The target RAP binder replacement used in this preliminary study was 15 percent, which approximately corresponds to a 20 percent RAP by weight of mixture. However, the RAP binder replacement of ATL RAP mortar was only 11 percent because of the low asphalt content of its R_{100} fraction.

Table 4-2. Components of mortar A sample (100 g of R_{100} as reference)

Mortar Specimen A (virgin binder and R_{100})						
Recycled material	Virgin binder (g)	R_{100} (g)		Total specimen weight (g)	RAP binder replacement (%)	Total binder content (%)
		Total R_{100} (g)	Recycled binder (g)		Target=15	Requirement≥35
ACO RAP	41.6	100.0	8.0	141.6	16	35
ATL RAP	45.4	100.0	5.5	145.4	11	35
WHI RAP	53.3	100.0	9.4	153.3	15	41
TO Shingle	150.0	100.0	26.5	250.0	15	71
MW Shingle	41.9	100.0	7.4	141.9	15	35

Table 4-3 presents the composition of mortar B samples which only contained virgin binder and recovered R_{100} aggregate. Note that mortar A and mortar B had identical total specimen weight with the only difference being the presence of RAP/RAS binder in mortar A samples. Since the properties of the virgin binder used in the mortar specimens were known, then the change in properties of the virgin binder due to blending with the RAP/RAS binder can be isolated and quantified by means of a shift factor.

Table 4-3. Components of mortar B sample (amount of recovered R_{100} aggregate was determined based on the asphalt content using 100 g of R_{100} as reference)

Mortar Specimen B (virgin binder and recovered R_{100} aggregate)					
Recycled materials	Virgin binder (g)	Recovered R_{100} aggregate (g)	Total specimen weight (g)	RAP binder replacement (%)	Total binder content (%)
				Target=0	Requirement ≥35
ACO RAP	49.6	92.1	141.7	0	35
ATL RAP	50.9	94.5	145.4	0	35
WHI RAP	62.7	90.6	153.3	0	41
TO Shingle	176.5	73.5	250.0	0	71
MW Shingle	49.3	92.6	141.9	0	35

4.1.3 Determination of Shift Factor

For a complete characterization of the effect of recycled binder on virgin binder performance, mortar samples were tested at high, intermediate, and low temperatures and corresponding shift factors were determined. High temperature shift factors were obtained by performing the DSR test (25 mm plate) on un-aged and RTFO-aged mortar samples. Fresh mortar samples referred to R_{100} material mixed with un-aged virgin binder, while RTFO-aged mortar samples were R_{100} materials mixed with RTFO-aged virgin binder. The intermediate temperature shift factor was obtained by performing the DSR test (8 mm plate) on PAV-aged mortar samples. PAV-aged mortar specimens were prepared by aging the RTFO-aged mortar samples in the PAV at 100°C for 20 hours. The amount of mortar in each PAV pan was determined so that 50 grams of binder were present in the pan. For example, if the total binder content of the mortar is 35 percent, the amount of mortar in each PAV pan will be 50 g/(0.35 binder content)=143 g mortar. Low temperature shift factor was obtained by conducting the BBR test on PAV-aged mortar samples. The testing load in the BBR test was adjusted using the air bearing to allow for adequate deflection in the mortar samples. Table 4-4 displays the appropriate loading for the BBR test following the AASHTO draft.

For each temperature level (i.e., high, intermediate, and low), mortar samples were tested at two temperatures as defined by the virgin binder grade. For example, for a PG 52-28 binder, $G^*/\sin\delta$ of un-aged and RTFO-aged mortar samples was measured at the binder high temperature performance grade (52°C) and plus one grade (58°C). Similarly, $G^*\sin\delta$ of PAV-aged samples was measured at the binder intermediate temperature grade (16°C) and plus one grade (19°C). Finally, BBR tests on PAV-aged mortar samples were conducted at the binder low temperature performance grade (-18°C) and plus one grade (-12°C) to obtain stiffness (S) and relaxation (m-value) values. Table 4-5 summarizes mortar testing temperatures based on the PG grade of selected binders. Measured mortar properties at high, intermediate, and low temperatures were documented in Appendix C.

Table 4-4. Modified bending beam rheometer testing loads for binder and mortar (in mN)

Testing temperature (°C)	PAV binder	PAV mortar
0	980	980
-6	980	1980
-12	980	2980
-18	980	3980
-24	980	4980

Table 4-5. Mortar testing temperatures determined based on the performance grade (PG) of virgin binders

Virgin binder type	High testing temp. (°C)	Intermediate testing Temp. (°C)	Low testing temp. (°C)
PG58-28	58/64	19/22	-12/-18
PG52-28	52/58	16/19	-12/-18
PG 64-34 PMA	64/70	10/13	-18/-24
PG 46-34 Hydrolene	46/52	10/13	-18/-24
PG 52-28 Hydrolene	52/58	16/19	-12/-18
PG 46-34 REOB	46/52	10/13	-18/-24

Mortar A property (i.e., G*/sinδ, G*sinδ, BBR stiffness and m-value) was divided by the mortar B property to obtain the corresponding shift value. Note that the draft AASHTO method T X-12 proposed by researchers at the University of Wisconsin-Madison defined shift values in terms of the logarithm of the properties, except for the m-value. For each property, two shift values corresponding to two testing temperatures were determined and the average was reported as the shift factor. Figure 4-2 exemplifies the determination of the m-value shift factor (δ_m) at low temperature. Shift factors for each testing combination can be found in Appendix D.

Each virgin binder property (Table 4-6) was multiplied by the corresponding shift factor to estimate the properties of the virgin-RAP/RAS binder blends. For example, the m-value results of PAV-aged PG 52-28 binder were multiplied by its corresponding shift factors to estimate the m-value of each RAP/RAS blends, as illustrated in Figure 4-3. Estimated m-value results were used to determine the failure temperature of relaxation of the blends. Likewise, other properties of virgin binders were multiplied by calculated shift factors to estimate the corresponding properties and true grade of the blended binders at the selected binder replacement rate (e.g., 15%).

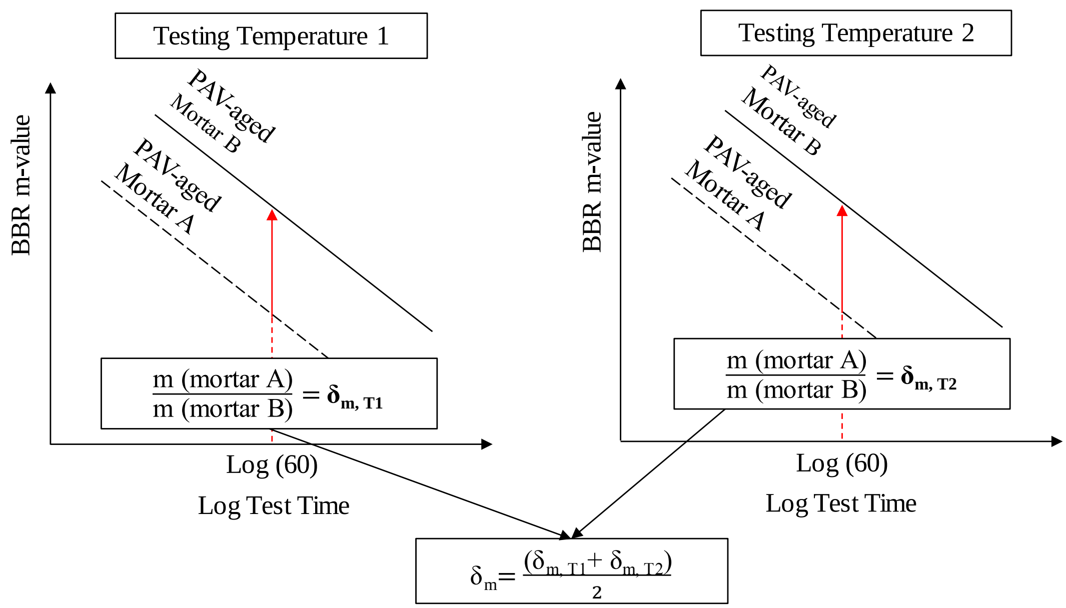

Figure 4-2. Determination of m-value shift factor (δ_m) at low temperature

Table 4-6. Rheological properties of virgin binders at selected testing temperatures

Virgin binder type		DSR Test			BBR test	
		High temp.		Intermediate temp.	Low temp.	
		Original	RTFO	PAV	PAV	
		G*/sin(δ) (kPa)	G*/sin(δ) (kPa)	G*sin(δ) (kPa)	S(MPa)	m
PG58-22	Temp.1	1.88	3.46	4350	98	0.390
	Temp.2	0.85	1.53	2900	230	0.321
PG52-28	Temp.1	2.02	5.01	3400	48	0.426
	Temp.2	0.90	2.20	2250	129	0.362
PG 64-34 PMA	Temp.1	1.55	2.85	4870	106	0.346
	Temp.2	0.86	1.58	3400	228	0.307
PG 46-XX Hydrolene	Temp.1	2.61	4.79	4420	86	0.443
	Temp.2	1.12	2.07	2720	246	0.359
PG 52-XX Hydrolene	Temp.1	2.24	4.50	3540	59	0.457
	Temp.2	0.99	1.97	2218	153	0.389
PG 46-XX REOB	Temp.1	1.90	4.42	2270	86	0.443
	Temp.2	0.85	1.89	1530	246	0.359

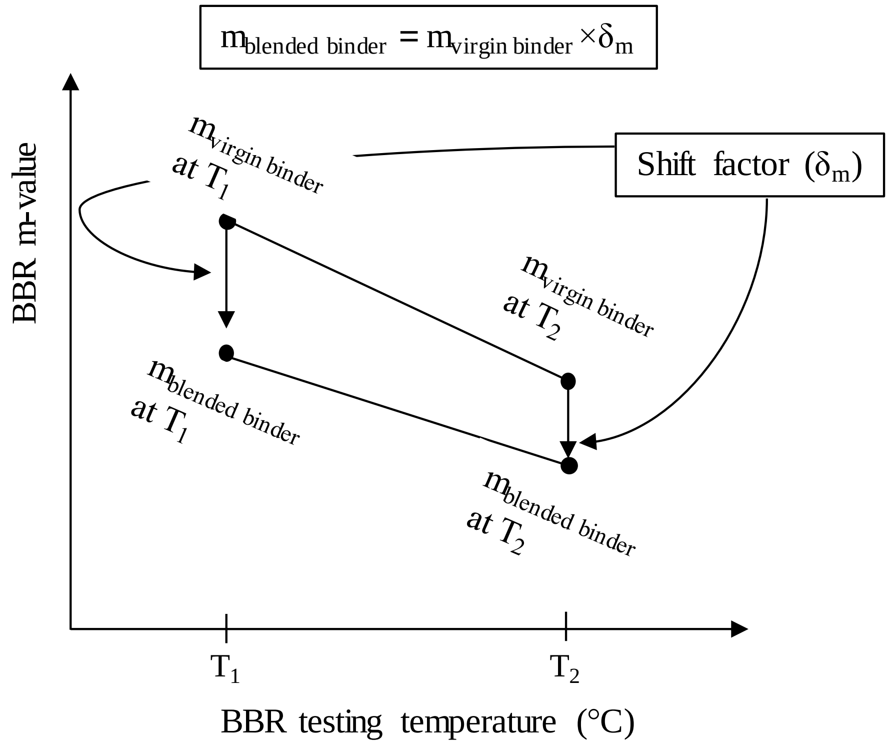

Figure 4-3. Application of m-value shift factor (δ_m) to PAV-aged binder

4.1.4 Determination of Grade Change Rate

The difference between the estimated true grade of a blend and the measured true grade of the virgin binder was calculated at the three temperature levels (i.e., high, intermediate and low temperatures). Then, the grade change rate (GCR) for each virgin binder, RAP or RAS combination was determined following Equation 2. As an example, Figure 4-4 illustrates the determination and application of GCR at high temperatures. Figure 4-4 also indicates that the GCR is independent of RAP/RAS binder replacement rate.

$$\frac{Estimated\ \ binder\ T.G.-Measured\ \ binder\ T.G.}{BRR} = \text{Grade Change Rate} \qquad [2]$$

where,

Estimated binder T. G.: estimated true grade of blended binder (°C);
Measured binder T. G.: measured true grade of virgin binder (°C);
BRR: binder replacement rate (%);
Grade change rate: rate of virgin binder grade increment per percent binder replaced (°C/% replacement).

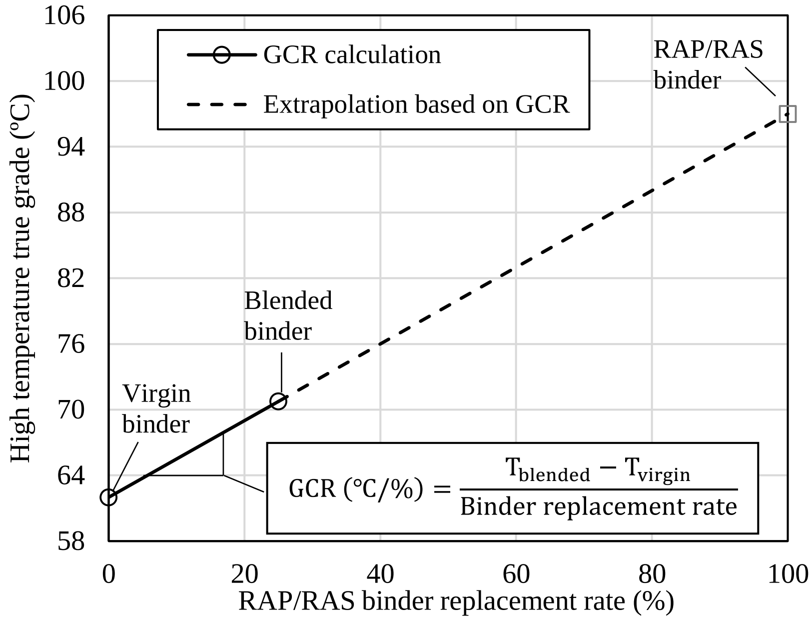

Figure 4-4. Determination and application of GCR to predict high temperature true grade

4.1.5 Preliminary Testing Results

Following the data interpretation procedure documented in the AASHTO provisional draft, grade change rate (GCR) of RAP/RAS mortars with various virgin binders were determined at high, intermediate and low temperatures. GCR results of each RAP/RAS and virgin binder combination can be found in Appendix E.

Figure 4-5 summarizes the high temperature GCR of the thirty blends, including three RAP sources, two RAS sources and six virgin binder types, based on the AASHTO provisional draft. For each RAP/RAS source, the individual columns correspond to a virgin binder type (average GCR value is shown above columns). The average GCR of TO shingles (the material with the stiffest binder) was the greatest; however, those of MW shingle, WHI RAP and ATL RAP were comparable. This was not expected because the MW shingles was much stiffer than those three RAP sources. Also, the high temperature GCR results in general were too small to be correct, although there were comparable to values reported by Swiertz and Bahia (2011). For example, for the range of GCR values obtained in this study (0.072-0.134), a binder replacement rate of 20% would increase the high temperature true grade of the virgin binder by only 2°C. Thus, it appears that the low GCR values obtained with the provisional draft significantly underestimated the effect of RAP/RAS on virgin binder high temperature grades. Swiertz and Bahia (2011) reported a similar observation and suspected the level of blending between virgin and RAP/RAS binder in mortar sample was too low to be captured by the DSR test.

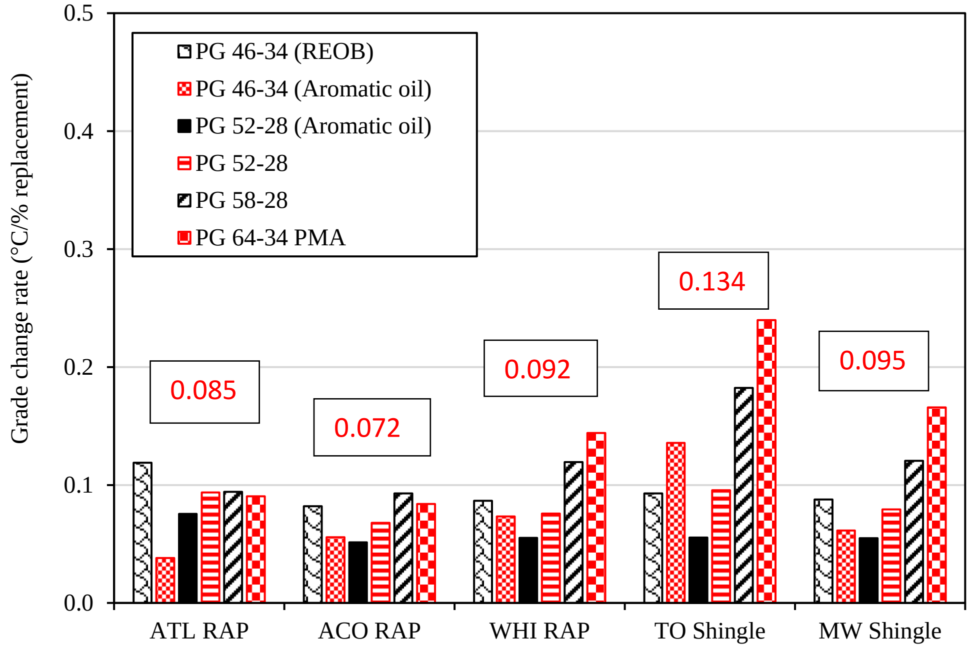

Figure 4-5. RAP/RAS grade change rate determined at high temperatures

As shown in Figure 4-6, GCR results at intermediate were also discouraging, although they were also comparable to those reported by Swiertz and Bahia (2011). There was a lack of pattern on the relative effect of different binders for a given RAP/RAS source. Also, it was not possible to differentiate RAS from RAP based on GCR results. Of note, it was difficult to trim DSR samples due to their small size (8 mm in diameter and 2 mm in thickness) and it was easy to introduce air voids at the specimen edge. The relatively low testing temperature (e.g., 10°C and 13°C for PG 46-34 binder) can potentially be another factor that contributed to unreliable DSR measurements due to the involvement of fine aggregate. Thus, a decision was made at this stage that mortar tests at intermediate temperatures were eliminated from the scope of this study. More discussions associated with intermediate temperature testing results can be found in Appendix F.

Two binder properties measured using the bending beam rheometer at low temperatures were stiffness (S) and stress relaxation (m-value). Thus, Figure 4-7 and Figure 4-8 show the RAP/RAS GCR values based on creep stiffness and m-value results, respectively. The mortar approach together with its data interpretation procedure appeared to capture the stiffening effect of RAP/RAS on virgin binders. GCR values based on m-value were higher than those from stiffness indicating the inclusion of RAP/RAS deteriorated the relaxation of virgin binder at a faster rate than the stiffness increased. ATL and ACO RAP, which had almost identical binder properties, also resulted in comparable low temperature GCR results and both were lower than that of WHI RAP. MW shingles exhibited the greatest GCR value, which resulted in the greatest negative impact on virgin binder low temperature cracking performance. It is interesting that TO shingles yielded lower average GCR than MW shingles because TO shingles were known to be stiffer although the low temperature true grades of both shingles cannot be determined.

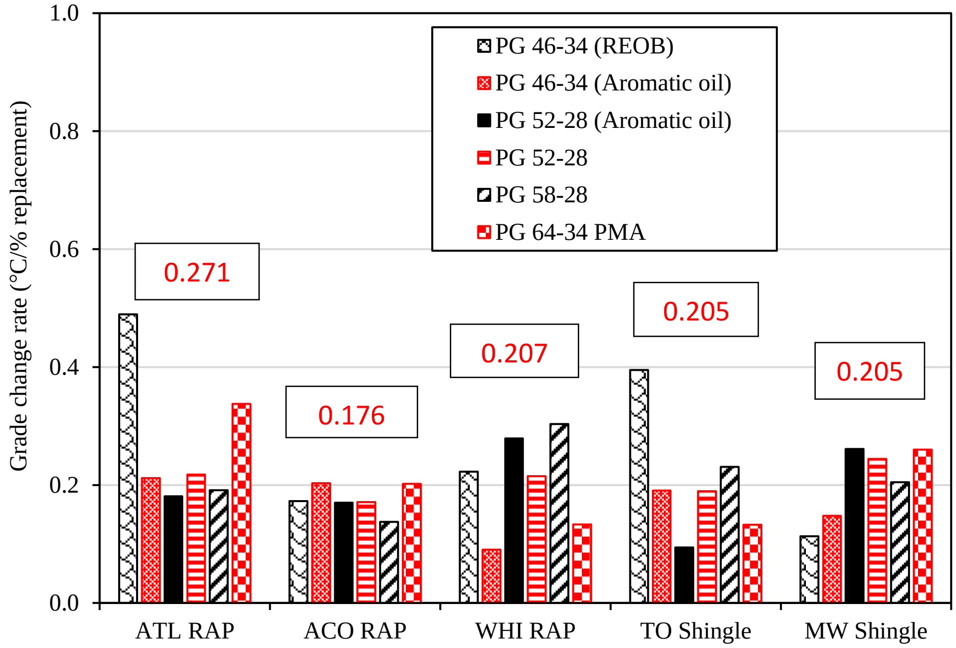

Figure 4-6. RAP/RAS grade change rate determined at intermediate temperatures

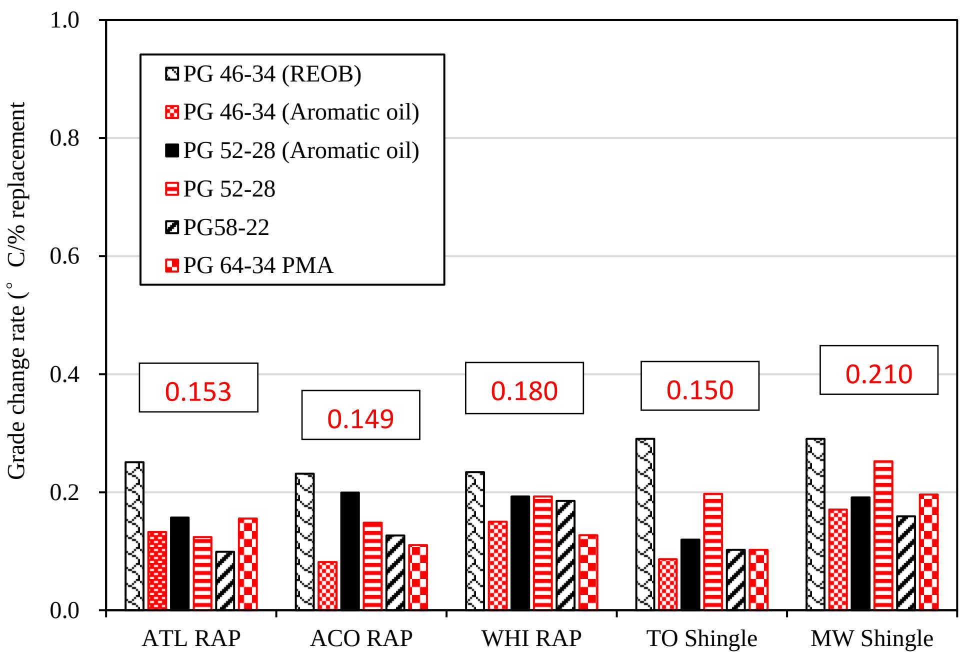

Figure 4-7. RAP/RAS grade change rate determined at low temperatures based on BBR stiffness

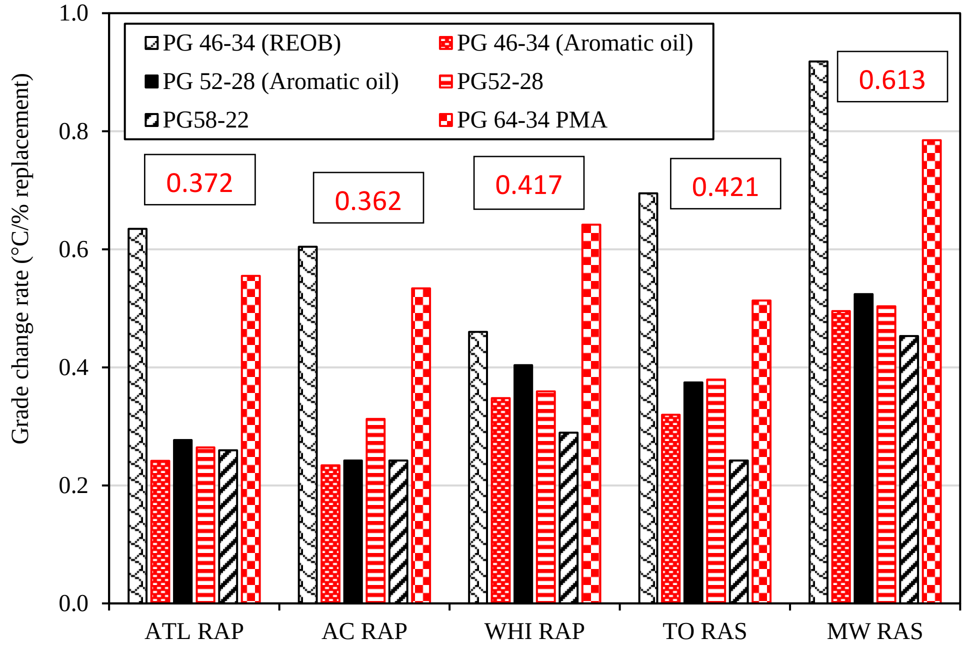

Figure 4-8. RAP/RAS grade change rate determined at low temperatures based on BBR m-value

Overall, two preliminary sets of mortar tests with RAP-alone and RAS-alone resulted in RAP GCR and RAS GCR results that were comparable to values reported by Swiertz and Bahia (2011). However, RAP/RAS GCR results at high temperature appeared to be too small to be correct. Also, questionable RAP/RAS GCR values were obtained at intermediate temperatures which could be attributed to the specimen deficiencies (presence of air voids on sample edge after trimming). Finally, RAP/RAS low temperature GCR results seemed to be reasonable as they differentiated different RAP sources and RAS sources as expected.

4.2 Enhanced Mortar Characterization Approach

Reasons for unreliable RAP/RAS GCR results at high, intermediate and possibly low temperatures have not been thoroughly investigated. However, they could be attributed to: 1) the presence of partial blending in mortar samples (whereas full blending was achieved in manually-blended binder samples); 2) lower level of blending of high temperature mortar samples as compared to low temperature mortar samples (the latter were additionally aged in a pressurized vessel for 24 hours at 100 ºC); and 3) the dynamic shear rheometer might not be sensitive to the effect of RAP binder when a low BRR (e.g., 15%) is used due to the small sample size (Swiertz and Bahia, 2011). Another possible source of underestimation not considered until this study lies within the factor δ used to shift properties from mortar to binder.

4.2.1 Evaluation of Existing Shift Method

Figure 4-9 illustrates the concept of shifting from mortar to binder. Note that mortar A and mortar B had the same total binder content, aggregate content and aggregate type. Since the only difference between mortar A and B is the presence of RAP/RAS binder, the RAP/RAS effect can be isolated from the two mortars by using a shift factor (δ) which is applied to the properties of the virgin binder to estimate the properties of the blended binder (Equation 3).

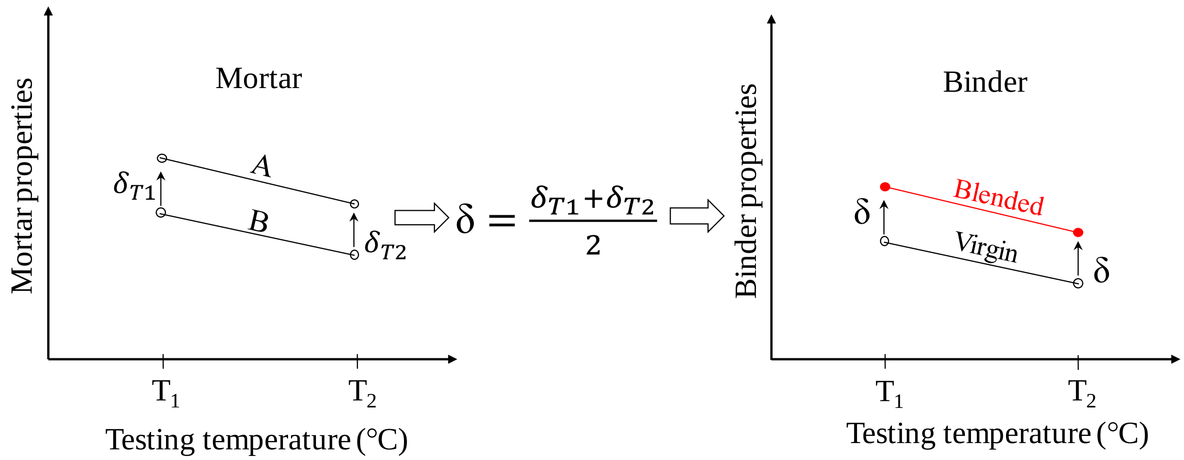

Figure 4-9. Determination and application of the shifting factor

$$\delta = \frac{\log(P_{\text{mortar A}})}{\log(P_{\text{mortar B}})} = \frac{\log(P_{\text{blended binder}})}{\log(P_{\text{virgin binder}})} \tag{3}$$

where P is the mortar and binder property under evaluation (note that for the low temperature relaxation parameter m, δ is defined as the ratio in m values instead of the ratio of their logarithm).

Unfortunately, the determination and application of shifting factor (δ) described in previous studies (Swiertz et al. 2011; Swiertz and Bahia, 2011; AASHTO draft) were found to be inconsistent. Nevertheless, the shifting method even in accordance to the latest document (i.e., AASHTO draft) remains questionable. Bonnaure et al. (1977) proposed Equation 4 to describe the relationship between binder and mixture stiffness.

$$\log(S_m) = \alpha \cdot \log(S_b) + \beta \tag{4}$$

where α and β are parameters calculated from the volume fractions of binder and aggregate in mixture, S_m is the mixture stiffness, and S_b is the asphalt binder stiffness.

Equation 4 shows that the properties of different asphalt mixtures depend only on binder properties when the aggregate type and volume fractions remain constant. Following Equation 4, a similar relationship can be established between mortar and binder properties:

$$\log(P_{\text{mortar}}) = c \cdot \log(P_{\text{binder}}) + d \tag{5}$$

where, P_{mortar} is the property of the mortar, P_{binder} is the property of the binder, and c and d are coefficients dependent upon the aggregate and binder volume fractions of the mortar. Applying Equation 5 to mortars A and B and substituting into Equation 3 yields:

$$\delta = \frac{\log(P_{\text{mortar A}})}{\log(P_{\text{mortar B}})} = \frac{c \cdot \log(P_{\text{blended binder}}) + d}{c \cdot \log(P_{\text{virgin binder}}) + d} \tag{6}$$

Comparison of Equations 3 and 6 reveals that an accurate determination of blended binder properties requires not only delta and the properties of the virgin binder, but also an additional term which depends on the aggregate and binder fractions of the mortar, as shown in Equation 7.

$$\log(P_{\text{blended binder}}) = \underbrace{\delta \cdot \log(P_{\text{virgin binder}})}_{\text{Existing approach}} + \underbrace{\frac{d}{c}(\delta - 1)}_{\text{Additional term}} \tag{7}$$

Since δ cannot be equal to one due to the stiffening effect of RAP/RAS, and d/c does not equal to zero, the additional term in Equation 7 affects the determination of blended binder properties. The effect of this additional term is schematically illustrated in Figure 4-10 (G*/sinδ is shown for illustration purposes). When the properties of the virgin binder are shifted, the additional term increases G*/sinδ of the blended binder and, consequently, its high temperature true performance grade. In other words, the shifting approach defined in the existing mortar characterization method clearly underestimates the true grade of blended binders. Therefore, an alternative mortar characterization method is needed to overcome the deficiencies of the existing method.

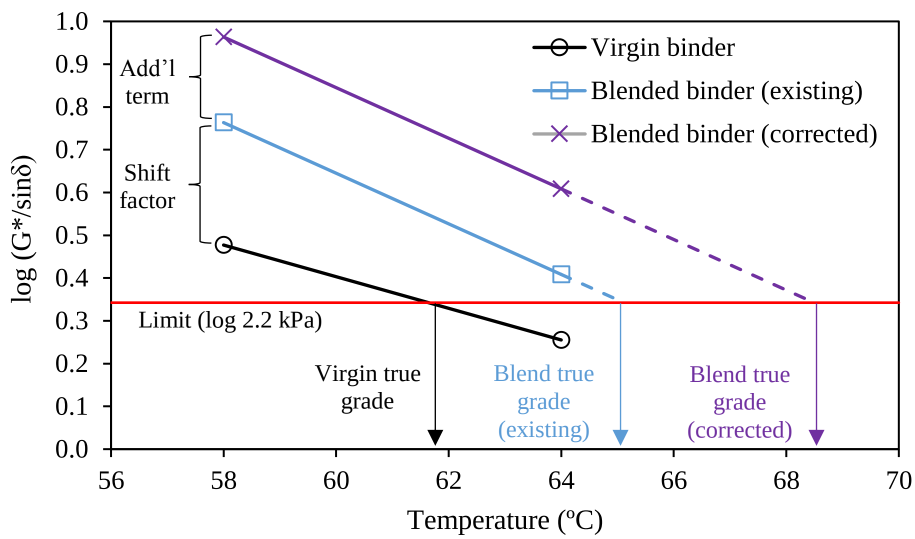

Figure 4-10. Effect of an additional term on the determination of blended binder true grade according to the existing mortar characterization method

4.2.2 Propose an Alternative Data Analysis Method

Equation 7 showed that an accurate prediction of blended binder properties following the existing method would require not only a shift factor δ obtained from mortar properties, but also two coefficients (c and d) defined by the aggregate and binder volume fractions of the mortars. Since the calculation of δ, c, and d may be a tedious process, an alternative and more effective procedure was developed, which eliminates the need for the shift factor δ.

The first step is to establish a relationship between G*/sinδ of mortar B (composed of virgin binder and R_{100} aggregate) and G*/sinδ of a selected virgin binder following Bonnaure et al.'s approach (Equation 8). The relationship is defined by measuring G*/sinδ at two temperatures: the high PG temperature of the virgin binder (T_1) and at T_1 plus 6°C (T_2).

$$\log\left(G^*/\sin\delta_{\text{mortarB}}\right) = c \cdot \log\left(G^*/\sin\delta_{\text{virgin binder}}\right) + d \quad (8)$$

Since the aggregate and volume fractions are the same for mortars A and B, the coefficients c and d remain constant, and the relationship established by Equation 8 can be applied to mortar A:

$$\log\left(G^*/\sin\delta_{\text{mortarA}}\right) = c \cdot \log\left(G^*/\sin\delta_{\text{blended binder}}\right) + d \quad (9)$$

Solving Equation 9 for the properties of the blended binder yields:

$$\log\left(G^*/\sin\delta_{\text{blended binder}}\right) = \frac{1}{c} \cdot \log\left(G^*/\sin\delta_{\text{mortarA}}\right) - \frac{d}{c} \quad (10)$$

Figure 4-11 illustrates the alternative mortar characterization approach proposed in this study. The true grade of the blended binder is obtained by determining the temperature at which Superpave G*/sinδ specification limits are met. Finally, GCR is calculated based on the true grade of virgin and blended binder, and the corresponding binder replacement rate.

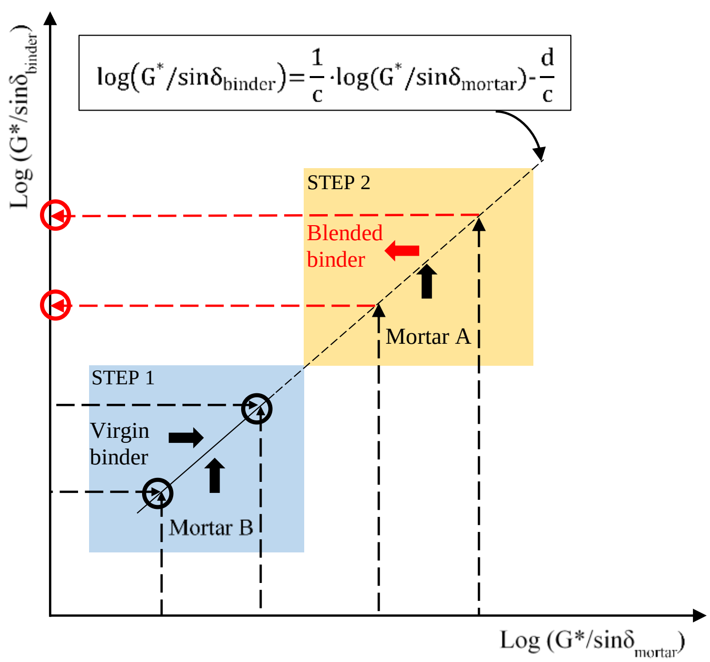

Figure 4-11. Illustration of alternative method for predicting properties of blended binders

4.2.3 Evaluation of the Existing and Alternative Data Analysis Methods

RAP/RAS binders were extracted and recovered using the solvent method and then manually blended with virgin binders at three RAP/RAS binder replacement rates (i.e., 15%, 30% and 100%). The alternative data analysis method was evaluated by comparing predicted grades of

RAP/RAS binder blends to measured values. The TO shingle binder did not melt and blend with virgin binders at a typical mixing/compacting temperature (e.g., 153°C). Thus, it was necessary to increase the oven temperature to 200°C to allow the blending to occur. Of note, a short period of 15 minutes was used to heat the TO binder blends to possibly minimize excessive aging. Evaluation was only conducted at high temperatures where significant underestimations were observed in this study and reported by Swiertz and Bahia (2011).

4.2.3.1 Grade Change Rate Based on Proposed Method

In the alternative method, mortar B and virgin binder are used to develop a relationship that is then applied to mortar A to obtain the properties of the blended binder. An example of the application of the alternative method is illustrated in Figure 4-12 and Figure 4-13 for a PG 58-28 binder with 15% WHI RAP. The solid line in Figure 4-12 represents the relationship between G*/sinδ of mortar B and virgin binder obtained at two temperatures (58 and 64 ºC in this case) in double logarithm scale. The equation obtained was applied to mortar A to compute G*/sinδ of the blended binder (dotted line). Figure 4-13 shows the determination of the high temperature true grade of the blend.

Of note, the equation in Figure 4-12 took the form of Equation 10, according to which, the coefficient (1/c) and intercept term (d/c) were determined to be 0.947 and 0.566, respectively. Consequently, the additional term in Equation 7 was not zero ($d/c \times (\delta-1) = 0.25$; $\delta = 1.45$ from Table D-3), which can be the reason for the low true grade predicted by the existing method.

Figure 4-14 compares the average high temperature GCR of the RAP/RAS blends following the existing and alternative methods. Results with the alternative method seemed to better illustrate the effect of RAP/RAS source on high temperature grade: the stiffer RAP (WHI RAP) yielded greater GCR values than the less stiff RAP (ATL and ACO RAP), RAS achieved higher GCR than RAP sources, and TO shingle exhibited the greatest GCR (i.e., largest impact on virgin binder grade). Furthermore, the alternative mortar characterization method consistently resulted in greater GCR values than those obtained with the existing method (almost five times greater), which may lead to more accurate predictions of binder true grade.

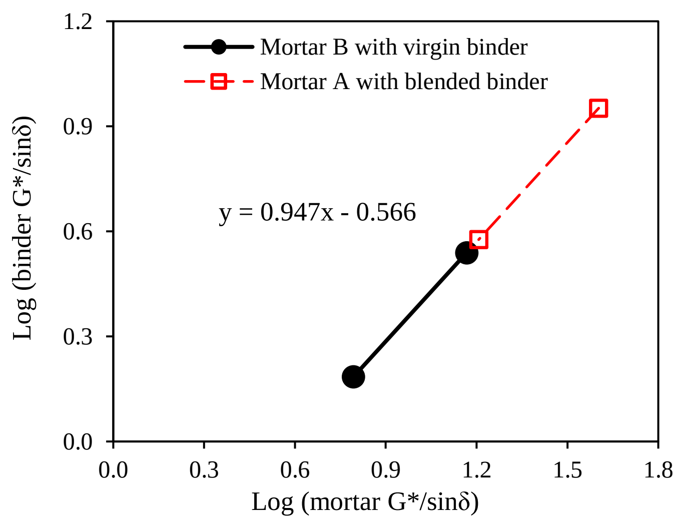

Figure 4-12. Mortar-binder relationship to predict G*/sin(δ) of the blended binder

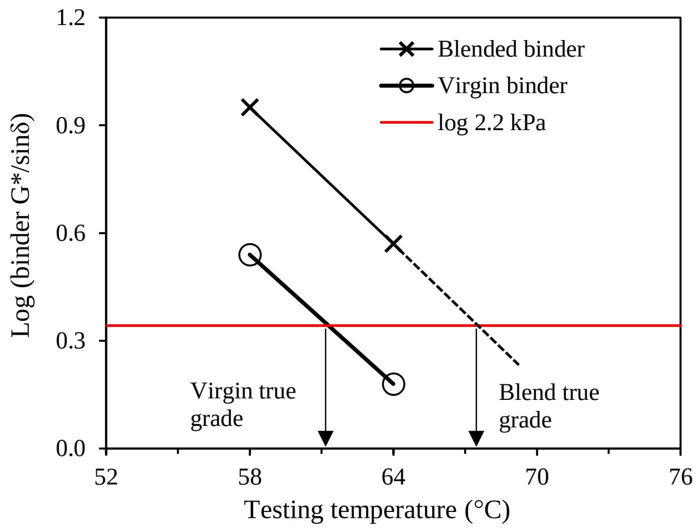

Figure 4-13. Determination of high temperature true grade of the blended binder

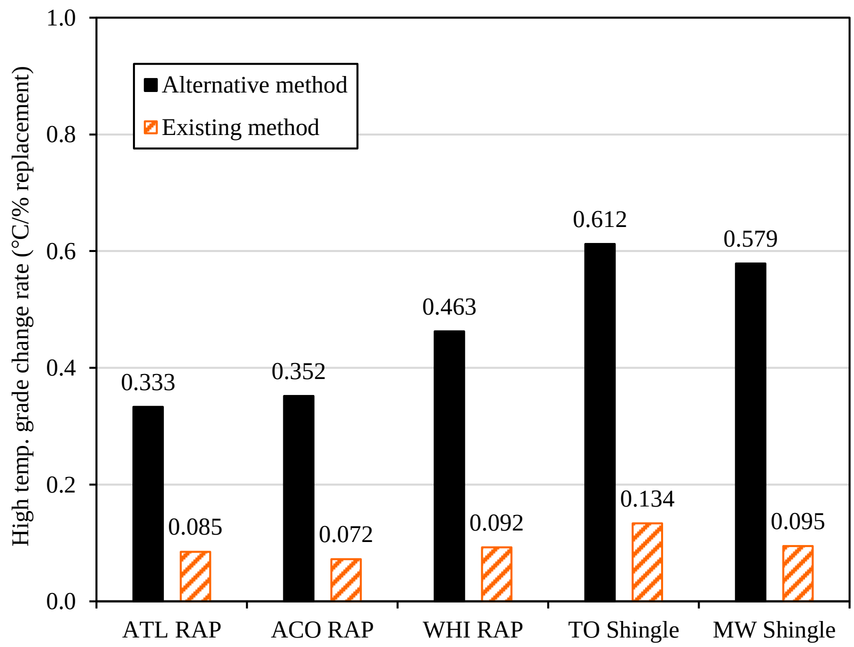

Figure 4-14. Average high temperature RAP/RAS GCR as determined using the existing and alternative data analysis methods

The alternative data analysis method relies on a direct relationship between binder and mortar properties, thus it was extended to low temperature evaluation although the shift factor method appeared to yield reasonable GCR results. For the combination of a PG 58-28 binder and 15% WHI RAP, Figure 4-15. Mortar-binder relationship to predict BBR m-value of the blend plots the relationship of the BBR m-value between mortar B and virgin binder obtained at two temperatures (-18 and -12ºC in this case) in an arithmetic scale. The intercept term of the equation that relates binder and mortar m-value in Figure 4-15 was 0.0735, which was much smaller than that in Figure 4-12 (i.e., 0.566). This was expected because asphalt binder exhibits more solid behavior at low temperatures and the effect of fine aggregates became less pronounced. This also explains why reasonable trends were obtained at low temperatures but not at high temperatures when the same data analysis method (i.e., shift factor approach) was used.

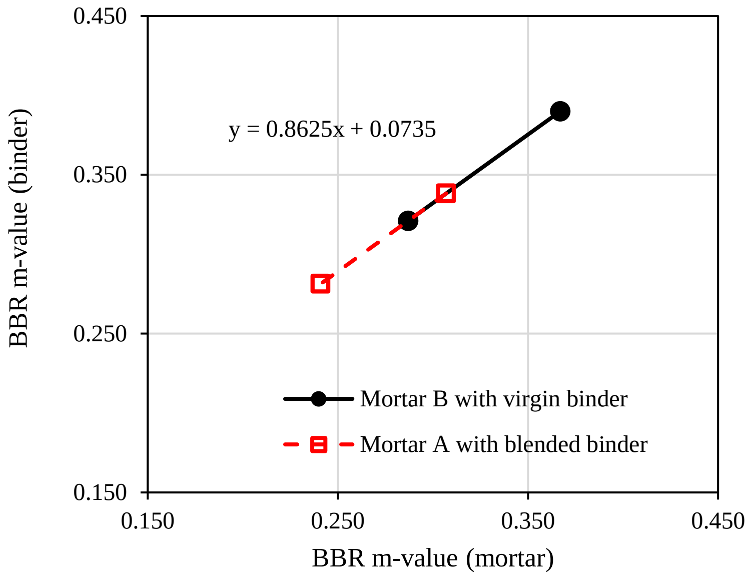

Figure 4-15. Mortar-binder relationship to predict BBR m-value of the blended binder

Figure 4-16 summarizes the average RAP/RAS low temperature GCR following the existing and alternative data analysis methods. As expected, trends observed from the shift factor method were generally in agreement with the alternative data analysis method. Nevertheless, it appears that the existing method overestimated the RAP/RAS effect at low temperatures.

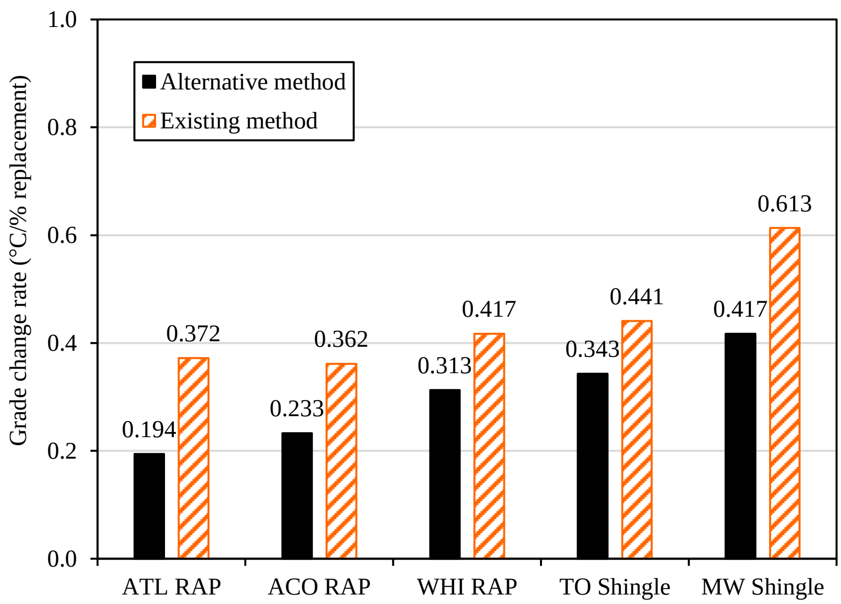

Figure 4-16. Average low temperature RAP/RAS GCR based on BBR m-value as determined using the existing and alternative data analysis methods

Overall, the alternative data analysis method potentially could lead to more accurate predictions of binder true grade. This method relies on a relationship between binder and mortar properties instead of a shift factor. As a result, it consistently yielded much greater high temperature GCR values and smaller low temperature GCR results than those obtained with the shift factor method. RAP/RAS GCR results determined following the alternative data analysis method can be found in Appendix G.

4.2.3.2 Prediction of Blended Binder High Temperature True Grade

Figure 4-17, Figure 4-18 and Figure 4-19 compared the measured and predicted high temperature true grades of ATL, ACO and WHI RAP binder blends, respectively. Regardless of virgin binder type, RAP source and RAP binder replacement rate, the alternative data interpretation procedure resulted in predicted grades comparable to values measured on binder samples. The average difference between predicted and measured grades were only 0.5°C and 0.9°C for binder blends at 15% and 30% binder replacement rates, respectively. Conversely, the existing method underestimated the true grade by 3.6°C on average at 15% RAP binder replacement rate. Moreover, the difference became more pronounced (i.e., 8.8°C on average) as the RAP binder replacement rate increased from 15% to 30%. These observations substantiated the feasibility of using DSR to perform mortar testing at high temperatures and adopting the alternative data interpretation procedure for determination of GCR. Furthermore, the fact that predicted and measured true grades were comparable indicates that the level of blending occurring in binder blends (i.e., possibly full blending) was equivalent to that occurring in mortar samples. This is an important finding because the mortar samples are believed to simulate the actual blending that occurs in asphalt mixtures, better than artificially fully blended binders.

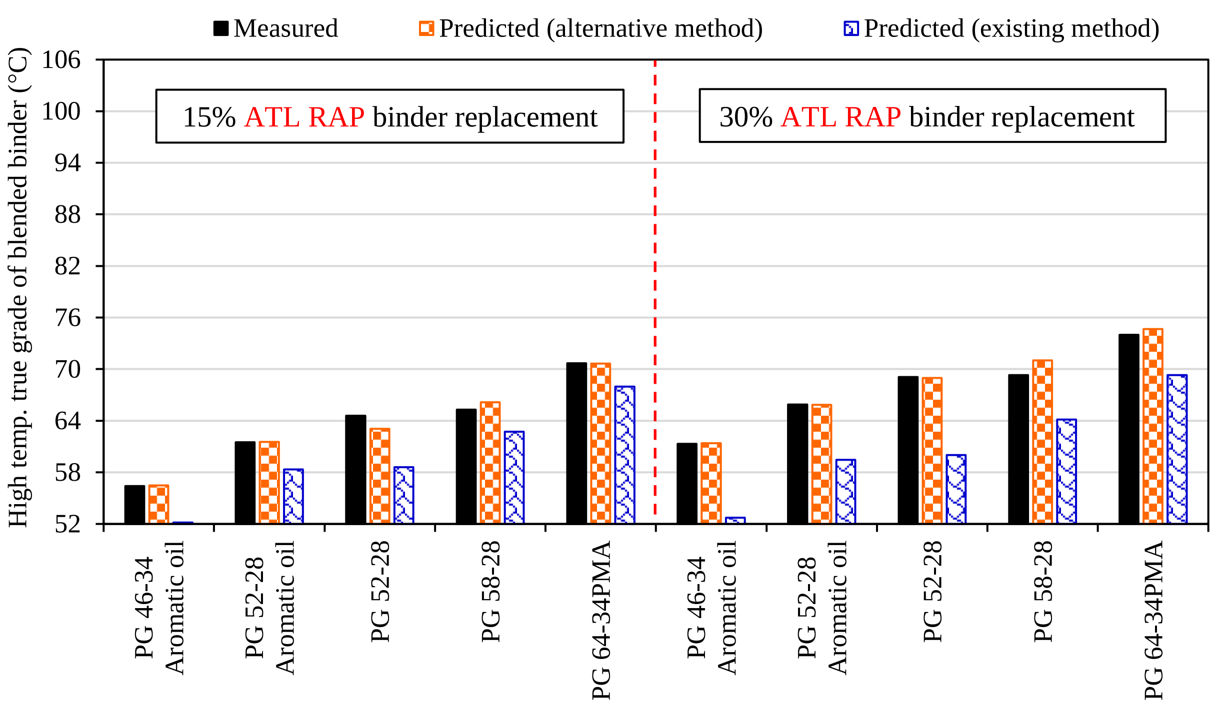

Figure 4-17. Measured and predicted grades of 15% and 30% ATL RAP binder blends

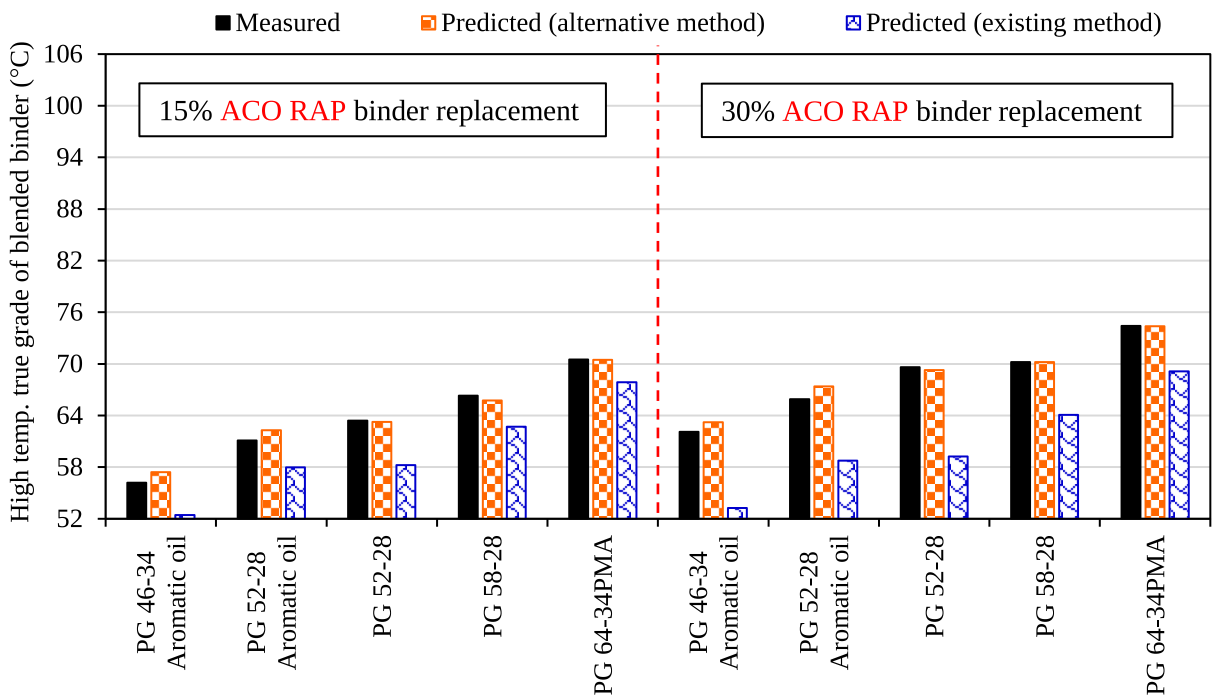

Figure 4-18. Measured and predicted grades of 15% and 30% ACO RAP binder blends

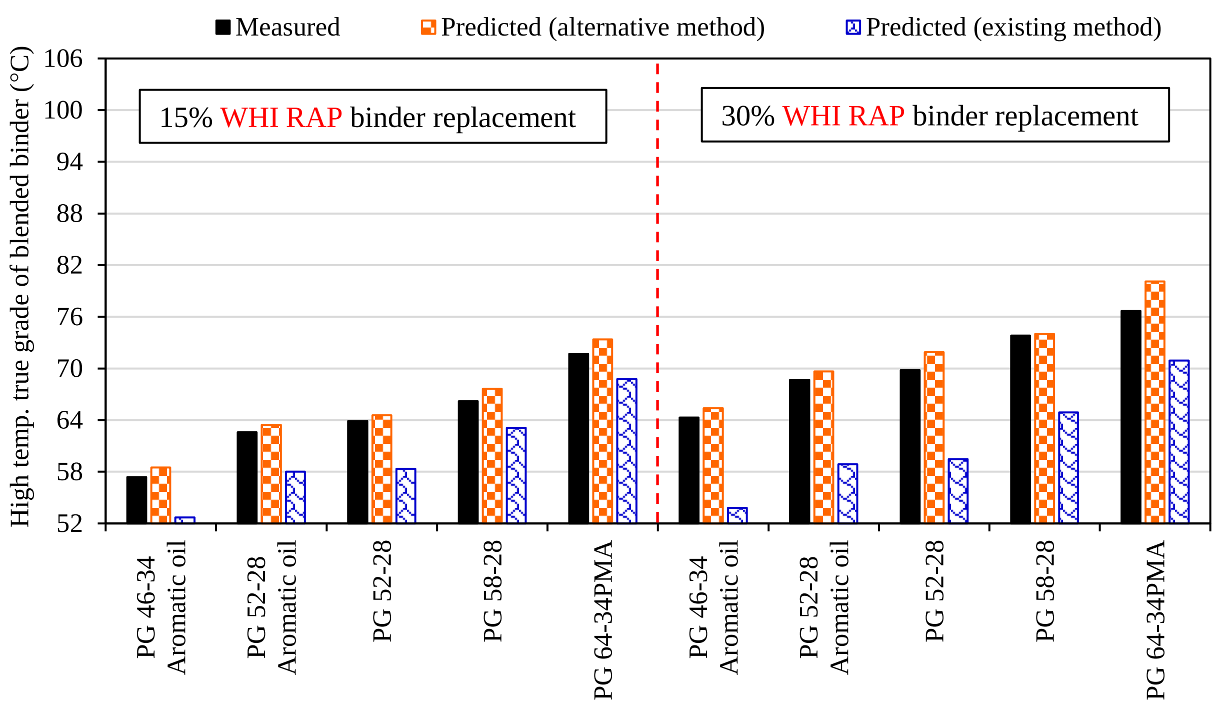

Figure 4-19. Measured and predicted grades of 15% and 30% WHI RAP binder blends

As shown in Figure 4-20, the alternative method also provided more accurate predictions for MW shingle binder blends at two binder replacement rates. This observation indicated that a high level of blending occurred in MW shingle mortars, which remained relatively unchanged when the binder replacement rate increased from 15% to 30%. Once again, the existing method significantly underestimated the true grades of binder blends (i.e., average of 7.5°C and 14.2°C at 15% and 30% binder replacement rates, respectively).

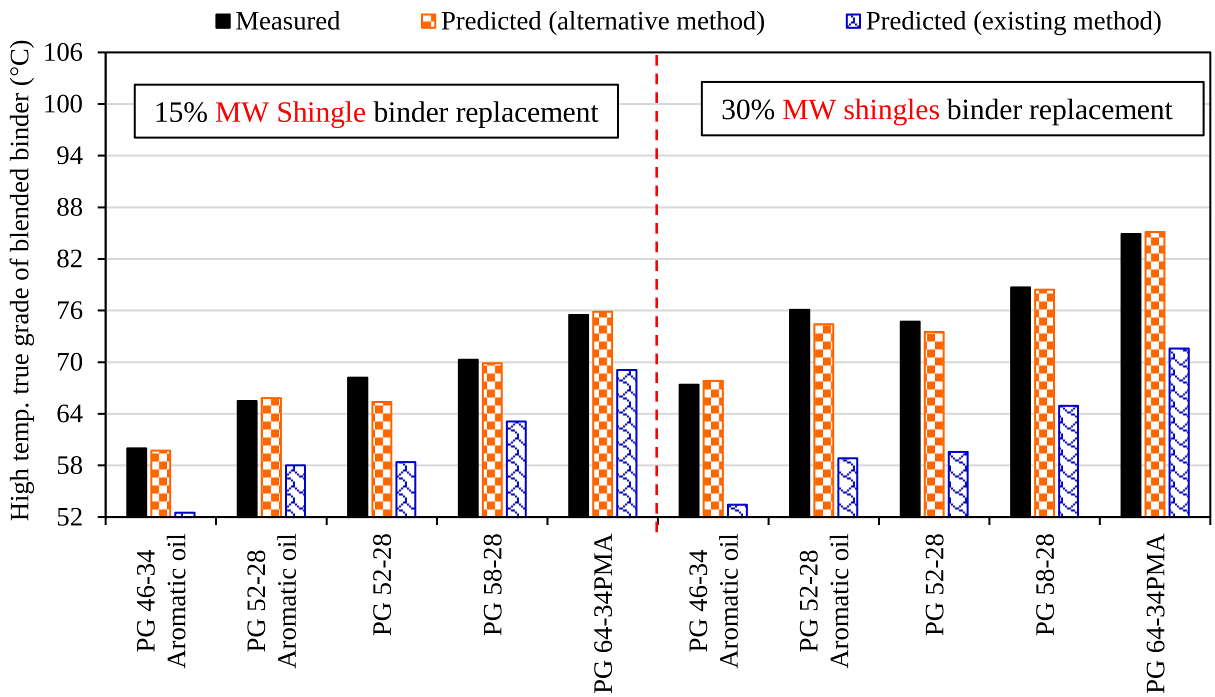

Figure 4-20. Measured and predicted grades of 15% and 30% MW shingle binder blends

However, the GCR values as determined by testing 15% TO shingle mortars only resulted in satisfactory predictions for the 15% binder replacement rate scenario but not for 30% (Figure 4-21). This observation implies that the TO shingle GCR may not be constant, as opposed to the RAP GCR.

Additional mortar tests were conducted to further investigate the TO shingle binder replacement rate dependency of GCR. Mortars with 30% TO shingle were tested to obtain corresponding GCR values. It is clear in Table 4-7 that 30% TO mortars yielded higher GCR values than those of 15% TO mortars, for all five virgin binders. Consequently, the use of updated GCR values resulted in accurate grade predictions for 30% binder replacement rate scenario, as shown in Figure 4-22. The measured grades were notably higher than all predictions when the PG 64-34 PMA was used as the virgin binder. This observation can be potentially attributed to the excessively high heating temperature (200°C), which may have induced an effect on properties/compositions of the SBS polymer modification.

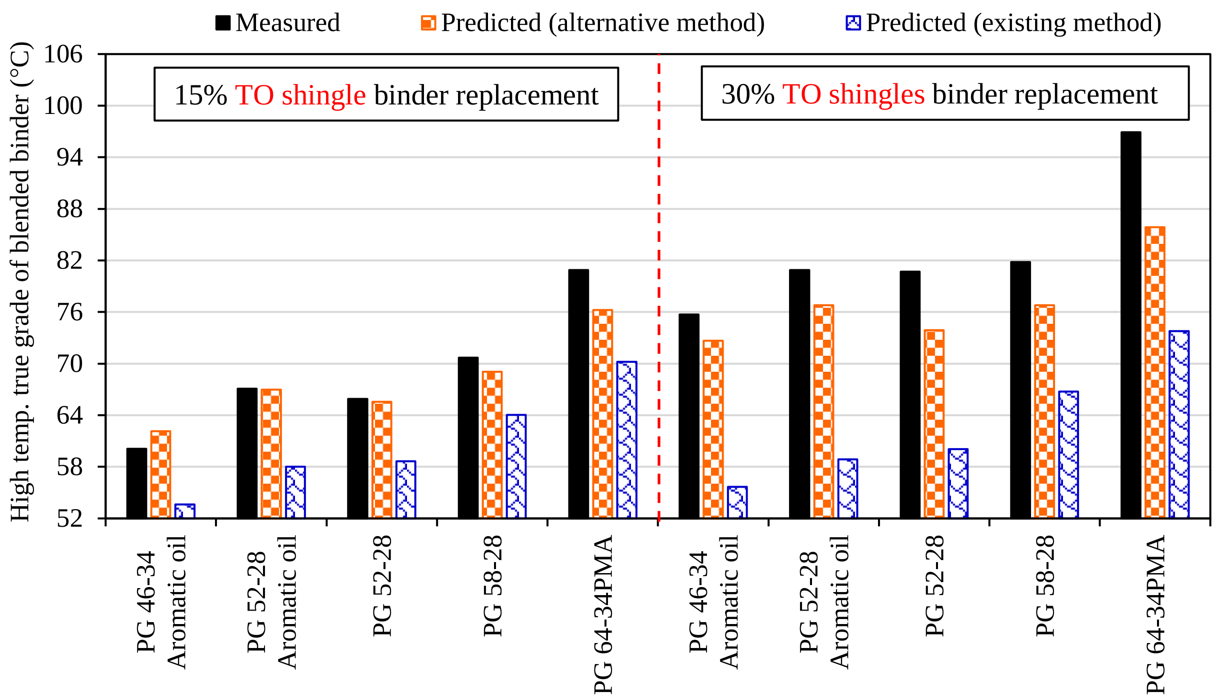

Figure 4-21. Measured and predicted grades of 15% and 30% TO shingle binder blends

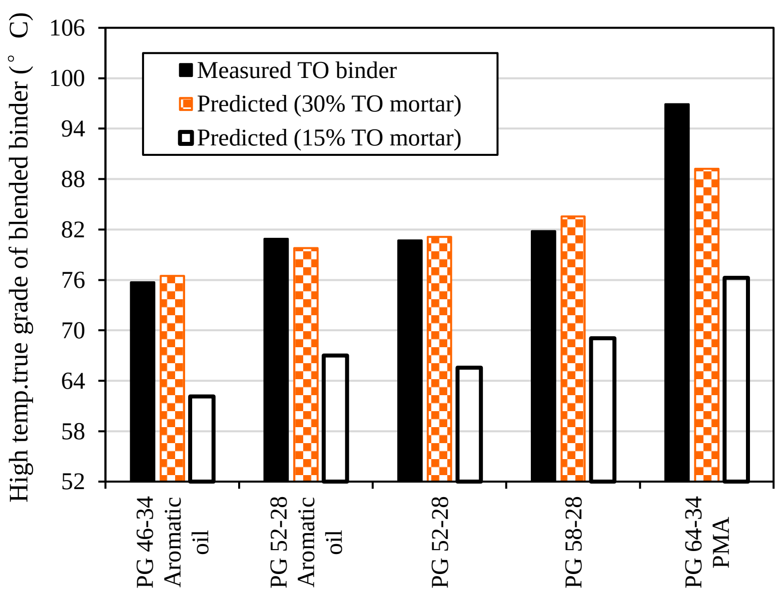

Figure 4-22. Predicted high temperature true grades based on grade change rates of 15% and 30% TO shingle mortars

Table 4-7. Grade change rate of TO shingle mortars

Virgin binder type	Grade change rate (°C/% TO shingle binder)	
	15% TO mortars	30% TO mortars
PG 46-34 Aromatic oil	0.702	0.829
PG 52-28	0.653	0.797
PG 52-28 Aromatic oil	0.556	0.753
PG 58-28	0.516	0.742
PG 64-34 PMA	0.642	0.754

4.2.3.3 Prediction of RAP/RAS Binder High Temperature True Grade

In addition to predicting the grade of RAP/RAS blended binders, another application of the mortar approach is to estimate the true grade of RAP/RAS binder without the need for binder extraction and recovery. This is achieved by extrapolating GCR to a 100% binder replacement rate, as shown in Figure 4-4.

Table 4-8 summarizes the high temperature true grade of the three extracted RAP binders and that predicted by the mortar characterization approach with the alternative data analysis method. In general, the alternative method successfully estimated the true grade of the three RAP sources such that the ratios between average prediction and measured grade were all close to 100 percent. It was also observed that predicted RAP binder grades varied among different virgin binders. One possible explanation could be different levels of blending associated with different virgin binders although they were all close to a complete blending scenario. Two rejuvenated binders (i.e., PG 46-34 Aromatic oil and PG 52-28 Aromatic oil) were found to consistently result in RAP binder grades lower than the other three binders.

Table 4-9 presents the predicted grades of MW and TO shingle binders. All virgin binders yielded predictions slightly lower than the measured grade of the MW shingle binder, except for the PG 64-34 PMA, which resulted in an almost identical prediction. As expected, the use of GCR values as determined at two TO shingle binder replacement rates (i.e., 15% and 30%) led to notably lower predictions than the measured grade. This observation substantiates the previously made hypothesis that the TO shingle GCR may not be constant and the virgin and RAS binder blending is nonlinear.

Overall, it appears the mortar approach as developed in this study can be used to characterize the binder properties of RAP without the need for solvent extraction and recovery. Although this method is not suitable for characterizing RAS materials, it provides accurate predictions of RAS binder blends for which the binder replacement rate has been limited to low values (e.g., maximum TO shingle binder replacement rate of 20% by weight of total binder) by many state highway agencies. Further research is needed to investigate the interaction between virgin and TO shingle binders to better understand the nature of nonlinear behavior.

Table 4-8. Predicted and measured high temperature true grades of three RAP binders

Virgin binder type	High temperature true grade (°C) of RAP binder					
	ATL RAP		ACO RAP		WHI RAP	
	Predicted	Measured	Predicted	Measured	Predicted	Measured
PG 46-34 Aromatic oil	84	92	91	91	98	104
PG 52-28 Aromatic oil	86		91		99	
PG 52-28	96		97		106	
PG 58-28	94		90		103	
PG 64-34 PMA	94		92		112	
Average prediction	91		92		104	
Average prediction/ measured (%)	99		100		100	

Table 4-9. Predicted and measured high temperature true grades of two RAS binders

Virgin binder type	High temperature true grade of RAS binder (°C)					
	MW Shingles		TO Shingles			
	Predicted	Measured	Predicted	Measured	Predicted*	Measured
PG 46-34 Aromatic oil	122	127	105	173	135	173
PG 52-28 Aromatic oil	122		114		132	
PG 52-28	113		111		137	
PG 58-28	113		118		136	
PG 64-34 PMA	130		128		142	
Average prediction	120		116		136	
Average prediction/ measured (%)	94		67		79	
*Note: Predictions were based on GCR values determined from 30% TO shingle mortars						

4.3 Determination of RAP-RAS GCR

It is assumed in the AASHTO draft that any combination of RAP and RAS binder percentages followed a linear combination of the RAP-alone and RAS-alone blends. Thus, grade change rate (GCR) results from RAP-alone and RAS-alone mortar tests can be used to predict the true grade of a virgin binder blended with any RAP and RAS binder replacement rates following the Equation previously presented in Chapter 2 (Equation 1). This is an important assumption because RAS is typically used together with RAP and the adoption of Equation 1 can significantly reduce the amount of laboratory work required to determine the GCR of any RAP and RAS combination.

Results from Equation 1 were used to develop charts of true grade of blended binder for different RAP/RAS replacement rates. This section randomly selected one combination (PG 52-28, ATL RAP and TO shingle) for illustration purpose. Figure 4-23 shows the predicted high temperature true grade of PG 52-28 binder combined with ATL RAP and TO shingle. In this figure, the horizontal axle represents %RAP binder, the vertical axle represents %RAS binder, and the shading illustrates the true grade of the blend. This chart can be used to optimize the combination of RAP and RAS contents for a target high temperature grade (note Figure 4-23 applies only to a combination of given virgin binder type, RAP and RAS sources). Likewise, Figure 4-24 presents the low temperature true grade prediction for the same virgin binder, RAP and RAS combination, which can be employed to estimate optimal RAP and RAS content for a target low temperature grade.

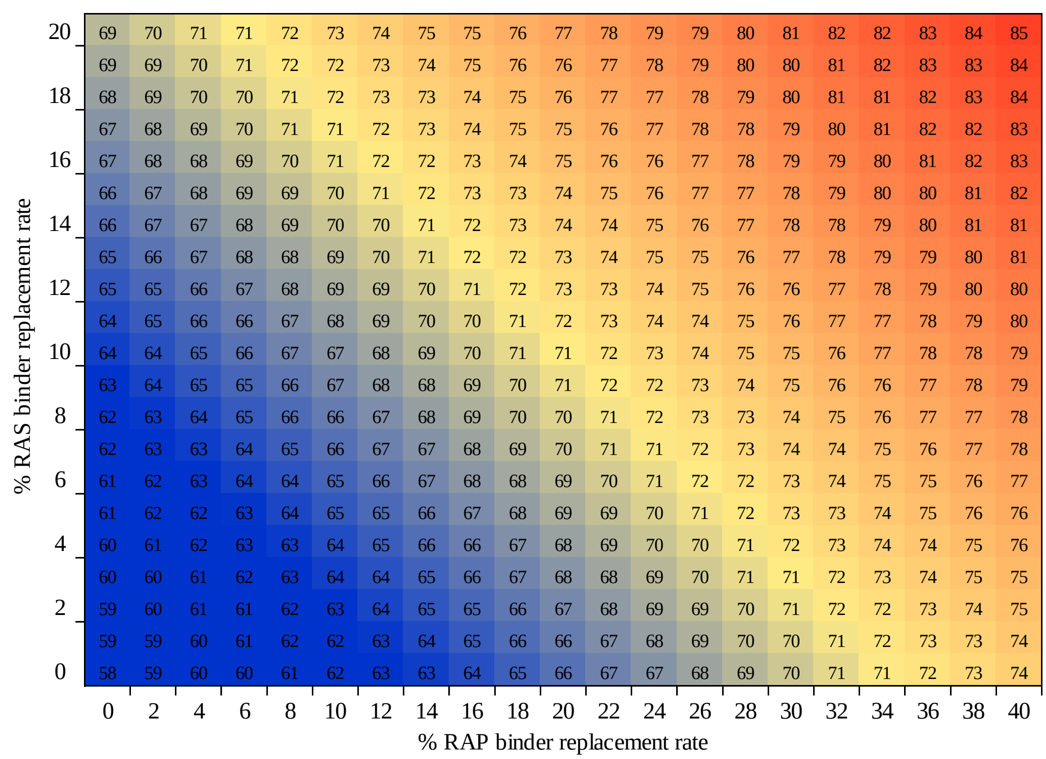

Figure 4-23. High temperature true grade prediction of a PG 52-28 blended with ATL RAP binder and TO shingle binder

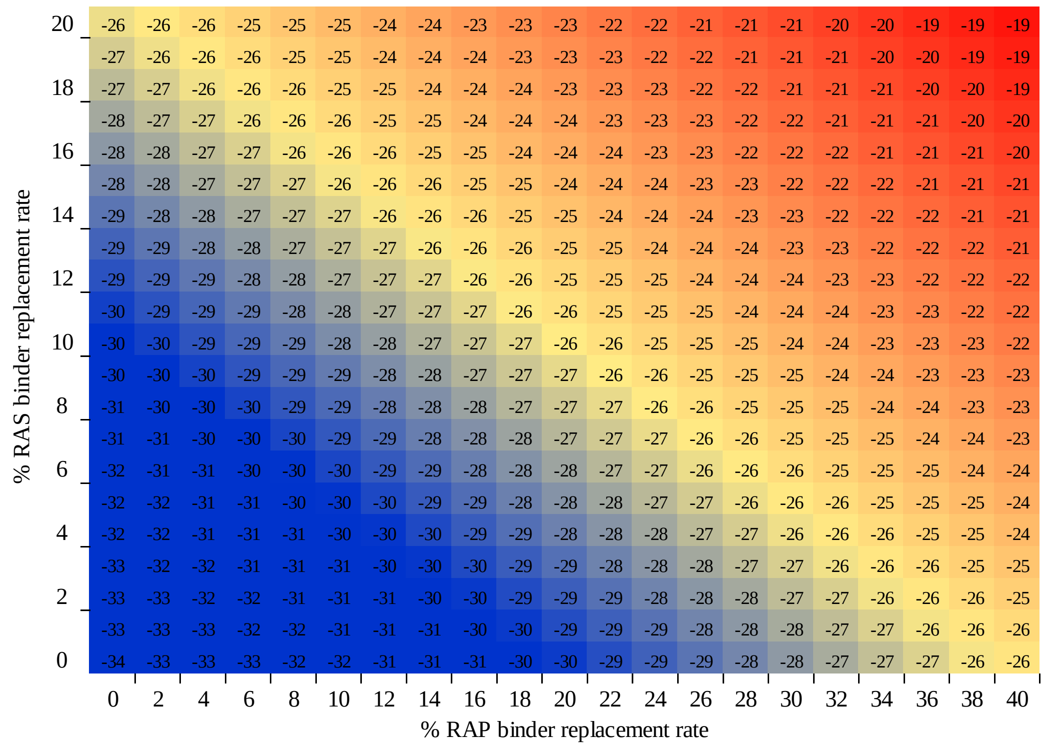

Figure 4-24. Low temperature true grade prediction of a PG 52-28 blended with ATL RAP binder and TO shingle binder

This linear assumption was established based on the hypothesis that RAP-alone/RAS-alone GCR were constant for any RAP/RAS binder replacement rate. However, results presented in section 4.2.3 indicated that RAP-alone GCR may be constant but RAS-alone GCR increased exponentially with increased RAS binder replacement rate. Therefore, this linear assumption was evaluated by comparing the grades of RAP-RAS binder blends predicted using two types of RAP-RAS GCR: 1) linearly combined RAP-alone GCR and RAS-alone GCR, and 2) determined from mortars simultaneously containing RAP and RAS. Since the previous task (Chapter 3) found that the DSR cannot provide repeatable mortar measurements at intermediate temperatures, tests on RAP-RAS mortars were only conducted at high and low temperatures.

4.4 Experimental Plan

Two preliminary sets of tests were conducted on mortars with RAP-alone and RAS-alone to determine the corresponding grade change rate (GCR) values. According to the AASHTO provisional standard draft, the GCR allows for the grade prediction of the virgin binder and RAP/RAS binder at any replacement rate. However, preliminary results indicated that the existing data interpretation method may be inappropriate as notable underestimations were obtained for high temperature true grade predictions. In response, a modified data analysis method, which eliminates the use of a shift factor was developed. In this method, a relationship is established between properties of mortar B and virgin binder, which allows for prediction of RAP/RAS blends based on mortar A properties. The alternative data analysis method was validated by satisfactory results of comparison between predicted grades of RAP/RAS blended binders and values measured from blends of virgin and extracted RAP/RAS binders at three RAP/RAS binder replacement rate (i.e., 15%, 30% and 100%). Therefore, reanalyzing the preliminary testing data with the alternative method was included as part of the experimental plan.

Moreover, the assumption made in the existing AASHTO draft that RAP-alone GCR and RAS-alone GCR can be linearly combined to predict the RAP-RAS GCR was identified as an essential element of the mortar characterization approach. True grades predicted by using Equation 1 were compared to values predicted using measured GCR from mortars simultaneously containing RAP and RAS. Table 4-10 lists the eight RAP-RAS mortar combinations which include two RAP sources, two RAS sources and two total RAP-RAS binder replacements. The RAP binder replacement rates employed in this task were lower than previously used values. This was because sufficient total binder content[2] in mortars were required to ensure the specimen workability; however, the binder content of the R_{100} material was low, which precluded the use of high RAP binder replacement rates.

Table 4-10. Mortars with different RAP and RAS combinations

RAP type	RAP binder replacement rate	RAS type	RAS binder replacement rate	Total RAP and RAS binder replacement rate	Total binder content in mortar samples
WHI RAP	5%	MW shingle	5%	10%	47.5%
	3%		10%	13%	39.3%
	5%	TO shingle	15%	20%	52.7%
	5%		20%	25%	49.1%
ATL RAP	5%	MW shingle	5%	10%	40.2%
	3%		10%	13%	36.2%
	5%	TO shingle	10%	15%	46.8%
	5%		15%	20%	44.1%

In addition to the Superpave testing on binder and mortar, the binder fracture energy (BFE) tests were used to assess the fracture tolerance of the virgin binder, RAP binder and the blends of virgin and RAP binder at various proportions. Table 4-11 details the combinations of RAP/RAS binder blends evaluated in this section. The fracture tests were anticipated to characterize the effect

[2] A total binder content of 35% was identified as the minimum in Task 3. However, this value changed with the stiffness of the blended binders. More than 35% total binder content was necessary when most of the recycled binder in mortar samples was contributed by the RAS.

of RAP/RAS on virgin binder cracking performance, better than the mortar approach that failed to provide reliable results at intermediate temperatures.

Table 4-11. Virgin binders and RAP/RAS binder blends evaluated by using the BFE test

Recycled binder / Virgin binder	WHI RAP binder			MW shingle binder		TO shingle binder	
	10%	20%	30%	10%	20%	10%	20%
PG 46-40 REOB	—	—	—	√	√	√	√
PG 46-34 Aromatic oil	√	√	√	√	√	√	√
PG 52-28 Aromatic oil	√	√	√	√	√	√	√
PG 52-28 Unmodified	—	—	—	√	√	√	√
PG 58-28 Unmodified	—	—	—	√	√	√	√
PG 64-34 PMA	√	√	√	√	√	—	—

4.5 Summary

In this task, two preliminary sets of tests were conducted on mortars with RAP-alone and RAS-alone to determine the corresponding GCR values which were used to predict the grade of a virgin binder blended at multiple RAP/RAS binder replacement rates. The existing data analysis procedure appeared to yield unreliable RAP/RAS high temperature GCR results, which were too small to be correct. Also, RAP/RAS intermediate GCR results failed to differentiate between RAP and RAS sources, as the latter was known to have a much stronger stiffening effect on virgin binders. The mortar approach seemed to capture the impact of RAP/RAS on low temperature grade of virgin binders such that stiffer RAP/RAS generally yielded greater GCR values.

Although GCR results of preliminary tests were comparable to values reported by Swiertz and Bahia (2011), this study revealed that there potentially could be a critical flaw in the existing data analysis procedure, which masks the RAP/RAS effect on virgin binder performance at high temperatures and possibly low temperatures as well. In response, an alternative method that predicts the properties of blended binder by establishing a relationship between binder and mortar measurements was proposed and evaluated.

The alternative method resulted in grade predictions comparable to values measured on manually blended virgin and RAP/RAS binders. This observation indicates that the level of blending occurring in mortars was equivalent to that occurring in blended binders (i.e., typically considered as a full blending scenario). Also, accurate predictions were made for the three extracted RAP binders by extrapolating the GCR values to 100 percent. Predicted RAS binder grades, especially for the TO shingles, were notably lower than measured values. This indicates that the RAS-alone GCR is not constant, potentially because the blending between the virgin and RAS binders is non-linear.

The enhanced mortar approach with the alternative data analysis method successfully captured the stiffening effect of RAP/RAS: 1) RAS had greater GCR at high and low temperatures than the three RAPs; 2) the WHI RAP (the stiffest RAP in this study) had greater GCR than the other two RAPs; and 3) TO shingles exhibited greater high temperature GCR and slightly lower low temperature GCR than the MW shingles.

Based on preliminary results, an experimental plan was developed which included four topics: 1) properly evaluate the RAP/RAS effect on performance of different virgin binders at high and low temperature by using the reanalyzed RAP/RAS GCR results; 2) determine the allowable RAS content (i.e., TO shingle) for a given binder type by meeting the current PG grade requirement specified for RAP; 3) evaluate the assumption made in the AASHTO draft that RAP-alone GCR and RAS-alone GCR can be linearly combined to predict the RAP-RAS GCR at high and low temperatures; and 4) evaluate the RAP/RAS effect on the fracture tolerance of virgin binders at intermediate temperatures.

CHAPTER 5 TESTING AND ANALYSIS OF RESULTS

5.1 Preliminary Testing Results Analyzed with Alternative Data Interpretation Method

A general discussion on RAP/RAS GCR results as determined using the alternative data analysis method was provided in section 4.2.3.1. This section evaluated the RAP/RAS effect on performance of different virgin binders at high and low temperature by using the reanalyzed RAP/RAS GCR results

5.1.1 RAP/RAS GCR at High Temperatures

The effect of virgin binder grade on GCR results varied depending on the relative stiffness of the RAP/RAS. As shown in Figure 5-1, the ATL and ACO seemed to exhibit greater GCR values for softer virgin binder, which indicated greater level of binder blending. However, there appeared to be a stiffness threshold above which the effect of virgin binder grade became less evident, like in the cases of WHI RAP, TO shingle and MW shingle.

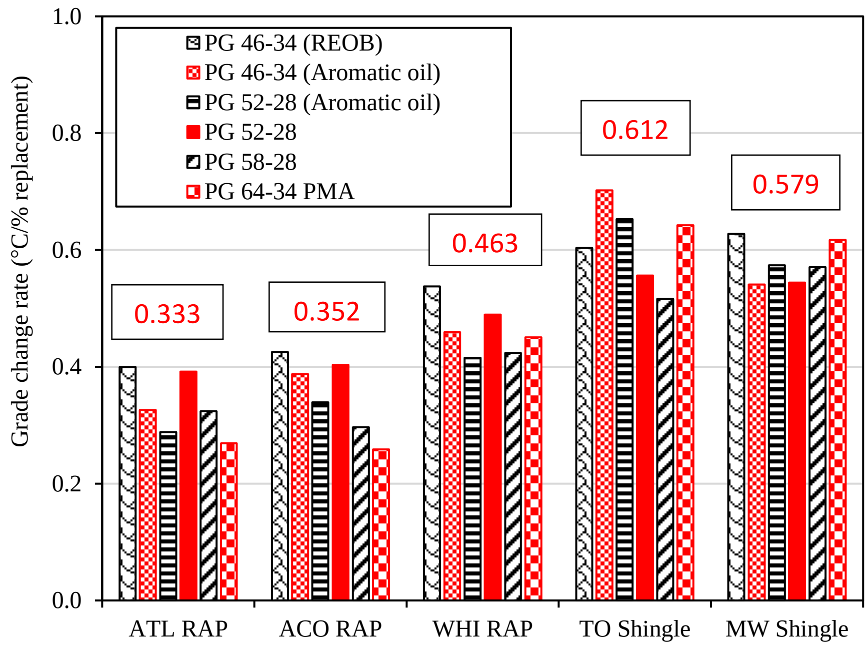

Figure 5-1. High temperature GCR results of RAP/RAS mortars with six virgin binders

Figure 5-2 compares the GCR value of blends with the PG 46-34 REOB and PG 46-34 Aromatic oil. Note that both binders had almost identical true grade but different base binder and rejuvenator dosage. PG 46-34 REOB appeared to be more effective than PG 46-34 Aromatic oil in activating the aged binder, except for the case of TO shingles.

PG 64-34 PMA, whose base binder was PG 52-28, was compared to the PG 52-28 used in this study to evaluate the effect of polymer modification. As shown in Figure 5-3, the unmodified binder yielded greater GCR values than the PMA binder for ATL and ACO RAP (typical RAP sources in Florida). However, the opposite trend was observed when a significantly aged material was introduced, like in case of TO shingle and MW shingle.

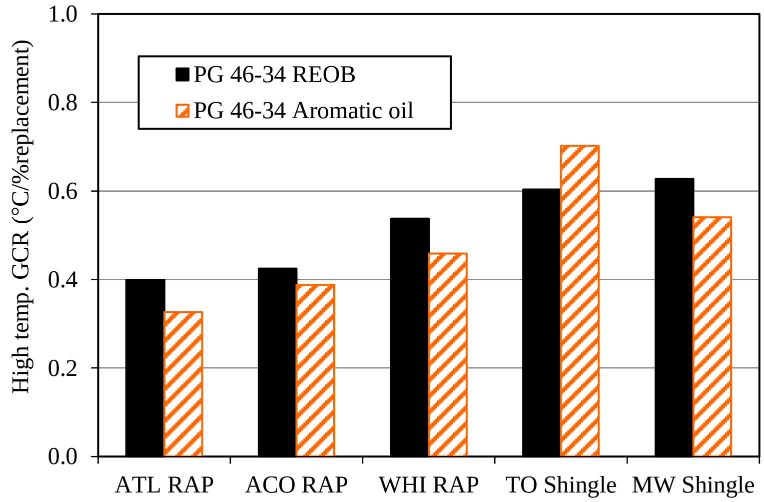

Figure 5-2. Comparison in high temperature GCR results of RAP/RAS mortars with PG 46-34 REOB and PG 46-34 Aromatic

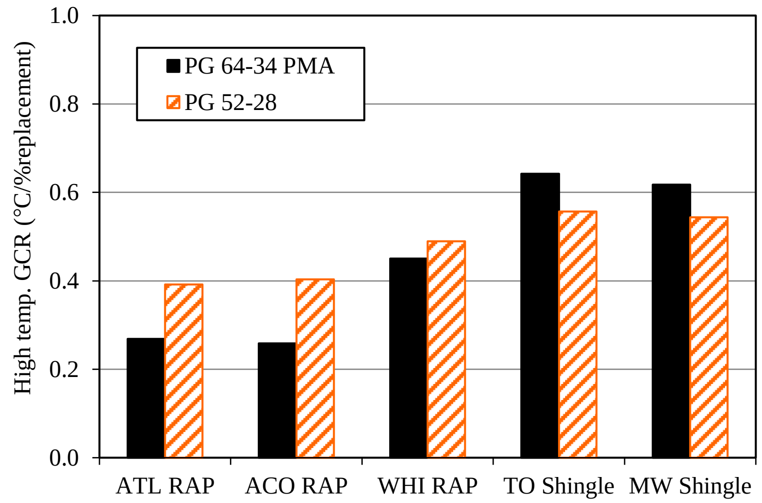

Figure 5-3. Comparison in high temperature GCR of mortars with PG 64-34 PMA and PG 52-28

5.1.2 RAP/RAS GCR at Low Temperatures

Two types of RAP/RAS GCR were obtained at low temperatures including the one based on the BBR stiffness and the other one based on the BBR m-value. As shown in Figure 5-4, GCR based on m-value was higher than that from stiffness and the difference became more evident as the stiffness of aged binder increased. This finding indicated the inclusion of RAP/RAS deteriorated the relaxation of virgin binder at a faster rate than the stiffness increased.

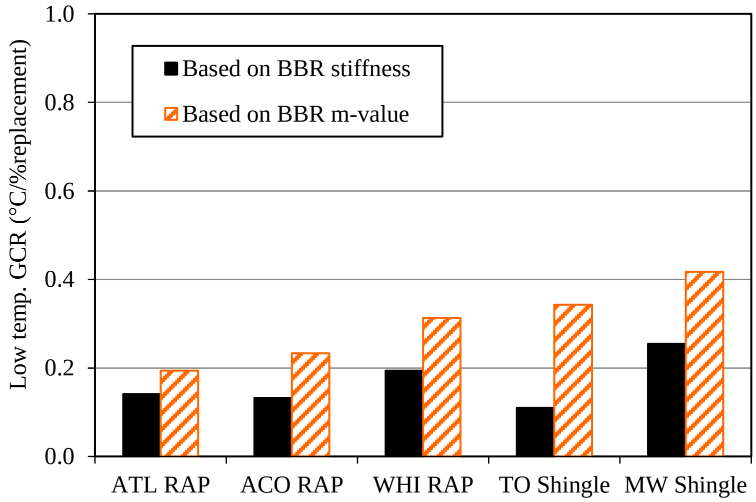

Figure 5-4. Average RAP/RAS low temperature GCR based on BBR stiffness and m-value

Figure 5-5 details the low temperature GCR for each RAP/RAS and virgin binder combination. The effect of RAP/RAS on GCR highly depended on virgin binder grade. For a given RAP/RAS source, the three binders with a low temperature grade of -28°C had a similar GCR value. Likewise, binders graded as -34°C (except PG 46-34 Aromatic oil) exhibited notably greater GCR values.

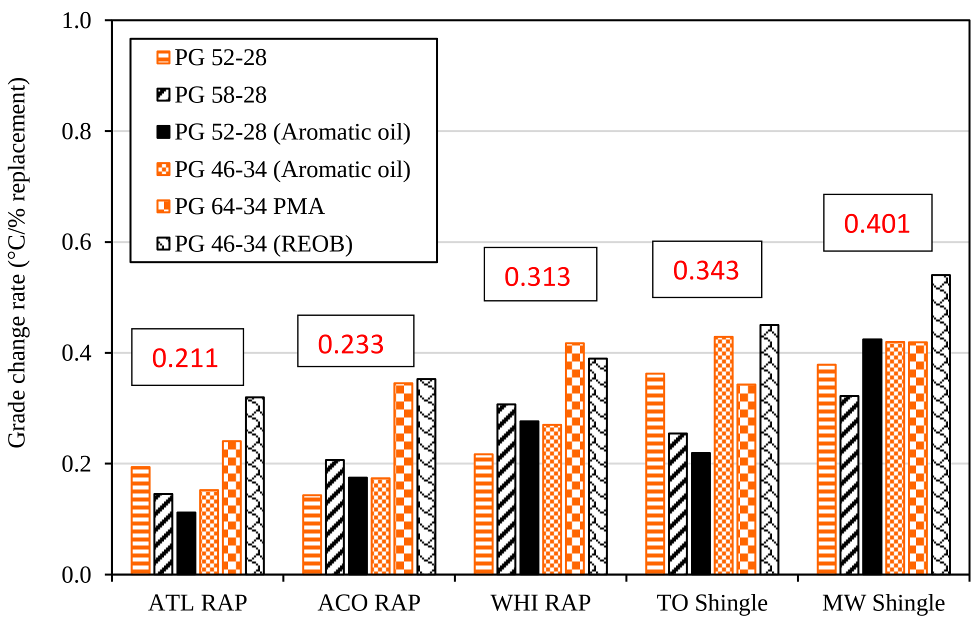

Figure 5-5. Low temperature GCR results of RAP/RAS mortars with six virgin binders

Figure 5-6 compares the low temperature GCR for blends with the PG 46-34 REOB and PG 46-34 Hydrolene. For a given RAP/RAS source, PG 46-34 REOB binder exhibited greater low temperature GCR value than that of the PG 46-34 Aromatic oil, which was consistent with the same comparison at high temperature (Figure 5-2). Overall, the REOB binder appeared to be more effective in activating the oxidized binder contained in the recycled material. Similar to observation made at high temperatures (Figure 5-3), the PMA binder exhibited greater GCR values than the PG 52-28 unmodified binder for the three RAPs but those of RAS mortars were comparable (Figure 5-7).

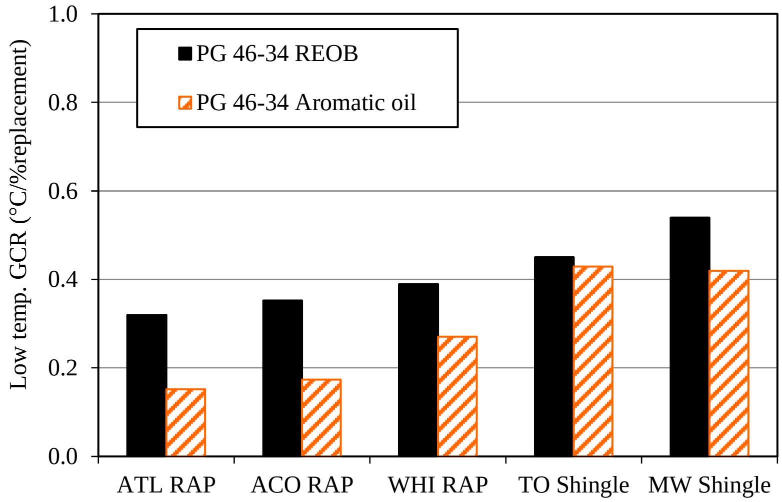

Figure 5-6. Comparison in low temperature GCR results of mortars with PG 46-34 Hydrolene and PG 46-34 REOB

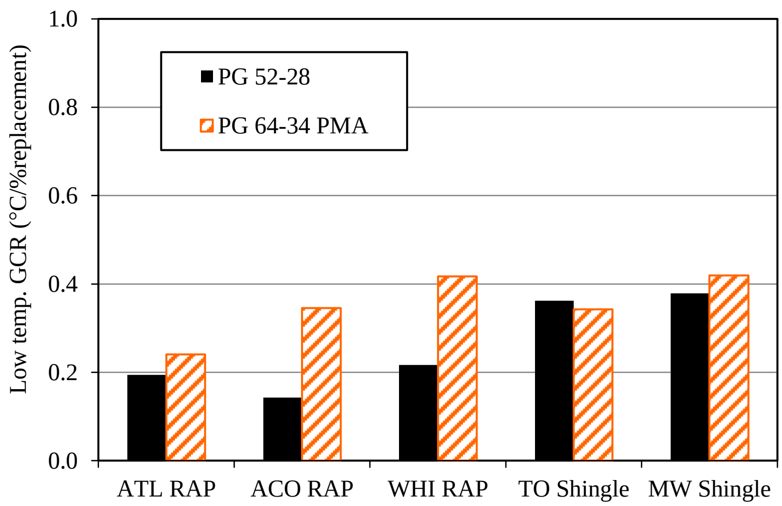

Figure 5-7. Comparison in low temperature GCR of mortars with PG 64-34 PMA and PG 52-28

5.2 Determination of Allowable RAS Contents Based on RAP/RAS GCR

The current design standard specification for asphalt mixtures (i.e., AASHTO M 323) recommends a three-tiered system to select virgin binder grades for mixtures to accommodate different RAP contents. The Florida Department of Transportation (FDOT) adopts the system and simplifies the three tiers to three default virgin binder grades based on results of extensive in-house research studies. Table 5-1 summarizes the recommendations documented in the FDOT 2017 Specification Section 334 and the AASHTO M323. A PG 67-22 binder can be used when RAP use is 15% or less (by weight of total aggregate). When the RAP is 16–30%, a softer virgin binder grade (PG 58-22) is needed. Finally, a PG 52-28 is required for mixtures with more than 30% RAP. This approach works for most RAP stockpiles in Florida, perhaps with a few exceptions being extremely stiff RAPs[3]. However, the existing rule may not work for RAS, which is known to be much stiffer and more brittle than even the stiffest RAP.

Table 5-1. Binder selection guidelines for RAP mixtures according to FDOT specification

Percent RAP		Virgin Asphalt Binder Grade	
		FDOT	AASHTO M323[4]
Tier 1	0–15	PG 67–22	No change in binder selection
Tier 2	16–30	PG 58–22	Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)
Tier 3	>30	PG 52–28	Follow recommendations from blending charts

RAP-alone and RAS-alone GCR values were used to determine whether changes in Table 5-1 are needed and how the changes can be made. Note that the unit of RAP content in Table 5-1 is percent by weight of total aggregate whereas the RAP/RAS GCR is percent by weight of total binder. For a given RAP mixture, the two parameters may not be the same but they are comparable (e.g., 15% by weight of total aggregate may equal to 17% by weight of total binder). For the purpose of a simple illustration, this section treated the two parameters equivalently. Since there is no target grade of RAP blended binders, those based on a typical RAP (i.e., ATL RAP) in Florida with qualified virgin binders (i.e., PG 52-28 and PG 58-28) at specified contents were used as thresholds for RAS binder blends.

At Tier 2, taking the combination of ATL RAP and PG 58-28 as an example, 15–30% ATL RAP increased the virgin binder true grade from 62.8°C to the range of 67.6-72.5°C (Figure 5-8). Using the limits of this range as thresholds, the corresponding allowable RAS content was determined to be within 7.5–15%, which happens to be half of the allowable RAP contents. Similarly, the low temperature thresholds defined by 15–30% ATL RAP with the PG 58-28 binder was from -25.7°C to -27.8°C, which allows for 8.5–17.1% TO shingles (Figure 5-9). Based on the high and low temperature results, it appears that a maximum of 15% TO shingles (more

[3] According to the FDOT RAP stockpile 2015 inventory, the WHI RAP can be considered as an extremely stiff RAP whereas the ATL and ACO are typical RAP sources, with respect to RAP binder stiffness.

[4] The allowable RAP content at Tier 2 in M323 is 15–25% and Tier 3 starts with 25% RAP.

conservative) can be used with the PG 58-28 still meet the requirements for the true grades of RAP blended binders.

At Tier 3, the high temperature grade of a PG 52-28 blended with 30% ATL RAP binder was 68.2°C. This allows for the use of 15.4% TO shingle binder to obtain the same grade of the RAS binder blend (Figure 5-10). Although there is no upper limit of RAP content at this level, this does not necessarily mean that unlimited RAP or RAS can be used with the PG 52-28 binder for satisfactory performance. At low temperatures, the threshold defined by the PG 52-28 binder and 30% ATL RAP binder was -29.1°C, which equals the grade of the same virgin binder blended with only 15.8% TO shingle binder (Figure 5-11).

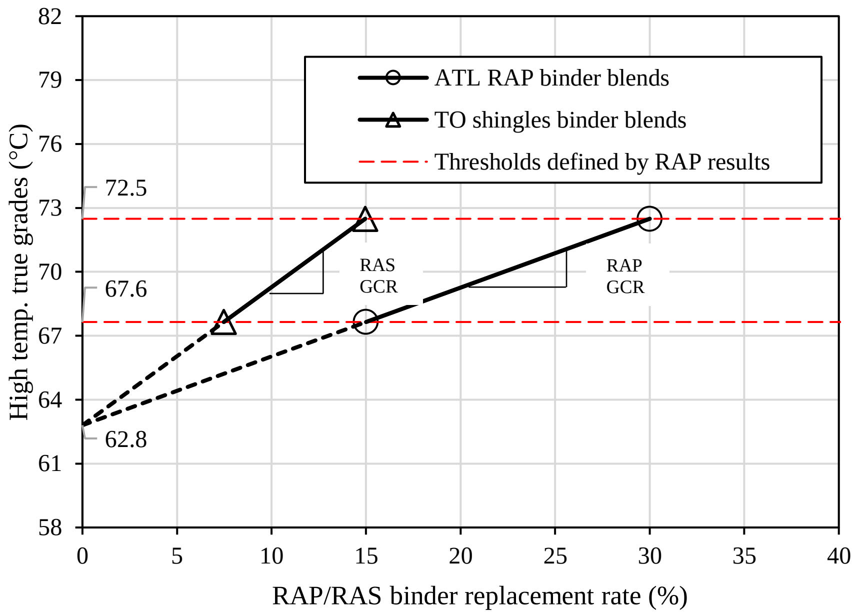

Figure 5-8. Determination of RAS contents with a PG 58-28 binder based on high temperature true grade thresholds

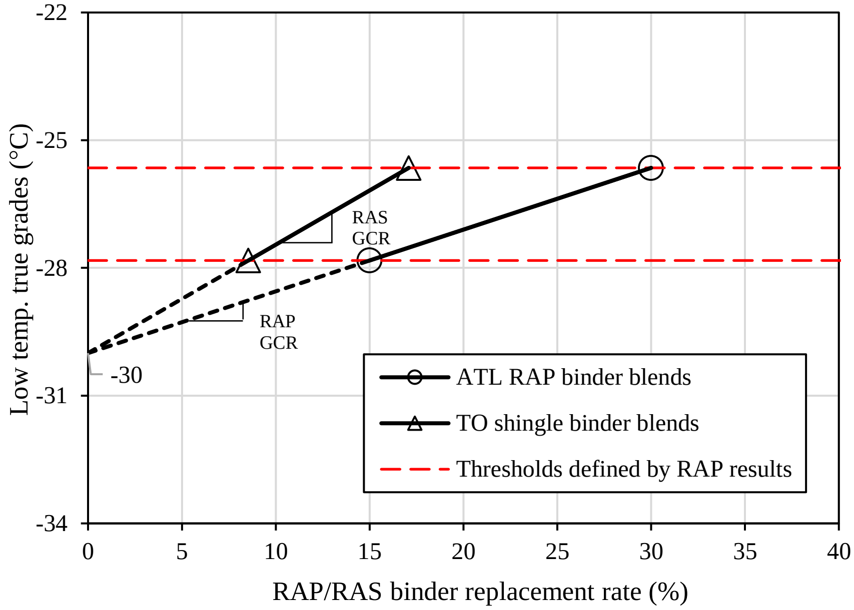

Figure 5-9. Determination of RAS contents with a PG 58-28 binder based on low temperature true grade thresholds

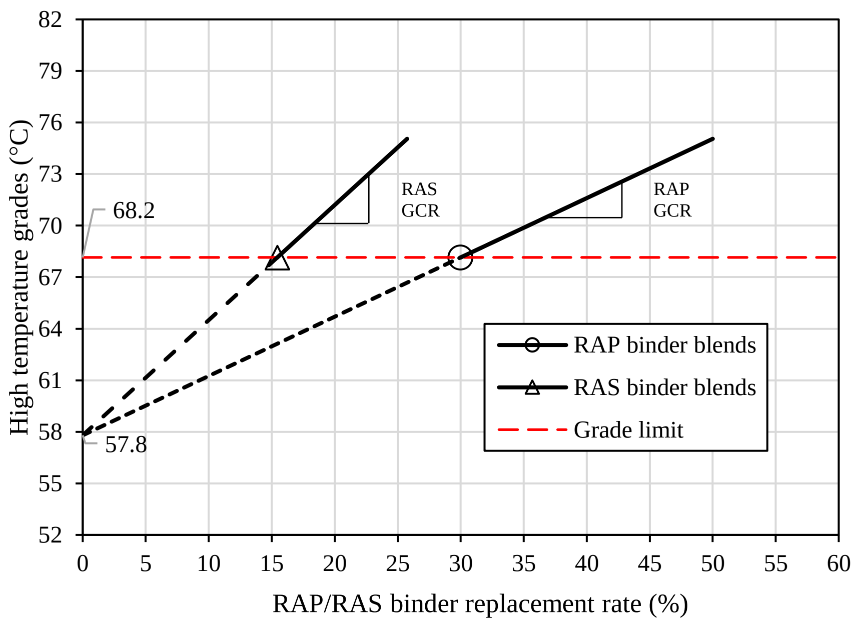

Figure 5-10. Determination of RAS content with a PG 52-28 binder based on high temperature true grade thresholds

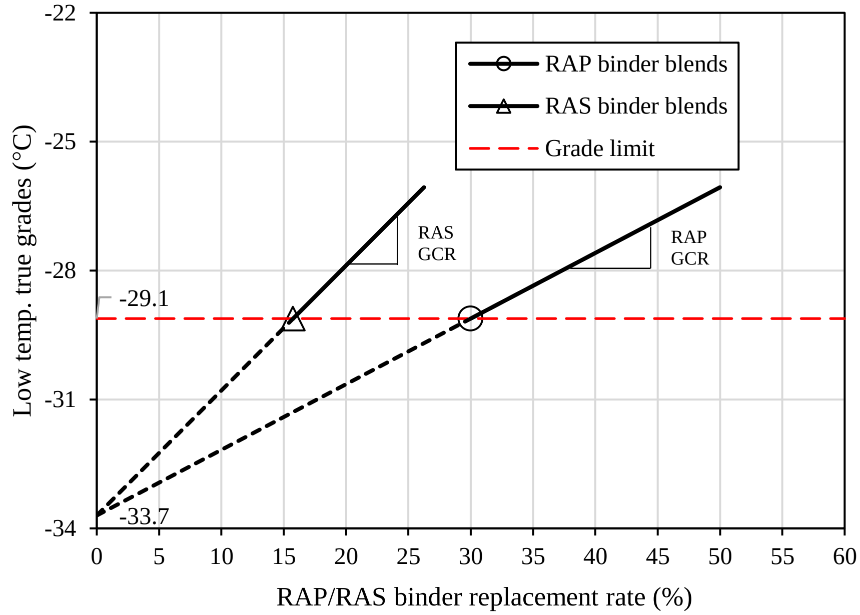

Figure 5-11. RAS content with a PG 52-28 binder based on low temperature true grade threshold

Overall, results of above analysis indicate that the RAS GCR can be used to determine the allowable RAS content for a given virgin binder type. The limit of RAS content at each tier was found to be approximately half of the allowable RAP content. Although the use of PG 52-28 binder is recommended for RAS mixtures in the upcoming FDOT Dev334RAS specification (FDOT, 2014), the use of RAS GCR provides a more consistent way of selecting the PG grade of virgin binder for different type and amount of RAS.

5.3 Evaluation of Linearly Combined RAP-RAS GCR

Table 5-2 lists the eight RAP-RAS mortar combinations which include two RAP sources, two RAS sources and two total RAP-RAS binder replacements. The RAP binder replacement rates employed in this task were lower than RAS binder replacement rates. This was because sufficient total binder content in mortars was required to ensure the specimen workability; however, the binder content of the RAP R_{100} material was relatively low, which precluded the use of high RAP binder replacement rates. A total binder content of 35% was identified as the minimum in Chapter 4. However, this value also changes with the stiffness of the blended binders. More than 35% total binder content was necessary when most of the recycled binder in mortar samples was contributed by the RAS.

Details regarding the mortar compositions can be found in Appendix H. Both predicted and measured RAP-RAS GCR of all mortar combinations were summarized in Appendix I. Predicted high and low temperature true grades of all RAP-RAS binder blends using the two types of GCR values can also be found in Appendix J.

Table 5-2. Binder compositions of eight RAP-RAS mortars

RAP type	RAP binder replacement rate	RAS type	RAS binder replacement rate	Total RAP and RAS binder replacement rate	Total binder content in mortar samples
WHI RAP	5%	MW shingle	5%	10%	47.5%
	3%		10%	13%	39.3%
	5%	TO shingle	15%	20%	52.7%
	5%		20%	25%	49.1%
ATL RAP	5%	MW shingle	5%	10%	40.2%
	3%		10%	13%	36.2%
	5%	TO shingle	10%	15%	46.8%
	5%		15%	20%	44.1%

5.3.1 Evaluation at High Temperatures

Figure 5-12 compares the high temperature true grades of the PG 46-34 Aromatic oil blended with various combinations of RAP and RAS binders, as predicted using the linearly combined RAP-RAS GCR and measured RAP-RAS GCR. The x-axis in Figure 5-12 lists eight RAP and RAS combinations. Both types of RAP-RAS GCR resulted in comparable high temperature true grades of blended binders with most combinations yielded a less than 2°C difference. This observation, which was reaffirmed by using different virgin binders as shown in Figure 5-13, Figure 5-14 and Figure 5-15, indicated that RAP-alone GCR and RAS-alone GCR can be linearly combined to predict the high temperature true grades of RAP-RAS binder blends.

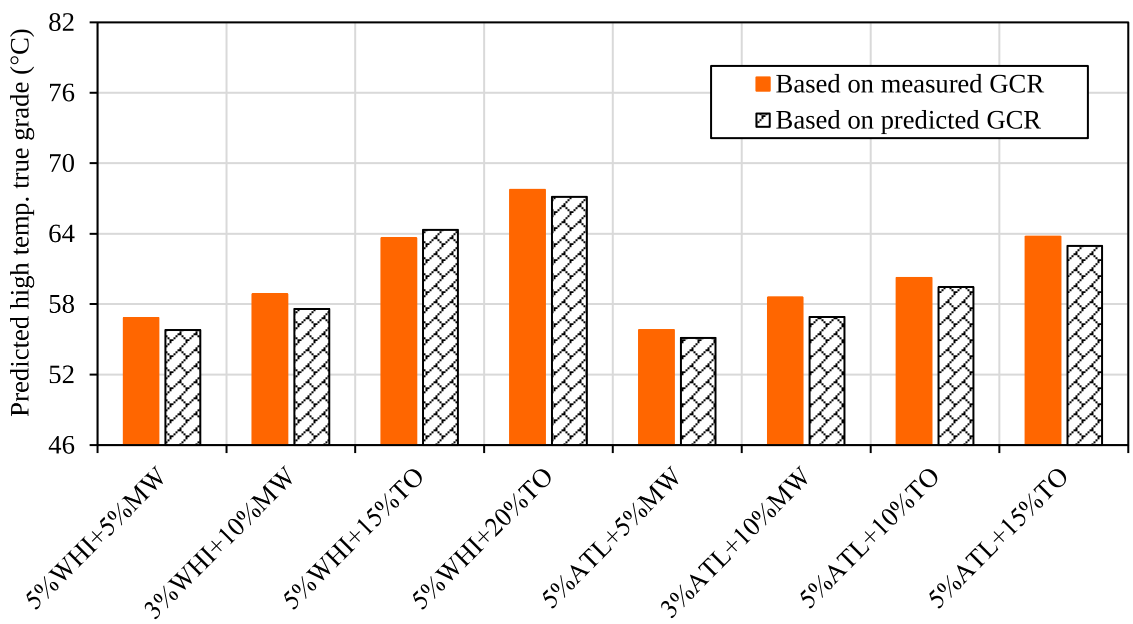

Figure 5-12. High temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 46-34 Aromatic oil

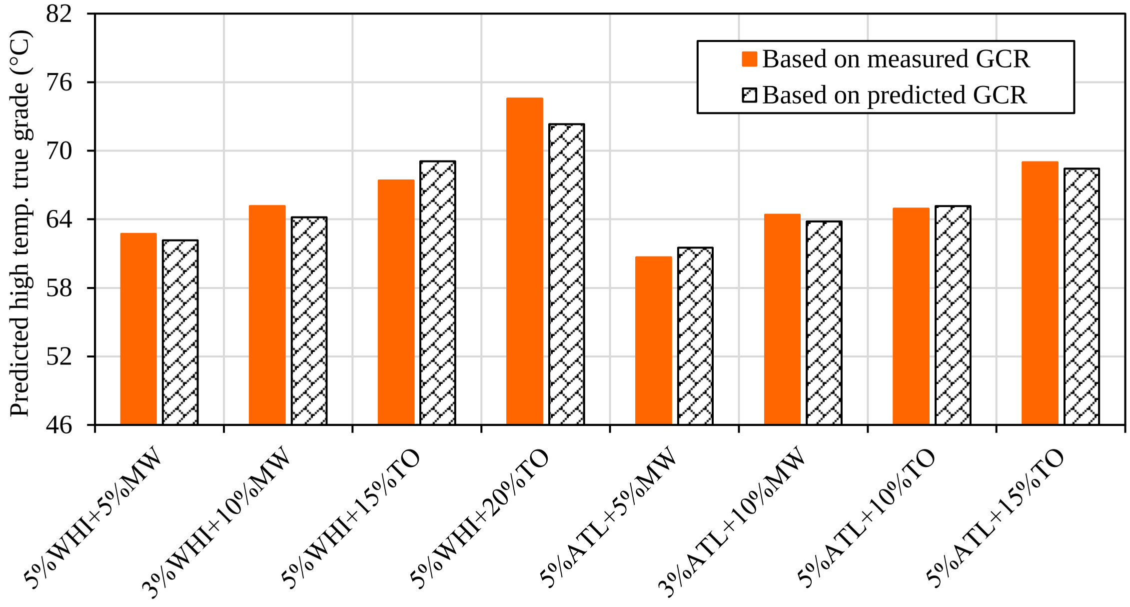

Figure 5-13. High temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 52-28 Aromatic oil

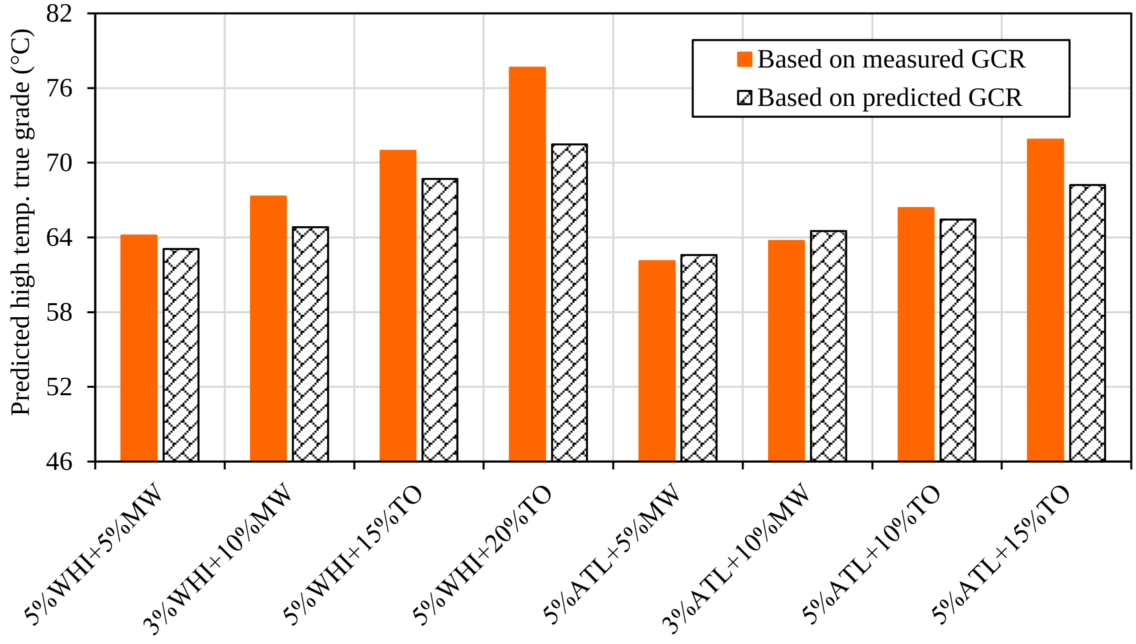

Figure 5-14 High temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 52-28 unmodified

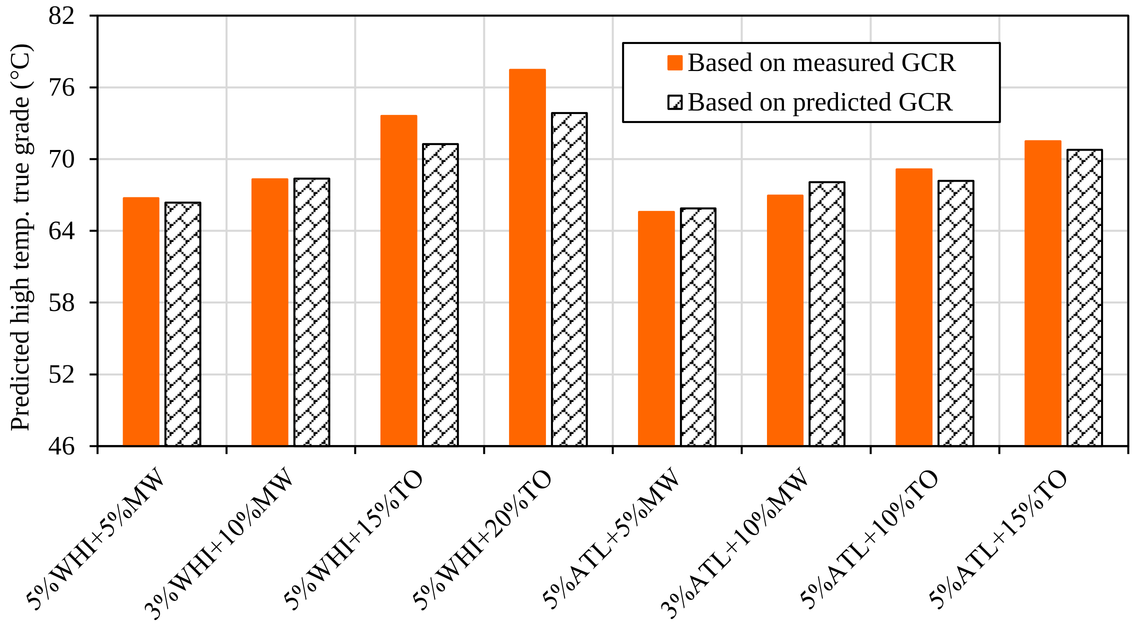

Figure 5-15. High temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 58-28 unmodified

Of note, the RAS-alone GCR of TO shingle used to predict the RAP-RAS GCR was based on the 15% TO shingle mortar measurements. However, the TO shingle GCR was speculated in section 4.3.3 to be binder replacement rate dependent. As a result, the greatest difference between measured and predicted grades was observed for the combination of 5% WHI RAP and 20% TO shingle, which employed the 15% TO shingle GCR for grade prediction.

5.3.2 Evaluation at Low Temperatures

The same eight RAP-RAS combinations and four virgin binders used for high temperature true grade prediction were adopted to validate the linear assumption at low temperatures. The combined use of RAP and RAS was found to have a more pronounced effect on the BBR relaxation (m-value) than the stiffness (S value) of virgin binders, which was consistent with the use of RAP-alone and RAS-alone as documented in section 5.1.2. Thus, all low temperature true grades of RAP-RAS binder blends were predicted using the GCR values that were determined based on the BBR relaxation results.

The use of linearly combined RAP-RAS GCR resulted in low temperature true grades comparable to the ones as determined by using the measured RAP-RAS GCR, as shown in Figure 5-16. Seven out of the eight RAP-RAS combinations exhibited less than 1.5°C difference (in absolute value) between the two-predicted low temperature true grades and the average difference of the eight combinations was 0.9°C. When changing the virgin binder type used for mortar testing, the average differences between two predicted grades were 0.9°C, 1.3°C and 0.6°C for PG 52-28 Aromatic oil (Figure 5-17), PG 52-28 unmodified (Figure 5-18) and PG 58-28 unmodified (Figure 5-19), respectively.

Overall, results presented in this section support the use of linearly combined RAP-alone GCR and RAS-alone GCR to determine the RAP-RAS GCR for high and low temperature true grade predictions of RAP-RAS binder blends.

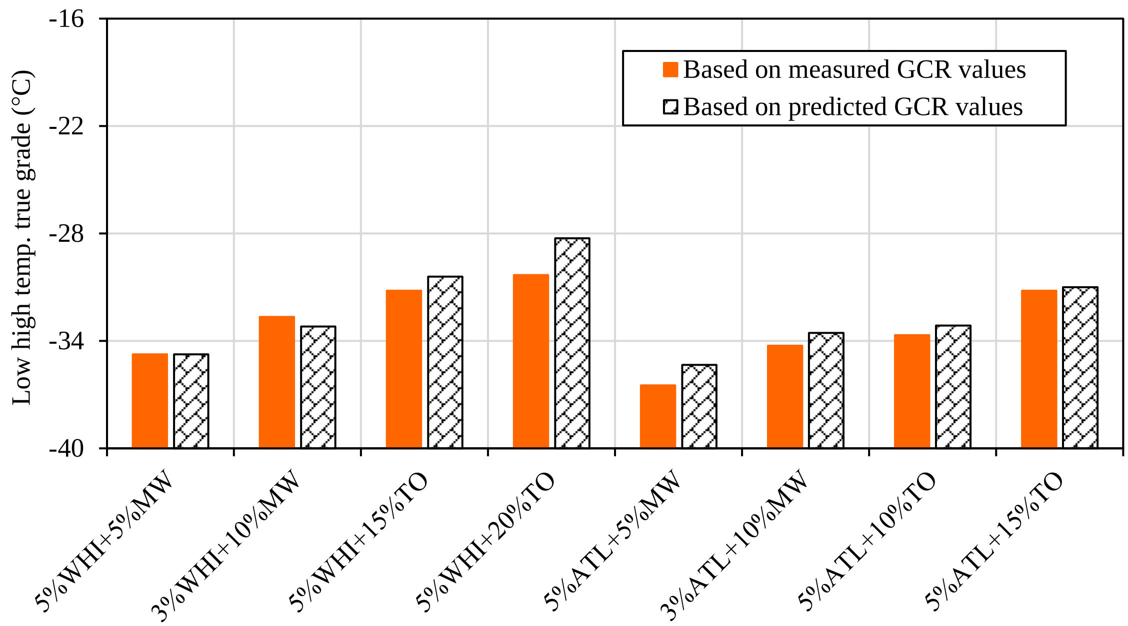

Figure 5-16. Low temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 46-34 Aromatic oil

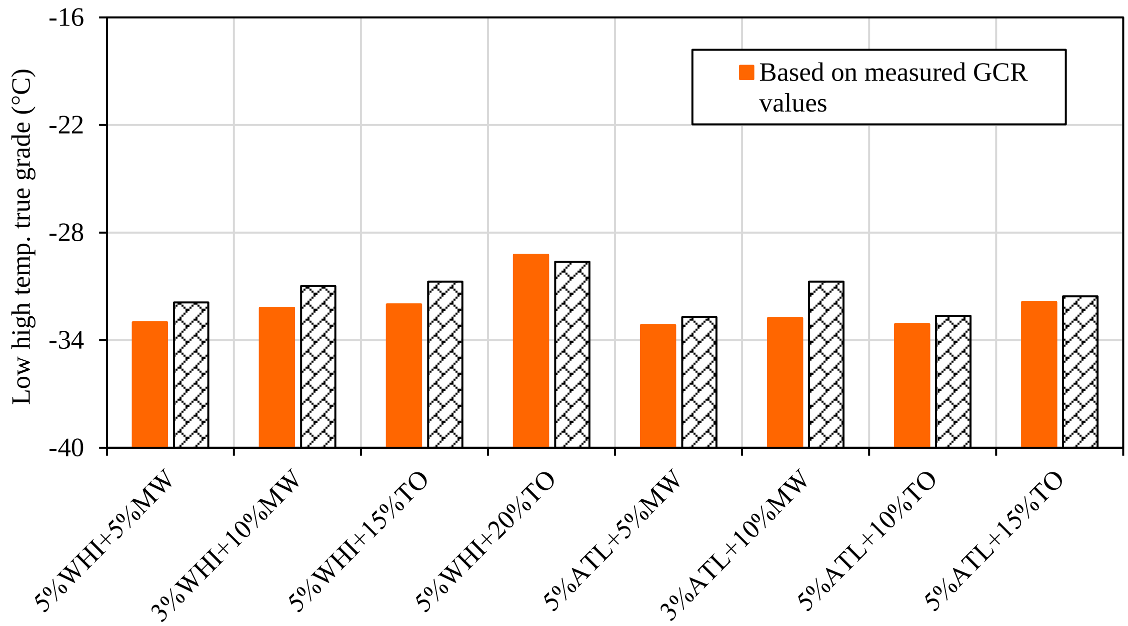

Figure 5-17. Low temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 52-28 Aromatic oil

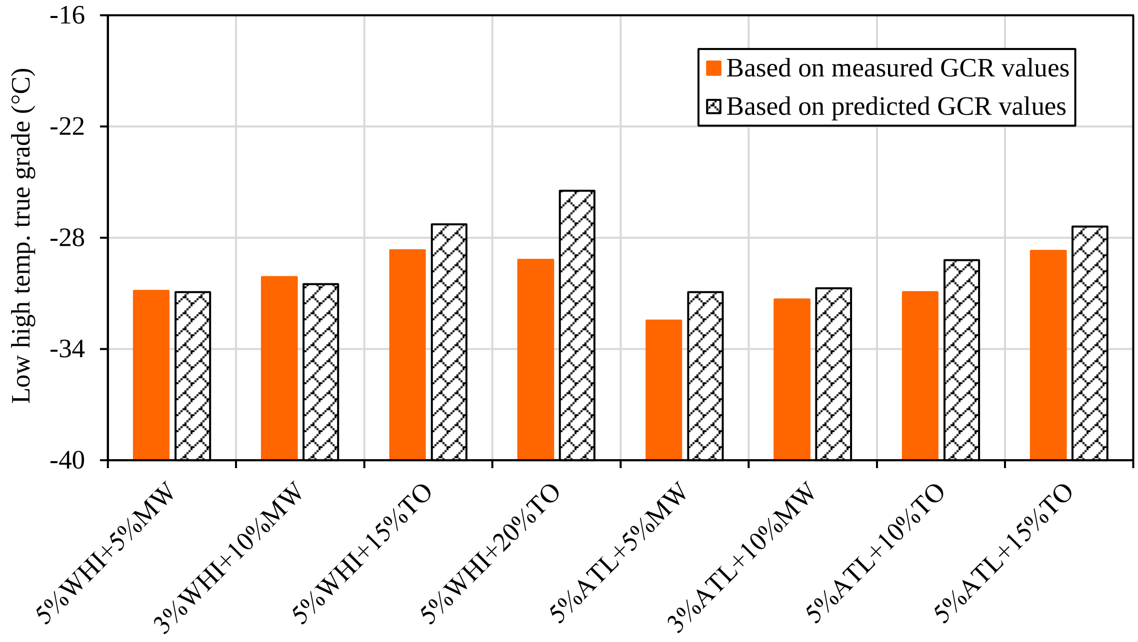

Figure 5-18. Low temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 52-28 unmodified binder

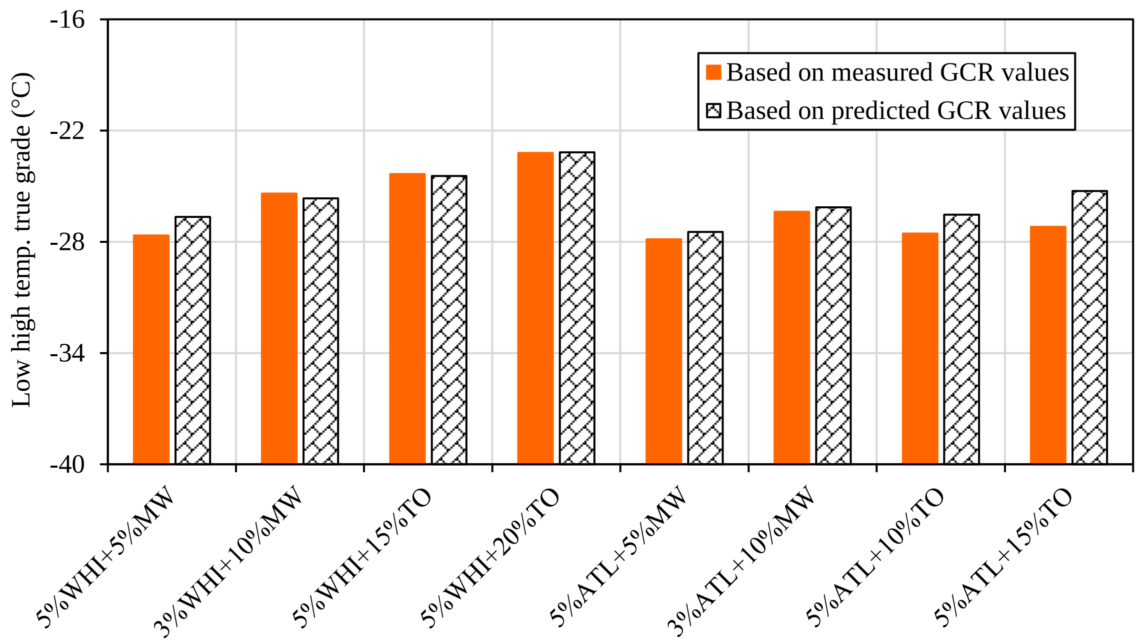

Figure 5-19. Low temperature true grades of RAP-RAS binder blends as determined using the measured and predicted RAP-RAS GCR values: PG 58-28 unmodified binder

5.4 Fracture Energy Density at Intermediate Temperatures

The RAP/RAS effect on the fracture tolerance of virgin binders was evaluated by using the BFE test. The BFE test was developed to determine the fracture energy density (FED) of asphalt binders at intermediate temperatures. Binder FED is defined as the energy per unit volume required to initiate fracture (i.e., local failure). It is calculated as the area under the true stress-true strain curve up to the point at which the true stress peaks and drops. The binder FED correlated well with mixture FED, thereby supporting the use of the BFE test as an effective tool to quantitatively evaluate the fracture tolerance of asphalt binder (Yan et al. 2016; Yan et al. 2017).

BFE samples were prepared by blending RTFO-aged virgin binder with extracted RAP/RAS binders. Then, the RTFO-aged binder blends were further conditioned through a standard PAV procedure that simulates the effect of long-term aging on binder blends. Table 5-3 details the combinations of RAP/RAS binder blends evaluated in this section. Since the primary focus of this study was on RAS effect, limited BFE tests were conducted on selected RAP binder blends. Nine combinations of the WHI RAP (the stiffest RAP in this study), three RAP binder replacement rates and three virgin binders were evaluated. Then, a total of twenty-two RAS binder blends including two RAS sources, two RAS binder replacement rates and six virgin binders were prepared and tested. Binder blends of the PG 64-34 PMA and TO shingle binder were not evaluated because of the previously identified effect caused by the excessively high heating temperature on the SBS polymer modification.

Table 5-3. Virgin binders and RAP/RAS binder blends evaluated by using the BFE test

Recycled binder / Virgin binder	WHI RAP binder			MW shingle binder		TO shingle binder	
	10%	20%	30%	10%	20%	10%	20%
PG 46-34 REOB	—	—	—	√	√	√	√
PG 46-34 Aromatic oil	√	√	√	√	√	√	√
PG 52-28 Aromatic oil	√	√	√	√	√	√	√
PG 52-28 Unmodified	—	—	—	√	√	√	√
PG 58-28 Unmodified	—	—	—	√	√	√	√
PG 64-34 PMA	√	√	√	√	√	—	—

Table 5-4 lists the displacement rates and temperatures used for the BFE tests. Previous studies found that a combination of 500 mm/min at 15°C worked for binders commonly used in the state of Florida (e.g., PG 67-22 and PG 76-22) (Niu et al.2014; Yan et al. 2017). However, it was necessary to lower the temperature and/or increase the rate for soft virgin binders to obtain ductile type fracture. Likewise, the temperature was increased and/or the rate was reduced to avoid premature fracture for stiff RAP/RAS binder blends. As long as a complete true stress-true strain curve is obtained, binder FED is a fundamental material property independent of temperature and loading rate, as opposed to other binder properties such as stiffness, failure stress, and failure strain. This characteristic allows for comparisons in FED between asphalt binders that are tested at different combinations of temperature and displacement rate. Four replicates of each binder type were tested and the average FED results were summarized in Table 5-5. FED values of virgin binders and RAP/RAS blended binders can be found in Appendix K.

Table 5-4. Temperatures and displacement rates employed for the BFE tests

BFE displacement rate (mm/min) / testing temperature (°C)								
Recycled binder / Virgin binder	Virgin binder	WHI RAP binder			MW shingle binder		TO shingle binder	
		10%	20%	30%	10%	20%	10%	20%
PG 46-40 REOB	500/5	—	—	—	500/10	500/10	500/10	500/10
PG 46-34 Aromatic oil	500/5	500/10	500/10	500/10	500/10	500/10	500/10	500/15
PG 52-28 Aromatic oil	500/10	500/10	500/10	500/10	500/15	500/15	100/10	100/15
PG 52-28 Unmodified	500/10	—	—	—	500/15	500/15	100/15	100/15
PG 58-28 Unmodified	500/15	—	—	—	500/15	500/15	300/15	100/15
PG 64-34 PMA	500/10	500/10	500/10	500/10	500/15	500/15	—	—

Table 5-5. Fracture energy density of virgin binders and RAP/RAS binder blends

Average binder fracture energy density (kJ/m³)								
Recycled binder / Virgin binder	Virgin binder	WHI RAP binder			MW shingles binder		TO shingles binder	
		10%	20%	30%	10%	20%	10%	20%
PG 46-34 REOB	1406	—	—	—	1213	1611	1190	1481
PG 46-34 Aromatic oil	2332	2440	2671	2980	1810	2190	1880	1511
PG 52-28 Aromatic oil	2545	3012	3267	3519	1875	2163	1411	1258
PG 52-28 Unmodified	2439	—	—	—	2085	2453	1471	1254
PG 58-28 Unmodified	2973	—	—	—	2546	2816	2045	1807
PG 64-34 PMA	10599	8476	8102	7810	5554	5181	—	—

5.4.1 WHI RAP Binder Blends

FED values of the WHI RAP binder blends were normalized with respect to those of the virgin binders, as shown in Figure 5-20. Increased RAP content consistently resulted in greater FED for the RAP blends with the two unmodified binders, which indicates improved binder fracture tolerance. A reverse trend was observed for the PMA blends: an abrupt reduction in FED occurred when 10% WHI RAP binder was introduced, and this reduction continued as RAP binder content was further increased.

Figure 5-21 depicts the true stress-true strain curves of the PG 52-28 Aromatic oil and its blends with the WHI RAP binder, which were tested at the same displacement rate and temperature (i.e., 500 mm/min at 10°C). The stiffening effect of RAP was observed in the true stress-true strain curves where as RAP content increased the blended binders became stronger (higher stress at each strain level including peak stress at fracture) and more brittle (lower failure strain). More importantly, the increases in stress caused by RAP binder overcame the reductions in failure strain. As a result, the FED of soft virgin binders was enhanced by inclusion of up to 30% RAP binder.

Figure 5-22 shows the true stress-true strain curves of the PMA binder blended with three contents of WHI RAP binder. The curve of virgin PMA binder was not included because it was tested at a lower temperature (i.e., 5°C instead of 10°C). Nevertheless, the stiffening effect of RAP binder on virgin binder was evident; where increased RAP binder content resulted in blended binders with higher true stress and lower failure strain. However, the peak stress at fracture, which is an indicator of the presence of SBS polymer, continuously decreased as RAP content increased.

This indicates that the RAP binder diluted the polymer modification and consequently, diminished the associated benefits on performance.

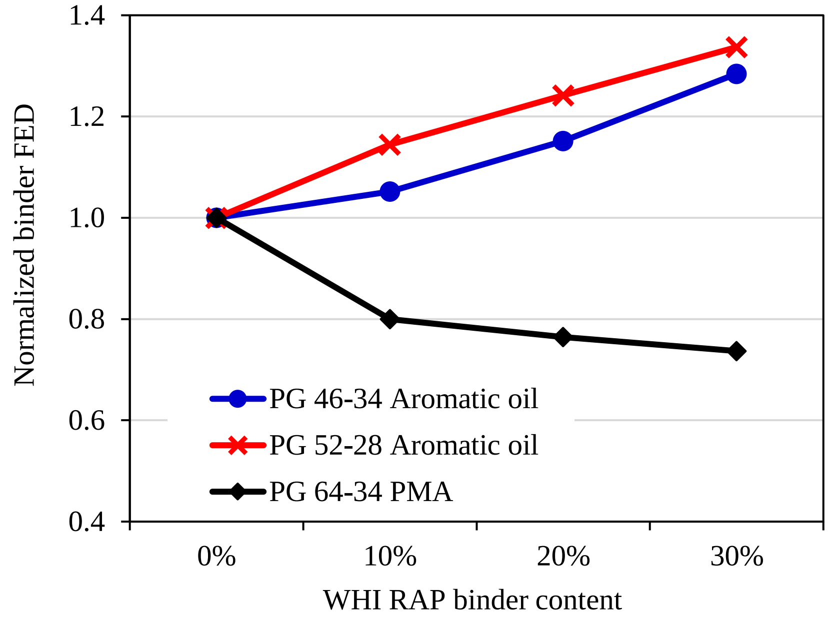

Figure 5-20. Normalized fracture energy density of WHI RAP binder blends

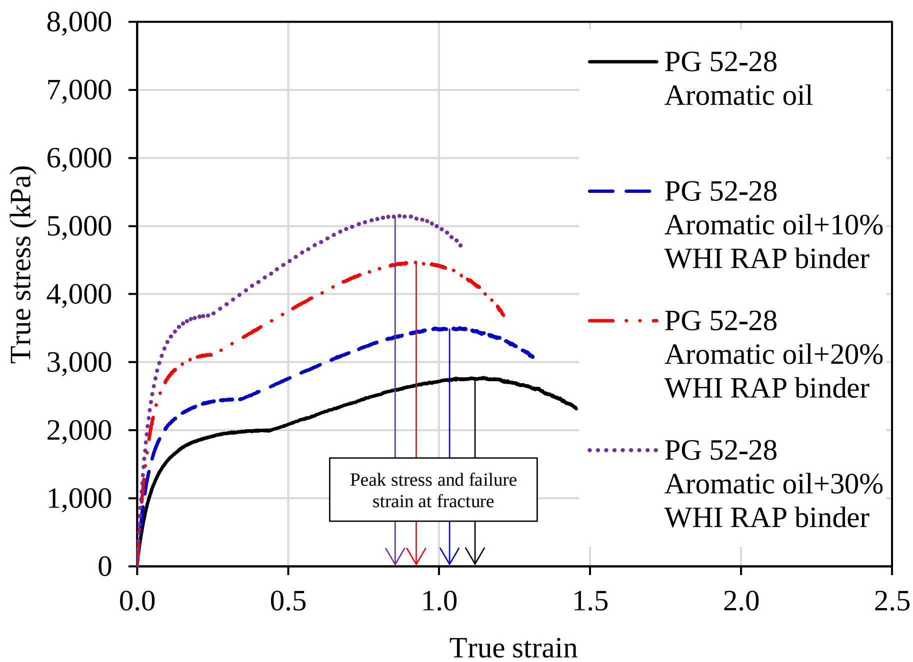

Figure 5-21. True stress-true strain curves of the PG 52-28 Aromatic oil and its blends with 10%, 20% and 30% WHI RAP binder obtained at 500 mm/min at 10°C

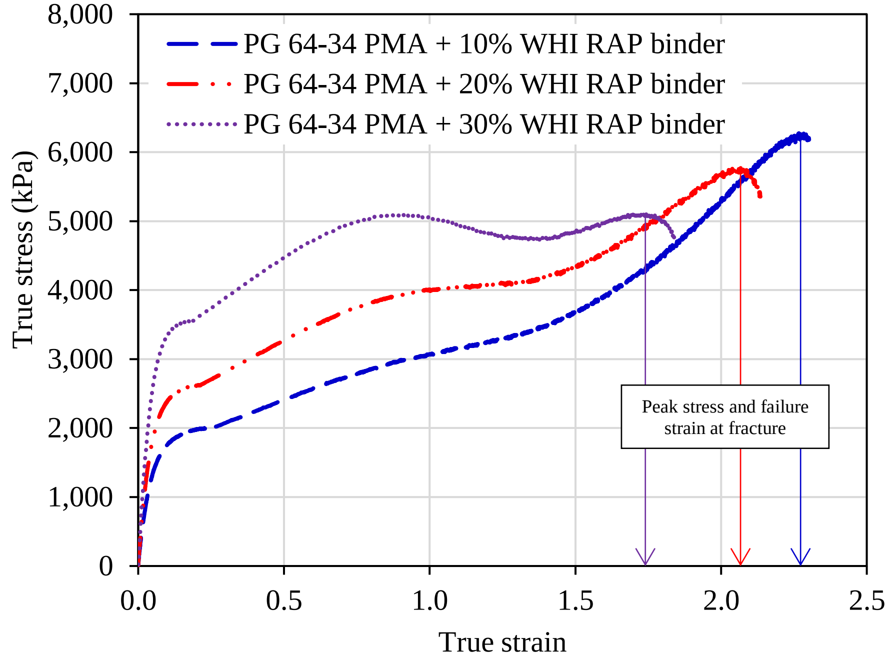

Figure 5-22. True stress-true strain curves of the blends of PG 64-34 PMA with 10%, 20% and 30% WHI RAP binder obtained at 500 mm/min at 10°C

5.4.2 MW Shingle Binder Blends

Figure 5-23 shows the normalized FED of MW shingle binder blends. The effect of MW shingle binder on virgin binder FED varied with shingle binder content. Adding 10% shingle binder yielded a notable reduction in the virgin binder FED. This trend was reversed for an additional 10% shingle binder (total 20%), although the resultant binder blends still exhibited FED lower than that of the virgin binders (except the PG 46-34 REOB). The PG 46-34 REOB has a very low initial FED, though 20% MW shingles did yield an incremental improvement. Unlike the RAP binder, which consistently increased the FED of soft virgin binders, small reductions were observed with up to 20% MW shingle binder.

Figure 5-24 illustrates the true stress-true strain curves of the PG 58-28 and its blends with the MW shingle binder which were all tested at the same displacement rate and temperature (i.e., 500 mm/min at 15°C). The MW shingle binder blends were stronger (higher true stress at each strain level) but more brittle (lower failure strain) than the virgin binder. The reduction in failure strain caused by the first 10% shingle binder had a more pronounced effect on the virgin binder FED than the corresponding increases in the true stress. However, when the MW shingle binder content increased from 10% to 20%, the increased true stress overwhelmed the reductions in failure strain which led to an increase in binder FED.

Adding the MW shingle binder continuously decreased the FED of the PMA binder, as shown in Figure 5-25. Moreover, the inclusion of MW shingle binder even at a low content of 10% caused a 50% FED reduction, which is more severe than that caused by the WHI RAP binder. Figure 5-26 depicts the true stress-true strain curves of MW shingle binder blends. Increasing the MW shingle binder content from 10% to 20% not only led to higher true stress and lower failure strain, but also yielded lower peak stress at fracture. Whereas the first two changes were associated with the stiffening effect of MW shingle, the third one could be attributed to the dilution effect which was also observed in the PMA RAP blends.

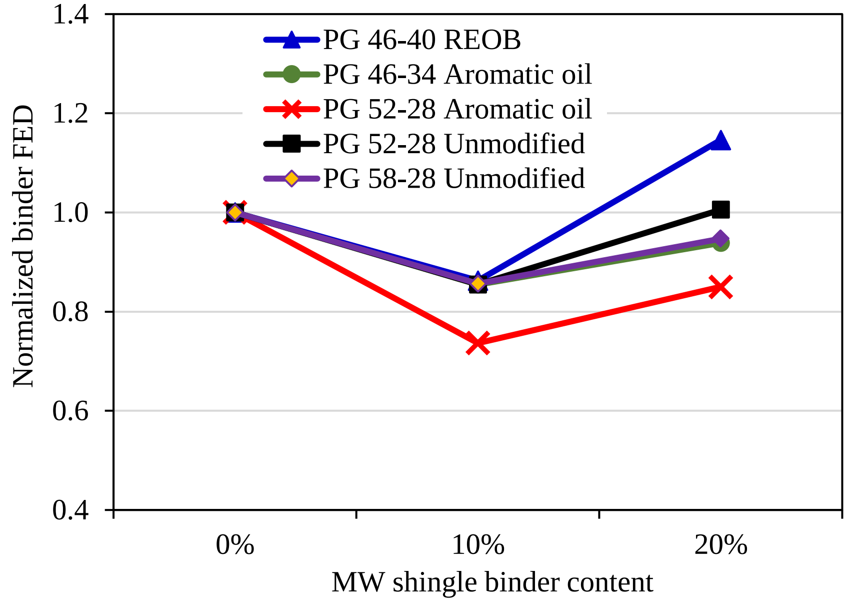

Figure 5-23. Normalized fracture energy density of MW shingle blended binders

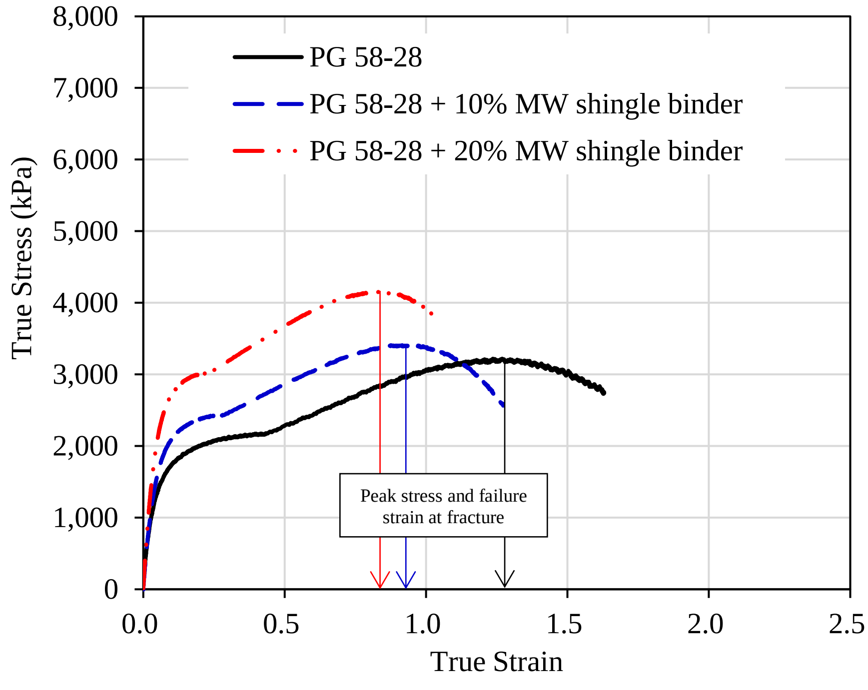

Figure 5-24. True stress-true strain curves of the PG 58-28 and its blends with 10% and 20% MW shingle binder obtained at 500 mm/min at 10°C

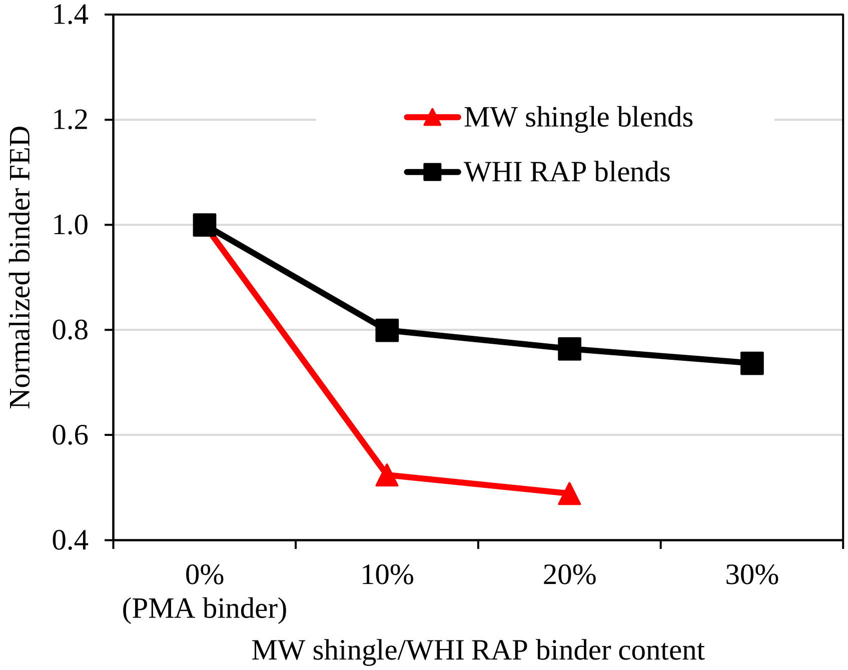

Figure 5-25. Fracture energy density of WHI RAP/MW shingle binder blends normalized with respect to the PG 64-34 PMA binder

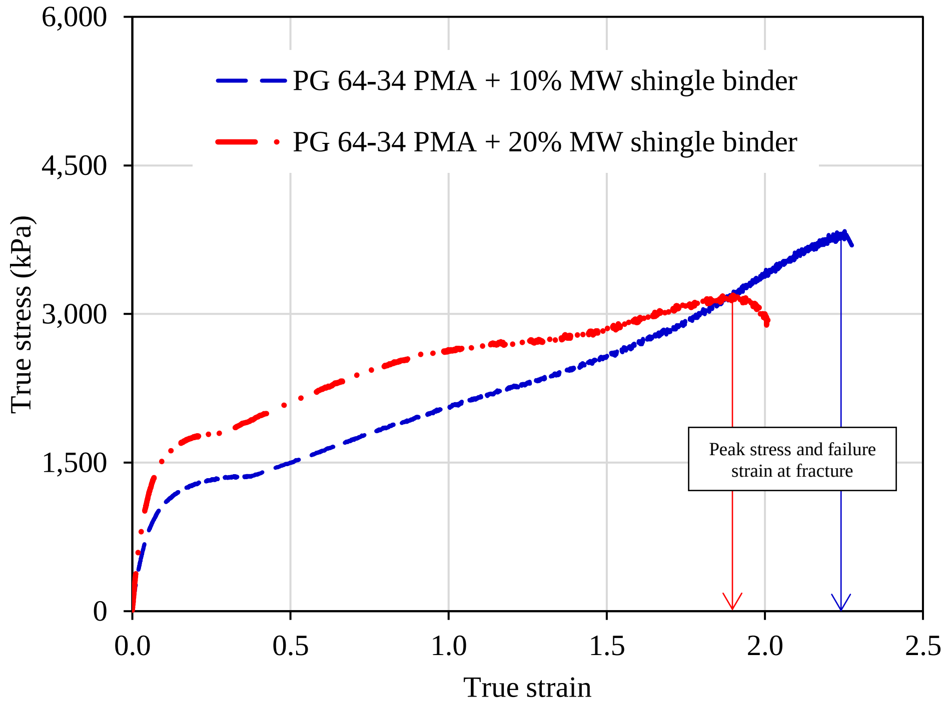

Figure 5-26. True stress-true strain curves of the binder blends of PG 64-34 PMA with 10% and 20% MW shingle binder obtained at 500 mm/min at 10°C

5.4.3 TO Shingle Binder Blends

Figure 5-27 shows the normalized FED of the TO shingle binder blends. Unlike the MW shingles, the effect of TO shingles on all virgin binders (except for the PG 46-40 REOB) was straightforward such that higher contents of TO shingle binder resulted in lower FED of the blended binders. This indicates diminished fracture tolerance. The TO shingle binder was so stiff and brittle, it was not possible to perform the BFE tests on virgin and blended binders at the same displacement rate and temperature. Thus, the true stress-true strain curve cannot be evaluated.

Figure 5-28 compares the effect of WHI RAP, MW shingles and TO shingles on the virgin binder FED (in this case the PG 46-34 Aromatic oil). The use of soft virgin binder appears to compensate well for RAP but not for RAS (both MW and TO shingles). Whereas RAP continuously increased the virgin binder FED, the addition of RAS binder led to reductions in FED, especially for the TO shingles.

Figure 5-28 also presents the true grades of the RAP/MW/TO binder blends as predicted by using the mortar characterization method[5]. All three recycled materials increased the true grades of the virgin binder; however, binders with similar true grades exhibited different FED values depending on whether RAP or RAS binder was used. Similar observations can be made from Figure 5-29, which presents the same set of data as in Figure 5-28 but using a different virgin binder (i.e., PG 52-28 Aromatic oil).

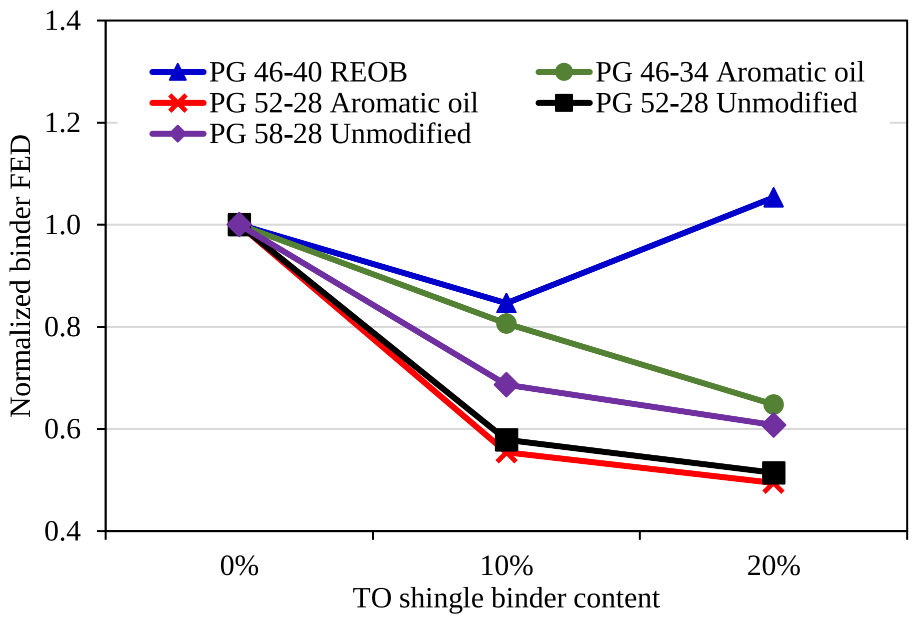

Figure 5-27. FED of TO shingle binder blends normalized with respect to virgin binders

[5] The intermediate temperature true grades were determined based on the predicted high and low temperature true grades.

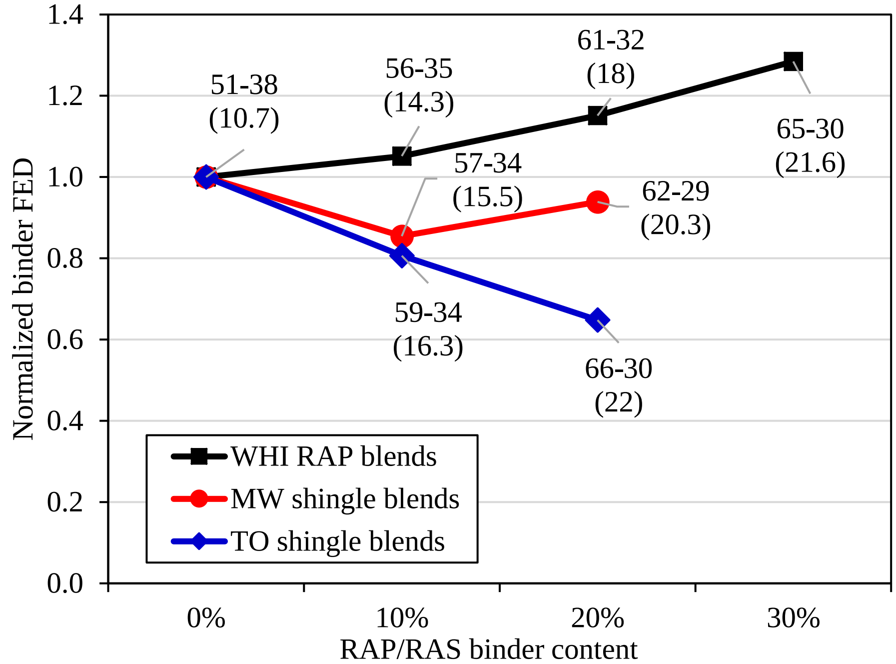

Figure 5-28. Normalized FED of RAP/RAS binder blends and their corresponding true grades using the PG 46-34 Aromatic oil as virgin binder

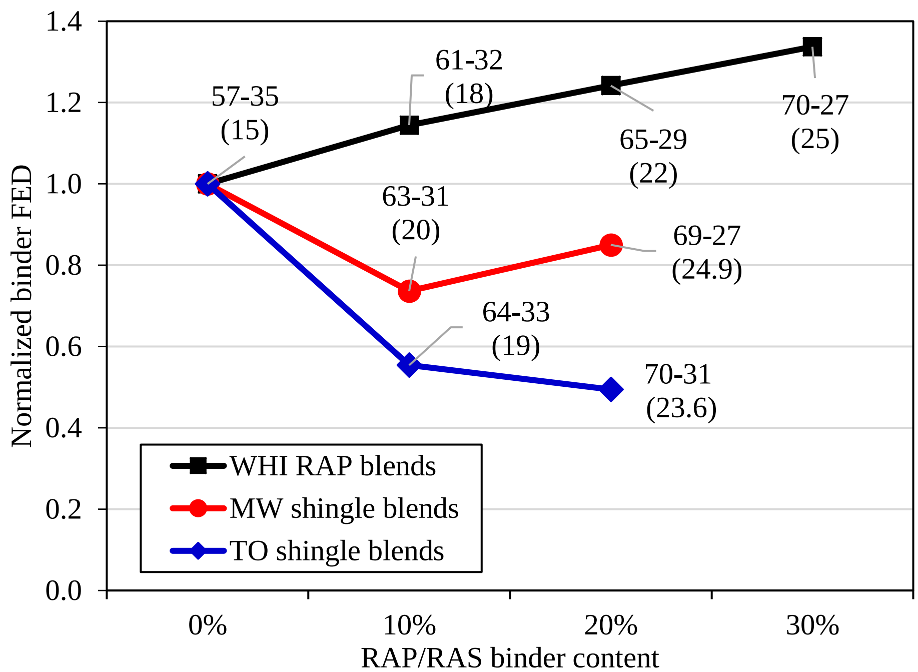

Figure 5-29. Normalized FED of RAP/RAS binder blends and their corresponding true grades using the PG 52-28 Aromatic oil as virgin binder

5.5 Summary

This chapter presents laboratory testing results to: 1) properly evaluate the RAP/RAS effect on performance of different virgin binders at high and low temperature by using the reanalyzed RAP/RAS GCR results; 2) determine the allowable RAS content (i.e., TO shingle) for a given binder type by meeting the current PG grade requirement specified for RAP; 3) evaluate the use of linearly combined RAP-alone GCR and RAS-alone GCR to predict the true grades of the blended virgin, RAP and RAS binders; and 4) evaluate the RAP/RAS effect on the fracture tolerance of virgin binders using the BFE test.

The effect of virgin binder grade on GCR results varied depending on the relative stiffness of the RAP/RAS. Use of a softer virgin binder with the less stiff RAP (i.e., ATL and ACO RAP) typically resulted in greater GCR values. However, there appeared to be a stiffness threshold above which the effect of virgin binder grade became less evident, like in the cases of WHI RAP, TO shingle and MW shingle. REOB appeared to be more effective than Aromatic oil in activating the aged binder, except for the case of TO shingles. The effect of polymer modification was complex: the PMA binder had greater GCR than the unmodified binder when the three RAPs were used; however, both binders resulted in comparable RAS GCR results.

A three-tiered system is normally used to select virgin binder grade for mixtures with different RAP contents. Since there is no target grade of RAP binder blends, those based on a typical RAP (e.g., ATL RAP) in Florida with qualified virgin binders (i.e., PG 52-28 and PG 58-28) at specified contents were used as thresholds for RAS binder blends. Based on the RAP/RAS GCR values, the allowable RAS content at each tier was found to be approximately half of the allowable RAP content.

Mortar samples simultaneously containing RAP and RAS were prepared and tested to obtain the RAP-RAS GCR. This task evaluated a total of thirty-two mortars which include eight RAP-RAS combinations with four virgin binders. The use of linearly combined RAP-alone GCR and RAS-alone GCR yielded true grades comparable to values as predicted using RAP-RAS GCR. The average differences between two predictions were 1.1°C and 0.9°C for the high and low temperature true grades of the RAP-RAS binder blends, respectively. This supports the use of the linear assumption for the contents of RAP/RAS evaluated in this study.

BFE tests were conducted on RAP/RAS binder blends at intermediate temperatures. To obtain ductile-type fracture, it was necessary to adjust the testing temperature and displacement rate for the soft virgin binders and the stiff RAP/RAS binder blends. The FED results indicated that soft virgin binders can be used to compensate the use of RAP but perhaps not that of RAS, especially for the TO shingles. The addition of RAP binder was found to increase the FED of virgin unmodified binder whereas the opposite trend was observed for RAS binder. More specifically, the introduction of MW shingle binder resulted in minor changes in virgin binder FED while the TO shingles caused notable FED reductions. Both RAP and RAS reduced the FED of the PMA binder, which potentially can be attributed to the combined effect of the dilution of polymer modification and increased binder stiffness.

CHAPTER 6 CLOSURE

6.1 Summary and Findings

The major objective of this research was to evaluate the effect of RAS on virgin binder performance. This study included two RAS types, three RAP sources and six virgin binders combined at different RAP/RAS binder replacement rates. A mortar approach, which avoids the need for solvent-based binder extraction and recovery, was adopted to assess how RAP/RAS binder affects the performance of virgin binders in terms of Superpave true grade. Mortar characterization was conducted by performing the Superpave binder tests (i.e., DSR and BBR) on blends of virgin binder and RAP/RAS fine fractions at high, intermediate and low temperatures. In addition, BFE tests were conducted on blends of virgin and RAP/RAS binders to determine the RAP/RAS effect on the fracture tolerance of virgin binders at intermediate temperatures. Impacts of RAS source, RAP source, virgin binder type, recycled binder replacement rate and the inclusion of rejuvenators on virgin binder performance were also evaluated. The main findings based on results of laboratory testing were listed below:

- RAS binders, especially from TO shingles, were too stiff to properly characterize through conventional Superpave binder testing.
    - It was difficult to obtain extracted RAS binder because it did not drain down from the recovery flask.
    - The high temperature true grades of RAS binders were obtained by using a special DSR with a temperature control device which allows measurements at up to 200°C.
    - It was practically impossible to obtain the low temperature true grade of RAS binder as they failed to meet the BBR m-value requirement even at 0°C.
- Virgin and extracted RAS binders were chemically blended together (i.e., through solvent-based binder extraction and recovery process) and the grades of blends indicated that the relationship between RAS binder content and resulting grades is generally nonlinear.
- Two preliminary sets of tests were conducted on mortars with RAP-alone and RAS-alone following the AASHTO provisional standard draft. However, the data analysis procedure in the existing draft failed to provide reliable grade change rate (GCR) results, especially at high and intermediate temperatures.
    - GCR results at high temperatures were too small to be correct and they significantly underestimated the stiffening effect of RAP/RAS on virgin binders.
    - GCR results at intermediate temperatures failed to differentiate between RAP and RAS. DSR measurements on PAV-aged mortar samples sometimes were not repeatable, which may be attributed to the specimen deficiencies (i.e., air voids at the edge of trimmed specimens).

    - GCR results at low temperatures were dominated by stress relaxation properties (m-value) rather than creep stiffness (S value).

- The use of a shift factor in the existing mortar approach to predict properties of RAP/RAS binder blends was identified as the source of underestimated RAP/RAS effect at high temperatures and possibly overestimated RAP/RAS effect at low temperatures.

- An alternative data analysis method that eliminates the use of a shift factor was developed and evaluated.

    - In this method, a relationship is established between properties of mortar B, which only contains virgin binder and recovered RAP/RAS binder, and virgin binder. This relationship allows for predictions of properties of RAP/RAS binder blends based on properties of mortar A, which is composed of virgin binder and RAP/RAS fine fractions.

    - The alternative method was validated by satisfactory comparisons between predicted and measured high temperature true grades of RAP binder blends at three RAP binder replacement rates (i.e., 15%, 30% and 100%).

- The enhanced mortar approach with alternative data analysis method was used to capture the stiffening effect of RAP/RAS on virgin binders.

    - For a given virgin binder type, the stiffest RAP (i.e., WHI RAP) had greater GCR values at high and low temperatures than the other two RAP sources.

    - Both RAS sources had greater GCR values at high and low temperatures than the three RAP sources.

    - TO shingles exhibited greater high temperature GCR but smaller low temperature GCR values than the MW shingles.

- Predicted grades based on RAP mortar measurements were almost identical to values measured from RAP binder blends at three binder replacement rates (i.e., 15%, 30% and 100%) indicating that: 1) a high level (close to complete) of blending occurred between virgin and RAP binder in blended binders and RAP mortars; and 2) RAP GCR was independent of RAP binder replacement rate.

- The RAS GCR determined from 15% RAS mortars was used to predict the grades of RAS binder blends at three binder replacement rates (15%, 30% and 100%). Although accurate grade predictions were made for 15% TO shingle binder blends, predictions for 30% and 100% were notably low. This indicates the RAS GCR or RAS effect increases exponentially with increased RAS binder replacement rate.

    - Predictions based on the GCR obtained from 30% RAS mortars matched the measured grades of 30% RAS blended binders. This implies that the RAS GCR needs to be determined at the RAS binder replacement rate intended for use.

  - Although the mortar sample workability may not allow high RAS binder replacements, it is unnecessary to predict the properties of RAS binder blends at high replacement rates since most state highway agencies limit the use of RAS (e.g., maximum of 20% binder replacement rate).

- The assumption that RAP-alone and RAS-alone GCR can be linearly combined to predict the RAP-RAS GCR at any RAP/RAS binder replacement rate was generally supported by the results of this study.

  - The use of predicted and measured GCR resulted in less than 2°C and 1.5°C difference in high and low temperature true grade of RAP-RAS blended binders, respectively.

  - Greatest difference was observed when using RAS-alone GCR as determined from 15% RAS mortars to predict grades of blended binders containing 20% RAS binder. This can be attributed to the nonlinearly increased RAS GCR with the RAS binder replacement rate.

- RAP/RAS GCR allows for accurate determination of RAP/RAS content for use in mixtures. The limit of RAS content for a given soft virgin binder was found to be approximately half of the allowable RAP content. Although the use of PG 52-28 binder is recommended for RAS mixtures, the use of RAS GCR provides a more consistent way of selecting the PG grade of virgin binder for different type and amount of RAS.

- Importantly, RAP binder was found to increase the FED of virgin unmodified binder whereas the opposite trend was observed for RAS binder. More specially, up to 20% MW shingle binder introduced minor changes in virgin binder FED while the TO shingles caused notable FED reductions.

- In addition, both RAP and RAS reduced the FED of the PMA binder, which potentially can be attributed to the dilution of polymer modification in addition to the stiffening effect.

6.2 Conclusions

In conclusion, the enhanced mortar approach with the alternative data analysis method can be used to accurately predict the high and low temperature true grade of RAP binder blends at any RAP binder replacement rate. The mortar method can also be adopted to predict RAS binder blends at a binder replacement rate identical to that used for RAS GCR determination. This allows for reliable selection of virgin binder grade and accurate determination of maximum RAP/RAS content.

Use of soft virgin unmodified binders, including binders rejuvenated with Aromatic oil and REOB, effectively compensates the stiffening effect of RAP/RAS in terms of Superpave binder true grades. However, whereas RAP binder increased the FED of virgin unmodified binders, the opposite trend was observed for RAS binder, especially for the TO shingles which caused significant reductions in virgin binder FED, indicating deteriorated fracture tolerance. In addition, great caution should be exercised when PMA binders are used as virgin binders in mixtures containing RAP and/or RAS.

It must be emphasized that neither binder nor mortar evaluation truly represents the actual blending between virgin and RAP/RAS binder in mixtures. Also, mixture performance is governed by factors that the two approaches cannot account for, such as RAP/RAS gradation and resulting mixture gradation. Thus, a follow-up study is strongly recommended to extend the research efforts to mixture evaluation.

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APPENDIX A TRUE PG GRADE DETERMINATION OF RAS

Since it is difficult to directly measure the continuous grade of recovered RAS binder, the procedure for indirect measurement is described below. A similar approach was adopted in research conducted by Bonaquist et al. (2010) and Zhou et al. (2013). Basically, the continuous grade of recovered RAS binder is extrapolated from a blend of virgin and RAS binder in a range where linear relationship applies.

1. Extract and recover RAS binder using Florida Method of Test 5-524, *Reflux Extraction of Bitumen from Bituminous Paving Mixtures*. In this study, trichloroethylene (TCE) will be used as a solvent. Extracted binders will be recovered following Florida Method of Test 3-D5404, *Recovery of Asphalt from Solution Using the Rotavapor Apparatus*.

2. Prepare a blend of 20% recovered RAS binder and 80% virgin binder of known continuous grade properties.

3. Condition the blended binder in the Rolling Thin Film Oven Test (RTFO), AASHTO T240 *Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)*.

4. Determine the temperature at which the RTFO conditioned blend meets the AASHTO M320 high temperature grade requirements. The high temperature grade of the recovered RAS binder is extrapolated using Equation 1:

$$T_{H_{RAS}} = T_{H_V} + \frac{100\times\left(T_{blend} - T_{H_V}\right)}{\%RAS} \quad (1)$$

where:

$T_{H_{RAS}} =$ extrapolated high temperature grade of the RAS binder, °C.

$T_{H_{blend}} =$ high temperature continuous grade of the blend of recovered RAS and virgin binder, °C.

$T_{H_V} =$ high temperature continuous grade of the virgin binder, °C.

%RAS= percent of RAS used in the blend, %.

5. Condition the RTFO blended binder in the Pressure Aging Vessel (PAV), AASHTO R28, *Accelerated Aging of Asphalt Binder Using a Pressure Aging Vessel.*

6. Determine the temperature at which the PAV conditioned blend meets the AASHTO M320 intermediate grade temperature requirements. Estimate the intermediate temperature grade of the recovered RAS binder using Equation 2:

$$T_{I_{RAS}} = T_{I_V} + \frac{100\times\left(T_{blend} - T_{I_V}\right)}{\%RAS} \quad (2)$$

where:

$T_{I_{RAS}} =$ extrapolated intermediate temperature grade of the RAS binder, °C.

$T_{I_{blend}} =$ intermediate temperature continuous grade of the blend of recovered RAS and virgin binder, °C.

$T_{I_V} =$ intermediate temperature continuous grade of the virgin binder, °C.

%RAS= percent of RAS used in the blend, %.

7. Determine the temperature at which the PAV conditioned blend meets the AASHTO M320 low temperature grade requirements. Estimate the low temperature grade of the recovered RAS binder following Equation 3:

$$T_{L_{RAS}} = T_{L_V} + \frac{100 \times \left(T_{blend} - T_{LS_V}\right)}{\%RAS} \qquad (3)$$

where:

$T_{L_{RAS}} =$ extrapolated low temperature grade of the RAS binder, °C.

$T_{L_{blend}} =$ low temperature continuous grade of the blend of recovered RAS and virgin binder, °C.

$T_{L_V} =$ low temperature continuous grade of the virgin binder, °C.

%RAS= percent of RAS used in the blend, %.

APPENDIX B SHINGLE BINDER AVAILABILITY FACTOR DETERMINATION

1. A calculated initial estimate of the percentage of asphalt binder Fc that is released from the recycled asphalt shingle and blends with the virgin asphalt binder may be made by subtracting the difference between the design binder content of a virgin mix without recycled asphalt shingle (P_{bv}) and the design binder content of the new hot mix asphalt with recycled asphalt shingle (P_{bvr}), and dividing this value by the total available asphalt shingle binder in the new hot mix asphalt. Expressed mathematically

$$F_C = \frac{P_{bv} - P_{bvr}}{(P_{sr})(P_{br})} \quad (1)$$

where:

F_C = the estimated shingle asphalt binder availability factor, percent;
P_{bv} = the design asphalt binder content of the mix without RAS, percent;
P_{bvr} = the design asphalt binder content of the same mix (new HMA) with RAS, percent;
P_{sr} = the percentage of RAS in the new HMA expressed as a decimal; and
P_{br} = the percentage of shingle asphalt binder in the RAS expressed as a decimal.

2. The initial estimate will underestimate the value of Fc. Since the maximum value of F is theoretically equal to 1, the true value of F can be expected to lie between the value of F_c and 1, or expressed mathematically, $F_c<F<1$. As a result, the best approximation of F can be expressed by Equation 2.

$$F = \frac{1 + F_c}{2} \quad (2)$$

where F_c is the initial estimation of SAF and F is the corrected value.

APPENDIX C PROPERTIES OF RAP-ALONE AND RAS-ALONE MORTARS

Table C-1. Measured properties of RAP-alone and RAS-alone mortars at high temperatures

Virgin binder	Mortar	DSR		ATL RAP		ACO RAP		WHI RAP		TO Shingles		MW Shingles	
				G*/sinδ (kPa)									
				Unaged	RTFO	Unaged	RTFO	Unaged	RTFO	Unaged	RTFO	Unaged	RTFO
PG 46-34 REOB	A	Temp.1	46	27.6	46.3	41.3	67.4	78.7	65.7	13.8	42.1	50.0	98.3
		Temp.2	52	11.9	19.1	18.1	28.2	31.4	27.3	5.9	18.6	21.9	43.1
	B	Temp.1	46	12.2	24.6	12.3	25.2	22.3	20.6	3.7	9.4	13.5	22.8
		Temp.2	52	5.5	10.1	5.4	10.5	9.1	8.4	1.7	4.0	6.0	9.4
PG 46-34 Aromatic Oil	A	Temp.1	46	27.5	46.0	45.7	63.3	38.8	55.7	18.0	38.6	66.8	108.0
		Temp.2	52	11.2	17.9	18.6	24.6	15.6	21.8	7.9	16.4	26.4	49.2
	B	Temp.1	46	15.8	24.4	14.8	23.1	10.5	18.7	4.3	6.4	18.3	25.1
		Temp.2	52	6.7	9.8	6.2	9.3	4.5	7.5	1.8	2.8	7.6	9.9
PG 52-28 Aromatic Oil	A	Temp.1	52	25.4	35.8	39.3	48.3	31.9	48.4	15.3	32.3	58.0	74.4
		Temp.2	58	10.6	14.3	16.2	19.7	13.2	19.4	6.8	15.1	24.0	30.7
	B	Temp.1	52	14.0	21.6	14.1	21.2	9.8	18.3	4.0	6.6	15.4	20.3
		Temp.2	58	6.1	8.9	5.1	8.8	4.3	7.5	1.8	2.9	6.7	8.7
PG52-28	A	Temp.1	52	22.2	46.4	33.5	71.2	32.1	57.3	12.8	23.5	60.6	74.2
		Temp.2	58	9.6	19.2	14.4	29.2	13.5	23.3	5.7	10.3	26.1	31.1
	B	Temp.1	52	11.9	24.2	12.9	27.2	10.8	18.4	3.4	7.5	13.6	22.7
		Temp.2	58	5.3	10.3	5.7	11.2	4.7	7.7	1.5	3.3	6.0	9.5
PG58-22	A	Temp.1	58	22.2	30.5	25.7	41.3	27.4	40.1	9.7	16.9	43.5	72.1
		Temp.2	64	9.6	12.7	11.1	17.1	11.4	16.1	4.3	7.3	18.5	29.8
	B	Temp.1	58	12.4	18.0	12.9	17.9	10.3	14.7	3.1	5.7	12.3	19.4
		Temp.2	64	5.6	7.7	5.8	7.6	4.6	6.2	1.4	2.5	5.5	8.2
PG 64-34 PMA	A	Temp.1	64	14.4	20.0	20.4	23.7	18.5	23.6	6.0	10.3	31.0	38.7
		Temp.2	70	7.5	10.3	10.8	12.0	9.7	12.1	3.4	6.0	16.6	20.0
	B	Temp.1	64	9.1	14.4	8.3	14.6	7.3	11.0	2.3	4.4	9.7	13.9
		Temp.2	70	4.9	7.5	4.6	7.7	4.0	5.8	1.3	2.4	5.4	7.3

Table C-2. Measured properties of RAP-alone and RAS-alone mortars at intermediate temperatures

Virgin binder	Mortar	DSR		ATL RAP	ACO RAP	WHI RAP	TO Shingles	MW Shingles
				G*sinδ (kPa)				
				PAV-aged				
PG 46-34 REOB	A	Temp.1	10	8,580	10,400	12,000	7,010	10,900
		Temp.2	13	6,080	7,410	8,280	5,410	8,340
	B	Temp.1	10	4,130	7,070	7,320	3,200	8,910
		Temp.2	13	2,960	5,020	5,250	2,400	6,310
PG 46-34 Aromatic Oil	A	Temp.1	10	23,500	40,700	14,000	11,900	21,200
		Temp.2	13	15,600	28,200	10,000	8,970	17,200
	B	Temp.1	10	15,100	20,300	11,100	7,690	15,200
		Temp.2	13	10,300	15,600	7,790	5,110	10,500
PG 52-28 Aromatic Oil	A	Temp.1	16	13,400	8,310	12,600	6,900	21,000
		Temp.2	19	8,990	5,420	9,060	4,980	14,500
	B	Temp.1	16	9,760	5,450	6,510	5,770	10,600
		Temp.2	19	6,360	3,440	4,250	3,810	7,100
PG52-28	A	Temp.1	16	15,000	15,900	14,500	8,050	19,000
		Temp.2	19	10,500	11,400	10,900	5,980	14,500
	B	Temp.1	16	10,700	10,600	9,340	5,570	11,200
		Temp.2	19	7,190	7,380	6,350	3,840	7,800
PG58-28	A	Temp.1	19	13,100	13,500	21,200	9,380	14,800
		Temp.2	22	9,450	9,870	18,300	6,950	11,100
	B	Temp.1	19	9,820	9,970	10,800	5,900	9,700
		Temp.2	22	6,850	6,970	8,620	4,120	6,750
PG 64-34 PMA	A	Temp.1	10	20,430	19,200	14,800	10,500	19,600
		Temp.2	13	16,300	16,000	11,300	8,750	16,600
	B	Temp.1	10	12,500	12,900	11,600	8,240	11,400
		Temp.2	13	9,750	9,810	8,480	6,680	9,740

Table C-3. Measured properties of RAP-alone and RAS-alone mortars at low temperatures

Virgin binder	Mortar	BBR		ATL RAP		ACO RAP		WHI RAP		TO Shingles		MW Shingles	
				PAV-aged									
				m	S (MPa)	m	S (MPa)	m	S (MPa)	m	S (MPa)	m	S (MPa)
PG 46-34 REOB	A	Temp.1	-18	0.367	320	0.340	406	0.345	330	0.316	135	0.309	449
		Temp.2	-24	0.300	657	0.277	759	0.286	523	0.271	249	0.259	794
	B	Temp.1	-18	0.428	195	0.423	206	0.399	155	0.386	71	0.429	202
		Temp.2	-24	0.355	452	0.346	439	0.342	376	0.356	143	0.341	409
PG 46-34 Aromatic Oil	A	Temp.1	-18	0.360	689	0.303	1,130	0.344	618	0.293	254	0.325	861
		Temp.2	-24	0.266	1,640	0.231	2,020	0.262	1,370	0.252	504	0.238	1,990
	B	Temp.1	-18	0.430	494	0.355	777	0.425	371	0.434	172	0.423	489
		Temp.2	-24	0.310	1,270	0.272	1,650	0.328	897	0.336	482	0.332	1,140
PG 52-28 Aromatic Oil	A	Temp.1	-12	0.426	362	0.480	256	0.377	407	0.376	144	0.354	475
		Temp.2	-18	0.323	984	0.368	739	0.295	797	0.301	324	0.274	1,170
	B	Temp.1	-12	0.472	260	0.553	140	0.466	222	0.461	105	0.455	274
		Temp.2	-18	0.372	770	0.432	481	0.370	546	0.367	267	0.368	724
PG52-28	A	Temp.1	-12	0.388	386	0.368	434	0.363	346	0.345	146	0.336	455
		Temp.2	-18	0.310	896	0.298	898	0.292	759	0.261	317	0.27	1,060
	B	Temp.1	-12	0.429	314	0.442	284	0.437	219	0.427	90.9	0.426	250
		Temp.2	-18	0.344	792	0.348	674	0.348	496	0.34	238	0.346	543
PG58-22	A	Temp.1	-12	0.334	623	0.316	720	0.307	575	0.311	239	0.283	804
		Temp.2	-18	0.255	1,280	0.253	1,390	0.241	1,260	0.237	504	0.231	1,590
	B	Temp.1	-12	0.369	518	0.365	501	0.367	397	0.362	196	0.364	509
		Temp.2	-18	0.279	1,170	0.285	1090	0.287	851	0.285	423	0.282	1,200
PG 64-34 PMA	A	Temp.1	-18	0.31	792	0.282	824	0.284	569	0.283	287	0.266	994
		Temp.2	-24	0.239	1,520	0.226	1,510	0.238	1,070	0.248	489	0.22	1,610
	B	Temp.1	-18	0.349	587	0.334	643	0.344	436	0.339	224	0.339	532
		Temp.2	-24	0.271	1,220	0.268	1,110	0.287	790	0.282	420	0.272	1,200

APPENDIX D SHIFT FACTOR

Table D-1. Shift factor of ATL RAP mortar

Shift factor: ATL RAP mortar					
Virgin binder type	High temp. (Un-aged)	High temp. (RTFO)	Intermediate temp.	Low temp.(S)	Low temp. (m)
PG58-28	1.27	1.21	1.03	1.02	0.91
PG52-28	1.31	1.24	1.04	1.03	0.90
PG 64-34 PMA	1.20	1.14	1.05	1.04	0.89
PG 46-34 Aromatic oil	1.24	1.23	1.05	1.05	0.89
PG 52-28 Aromatic oil	1.27	1.19	1.04	1.05	0.89
PG 46-34 REOB	1.39	1.24	1.09	1.08	0.85

Table D-2. Shift factor of ACO RAP mortar

Shift factor: ACO RAP mortar					
Virgin binder type	High temp. (Un-aged)	High temp. (RTFO)	Intermediate temp.	Low temp.(S)	Low temp. (m)
PG58-28	1.32	1.34	1.04	1.05	0.88
PG52-28	1.45	1.34	1.05	1.06	0.84
PG 64-34 PMA	1.49	1.20	1.05	1.04	0.84
PG 46-34 Aromatic oil	1.51	1.38	1.07	1.04	0.85
PG 52-28 Aromatic oil	1.55	1.32	1.05	1.10	0.86
PG 46-34 REOB	1.60	1.36	1.04	1.11	0.80

Table D-3. Shift factor of WHI RAP mortar

Shift factor: WHI RAP mortar					
Virgin binder type	High temp. (Un-aged)	High temp. (RTFO)	Intermediate temp.	Low temp.(S)	Low temp. (m)
PG58-28	1.51	1.45	1.08	1.07	0.86
PG52-28	1.57	1.47	1.05	1.08	0.83
PG 64-34 PMA	1.55	1.37	1.03	1.04	0.83
PG 46-34 Aromatic oil	1.69	1.45	1.03	1.07	0.80
PG 52-28 Aromatic oil	1.64	1.40	1.08	1.09	0.80
PG 46-34 REOB	1.49	1.47	1.05	1.10	0.85

Table D-4. Shift factor of TO shingle mortar

Shift factor: TO shingles mortar					
Virgin binder type	High temp. (Un-aged)	High temp. (RTFO)	Intermediate temp.	Low temp.(S)	Low temp. (m)
PG58-28	2.47	1.89	1.06	1.03	0.88
PG52-28	2.96	1.77	1.05	1.08	0.83
PG 64-34 PMA	3.19	1.81	1.03	1.04	0.86
PG 46-34 Aromatic oil	2.29	2.34	1.06	1.04	0.82
PG 52-28 Aromatic oil	2.63	2.19	1.03	1.05	0.82
PG 46-34 REOB	2.75	1.88	1.10	1.13	0.79

Table D-5. Shift factor of MW shingle mortar

Shift factor: MW shingles mortar					
Virgin binder type	High temp. (Un-aged)	High temp. (RTFO)	Intermediate temp.	Low temp.(S)	Low temp. (m)
PG58-28	1.55	1.42	1.05	1.06	0.80
PG52-28	1.70	1.45	1.06	1.11	0.78
PG 64-34 PMA	1.59	1.45	1.06	1.07	0.80
PG 46-34 Aromatic oil	1.53	1.42	1.04	1.09	0.74
PG 52-28 Aromatic oil	1.58	1.51	1.08	1.09	0.76
PG 46-34 REOB	1.61	1.57	1.03	1.13	0.74

APPENDIX E RAP/RAS GRADE CHANGE RATE VALUES BASED ON EXISTING DATA ANALYSIS METHOD

Table E-1. RAP/RAS grade change rate determined at high, intermediate and low temperatures

GCR (°C/% replacement)		Virgin binders	Recycled materials				
			ATL RAP	ACO RAP	WHI RAP	TO Shingle	MW Shingle
High temperature	Original	PG 46-34 (REOB)	0.119	0.082	0.087	0.093	0.088
		PG 46-34 (Aromatic oil)	0.110	0.104	0.125	0.136	0.113
		PG 52-28 (Aromatic oil)	0.075	0.051	0.055	0.055	0.055
		PG 52-28	0.094	0.068	0.076	0.095	0.079
		PG 58-28	0.094	0.093	0.119	0.182	0.121
		PG 64-34 PMA	0.090	0.084	0.144	0.240	0.166
	RTFO	PG 46-34 (REOB)	0.197	0.161	0.194	0.255	0.212
		PG 46-34 (Aromatic oil)	0.038	0.056	0.073	0.170	0.061
		PG 52-28 (Aromatic oil)	0.085	0.087	0.109	0.207	0.129
		PG 52-28	0.102	0.092	0.122	0.167	0.119
		PG 58-28	0.094	0.093	0.119	0.182	0.121
		PG 64-34 PMA	0.090	0.084	0.144	0.240	0.166
Intermediate temperature		PG 46-34 (REOB)	0.489	0.173	0.222	0.395	0.113
		PG 46-34 (Aromatic oil)	0.212	0.203	0.090	0.190	0.148
		PG 52-28 (Aromatic oil)	0.181	0.170	0.279	0.094	0.261
		PG 52-28	0.218	0.171	0.215	0.190	0.244
		PG 58-28	0.191	0.137	0.303	0.231	0.205
		PG 64-34 PMA	0.337	0.202	0.133	0.133	0.260
Low temperatures	Stiffness	PG 46-34 (REOB)	0.251	0.231	0.234	0.290	0.290
		PG 46-34 (Aromatic oil)	0.132	0.082	0.150	0.086	0.170
		PG 52-28 (Aromatic oil)	0.157	0.199	0.193	0.120	0.191
		PG 52-28	0.124	0.148	0.193	0.197	0.252
		PG 58-28	0.099	0.126	0.185	0.102	0.159
		PG 64-34 PMA	0.155	0.110	0.127	0.102	0.196
	m-value	PG 46-34 (REOB)	0.635	0.604	0.460	0.695	0.918
		PG 46-34 (Aromatic oil)	0.241	0.234	0.348	0.400	0.495
		PG 52-28 (Aromatic oil)	0.277	0.242	0.403	0.378	0.524
		PG 52-28	0.264	0.313	0.359	0.381	0.503
		PG 58-28	0.259	0.242	0.289	0.277	0.453
		PG 64-34 PMA	0.555	0.534	0.642	0.513	0.785

APPENDIX F VALIDATY OF MORTAR MEASUREMENTS AT INTERMEDIATE TEMPERATURES

Bonnaure et al. (1997) proposed a linear relationship to related binder and mixture stiffness in a logarithm scale (Equation 1).

$$\log(S_{mix}) = \alpha \cdot \log(S_{binder}) + \beta \quad (1)$$

where α and β are parameters calculated from the volume fractions of binder and aggregate in the mixture, S_{mix} is the mixture stiffness, and S_{binder} is the asphalt binder stiffness.

Equation 1 shows that the properties of different asphalt mixtures depend only on binder properties when the aggregate type and volume fractions remain constant. The alternative data analysis method proposed in this study adopted Equation 1 and applied it to correlate binder and mortar properties. Taking the combinations of ACO RAP and six virgin binders as an example, properties between those mortars and corresponding binders were anticipated to establish a relationship with high coefficient of determination (R^2). In other words, the established relationship between ACO RAP mortars and virgin binder should be affected by changing the virgin binder type. Figure F-1 shows the relationship in G*/sinδ between ACO RAP mortars and six virgin binders measured at two temperatures under both un-aged and RTFO-aged conditions. Excellent R^2 of 0.93 and 0.95 for measurements under un-aged and RTFO-aged conditions were expected and they support the adoption of Equation 1.

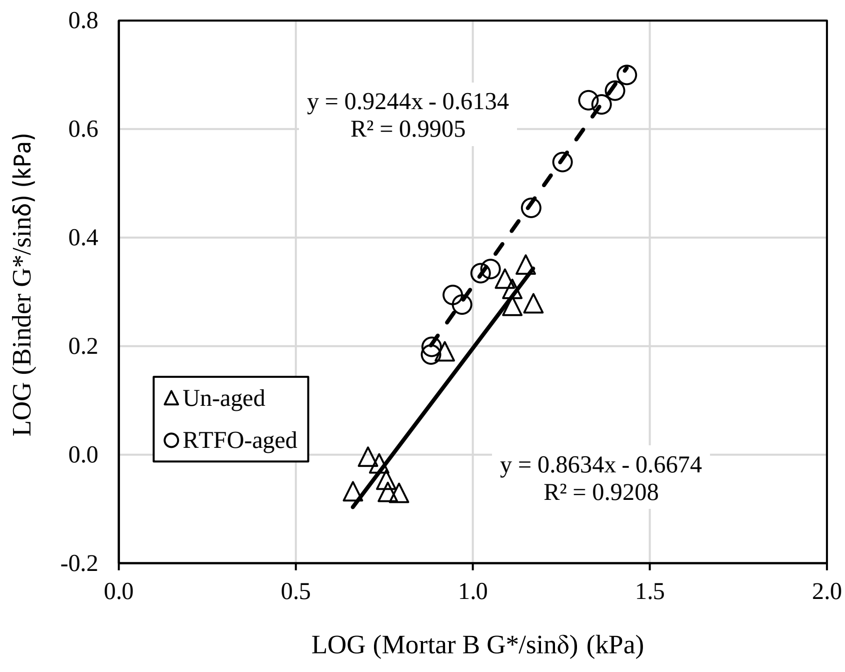

Figure F-1. Relationship between binder and mortar B G*/sin(δ) measured under two conditions

Figure F-2 shows the relationship in G*sinδ obtained from ACO RAP mortars with six virgin binders at two temperatures under two conditions. Scattered data points and the low R^2 (0.4245) indicate that those measurements were not reliable. Table F-1 summarizes the coefficients and R^2 determined from the other two RAP sources, two RAS sources and six virgin binders. Although the R^2 for the combinations of TO shingles and virgin binders were considerably high, it should be noted that the asphalt content of TO shingles mortars were much higher than RAP mortars, which reduces the possibility of introducing specimen deficiencies (i.e., presence of air voids at the edge of trimmed specimens). Therefore, the decision was made that tests on mortars simultaneously containing RAP and RAS at intermediate temperatures were eliminated.

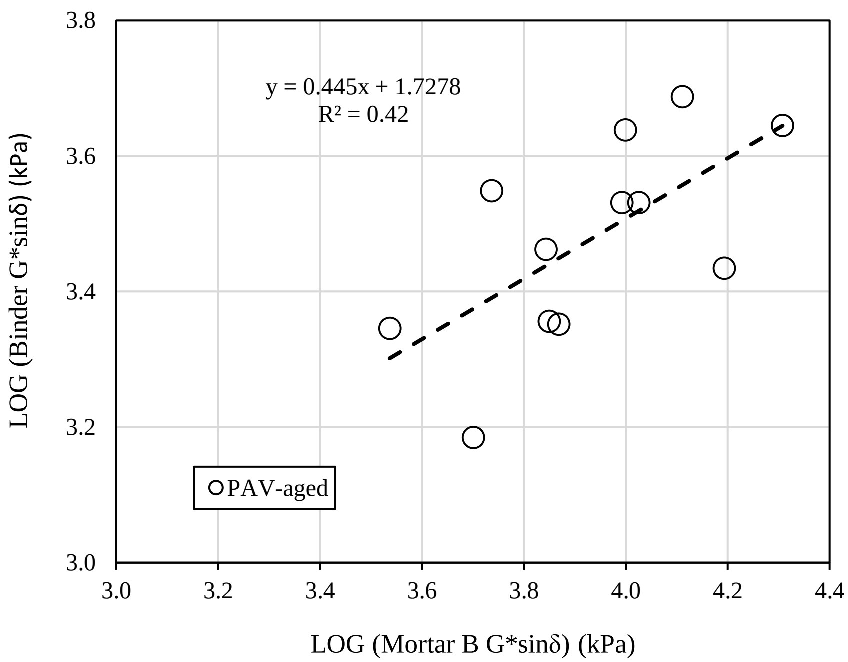

Figure F-2. Relationship between binder and mortar-B G*sin(δ) measured under two conditions

Table F-1. Established relationship in G*sinδ between RAP/RAS mortars and virgin binders

LOG (binder G*sinδ) = a·LOG (mortar B G*sinδ) + b			
	a	b	R2
ATL RAP	0.657	0.9103	0.79
ACO RAP	0.445	1.7278	0.42
WHI RAP	0.9374	-0.1714	0.70
TO Shingles	0.8875	0.2017	0.90
MW Shingles	1.0671	-0.7591	0.62

APPENDIX G RAP/RAS GRADE CHANGE RATE VALUES BASED ON ALTERNATIVE DATA ANALYSIS METHOD

Table G-1. RAP/RAS grade change rate determined at high, intermediate and low temperatures

GCR (°C/% replacement)		Virgin binders	Recycled materials				
			ATL RAP	ACO RAP	WHI RAP	TO Shingle	MW Shingle
High temperature	Original	PG 46-34 (REOB)	0.514	0.547	0.542	0.603	0.628
		PG 46-34 (Aromatic oil)	0.326	0.462	0.553	0.702	0.541
		PG 52-28 (Aromatic oil)	0.352	0.493	0.505	0.653	0.582
		PG 52-28	0.405	0.414	0.489	0.649	0.702
		PG 58-28	0.364	0.297	0.424	0.542	0.571
		PG 64-34 PMA	0.381	0.512	0.558	0.642	0.731
	RTFO	PG 46-34 (REOB)	0.399	0.425	0.538	0.747	0.739
		PG 46-34 (Aromatic oil)	0.359	0.388	0.459	0.828	0.802
		PG 52-28 (Aromatic oil)	0.288	0.339	0.415	0.860	0.574
		PG 52-28	0.392	0.403	0.495	0.556	0.544
		PG 58-28	0.324	0.349	0.427	0.516	0.589
		PG 64-34 PMA	0.269	0.259	0.450	0.648	0.617
Intermediate temperature		PG 46-34 (REOB)	0.558	0.549	0.551	0.632	0.547
		PG 46-34 (Aromatic oil)	0.205	0.207	0.212	0.202	0.215
		PG 52-28 (Aromatic oil)	0.082	0.112	0.075	0.078	0.078
		PG 52-28	0.259	0.261	0.261	0.260	0.263
		PG 58-28	0.099	0.099	0.110	0.102	0.101
		PG 64-34 PMA	0.032	0.027	0.024	0.027	0.044
Low temperatures	Stiffness	PG 46-34 (REOB)	0.271	0.313	0.217	0.352	0.448
		PG 46-34 (Aromatic oil)	0.155	0.110	0.169	0.012	0.265
		PG 52-28 (Aromatic oil)	0.178	0.108	0.129	0.053	0.191
		PG 52-28	0.034	0.088	0.203	0.065	0.345
		PG 58-28	0.047	0.072	0.182	0.090	0.133
		PG 64-34 PMA	0.163	0.103	0.263	0.088	0.146
	m-value	PG 46-34 (REOB)	0.320	0.352	0.390	0.450	0.540
		PG 46-34 (Aromatic oil)	0.152	0.173	0.270	0.429	0.419
		PG 52-28 (Aromatic oil)	0.112	0.175	0.277	0.220	0.424
		PG 52-28	0.194	0.143	0.217	0.362	0.378
		PG 58-28	0.145	0.206	0.307	0.255	0.322
		PG 64-34 PMA	0.241	0.345	0.417	0.343	0.419

APPENDIX H COMPOSITIONS OF MORTARS CONTAINING RAP AND RAS

Table H-1. Compositions of mortars simultaneously containing RAP and RAS

RAP-RAS combination	Mortar type	Virgin binder (g)	RAP			RAS			Total binder (g)	Total weight (g)	%WHI RAP binder	%RAS binder	%Total binder
			Aggregate (g)	RAP binder (g)	RAP (g)	Aggregate (g)	RAS binder (g)	RAS (g)					
5%WHI+15%TO	A	16.9	10.1	1.1	11.2	8.8	3.2	11.9	21.1	40.0	5.0%	15.0%	52.7%
	B	21.1	10.1	—	—	8.8	—	—	21.1	40.0	—	—	52.7%
5%WHI+20%TO	A	14.7	9.5	1.0	10.5	10.9	3.9	14.8	19.6	40.0	5.0%	20.0%	49.1%
	B	19.6	9.5	—	—	10.9	—	—	19.6	40.0	—	—	49.1%
5%WHI+5%MW	A	17.1	9.1	0.9	10.1	11.9	0.9	12.8	19.0	40.0	5.0%	5.0%	47.4%
	B	19.0	9.1	—	—	11.9	—	—	19.0	40.0	—	—	47.4%
3%WHI+10%MW	A	13.7	4.6	0.5	5.1	19.7	1.6	21.3	15.7	40.0	3.0%	10.0%	39.3%
	B	15.7	4.6	—	—	19.7	—	—	15.7	40.0	—	—	39.3%
5%ATL+5%MW	A	14.5	13.8	0.8	14.6	10.1	0.8	10.9	16.1	40.0	5.0%	5.0%	40.2%
	B	16.1	13.8	—	—	10.1	—	—	16.1	40.0	—	—	40.2%
3%ATL+10%MW	A	12.6	7.4	0.4	7.8	18.1	1.4	19.6	14.5	40.0	3.0%	10.0%	36.2%
	B	14.5	7.4	—	—	18.1	—	—	14.5	40.0	—	—	36.2%
5%ATL+10%TO	A	15.9	16.1	0.9	17.0	5.2	1.9	7.1	18.7	40.0	5.0%	10.0%	46.8%
	B	18.7	16.1	—	—	5.2	—	—	18.7	40.0	—	—	46.8%
5%ATL+15%TO	A	14.1	15.0	0.9	15.9	7.3	2.6	10.0	17.6	40.0	5.0%	15.0%	44.1%
	B	17.6	15.0	—	—	7.3	—	—	17.6	40.0	—	—	44.1%

APPENDIX I MEASURED AND PREDICTED GRADE CHANGE RATE OF MORTARS CONTAINING RAP AND RAS

Table I-1. RAP-RAS GCR values as determined at high and low temperatures

RAP-RAS combination \ Virgin binder		Grade change rate (°C/%RAP/RAS binder replacement rate)							
		PG 46-34 Aromatic oil		PG 52-28 Aromatic oil		52-28		58-28	
		Mea.	Pre.	Mea.	Pre.	Mea.	Pre.	Mea.	Pre.
High temp. (conservative)	5%WHI+5%MW	0.604	0.500	0.551	0.495	0.624	0.517	0.534	0.497
	3%WHI+10%MW	0.619	0.522	0.613	0.537	0.723	0.531	0.533	0.537
	5%WHI+15%TO	0.640	0.676	0.510	0.593	0.653	0.540	0.611	0.493
	5%WHI+20%TO	0.678	0.653	0.695	0.605	0.789	0.543	0.643	0.498
	5%ATL+5%MW	0.499	0.434	0.347	0.431	0.421	0.468	0.419	0.447
	3%ATL+10%MW	0.598	0.469	0.554	0.508	0.447	0.509	0.428	0.514
	5%ATL+10%TO	0.629	0.577	0.516	0.531	0.563	0.502	0.517	0.452
	5%ATL+15%TO	0.648	0.608	0.589	0.562	0.698	0.515	0.505	0.468
Low temp. (based on m-value)	5%WHI+5%MW	0.345	0.345	0.240	0.350	0.293	0.286	0.214	0.315
	3%WHI+10%MW	0.426	0.385	0.246	0.340	0.283	0.254	0.339	0.319
	5%WHI+15%TO	0.350	0.389	0.170	0.234	0.256	0.326	0.273	0.268
	5%WHI+20%TO	0.315	0.397	0.247	0.231	0.184	0.333	0.264	0.265
	5%ATL+5%MW	0.171	0.286	0.223	0.268	0.132	0.286	0.193	0.234
	3%ATL+10%MW	0.302	0.358	0.202	0.360	0.190	0.236	0.263	0.281
	5%ATL+10%TO	0.301	0.337	0.153	0.184	0.191	0.306	0.149	0.218
	5%ATL+15%TO	0.350	0.360	0.176	0.193	0.255	0.320	0.131	0.227

APPENDIX J MEASURED AND PREDICTED TRUE GRADES OF RAP-RAS BINDER BLENDS AT HIGH AND LOW TEMPERATURES

Table J-1. True grades of RAP-RAS binder blends as predicted at high and low temperatures

RAP-RAS combination \ Virgin binder		True grade of RAP-RAS binder blends (°C)							
		PG 46-34 Aromatic oil		PG 52-28 Aromatic oil		52-28		58-28	
		Mea.	Pre.	Mea.	Pre.	Mea.	Pre.	Mea.	Pre.
High temp. (conservative value)	5%WHI+5%MW	56.8	55.8	62.7	62.1	64.1	63.1	66.7	66.4
	3%WHI+10%MW	58.9	57.6	65.2	64.2	67.3	64.8	68.3	68.4
	5%WHI+15%TO	63.6	64.3	67.4	69.1	71.0	68.7	73.6	71.3
	5%WHI+20%TO	67.7	67.1	74.6	72.3	77.6	71.5	77.5	73.8
	5%ATL+5%MW	55.8	55.1	60.7	61.5	62.1	62.6	65.6	65.9
	3%ATL+10%MW	58.6	56.9	64.4	63.8	63.7	64.5	67.0	68.1
	5%ATL+10%TO	60.2	59.5	64.9	65.2	66.4	65.4	69.1	68.2
	5%ATL+15%TO	63.8	63.0	69.0	68.4	71.9	68.2	71.5	70.8
Low temp. (based on m-value)	5%WHI+5%MW	-34.8	-34.8	-33.0	-31.9	-30.9	-30.9	-27.7	-26.7
	3%WHI+10%MW	-32.7	-33.2	-32.2	-31.0	-30.1	-30.5	-25.4	-25.7
	5%WHI+15%TO	-31.2	-30.4	-32.0	-30.7	-28.7	-27.3	-24.3	-24.4
	5%WHI+20%TO	-30.3	-28.3	-29.2	-29.6	-29.2	-25.5	-23.2	-23.2
	5%ATL+5%MW	-36.5	-35.3	-33.2	-32.7	-32.5	-30.9	-27.9	-27.5
	3%ATL+10%MW	-34.3	-33.5	-32.8	-30.7	-31.3	-30.7	-26.4	-26.1
	5%ATL+10%TO	-33.7	-33.1	-33.1	-32.6	-30.9	-29.2	-27.6	-26.5
	5%ATL+15%TO	-31.2	-31.0	-31.9	-31.5	-28.7	-27.4	-27.2	-25.3

APPENDIX K BINDER FRACTURE ENERGY DENSITY OF VIRGIN AND RAP/RAS BINDER BLENDS

Table K-1. Fracture energy density of WHI RAP binder blends

Fracture energy density (kJ/m3)	SPE1	SPE2	SPE3	SPE4	AVE	
10% WHI RAP	2,450	2,520	2,350	—	2,440	PG 46-34 Aromatic oil
	3,073	2,954	2,771	3,250	3,012	PG 52-28 Aromatic oil
	7,348	7,617	9,423	9,516	8,476	PG 64-34 PMA
20% WHI RAP	2,696	2,647	2,670	—	2,671	PG 46-34 Aromatic oil
	3,260	3,245	3,210	3,357	3,268	PG 52-28 Aromatic oil
	8,254	7,754	7,954	8,447	8,102	PG 64-34 PMA
30% WHI RAP	2,786	2,888	2,992	3,255	2,980	PG 46-34 Aromatic oil
	3,475	3,555	3,520	3,527	3,519	PG 52-28 Aromatic oil
	7,653	7,737	7,905	7,946	7,810	PG 64-34 PMA

Table K-2. Fracture energy density of MW shingles binder blends

Fracture energy density (kJ/m3)	SPE1	SPE2	SPE3	SPE4	AVE	
10%MW	1,237	1,210	1,191	1,212	1,213	PG 46-34 REOB
	1,825	1,796	1,770	1,850	1,810	PG 46-34 Aromatic oil
	1,818	1,793	1,969	1,918	1,875	PG 52-28 Aromatic oil
	2,105	2,215	2,032	1,988	2,085	PG 52-28 Unmodified
	2,542	2,535	2,560	—	2,546	PG 58-28 Unmodified
	4,786	4,987	6,068	6,376	5,554	PG 64-34 PMA
20%MW	1,762	1,519	1,599	1,565	1,611	PG 46-34 REOB
	2,062	2,380	2,025	2,291	2,190	PG 46-34 Aromatic oil
	2,065	2,211	2,227	2,150	2,163	PG 52-28 Aromatic oil
	2,488	2,417	2,495	—	2,467	PG 52-28 Unmodified
	2,816	2,895	2,838	2,715	2,816	PG 58-28 Unmodified
	4,774	4,585	5,645	5,720	5,181	PG 64-34 PMA

Table K-3. Fracture energy density of TO shingles binder blends

Fracture energy density (kJ/m3)	SPE1	SPE2	SPE3	SPE4	AVE	
10%TO	1,174	1,106	1,284	1,195	1,190	PG 46-34 REOB
	1,937	1,745	1,959	—	1,880	PG 46-34 Aromatic oil
	1,414	1,408	—	—	1,411	PG 52-28 Aromatic oil
	1,650	1,474	1,440	1,320	1,471	PG 52-28 Unmodified
	2,024	2,060	2,050	—	2,045	PG 58-28 Unmodified
20%TO	1,509	1,470	1,420	1,524	1,481	PG 46-34 REOB
	1,489	1,565	1,471	1,520	1,511	PG 46-34 Aromatic oil
	1,223	1,260	1,291	—	1,258	PG 52-28 Aromatic oil
	1,265	1,237	1,260	—	1,254	PG 52-28 Unmodified
	1,887	1,726	—	—	1,807	PG 58-28 Unmodified