Final Report

PERFORM AN INVESTIGATION OF THE EFFECTS OF INCREASED RECLAIMED ASPHALT PAVEMENT (RAP) LEVELS IN DENSE GRADED FRICTION COURSES

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DISCLAIMER

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square 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.

Symbol	When You Know	Multiply By	To Find	Symbol
		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	Fahrenheit 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.

(Revised August 1992)

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16. Abstract

In this study, a total of 28 mixture combinations were designed and evaluated to determine the maximum allowable amount of reclaimed asphalt pavement (RAP) material in friction courses without jeopardizing pavement cracking performance. The experimental factors included two RAP sources, four RAP contents, two virgin binders, and two mixture conditioning levels. RAP binder was recovered and blended with virgin binders at various RAP binder replacement ratios. All blended binders not only met the FDOT's specifications for virgin modified binders, but also had satisfactory binder fracture energy density (FED) values. Increased RAP content resulted in stronger (higher tensile strength) but more brittle (lower failure strain and lower FED) mixtures. However, even after long-term oven aging (LTOA) + cyclic pore pressure conditioning (CPPC), all RAP mixtures exhibited FED values above 0.75 kJ/m^3 and ER values well above1.0, indicating adequate cracking performance. Higher RAP content generally resulted in higher ER values. Although the increasing trend was reversed between 30% and 40% RAP content, the ER at 40% RAP was still well above 1.0 and greater than the ER for 20% RAP mixtures. It should be noted that all RAP mixtures evaluated not only met Superpave design criteria, but also dominant aggregate size range and the interstitial component (DASR-IC) requirements. Satisfactory inclusion of up to 40% RAP was for well-designed mixtures with good gradation characteristics and with the use of modified asphalt binders.

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EXECUTIVE SUMMARY

While RAP use in asphalt pavement has many economic and environmental benefits, its use has been limited both as to percentage added and to type of asphalt mixture. A review of the published literature revealed inconsistent conclusions regarding the effect of reclaimed asphalt pavement (RAP) components on blended hot mix asphalt (HMA) mixture performance, especially at high RAP content.

The primary objective of this research was to determine if FDOT's existing specification limits for the allowable amount of RAP material in asphalt concrete friction courses could be increased without jeopardizing pavement cracking performance. To achieve this objective, a laboratory experimental program was developed to characterize the effect of RAP content on dense-graded friction course, mixes designated as FC-12.5. Two FDOT-approved RAP stockpiles were selected; Atlantic Coast (ATL) RAP, which was a fine RAP, composed of mainly granite with medium aged RAP binder, and Whitehurst (WHI) RAP, which was a coarse RAP and composed of mainly limestone with heavily aged RAP binder. The effects of binder modification on RAP mixture properties were also investigated as only modified binders are allowed by the FDOT for use in surface friction courses. Assessment of the effects of RAP on performance were made at both the binder and mixture levels.

A reference mixture was selected and modified by additions of RAP to produce a series of test mixtures with increasing percentages of RAP. By changing virgin aggregate stockpiles, all RAP blends were designed and produced to have the same or as close as possible gradation to the reference mixture. As expected, the use of RAP reduced the need for virgin binder, and the reduction was more pronounced for fine gradation RAP than coarse gradation RAP. All mixtures met the Superpave volumetric criteria and dominant aggregate size range and interstitial component (DASR-IC) requirements, except the voids in mineral aggregate (VMA) of 40% ATL RAP mixture was slightly low (13.6% to 14% required).

Extracted and recovered RAP binder was manually blended with virgin binders at various RAP binder replacement ratios. Binder tests, including Superpave binder tests, multiple stress creep recovery (MSCR) test, and the binder fracture energy (BFE) test, were conducted on blended binder as well as virgin binders. As expected, the addition of RAP binder increased the stiffness of virgin binder. However, all blended binders met the FDOT specification for virgin modified binders. Both MSCR and BFE test results showed that even 40% RAP blend binder exhibited good elastomeric behavior. Binder test results indicated that use of up to 40% RAP was potentially acceptable.

Fracture properties from the Superpave IDT test at 10 ºC and the energy ratio (ER) parameter derived from HMA fracture mechanics (HMA-FM) model were used to evaluate the relative cracking performance of mixtures with various RAP contents. For both RAP sources evaluated, increased RAP content generally resulted in stronger (high tensile strength) but more brittle (lower failure strain and lower fracture energy density (FED)) mixtures. Coarser RAP generally resulted in higher FED (except at 40% RAP content where limestone aggregate weakness controlled FED) and a lower resilient modulus than finer RAP because the coarser RAP mixture required introduction of finer virgin aggregate and more virgin binder that controls these two properties. PG 76-22PMA resulted in lower rate of damage (creep compliance) but lower FED than PG 76-22ARB. PG 76-22PMA appears to result in a more integrated binder that better resists permanent deformation, whereas PG 76-22ARB was hypothesized to have more asphalt that is free to blend with RAP binder, which resulted in less brittle, higher FED mixture.

After long-term oven aging (LTOA) + cyclic pore pressure conditioning (CPPC) which simulates long-term field conditioning, all RAP mixtures still exhibited ER values well above 1.0, which is the minimum value proposed by the UF research group to ensure adequate cracking performance. For mixtures and RAP sources evaluated in this study, higher RAP content generally resulted in higher ER values. However, the increasing trend was reversed between 30% and 40% RAP content, but the ER at 40% RAP was still well above 1.0 and greater than ER for 20% RAP mixtures.

It should be emphasized that all RAP mixtures evaluated not only met Superpave design criteria but also DASR-IC requirements. Up to 40% RAP content, well-designed RAP mixtures with good gradation characteristics and mixed with modified asphalt binders exhibited satisfactory relative cracking performance.

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CHAPTER 1 INTRODUCTION

1.1 Background

As a result of the latest economic changes and the development of recycling technologies, there is a trend towards increasing the use of Reclaimed Asphalt Pavement (RAP) contents in asphalt mixtures, including those use in friction courses. The use of increased RAP contents not only reduces construction costs, but also preserves natural resources such as aggregate, binder and energy. The Florida Department of Transportation (FDOT) carried out its first RAP project in 1977, and started using RAP routinely in 1980s. Although RAP has been extensively used since then for structural layers, it was in 2009 when the FDOT relaxed its specifications to allow the use of up to 15% RAP in dense-graded friction courses. At present, the maximum amount of RAP that can be used in friction courses is limited to 20%.

The major concerns involved in the use of higher RAP contents in wearing courses are related to the quality of the combined binder and its performance during service life. The use of RAP as a raw material for asphalt mixtures involves the combination of an aged and a virgin binder. Previous studies performed by FDOT have shown that, although the asphalt content of RAP can vary as a function of the location, typical RAP material contains about 5.5% binder. Because modified binders are commonly used in surface layers, there is concern that increased RAP content may result in diminished properties of the combined binder as compared to the properties of the virgin modified binder. Kim et al. (2009) analyzed the effect of mixing aged asphalt from RAP with polymer-modified (SBS) virgin binder. The laboratory tests run on binders showed that both $G^*/\sin\delta$ (rutting parameter) and $G^*\cdot\sin\delta$ (cracking parameter) increased with increasing RAP content (0%, 15%, 25%, and 35% RAP). However, the RAP content seemed to have little effect on mixture performance based on the results obtained from asphalt pavement analyzer (APA) and Superpave indirect tension (IDT) tests.

FDOT has previously studied the long-term performance of pavement sections composed of a non-RAP friction course and a structural layer containing more than 30% RAP (Nash et al, 2011). Using the first year of a deficient crack rating as a performance criterion, lower number of loads application to failure with increasing RAP content were reported. However, the mixtures within the range analyzed (30-50% RAP) seemed to perform better than the mixtures without RAP.

Huang et al. (2011) have also studied the cracking performance of surface mixtures containing various RAP contents (0%, 10%, 20%, and 30% RAP). The results from Superpave IDT, beam fatigue, and semicircular bending (SCB) tests indicated that RAP generally increased stiffness and indirect tensile strength; however, it generally compromised the cracking resistance of the mixture, especially at 30% RAP content. These laboratory results were also validated by field-test sections after 4 years in service.

Regarding the friction resistance of mixtures containing RAP, the use of reclaimed material implies the incorporation of polished aggregate. Kowalski et al. (2010) state that about 30% of RAP can be used in friction courses without detrimental effect, even when the RAP contains a highly polishable aggregate. That threshold of 30% RAP based on friction performance is compatible with the minimum requirement of 60% granite rock established by FDOT for friction courses containing RAP.

In summary, there appears to be limited, and sometimes conflicting, scientific data regarding the use of higher RAP content, particularly in friction course mixtures that use modified binder. Therefore, there is a strong need to evaluate the effect of RAP content on the performance of friction courses, specifically to determine whether RAP material in friction courses can be increased above 20% without jeopardizing performance.

1.2 Objectives

The primary objective of this research was to determine if FDOT's existing specification limit in the allowable amount of RAP material in friction courses could be increased above 20% without jeopardizing pavement performance.

The detailed objectives of this project are summarized below:

1. Conduct a comprehensive literature review to gather and examine available information regarding current understanding of RAP material and issues associated with the use of RAP in asphalt mixtures, more specifically, surface friction courses.

2. Design and conduct laboratory experiments to assess characteristics of RAP blend binder and cracking performance of RAP mixtures. Findings were used to make determinations include:

    - % RAP at which binders no longer effectively behave as modified binders, significant reductions occur in binder fracture energy or other relevant binder properties relative to virgin binders.

    - % RAP at which significant reductions in fracture properties and energy ratio relative to mixtures without RAP.

3. Based on the binder and mixture testing results, evaluate the effects of experimental factors, i.e., RAP content, RAP characteristics and virgin binder type, on the cracking performance of RAP mixtures and determine the maximum allowable RAP content that can be used in surface friction course without jeopardizing performance.

1.3 Scope

One FC-12.5 mixture, commonly used as surface fraction courses in the state of Florida, was selected and modified to introduce various RAP contents. Two different RAP sources were utilized; Atlantic Coat RAP represented a normal scenario and the Whitehurst RAP represented an extreme scenario in the state of Florida. PG 76-22PMA and PG 76-22ARB were selected since both binders are allowed for use in surface friction courses. Assessment of the effects of RAP on mixture performance were made at both the binder and mixture levels.

Superpave binder test methodologies were employed to obtain the conventional properties from virgin and RAP blended binders. In addition, both multiple stress creep recovery (MSCR) and binder fracture energy (BFE) tests were used to qualitatively assess whether blended binders composed of virgin and RAP binder were effectively behaving as polymer-modified, rubber-modified, or unmodified binder. Particular emphasis were placed on the BFE test for evaluation of effects of RAP on relative cracking performance.

The Superpave IDT testing conditions were limited to one testing temperature (10 °C) and the mixtures were subjected to two different conditioning levels: short-term oven aging (STOA) and long-term oven aging (LTOA) followed by cyclic pore pressure conditioning (CPPC). Relative cracking performance of RAP mixtures were evaluated by using fracture properties from Superpave IDT test and the energy ratio (ER) parameter derived from the hot-mix-asphalt mixture mechanics (HMA-FM) model. Effects of RAP on thermal-induced cracking was not include in this study as it is less concerned in the state of Florida.

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 focusing on current understanding of RAP material and issues associated with the use of RAP in asphalt mixture. One emphasis was to identify threshold levels of RAP and/or trends in RAP percentage that may help to define the percentages of RAP to be assessed in the experimental portion of the study. Whether or not the effect of RAP percentage on performance has been different for modified asphalt mixes than for mixtures using conventional binder was also of great interest. Findings from the literature review were used to help finalize the laboratory test plan, including specific percentages of RAP to be evaluated.

Task 2 – Experimental Testing Plan: Findings from the literature review were used to finalize a full testing plan to best accomplish takes 3 and 4. The general factors involved in the testing plan are shown in Figure 1-1. Assessment of the effects of RAP on performance was made at both the binder and mixture levels.

Task 3 – Binder Evaluation: A total of 14 different binders composted of two virgin binders and two RAP binders at four proportions were evaluated. RAP binders were extracted and recovered in bulk using the solvent method. The percentage of RAP binder blended with virgin binders, named binder replacement ratio, was different from the percentage of RAP in mixtures, as it was calculated as the percentage of RAP binder divided by the mixture’s total binder content. Prior to any binder test, mixture designs were finalized and verified as all mixtures had to meet not only the Superpave criteria but also the DASR-IC requirements. Determination of asphalt content for each percentage of RAP was based on results of Superpave Gyratory compaction of mixture produced with the combined virgin and RAP aggregate using PG 76-22PMA binder.

The Superpave binder testing methodologies were conducted to assess changes induced by the RAP binder in more conventional properties from which relative cracking performance might be deduced. In addition, both multiple stress creep recovery (MSCR) test and binder fracture energy (BFE) test were used to qualitatively assess whether blended binder composed of virgin and RAP binder were effectively behaving as polymer-modified, rubber-modified, or unmodified binder.

Task 4 – Mixture Evaluation: Relative cracking performance were evaluated for 14 mixtures (1 mixture gradation, 2 RAP sources, 2 virgin binder types, 4 RAP percentages) by using fracture properties from Superpave IDT test at 10 °C and the energy ratio (ER) parameter derived from the hot-mix-asphalt mixture mechanics (HMA-FM) model. Mixtures were tested in both unconditioned (STOA only) and conditioned states. The conditioned state corresponded to the new conditioning procedure developed as part of a recently completed FDOT research effort (Roque et al, 2013), which involves heat oxidation conditioning (HOC: STOA followed by LTOA) followed by cyclic pore pressure conditioning (CPPC).

Task 5 – Findings and Conclusions: All binder and mixture test results were thoroughly evaluated for consistency and to determine the maximum percentage of RAP that can be used in friction courses without jeopardizing pavement performance.

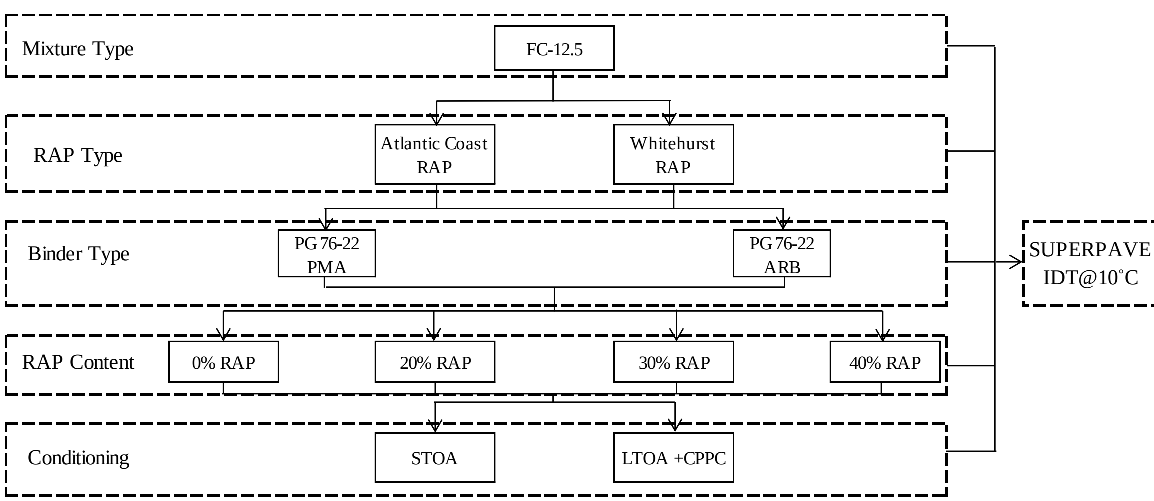

Figure 1-1 Flowchart for the experimental testing plan

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

Reclaimed Asphalt Pavement (RAP) material is generated when damaged pavement is milled, crushed, sometimes fractionated, and stockpiled for use as an additional component in asphalt mixture. The high cost and limited availability of asphalt binder caused by the 1973 oil embargo spurred the wide use of RAP in the United States. Other factors that may lead to increased RAP use are the increasing need to rehabilitate and reconstruct aging pavement infrastructure, environmental considerations, and depletion of natural resources.

In 2007, the Federal Highway Administration (FHWA) created the RAP Expert Task Group (ETG) to advance the use of recycled materials. In cooperation with the American Association of State Highway and Transportation Officials (AASHTO), the RAP ETG conducts a survey every 2 years. In general, the survey, which garners good results from most states, seeks information such as how much RAP is permitted in mixtures by State DOTs and how much RAP contractors actually use in mixtures. Although RAP use varies considerably, the average RAP content was estimated to be around 12% in 2007 (Jones, 2009). The most recent survey (Pappas, 2011) indicated little change in RAP use specified by state DOTs, while contractors did report a significant increase in mixtures using 20-30% RAP with no change in mixtures containing other percentages of RAP. A survey conducted by the National Asphalt Pavement Association (NAPA) indicated that the amount of RAP used in HMA/warm mix asphalt (WMA) increased from 56 million tons to 62.1 million tons between 2009 and 2010. Assuming 5% liquid asphalt in RAP, the 10% increase in RAP use represents over 3 million tons of asphalt binder conserved (Hansen and Newcomb, 2011).

In the late 1980s, the Asphalt Institute developed a viscosity blending chart for the selection of virgin asphalt binders and recycling agents for projects incorporating RAP in HMA design. Many states used this approach to establish their own maximum RAP percentage of RAP, ranging typically from 10-50%. In 1993, Superpave was introduced as part of the Strategic Highway Research Program (SHRP). The original Superpave design procedure did not include guidance on how to incorporate RAP into the new mix design system. However, economic and environmental benefits have made the incorporation of RAP content into Superpave mixtures desirable.

In 1997, a subgroup of the FHWA Asphalt Mixture ETG developed interim guidelines for inclusion of RAP into Superpave mixture design procedures based on the experience and performance of Marshall Mixes with RAP content (Bukowski, 1997). A three-tiered approach for RAP usage was established. When RAP use is less than 15%, the virgin asphalt binder grade can remain unchanged. Virgin asphalt binder should be reduced by one grade (6˚ increment) on both the low and high temperature grades when the additional RAP is 15-25%. Superpave blending charts should be used to determine the grade of virgin asphalt binder for RAP content greater than 25%. The Superpave blending chart determines the temperature values required for the recycled binder to have a specified viscosity (stiffness), as opposed to the conventional viscosity-blending chart, which determines recycled asphalt binder viscosity at a specified temperature.

Kandhal and Foo (1997) confirmed the viability of the three-tier system, but found that the intermediate temperature sweep chart, G*/sinδ, overestimated the maximum amount of RAP, as compared to field mixes using recycled HMA. The researchers also recommended using a specific-grade blending chart that only relied on the G*/sinδ value of both the aged asphalt binder and the virgin asphalt binder at high pavement service temperatures, rather than formulating six Superpave blending charts at high, intermediate, and low temperatures (Table 2-1).

Table 2-1 High, Intermediate, and Low Temperature Definition (Kandhal and Foo, 1997)

Temperature	Number of Tests	Definition
High	2	The lower temperature value of a) temperature at which G*/sinδ of unaged binder = 1.0 kPa b) temperature at which G*/sinδ of RTFO residue = 2.2 kPa
Intermediate	1	Temperature at which G*sinδ of RTFO+PAV residue = 5 MPa
Low	3	The higher temperature value of a) temperature at which S = 300 MPa and m >0.300 a) temperature at which S <300 MPa and m = 0.300 or if 300 MPa <S <600 MPa and m ≥0.300 c) temperature at which failure strain = 1˚/0

In the National Cooperative Highway Research Program (NCHRP) Project 9-12 entitled *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*, McDaniel and Anderson (2011) confirmed the benefits of applying a tiered approach to RAP use, supported the use of blending charts, and proposed a modified tiered approach. The new three-tiered system (Table 2-2) allows a maximum of 20% RAP without changing the binder selection, considering that even hardened RAP binder would not change total binder properties when introduced at levels of 20% or lower. For intermediate ranges of 20-30%, the virgin binder grade can simply be lowered one grade. For mixes using more than 30% RAP, a blending chart is recommended in order to adjust the binder grade accordingly.

There are five commonly used asphalt recycling methods, including hot in-place recycling, cold mix recycling, cold in-place recycling, full depth reclamation, and hot mix recycling (Santucci. L, 2007), the latter being the most common. In this method, RAP content, virgin aggregate, asphalt binder, and/or recycling agents are blended in a central mix plant to produce a recycled mix. Recycling agents are normally used to help soften aged RAP binder and restore the physical and chemical properties of the old binder. This research project focuses on the hot mix recycling approach.

Table 2-2 Binder Selection Guidelines for RAP Mixture (McDaniel and Anderson, 2001)

Recommended Virgin Asphalt Binder Grade	RAP percentage		
	Recovered RAP Grade		
	PG xx-22 or lower	PG xx-16	PG xx-10 or higher
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., PG 58-28 if normally using PG 64-22)	20-30%	15-25%	10-15%
Follow recommendations from blending charts	>30%	>25%	>15%

2.2 Reclaimed Asphalt Pavement (RAP) Characteristics

Although high RAP content has been used for intermediate and base layers, use as the major load-carrying surface layer of asphalt pavements is relatively low (Jones, 2009, Pappas, 2011 and Hansen and Newcomb, 2001). The two main concerns related to RAP use in surface mixes are the potential of RAP on friction resistance and the possibility that a high percentage of RAP or aged RAP could over-stiffen the surface course, making the surface more susceptible to cracking or raveling.

2.2.1 RAP Aggregate Properties

The current AASHTO Standards depict the same requirements for mixtures with and without RAP content in order to ensure performance. RAP aggregate should be considered when determining the mixture gradation and consensus properties, except for sand equivalent value, which is waived for its instability in tests (Shah et al, 2007).

Watson et al. (2008) evaluated the use of RAP in stone matrix asphalt (SMA) mixtures, which was first used in Europe in 1990. The study recommends stringent requirements for aggregate selection since SMA requires higher cubical aggregate content than conventional mixtures to offset potential degradation due to stone-on-stone contact. The researchers obtained RAP aggregate by removing asphalt coating from RAP particles. The physical properties of SMA were evaluated by blending up to 30% RAP aggregate with virgin aggregate and measuring Los Angeles abrasion loss as well as percent flat and elongated particles. In an analysis of variance to study the effects of RAP aggregate content, RAP types and virgin aggregate sources on physical performance of RAP mixtures, the virgin aggregate sources was found to be the significant factor (p-value less than 0.001). The researchers concluded that RAP aggregate could, in fact, contribute to the physical properties of a blend since some irregular edges may have already broken off during initial manufacturing and the initial pavement life.

2.2.2 RAP Binder Properties

2.2.2.1 Blending Ratio of RAP Binder and Virgin Asphalt Binder

Previous research has shown that the structural performance of well-designed asphalt mixtures containing RAP is generally similar to that of the conventional virgin asphalt mixtures (Li et al, 2008). The properties of mixtures containing RAP are influenced mainly by aged RAP binder properties and the amount of RAP in the mixture. Field practice assumes that complete blending occurs between the RAP binder and the virgin binder. However, this assumption may not be accurate, as it is unlikely that a certain amount of binder absorbed by RAP aggregate will be released into the virgin asphalt binder and reabsorbed by RAP aggregate and virgin aggregate (Al-Qadi et al, 2009).

The amount of virgin asphalt binder can be reduced by the full amount of aged RAP binder when a low percentage of RAP is used; however, if the RAP percentage or aged is too great, the particles may act like black rock in which case the RAP binder will not combine with the virgin binder to any appreciable extent, leading to erroneous results. In the NCHRP 9-12 project, McDaniel and Anderson (2001) simulated three possible RAP mixture production scenarios, namely “black rock (no blending), total blending (100% blending) and actual practice (blending as it usually occurs in practice). The overall gradation and total asphalt binder content in three cases were kept constant. Three different RAPs, two different virgin binders and two RAP contents (10 and 40%) were investigated in this study. Produced mixtures were compared using Superpave performance parameters obtained from the Frequency Sweep (FS) test, the Simple Shear (SS) test, and the Repeated Shear at Constant Height (RSCH) test, as well as the Indirect Tensile Creep (ITC) and Strength (ITS) tests for HMA performance evaluation at low temperature. Results indicated that, although a 10% variance of RAP caused no significant difference between the three scenarios, the black rock case was significantly different from the other two cases at 40% RAP content. The study also found that only 42% of all comparisons indicated similar scenarios in the performance parameters in total blending and actual practice cases, which may suggest that total blending does not happen in every scenario.

Today, it is understood that the amount of blending occurring between the RAP binder and the virgin asphalt binder lies between complete blending and no blending (Al-Qadi et al, 2009). However, there is currently no direct method available to accurately determine the amount of blending that occurs. Also unclear are the ways in which RAP binder is blended with virgin asphalt binder and the extent to which blending affects final mixture properties and performance.

Huang et al. (2005) conducted a coating study to determine how much RAP binder would be active when blended with virgin aggregate. A No. 4 sieve was used to screen RAP particles while virgin coarse material larger than No. 4 was mechanically blended (without virgin asphalt binder), allowing the RAP and virgin aggregate to be distinguished visually. National Center of Asphalt Technology (NCAT) oven ignition tests were performed on coarse virgin aggregate and fine RAP aggregate to obtain the corresponding asphalt contents (Figure 2-1).

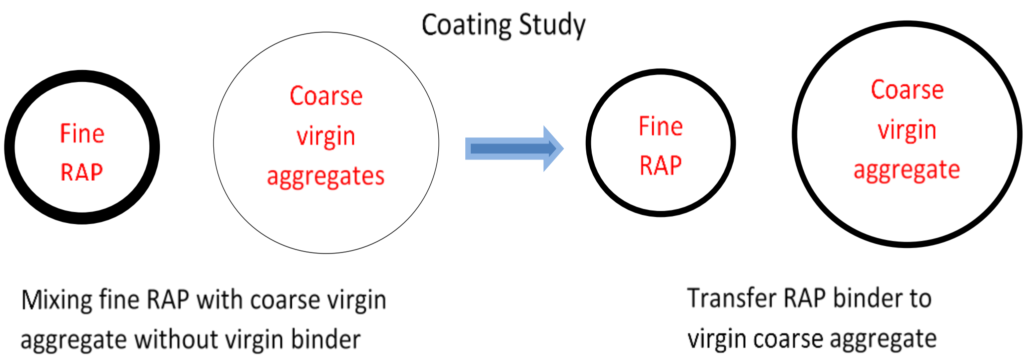

Figure 2-1 Schematic representation of procedure of coating study (Huang et al, 2005)

Regardless of RAP proportion (10-30%), the asphalt content of RAP particles decreased from 6.8% to 6.0% after mixing, which indicates that 11% of RAP binder shifted to virgin aggregate. Huang et al. (12) concluded that RAP binder tends to stick with RAP aggregate, making only a small portion (11% in this study) available to blend with virgin aggregate. It should be noted that the mixing time is longer and the mixing temperature is higher in this study than what is recommended in the AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design*, therefore, 11% is unlikely in a real-world scenario.

In addition to the coating study, Huang et al. (2005) attempted to determine how much virgin asphalt binder was cut into RAP aggregate by performing staged extraction and recovery tests on RAP blended mixtures. Both RAP aggregate and virgin aggregate were limestone, and PG 64-22 was used as virgin asphalt binder. Binder rheological tests, including the rotational viscometer test and the dynamic shear rheometer test, were performed to characterize the rheological properties of recovered asphalt binder at mixing (high) temperatures and service (high and intermediate) temperatures. The asphalt viscosity around the RAP aggregate increased at both temperatures when the sample was moved from outside to inside. Around 60% of the inner portion of the binder (nearest the RAP aggregate) had asphalt properties close to pure RAP binder, which indicates that a large portion of aged RAP binder may form a stiff layer which coats RAP aggregate rather than blending with virgin asphalt.

Research by Shirodkal et al. (2011) found that the coating study may have underestimated the amount of RAP binder that blends with virgin aggregate, as some RAP working binder also coated RAP aggregates and was not included in the calculations. However, it should be noted that the blending that occurred in the coating study was less than the 100% usually assumed in similar studies. The researchers took a further step to determine the degree of partial blending. Virgin binder was blended with coarse virgin aggregate and fine RAP (Figure 2-2).

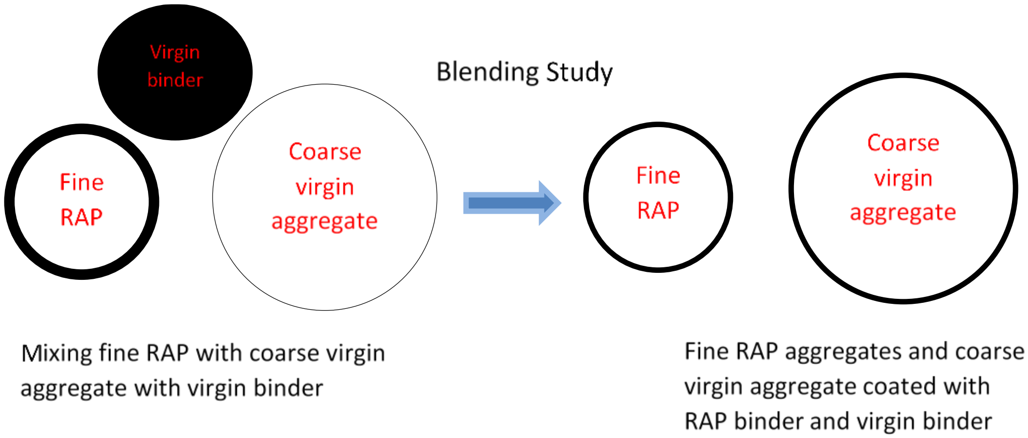

Figure 2-2 Schematic representation of procedure of blending study (Shirodkar et al, 2011)

After mixing, the blended binder coating the RAP and virgin aggregate was extracted and recovered separately for binder rheological tests. The theory was that full blending would cause the properties of recovered RAP aggregate binder and recovered virgin aggregate binder to be similar or the same. In partial blending cases, the difference between the measured properties of recovered RAP aggregate binder and recovered virgin aggregate binder should increase as the respective blending ratios decrease. In zero blending cases, the properties of recovered virgin aggregate binder should be the same as virgin binder properties, and the properties of recovered RAP aggregate binder should be the same as a blend of RAP binder and the corresponding proportion of virgin binder coating RAP particles. The proportion of RAP binder and virgin binder around the RAP aggregate under a zero blending condition was calculated by determining film thickness of RAP binder and virgin binder following the Bailey method. An equation was proposed to calculate the blending ratio and the corresponding degree of partial blending (Equations 1 and 2). The Superpave PG property measured and evaluated in this study was RTFO G*/sin(δ), and the degree of partial blending measured for 25% RAP by weight of aggregates with PG 70-28 and 35% RAP by weight of aggregates with PG 58-28 were 70% and 96%, respectively.

Equation 1:

$$Blending\ ratio = \frac{\left| \left(\frac{G^*}{\sin(\delta)}\right)_{blend\ binder\ virgin\ agg} - \left(\frac{G^*}{\sin(\delta)}\right)_{blend\ binder\ RAP\ agg} \right|}{\left| \left(\frac{G^*}{\sin(\delta)}\right)_{virgin\ binder} - \left(\frac{G^*}{\sin(\delta)}\right)_{RAP\ virgin\ binder\ zero\ blend} \right|} \qquad (1)$$

Where:

$(G^*/\sin(\delta))_{\text{blend binder virgin agg}}$ Rolling Thin-Film Oven (RTFO) G*/sin(δ) of blended binder coating the coarse virgin aggregate,

$(G^*/\sin(\delta))_{\text{blend binder RAP agg}}$ RTFO G*/sin(δ) of blended binder coating the fine RAP aggregate,

$(G^*/\sin(\delta))_{\text{virgin binder}}$ RTFO G*/sin(δ) of virgin binder, and

$(G^*/\sin(\delta))_{\text{RAP virgin binder 0 blend}}$ RTFO G*/sin(δ) of RAP and virgin binder that coated RAP aggregate assuming 0% blending

Equation 2:

$$Degree\ of\ partial\ blending\ (\%) = 100|1 - blending\ ratio| \quad (2)$$

2.2.2.2 Stiffness of Blended Asphalt Binder

In general, asphalt binder ages in two stages: short-term during construction and long-term during service. Short-term aging occurs when asphalt binder is exposed to hot air at high construction temperatures which alter the asphalt binder viscosity significantly, as well as rheological and physiochemical properties such as complex shear modulus and adhesion. Long-term aging and hardening occurs progressively throughout the service life of asphalt binder due to oxidation, volatilization, polymerization, thixotropy, syneresis, and separation (Roberts et al, 1996). As a result of aging, RAP binder is generally harder and stiffer than virgin binder, except for RAP that has been removed from a new road that failed to meet construction specifications. Kemp and Predoehl (1981) found that HMA air void content also significantly affects the level of aging, as recovered binder from porous HMA is much stiffer than regular HMA.

While RAP mixture stiffness can be affected by the aggregate and gradation, the most important factor is the recycled binder stiffness. When RAP is added to a mix, aged binder is incorporated as well. As RAP content increases, the proportion of aged binder also increases, causing the resulting asphalt blend to be stiffer (Watson et al, 2008).

Research by Mohammad et al. (2003) found the Superpave binder-rutting factor of $G^*/\sin(\delta)$ to be fairly sensitive to the mixture performance properties of asphalt mixtures containing recycled polymer-modified asphalt cement. An eight-year-old polymer-modified asphalt binder was recovered from a wearing course mixture and blended proportionally with virgin aggregate and virgin styrene-butadiene-styrene (SBS) polymer-modified binder to form a 19 mm Superpave mixture for rutting resistance tests. As expected, there was a good correlation between binder $G^*/\sin(\delta)$ values and asphalt pavement analyzer (APA) mixture rutting depth. There was also a strong relationship between indirect tensile (IDT) creep test slopes and permanent shear strain from the repeated shear at constant height tests. Similarly, increasing high-temperature binder stiffness leads to increased blended mixture rutting resistance. Both the indirect tensile creep test and APA test identified a threshold value of 20% aged SBS polymer-modified binder in mixtures. The rutting potential increased as the aged binder increased from 0% to 20% and then decreased gradually as the aged binder increased from 20% to 60% in mixtures.

Watson et al. (2008) concluded that performance properties may show increased sensitivity to RAP content at high temperatures. Dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests were conducted to evaluate the rheological properties and performance grade of recovered binder from both RAP materials and samples of the proposed blends. A 10% RAP use showed negligible effects on performance grade, and adding up to 30% RAP had little effect on low-temperature performance grade properties. Aged-to-virgin binder ratio was evaluated through this study to explain the different effects of fine- and coarse-graded RAP on recycled mix performance.

Kim et al. (2009) evaluated the rheological properties of binder by combining recovered RAP binder with virgin SBS polymer-modified binder. Rotational viscosity tests were performed before the (RTFO) and Pressurized Aging Vessel (PAV) tests. Though pure RAP binder has the largest rotational viscosity value and pure SBS-modified binder has the smallest value, little difference was observed between blended binders containing 15%, 25%, and 35% recovered RAP binder. The Superpave rutting parameter G*/sin (δ) and cracking parameter G*sin (δ) values obtained from DSR tests increase as RAP content increases, which indicates the presence of RAP binder in these mixtures. Results from Multiple Stress Creep Recovery (MSCR) tests show that the maximum strain decreases with increased RAP contents, indicating an increase in stiffness.

West et al. (2009) concluded that the use of RAP caused an increase in blended mix stiffness, which impacts field compatibility. By monitoring density changes at a single point in the sections after each paver and roller pass, it was found that mixtures with 20% RAP were more easily compacted than mixtures with 45% RAP. Among four mixes with 45% RAP, two sections which were blended with softer binder required less compaction effort than mixtures with polymer-modified binder.

2.3 Volumetric Properties of RAP Mixtures

2.3.1 Gradation of RAP Mixtures

In order for design mixes containing RAP to have acceptable volumetric properties, the common practice is to account for RAP by adjusting the virgin aggregate gradation to meet final blend gradation specifications (Gardiner and Wagner, 2007). However, finer RAP aggregate gradation presents challenges, as the nature of milling, ripping, and crushing, tends to break the coarse material into fine material. It is unclear how much binder and fine aggregate are released by RAP particles throughout the remixing process, making a true determination of RAP aggregate gradation difficult.

Gardiner and Wagner (2007) suggested that RAP be split into a coarse and fine fraction in order to meet the Superpave mix design requirements when incorporating high percentages of RAP. In that study, coarse RAP fraction was used in a 12.5 mm (below the restricted zone) Superpave gradation. The researchers selected two sources of RAP (Georgia and Minnesota) and two 12.5 mm Superpave gradations (one below and one above the restrict zone). Up to 40% coarse RAP fraction was found to satisfy the below-the-restricted-zone Superpave gradation requirements, mainly due to reduction in the finer aggregate fractions, especially the -0.075 mm (No. 200) material. Meanwhile, a maximum of 15% fine RAP fraction was used to produce an acceptable above-the-restrict-zone Superpave gradation.

In general, there are two types of RAP aggregate gradation. Black curves are the gradation of RAP particles obtained from fractioned RAP and white curves are the gradation of recovered RAP aggregate after binder extraction. It should be noted that the two gradations may differ significantly (Figure 2-3). By comparing the gradation of fractioned RAP particles and recovered RAP aggregate, Al-Qadi et al. (2009) found that fractioned RAP particles tend to have higher amounts of large particles and lower amounts of fine particles. Some fine materials may not be released from the large RAP particles during the mechanical mixing process, causing the difference between the two gradations (Figure 2-4). To avoid the detrimental effects caused by unexpected extra fine particles, black curves are not suggested for use in job mix formula calculations.

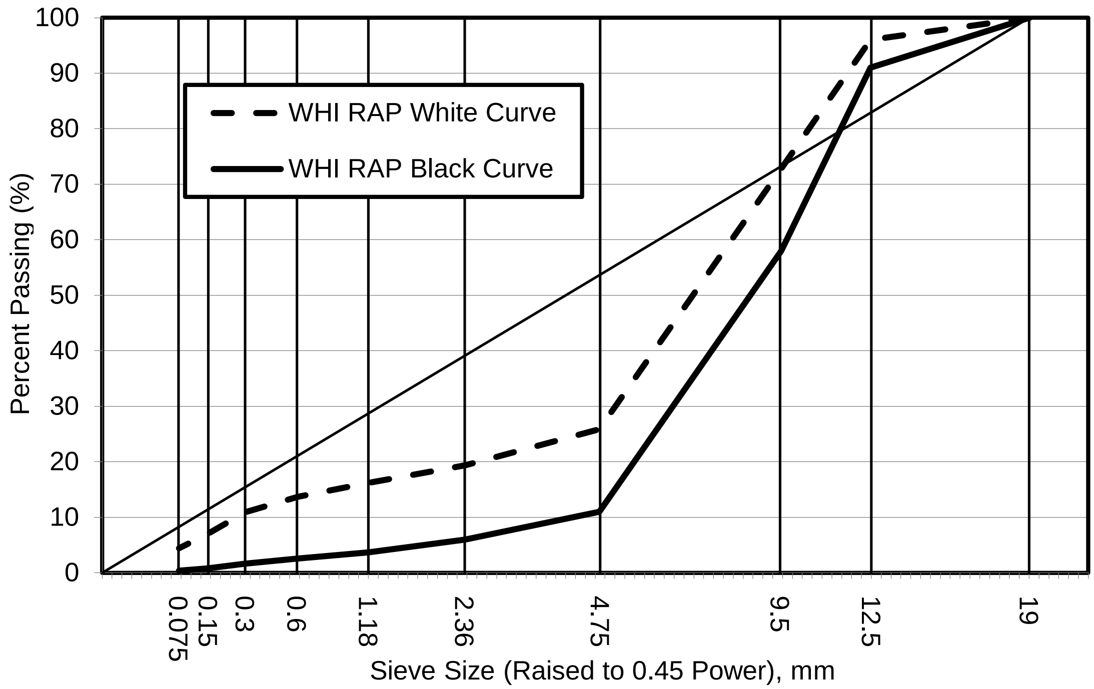

Figure 2-3: Black curve and white curve of Whitehurst (WHI) RAP

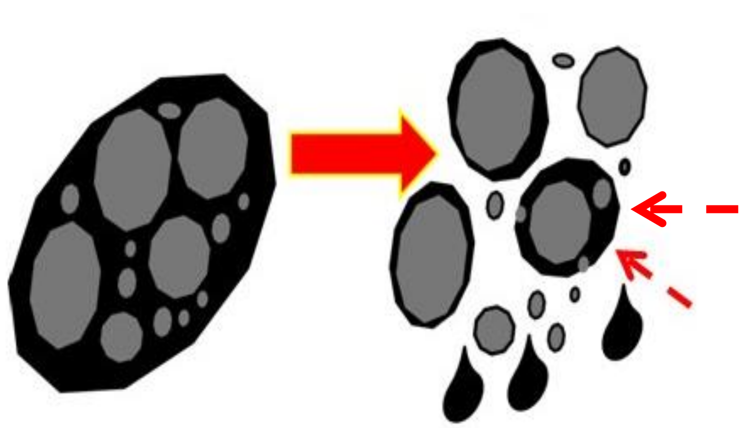

Figure 2-4: Breakup of RAP large size particles

It is common practice to use a white curve when performing mix design with RAP, in which case, full blending of RAP binder and virgin asphalt binder is assumed. However, in a plant, a coarser aggregate gradation can be obtained when white curve is used. During the mixing process, not only some fine particles may fail to be released, also some aged binder may not fully melt but coat the RAP aggregate forming a “shell” which has high viscosity and acts together with the RAP aggregate like a black rock (Figure 2-5).

It should be noted that neither black curve nor white curve represents the actual gradation of the RAP material that resulted from the mixing process, and the real gradation lies somewhere between them.

Figure 2-5: Some aged binder failed to be released from RAP particles

2.3.2 Voids in Mineral Aggregate (VMA)

Tran and Hssan (2011) indicated that VMA decreases with increased RAP content. In this study, four mixes containing 0%, 10%, 20%, and 30% RAP were designed to have similar blending gradation and acceptable film index. Cylindrical samples were prepared by using a gyratory compactor at 120 cycles. VMA decreased from 16.3% to 14.2% as RAP content increased from 0% to 30%. Reduced design binder content and an increase in the amount of material passing through a No. 200 (0.075 mm) sieve may explain the decrease in VMA. In addition, there is a reduction in binder absorption when higher binder viscosity is reached, which may lead to decreased VMA. West et al. (2009) demonstrated similar results (i.e., decreased VMA with increased RAP).

Other researchers achieved contrary results. Al-Qadi et al. (2009) investigated the effect of RAP on the volumetric and mechanical properties of HMA. In that study, six job mix formulas (JMF) were designed with three sources of RAP at 0%, 20%, and 40%. For two RAP sources, an increased RAP content resulted opposite VMA trends. Daniel and Lachance (2005) reported increased VMA of mixtures with 25% and 40% RAP content. The researchers attributed this increase to the blending of the RAP material with the virgin materials and the pre-heating time for RAP material. In order to achieve the greatest extent of blending between RAP binder and virgin binder, it is essential to preheat RAP in an oven for two hours before mixing, a process that simulates plant operations. If not heated sufficiently, RAP particles tend to act like black rock rather than breaking down and blending with virgin materials. Insufficient heating also may result in coarser gradation, as RAP particles have coarser gradation than RAP aggregates. Conversely, if RAP is overheated, the RAP binder may age more quickly, allowing fewer

RAP particles to break down and blend with virgin material. In this study, VMA was found to decrease by 0.5% when the heating time increased from 2 to 3.5 hours, and then increased by almost 3% with a heating time of 8 hours.

2.4 Performance of RAP Mixtures

The aim of designing HMA containing RAP is to optimize RAP content and achieve a mix with good performance in rutting, fatigue, thermal resistance, and overall durability, in addition to meeting stability and compatibility requirements. In general, related literature indicates that the stiffness and rutting resistance of a mix at high temperatures increases with increased RAP content; however, increased stiffness and brittleness at intermediate and low service temperatures may result in reduced resistance to fatigue and low-temperature cracking.

2.4.1 Surface Friction Properties

The results of a 2009 survey indicate that average RAP use in base and intermediate mixes is higher than use in surface mixes. One concern related to RAP use in surface mixes is its potential effects on friction. To obtain good friction performance in regions deficient in non-polishing aggregates, RAP is not commonly recommended in mainline surface courses for high volume roadways.

Kowalski et al. (2010) concluded that, in order to maintain good frictional properties, the amount of RAP added to surface mixes should not exceed 30%. In this study, field RAP samples were collected and NCAT oven ignition tests were performed to determine binder content and aggregate gradation. A mix using highly polishable coarse limestone was produced and aged in the laboratory to simulate a worst-case scenario RAP. Materials commonly used for dense-graded asphalt and stone asphalt matrix mixes for Indiana high volume roads were selected and mixed with various contents of laboratory produced RAP. Before and during the polishing process, the texture and friction of the compacted specimens were measured to calculate an International Friction Index and to evaluate the frictional resistance of the mixes.

2.4.2 Resistance to Rutting

By performing HMA dynamic modulus tests on gyratory compacted specimens prepared at target 4% air voids, Al-Qadi et al. (2009) found that increased RAP content caused a mixture to have increased dynamic modulus and a decreased phase angle. The same trend was observed by Swamy et al. (2011). The effect of RAP binder on the dynamic modulus of a mix is more pronounced at high temperatures (low frequency) and high RAP percentage. The effects of 20% RAP on the dynamic modulus of a mix were considered insignificant. Li et al. (10) reported that mixtures with high RAP percentages tend to have higher dynamic modulus under low frequency or high temperature testing conditions. Comparing -20˚C to -10˚C, the dynamic modulus data showed higher variability, which could be explained by the significant effects of machine compliance, electronic noise in the sensors, and non-uniform contact of the loading platens causing stress distribution changes at low temperatures.

Many researchers have conducted APA rutting tests to evaluate how RAP contents affect the rutting potential of a blended mix (Watson, 2008, Kim, 2009, West, 2009, and Drakos, 2005). West et al. (2009) evaluated the rutting potential of surface mixes with no RAP (control mix), 20% RAP, and 45% RAP after three years of traffic. Field cores were collected and APA rutting tests were performed. For mixes blended with the same grade of virgin binder (PG 67-22), the increases in RAP content caused significant decreases in rutting depth. All specimens with 45% RAP showed rutting depths of less than 6 mm while four out of the six control specimens showed rutting depths larger than 10 mm. It was also observed that softer binders reduce the rutting resistance of blended mixes.

In 2007, the Virginia Department of Transportation began permitting the use of surface mixtures with higher than 20% RAP content without requiring binder grade adjustment. Maupin et al. (2009) found no significant difference between higher RAP mixes (more than 20%) and control mixes (less than 20%) for rutting potential. The results of rut tests performed on beams using APA showed averages of 3.5 mm and 3.6 mm for higher RAP mixes and the control mixes, respectively. As expected, 12.5 mm mixes had less rutting depth than 9.5 mm mixes with the same amount of RAP, and mixes blended with PG 70-22 virgin binder showed higher rutting resistance than mixes with PG 64-22.

Kim et al. (2009) evaluated the rutting performance of SBS polymer-modified binder with RAP added. Four different percentages of RAP materials (0%, 15%, 25%, and 35%) were blended with virgin limestone and virgin SBS polymer-modified binder to form same-gradation mixes. The average rutting depth for all mixtures was approximately 2 mm, indicating sufficient rutting resistance. No significant difference was identified between mixtures blended with different proportions of RAP.

In addition to conventional consolidation rutting, instability rutting, which only exists in the surface layer, can also occur under the traffic wheel path. Drakos et al. (2005) reported that traditional APA test measures may not be sensitive to instability rutting resistance of a mixture. The pressurized loading hose of a specimen is generally considered a line load, as the loading area is very narrow. This loading area fails to introduce sufficient shear stress, which may be the main cause for instability rutting (Darkos et al, 2005). By comparing the rut depths of three asphalt mixtures obtained from APA results to the rutting performance measured with a heavy vehicle simulator, Sholar (2010) found that APA tests failed to yield comparable results.

2.4.3 Resistance to Fatigue Cracking

Though aged binder from RAP materials increases the rutting resistance of blended mixtures at high temperature, it also causes an increase in stiffness and brittleness at intermediate and low service temperatures, resulting in reduced resistance to fatigue and low temperature cracking (Li et al, 2008).

Watson et al. (2008) conducted beam fatigue tests to evaluate the stiffening effect of RAP on mixtures and its impact on the long-term fatigue resistance of the pavement.

Following the AASHTO T321 standards, the fatigue tests were performed under a constant-strain condition, at strain levels of 400με and 800με and at a temperature of 20˚C. The results indicated that, in general, fewer cycles were needed to fail specimens as RAP content increased. Up to 20% RAP had negligible effects on fatigue life, whereas specimens with 30% RAP had approximately half the fatigue life of control samples without RAP.

West et al. (2009) used high-strain laboratory fatigue tests to compare the fatigue resistance of mixtures blended with 0%, 25%, and 45% RAP. The fatigue life of specimens tended to decrease when RAP content increased in the blended mixes. An Analysis of variance test indicated that significant differences exist in the fatigue lives of mixtures blended with 0%, 25%, and 45% RAP. A Tukey pairwise comparison analysis indicated that 45% RAP mixtures required significantly fewer cycles to fail the beam fatigue test than the control mix and the 25% RAP mix. However, no significant difference between 45% RAP mixtures blended with different grade virgin binder was identified, suggesting that binder stiffness may be less important than effective binder volume.

Maupin et al. (2009) used beam fatigue tests at high, low, and intermediate strain levels to compare the fatigue performance of mixes containing less than 20% RAP with mixes containing 21-30% RAP. The researchers used the endurance limit concept, defined as the strain at which the specimen could endure an infinite number of load cycles. An average failure strain level of 50 million cycles was projected based on test results. The endurance limit in this study was estimated from the 95% one-sided lower prediction confidence limit of a 50 million cycle fatigue life (Figure 2-6). At each strain level, at least nine specimens were prepared for fatigue beam tests, and a 95% confidence limit t-test identified no significant difference between the average endurance limits of 104ϵμ for high-RAP mixes (21-30%) and 121ϵμ for control mixes (less than 20%).

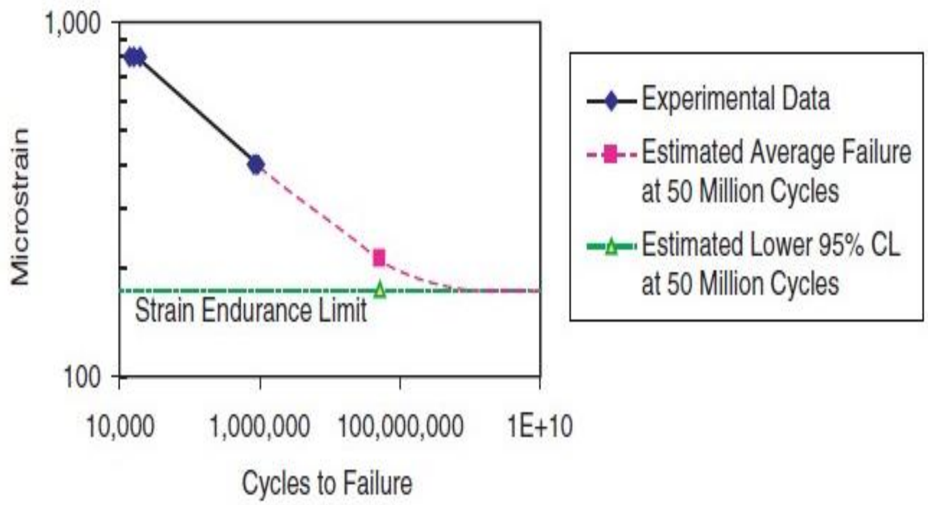

Figure 2-6: Example of estimated endurance limit (CL=confidence limit) (Maupin et al, 2009)

Huang et al. (2011) evaluated the cracking resistance of HMA surface mixture blended with 0%, 10%, 20%, and 30% RAP content screened with a No. 4 sieve. The study included limestone, gravel, and three types of virgin asphalt binder (PG 64-22, PG 70-22, and PG 76-22). The cracking resistance of mixtures was evaluated through beam fatigue, Superpave indirect tension, and semicircular bending tests. The traditional loading-cycles-to-failure results obtained from fatigue beam tests suggested that RAP content increases the fatigue resistance of HMA mixtures, especially for mixtures blended with PG 64-22 virgin asphalt binder. However, when using the ratio of dissipated energy change approach and based on fatigue beam testing data, increased RAP content appears to result in higher plateau values, which suggests a decreased fatigue resistance in blended mixtures. The latter conclusion was confirmed by the results of indirect tensile (IDT) tests, which indicated that increased RAP content decreased fracture energy and dissipated creep strain energy at failure ($DCSE_f$) of specimens. Semicircular Bending (SCB) test results indicated that the addition of RAP increased the tensile strength, but significantly decreased the strain at peak load and toughness indices, especially when RAP contents are 20% and 30%. It should be noted that the reduction in cracking resistance is more significant for mixtures blended with conventional PG 64-22 virgin asphalt binder than for mixtures blended with SBS polymer-modified asphalt binder. The laboratory study was roughly validated from field observation, which found that, after four years of service, pavement sections with 30% RAP had slightly more cracking than mixes with less or no RAP.

Kim et al. (2012) compared the cracking performance of both WM mixtures and conventional HMA mixtures by using intermediate temperature fracture resistance. Tensile strength and strain were computed based on IDT strength tests and the toughness index (TI). The TI describes the toughening characteristics of a mixture in post-peak stress regions and is computed using the normalized stress-strain curve. The fracture resistance indicator was either the critical strain energy release rate or the critical J-integral (J_c) obtained from the SCB test. The results of a paired t-test identified no significant difference between HMA and WMA in terms of IDT strength and TI values. There was also no significant difference observed for WMA mixtures when RAP content increased up to 30% in terms of tensile strength and TI.

Watson et al. (2008) concluded that testing temperature has a significant effect on the fracture energy measurements when performing SCB tests. Additional RAP reduces the fracture energy of blended mixtures, a trend more obvious when the testing temperature ranges from -12 ˚C to -24 ˚C as opposed to testing temperatures ranging from -24 ˚C to -36 ˚C in which more brittle material property was obtained. Mixtures blended with 20% RAP have similar fracture energy with 0% RAP mixtures, and significant reduction in fracture energy was observed when RAP content increased to 40%.

2.4.4 Resistance to Low-Temperature Cracking

Behnia et al. (2011) investigated the effects of RAP on the low-temperature cracking performance of asphalt mixtures. The study evaluated a total of twelve mixtures using PG 64-22 and PG 58-28 as virgin binder and RAP content blend ranging from 0%

to 50%. Disk-shaped compact tension [DC (T)] tests were performed at -12˚C to determine the fracture energy of blended asphalt mixtures. In addition, IDT creep tests were conducted at 0˚C, -10˚C, and -20˚C on HMA specimens containing 20% and 40% RAP. The study employed the acoustic emissions (AE) technique to capture the transient elastic mechanical waves from thermal crack formation. Thermal stresses were induced by subjecting the specimens to a cooling environment (from ambient to -50˚C), and the embrittlement temperature (T_{EMB}) at which macro cracks propagated was recorded using AE technique. The results of DC (T) tests indicated that the fracture energy of mixtures using PG 58-28 as virgin binder decreased with increased RAP content, and a drastic reduction (59%) in fracture energy was observed when RAP content increased from 10% to 20%. However, for mixtures using PG 64-22 as virgin binder, a threshold of 30% RAP was identified, as the fracture energy increased initially and then decreased later in the process.

Watson et al. (2008) suggested that it might not be necessary to adjust the virgin binder grade to achieve desired low-temperature performance when RAP content is less than 30%. Comparing the fracture energy of 50% RAP mixtures using PG 58-28 as virgin binder with 0% RAP mixtures using PG 64-22 as virgin binder, the use of softer asphalt binder compensated for the presence of RAP in terms of fracture energy and cracking performance. The m-value obtained from IDT tests was found to decrease with the increase of RAP content, which indicated that 20% RAP mixtures performed better than 40% RAP mixtures in terms of thermal stress relaxation. A significant difference in T_{EMB} was observed when comparing mixtures with and without RAP content, but not in mixtures containing varying percentages of RAP. This observation implies that partial blending occurs between RAP and virgin materials, as AE tests measure material properties at a local scale and capture the weakest spot of a composite material system. Stated differently, RAP suffers damage and incurs fractures before virgin material in a RAP mixture.

2.4.5 Resistance to Moisture Damage Susceptibility

Maupin et al. (2009) identified no significant difference between mixtures with high RAP content (21-30%) and control mixtures (0-20% RAP) in terms of resistance to moisture susceptibility. According to AASHTO T283 *Resistance of Compacted Bituminous Mixture to Moisture Induced Damage*, average tensile strength ratio (TSR) for mixtures with high RAP content is 0.82 and 0.84 for the control mixtures.

Watson et al. (2008) evaluated the moisture susceptibility of SMA mixtures blended with various RAP contents from 0% to 30% following a version of AASHTO T283 modified by the Georgia Department of Transportation. The tensile strength of both dry and saturated specimens increased as the percentage of RAP increased; however, the TSR did not increase significantly with the addition of RAP.

Al-Qadi et al. (2009) confirmed that RAP content increases the tensile strength of blended mixtures and therefore the resistance to moisture susceptibility. Partial blending between RAP binder and virgin binder may cause double coating on RAP particles, which improves the stripping resistance of the particles. However, selective absorption of binder that creates a bond and improves the stripping resistance does not occur immediately for virgin aggregate during the mixing process, causing mixtures composed of virgin material to have weaker stripping resistance. The study found that 40% RAP mixtures have higher TSR than 0% RAP mixtures, but lower TSR than the 20% RAP mixtures.

2.5 Summary

While RAP use in asphalt pavement has many economic and environmental benefits, its use has been limited to certain types of asphalt mixes with limited percentages. A review of the published literature revealed inconsistent conclusions regarding the effect of RAP components on blended HMA mixture performance, especially at high RAP content. RAP use can improve the rutting resistance of a mixture, but simultaneously raise concerns of blended mixture fatigue and thermal performance. Some reports indicate that certain percentages of RAP have negligible effects on mixture fatigue and thermal performance; however, this particular value varies in different research approaches.

The stiffer nature of aged RAP binder has undeniable effects on blended mixtures; however, it remains unclear how and to what extent aged RAP binder interacts with virgin asphalt binder. Therefore, it currently is not possible to accurately predict the performance of mixtures with high RAP content. Long-term performance of RAP mixtures is especially difficult to predict since other factors will be introduced during the construction period and service life that may influence the mixtures endurance.

Material properties and mixture characterizations of RAP materials vary with each construction projects. The storage technique can also cause the same RAP materials to vary vastly. The tiered usage concept from the NCHRP 9-12 standards may improve the longevity and stability of RAP material, but the standards provide only rough estimates and overly simplistic percentage limits. Although it is important to establish a comprehensive characterization system for RAP materials, such a tool does not exist at this time.

CHAPTER 3 EXPERIMENTAL PROGRAM

3.1 Introduction

Laboratory experimental program was developed to characterize the effect of RAP content on dense-graded friction course, i.e., mixes designated as FC-12.5. Table 3-1 shows the various RAP mixture combinations examined in this study. One source of virgin aggregate and two sources of RAP material were used in this project. PG 76-22PMA binder were used to determine asphalt content for mixes with each percentage of RAP. Current FDOT specifications allow for use of PG 76-22 Polymer Modified Asphalt (PMA) or PG 76-22 Asphalt Rubber Binders (ARB), so the effect of RAP on both types of binder were assessed. In this project, two major concerns were dealt with: 1) cracking performance of binder and 2) degradation of cracking performance of mixture.

Table 3-1 FC-12.5 Mix Design Matrix

Mix Types	Binder Types	RAP Types	RAP Percentages	Total Mixes
FC-12.5	PG 76-22 PMA	Whitehurst (Coarse)/ Atlantic Coast (Fine)	0%	14
			20%	
	PG 76-22 ARB		30%	
			40%	

3.2 Material

3.2.1 Virgin Aggregate

The virgin aggregates were used throughout this research was Georgia granite and local sand. Table 3-2 presents virgin aggregate source information and Figure 3-1 shows the virgin aggregate gradations.

Table 3-2 Virgin Aggregate Sources

Source	Product Name	FDOT Code	Plant/Pit No.	Producer
Georgia Granite	# 7 Stone	C43	GA-185	Martin Marietta Materials
	# 89 Stone	C51	GA-185	
	W-10 Screenings	F20	GA-185	
Hydrated Lime	Uttrel Co.	337-HL	-	Global Stone Corporation
Local Sand	Shad	334-LS	-	Atlantic Coast Asphalt

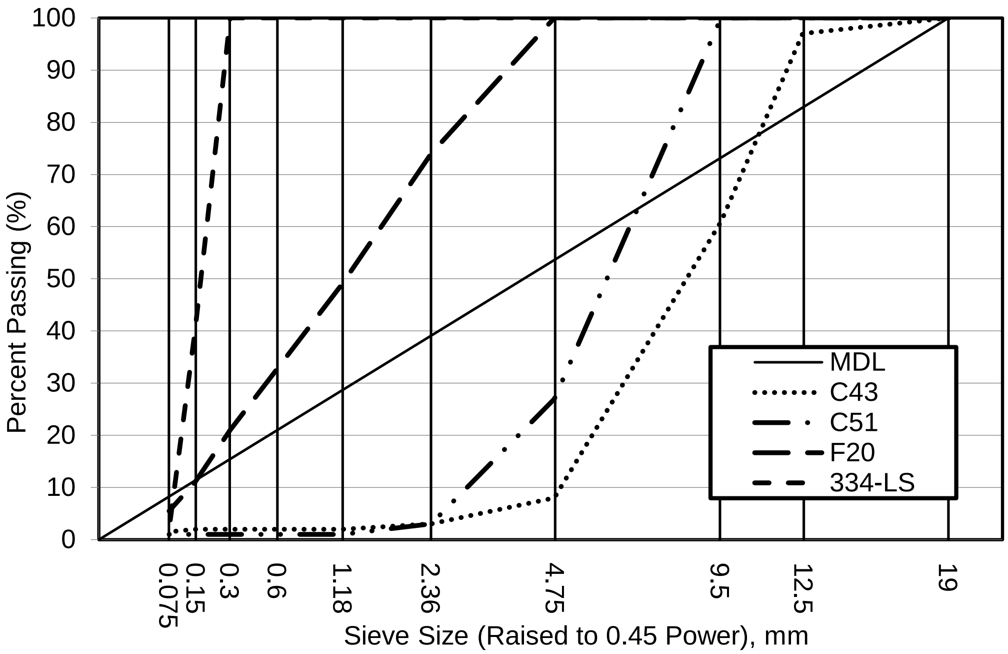

Figure 3-1 Virgin aggregate gradations

3.2.2 Virgin Binder

Two binders assessed in the study were: PG 76-22 Polymer Modified Asphalt (PMA), and PG 76-22 Asphalt Rubber Binders (ARB). Current specification (FDOT, 2015) allows contractor to substitute a PG 76-22 (PMA) or PG 82-22 (PMA) for the PG 76-22 (ARB) when the total quantity of a FC-12.5 project is less than 500 tons.

3.2.3 RAP Sources

Two FDOT approved source stockpiles were selected. RAP from stockpile I-10, Atlantic Coast (ATL), has a fine aggregate gradation and RAP from stockpile II-12, Whitehurst (WHI), has a coarse aggregate gradation. Based on visual inspection of the extracted aggregate, the ATL RAP is mainly composed of granite aggregate and the WHI RAP is mainly composed of limestone aggregate, as shown in Figure 3-2.

Figure 3-2 Aggregate components of ATL (left) and WH (right) RAP

3.3 RAP Material Characterization

Properties of RAP needed for mix design include asphalt content, basic RAP aggregate properties, and, when a high RAP content is desired, the true or continuous grade of the recovered RAP binder for purpose of developing the blending chart to select virgin binder. In this study, blending chart approach was not adopted and PG 76-22 modified binders, required by the FDOT for surface friction courses, were used as virgin binders. As excessive fines (minus #200 sieve), high aggregate gradation variability, high asphalt content variability and aggregate quality can all limit the maximum allowable amount of RAP, it is import and necessary to characterize the RAP materials.

3.3.1 RAP Specimen Preparation

It is understood that RAP stockpiles have inherent variability as RAP material can be collected from different pavement layers and/or multiple source locations. The agglomeration of RAP particles introduces additional variability issue as it affects the determination of RAP aggregate gradation used for mix design as well as the RAP binder content which varies significantly with RAP particle sizes.

To minimize these variability issues, the researchers fractionated the RAP. Bags of sampled RAP material was first dried in an oven at 122˚F (50˚C) for 36 to 48 hours, and then dried at an increased temperature of 230˚F (110˚C) to a constant weight. This approach was taken to avoid further aging the RAP material. Before conducting the sieve separation, oven-dried RAP materials from different bags were mixed together for the purpose of homogenization. Then, RAP materials were separated into various sizes (+12.5 mm, +9.5 mm, +4.75 mm, +2.36 mm and -2.36 mm) and stored in flat pans. Batch gradations, provided by the contractors were used to prepare samples for determinations of G_{mm}, RAP aggregate gradation, and binder content. Table 3-3 presents the batching gradations. Minus # 8 sieve size RAP material was further sieved to complete the batching gradation, or “black curve” entitled in this study.

Table 3-3 Plant Provided RAPs Batching Gradations (Black Curve)

Sieve Size	Atlantic Coast	Whitehurst
	% Retaining	
1/2"	1	9
3/8"	12	33
#4	29	47
#8	20	5
Minus #8	38	6

3.3.2 RAP Binder and Aggregate Recovery

According to a survey conducted by West (2008), most contractors use the ignition method routinely to determine RAP binder contents and recover the aggregates for sieve analyses. However, Kvasnak et al. (2010) reported that the ignition oven method may cause significant changes in specific gravity for some aggregate types, such as the soft Florida limestone due to the extreme temperatures used in the ignition method. On the other hand, it is also reported that the solvent extraction methods fail to remove all of the aged binder from RAP resulting in lower RAP binder contents than they actually are.

In this study, both solvent extractions and ignition furnace methods were used to provide more accurate determination of RAP binder contents and RAP aggregate gradation. Figure 3-3 illustrates the testing plan. For each RAP, four representative samples of each RAP were tested using both ignition furnace and solvent extraction methods. Recovered RAP aggregate from both methods was washed, dried and sieved to obtain the "white curve", the RAP aggregate gradation for mix design. Detailed data can be found in Appendix A.

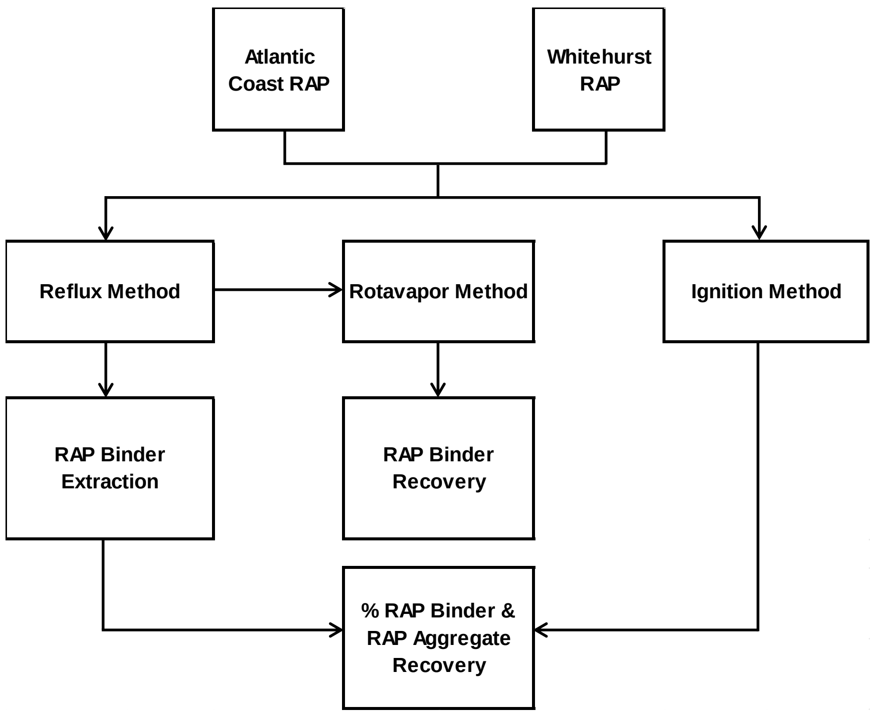

Figure 3-3 RAP binder extraction and recovery

3.3.2.1 Solvent Method

RAP binder was extracted using reflux method in accordance to Florida Method of Test 5-524, Reflux Extraction of Bitumen from Bituminous Paving Mixtures. In this study, trichloroethylene (TCE) was used as a solvent. NCHRP 370 (NCHRP, 2012) reported that the type of solvent used between TCE, toluene, and n-propyl bromide did not produce statistically significant differences in the results for Superpave Binder Tests. Extracted binders were recovered following Florida Method of Test 3-D5404, Recovery of Asphalt from Solution Using the Rotavapor Apparatus. Figures 3-4 and 3-5 show the asphalt binder extraction and recovery device. Four representative samples for each RAP were tested. Table 3-4 presents the averaged recovered aggregate gradations and binder contents of two RAPs. Figure 3-6 shows the RAP aggregate gradations. The penetration number, viscosity and high true PG grade for RAP binders were determined, as shown in Table 3-5.

Figure 3-4 Asphalt binder extraction (reflux)

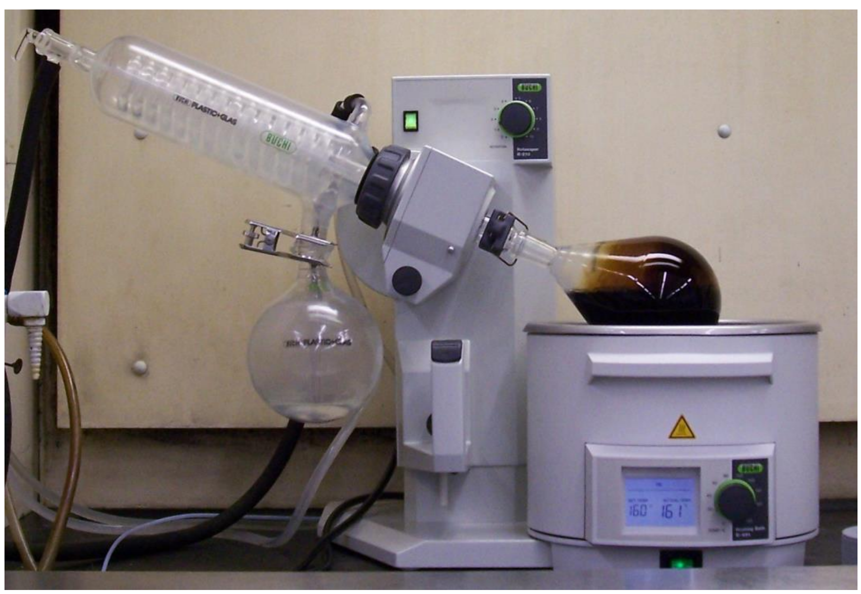

Figure 3-5 Rotavapor evaporator used for asphalt binder recovery

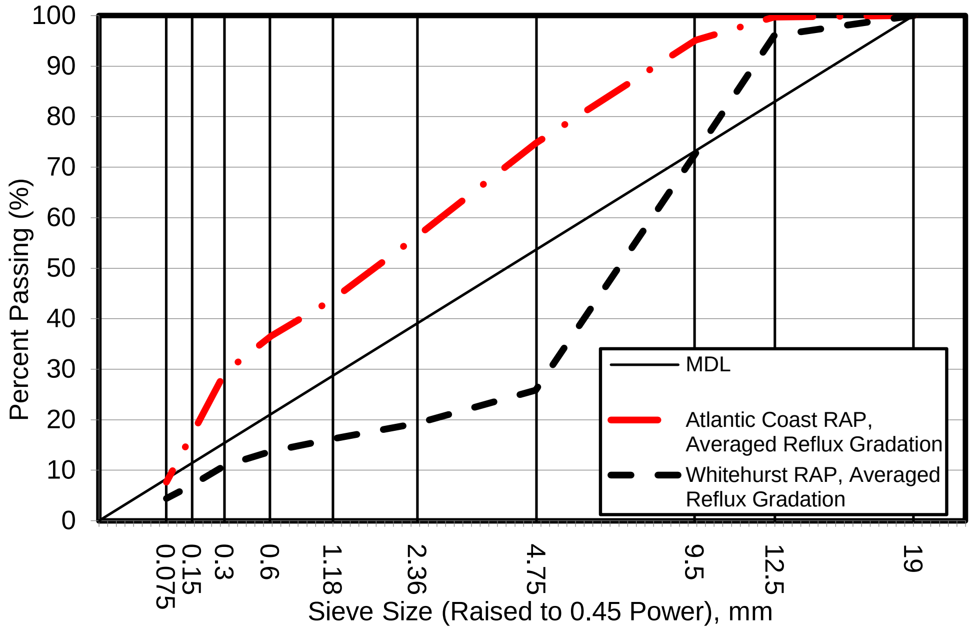

Figure 3-6 “White curve” for two RAPs: reflux method

Table 3-4 “White Curve” of Two RAPs: Reflux Method

Sieve Size	Atlantic Coast Passing (%)	Whitehurst Passing (%)
3/4"	100.0	100.0
1/2"	99.8	96.3
3/8"	95.2	74.3
#4	74.3	26.8
#8	56.0	20.2
#16	43.8	17.2
#30	36.6	14.7
#50	29.8	11.9
#100	16.5	7.5
#200	7.73	4.76
%AC	4.50%	4.35%

Table 3-5 Recovered RAP Binder Properties

RAP Types / Properties	Whitehurst	Atlantic Coast
Penetration Value	9	15
Viscosity (poise)	624162	98433
DSR True Grade (˚C)	104.2	94.2

3.3.2.2 Ignition Method

Meanwhile, AASHTO T308-10, Standard Method for Test for Determining the Asphalt Binder Content of Hot-Mix Asphalt (HMA) by the Ignition Method, was chosen to determine RAP binder content and aggregate gradation as well. Unlike solvent method, no binder can be recovered for further analysis, as it is burned off in the ignition oven. The clean recovered aggregate gradation of both RAP obtained by using ignition oven test, were provided by the local contractor. Four representative samples for each RAP were tested. Residual aggregate was washed, dried and sieve analyzed. Slight differences between contractor provided and UF laboratory obtained gradations were observed. Table 3-6 presents the recovered aggregate gradations and binder contents of two RAPs obtained at UF laboratory. Figure 3-7 shows the RAP aggregate gradations.

Table 3-6 "White Curve" for Two RAPs: NCAT Ignition Oven Method

Sieve Size	Atlantic Coast	Whitehurst
	Passing (%)	Passing (%)
3/4"	100.0	100.0
1/2"	99.8	96.3
3/8"	95.7	73.1
#4	74.8	27.3
#8	57.5	20.8
#16	47.5	17.7
#30	40.5	15.5
#50	33.4	12.4
#100	17.7	8.1
#200	8.44	5.21
%AC	5.42%	4.79%

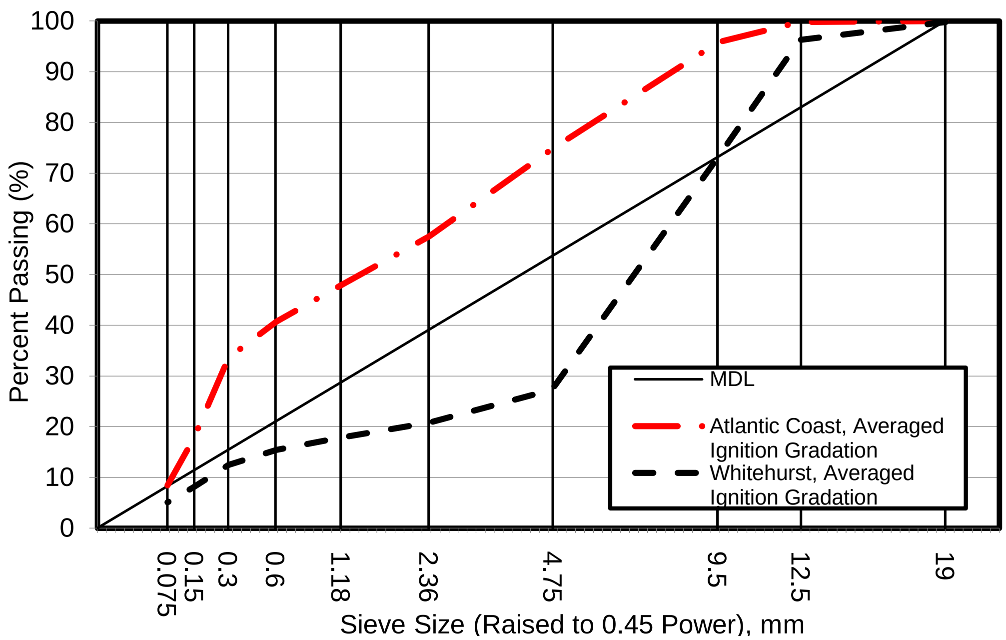

Figure 3-7 "White Curve" for two RAPs: NCAT ignition oven method

As expected, NCAT ignition oven test resulted in higher asphalt binder content and finer aggregate gradation than solvent method. To be conservative, solvent method results were employed in mixture design.

3.3.3 RAP Aggregate Bulk Specific Gravity

To calculate the voids in the mineral aggregate (VMA) or to use the Superpave method for estimating the binder content of a mixture, it is necessary to know the combined aggregate bulk specific gravity (G_{sb}). Computing the combined G_{sb} requires knowing the G_{sb} of each aggregate component. However, the RAP binder extraction process can change the aggregate properties and may also change the amount of fine material. Generally, there are two approaches to avoid this problem. In the past, many states used the effective specific gravity (G_{se}) of the RAP aggregate instead of its G_{sb}. The G_{se} can be calculated from the RAP maximum specific gravity (G_{mm}), Equation 3. For a given aggregate, G_{sb} is always smaller than G_{se} therefore the substitution of G_{se} for G_{sb} will result in overestimating both the combined aggregate G_{sb} and the VMA. As the percentage of RAP used increases, the overestimation becomes greater. Later, some State DOTs applied a reduction factor to minimize this overestimation. For example, Illinois DOT uses 0.1 as a reduction factor for slag RAP to determine G_{sb} of RAP aggregate, Equation 4. The second approach is to assume a value for the asphalt absorption of the RAP aggregate based on past experience with the same virgin aggregates. Once the asphalt absorption and G_{se} of RAP aggregate are determined, the G_{sb} can be calculated by using Equation 5. To estimate the asphalt absorption accurately, FDOT specifies the RAP aggregate for visual inspection should be recovered using the solvent method, which prevents any discoloring of the aggregate that would occur with ignition oven method.

Equation 3:

$$G_{se} = \frac{100 - P_{b(RAP)}}{\frac{100}{G_{mm(RAP)}} - \frac{P_{b(RAP)}}{G_b}} \tag{3}$$

Where

G_{se}= effective specific gravity of RAP aggregate
G_{mm}= theoretical maximum specific gravity of RAP
P_b= RAP binder content; and
G_b= specific gravity of RAP binder

Equation 4:

$$G_{sb} = G_{se} - 0.1 \tag{4}$$

Where

G_{sb}= bulk specific gravity of RAP aggregate
G_{se}= effective specific gravity of the RAP aggregate

Equation 5:

$$G_{sb} = \frac{G_{se}}{\frac{P_{ba} \times G_{se}}{100 \times G_b} + 1} \quad (5)$$

Where

P_{ba}= absorbed binder, percent by mass of RAP aggregate, and others are the same as previous defined.

In this study, the G_{sb} of RAP aggregate was calculated based on the measured RAP G_{mm} results and assumed asphalt absorption values, Equation 5.

3.4 Binder Evaluation

A key concern associated with use of additional RAP in friction course is that the resulting binder may be significantly lower quality than the modified binders (asphalt rubber or polymer) typically specified for use in the friction courses. RAP binder was extracted and recovered in bulk using solvent method. A total number of 14 different binders composed of two different virgin binders, two recovered RAP binders and four different proportions of virgin and RAP binder, were evaluated. Note the final relative percentage of binder to be blended may not correspond exactly to the relative percentage of RAP and virgin aggregate, because slight adjustments in asphalt content may be required for mixtures with different RAP contents.

The Superpave binder testing methodologies, including Brookfield viscosity (BV), Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR), were conducted to evaluate the resulting binder characteristics of blended binders. However, it is well known that there is no existing binder test or parameter that reliably predicts cracking performance. The cracking performance of pavements in Florida has been determined to be highly correlated with the fracture energy of mixture, which is strongly affected, by the fracture energy of binder. Therefore, particular emphasis was placed on the new binder fracture energy (BFE) test, as it is capable of accurately determining the fracture energy of binder at intermediate temperature (Niu et al, 2014 and Yan et al, 2015). In addition, both MSCR and FE were used to qualitatively assess whether blended binders composed of virgin and RAP binder would effectively behaving as polymer-modified, rubber-modified, or unmodified binder (both MSCR and the new binder FE test are capable characterizing binder in this way). The MSCR test has been adopted by many state highway agencies, including FDOT, to more accurately evaluate the rutting performance and identify the polymer modification of asphalt binder. Figure 3-8 illustrates the MSCR testing device which has the capacity of performing both conventional DSR and MSCR tests. Figure 3-9 shows the overall binder-testing plan.

Figure 3-8 MSCR testing device located at FDOT SMO laboratory

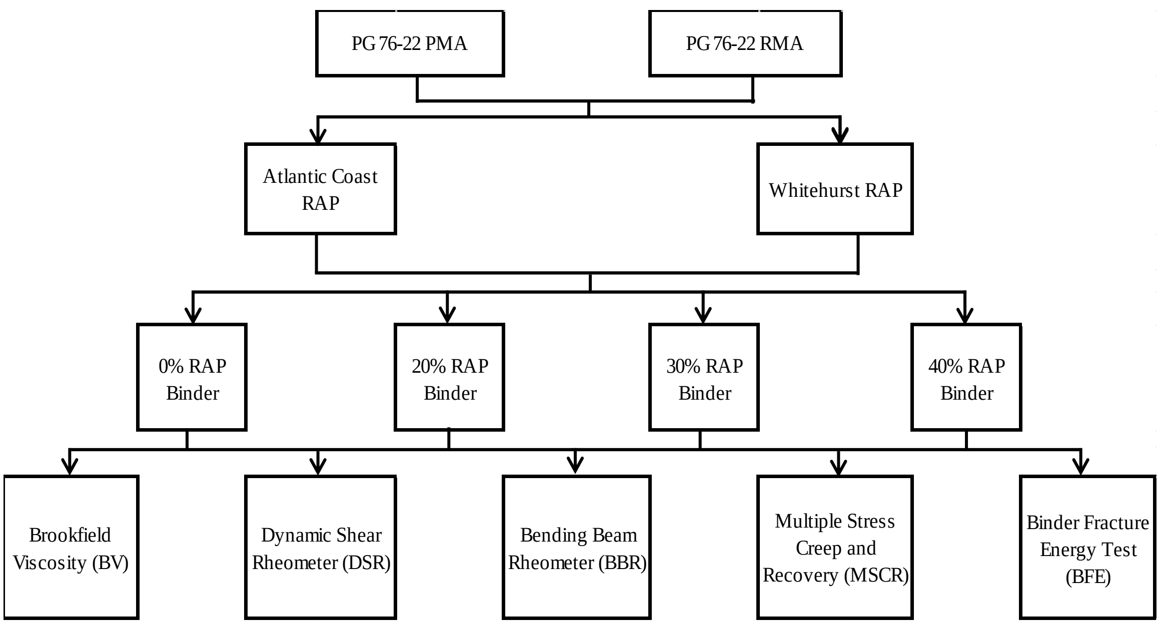

Figure 3-9 Blended binder properties evaluation

Specific anticipated findings were used to determine the maximum percentage of RAP that can be used in friction courses without jeopardizing pavement performance include: 1) %RAP at which binders no longer effectively behave as modified binders, and 2) %RAP at which a significant reduction in FE or change in other relevant binder properties is observed relative to the virgin binders.

3.4.1 Binder Fracture Energy (BFE) Test

A new binder fracture energy (BFE) test was developed to accurately predict cracking performance at intermediate temperatures (Niu et al, 2014). The optimized specimen geometry allows for accurate determination of fracture energy by consistently locating the failure plane at the center of the specimen and accurately determining the true stress and true strain on the fracture plane (Niu et al, 2014 and Yan et al, 2015), as Figure 3-10 shown.

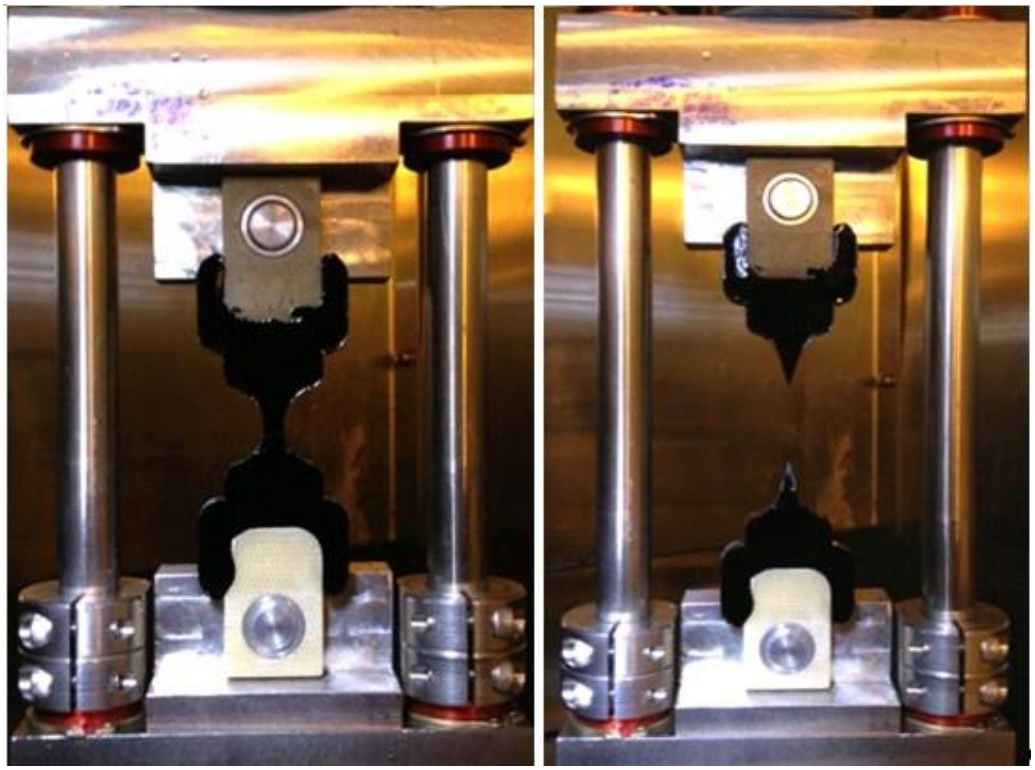

Figure 3-10 Specimen configurations before (A) and after (B) BFE test (Yan et al, 2015)

The specimen is created by pouring preheated asphalt binder into the mold and then trimming the specimen surface to flat. In this study, the BFE tests were performed on RTFO+PAV-aged specimens, using a material testing system (MTS) closed-loop servo-hydraulic loading system. The testing temperature was 15˚C, as the least variance in measured fracture energy occurred at this temperature (Niu et al, 2014).

Testing data, including time, deformation, and loading magnitude, was generated using the MTS acquisition software at an adjusted rate of 455 points per second. The data interpretation system established in previous work (Niu et al, 2014) converts the measured force vs. displacement data into average true stress vs. average true strain data in the central cross-sectional area of the specimen where fracture initiates and propagates. Generally, the BFE test is able to differentiate unmodified, rubber-modified, and polymer-modified binders based on binder fracture energy and characteristic shape of corresponding true stress vs. true strain curve. Further details on testing procedures and data interpretations can be found in previous research works (Niu et al, 2014).

3.5 Mixture Designs

Reference mix designs for FC-12.5 mixture was provided by local contractor and approved by the FDOT. The optimum binder content and other volumetric properties, e.g., VMA, VFA, etc., was verified by preparing and testing laboratory produced samples. Reference mix designs were modified to include various percentages of RAP material.

Virgin aggregate components were adjusted as needed to maintain the gradation of all RAP blends the same or as close as possible to the reference mixtures. This eliminated the effects of gradation differences on performance to assure that observed differences are in fact associated with the difference in RAP content and not in differences in gradation between mixtures having different RAP contents.

Determination of asphalt content for each percentage of RAP was based on results of Superpave Gyratory compaction (SGC) of mixture produced with the combined virgin and RAP aggregate. The asphalt content was determined as that resulting in 4% air voids at N_{design}. For FC-12.5 mixes, PG 76-22 PMA was used for mix design and same optimum binder content was adopted for mixes with PG 76-22 ARB binder. Current FDOT practice for RAP mixtures assumes 100% working binder, therefore any change in asphalt content was achieved by changing the amount of virgin binder, as the amount of RAP binder was fixed once the RAP content was fixed. Detailed information regarding the mixture design is described herein.

3.5.1 Aggregate Blend and Gradation

3.5.1.1 FC-12.5: reference and low RAP content mixtures

During the literature review, it is identified that a level of 20% RAP is well-accepted as the threshold below which no change in binder selection is required. Meanwhile, current specification (FDOT, 2015) specifies a maximum amount of 20% RAP by aggregate weight for FC-12.5 with an exception that higher percentage of RAP can be used only when less than 20% by weight of total asphalt binder is contributed by the RAP material. Therefore, preliminary study for FC-12.5 evaluation included a reference mixture (0% RAP) and a blended mixture with 20% RAP. The DASR-IC evaluation was conducted to ensure the FC-12.5 reference mixture was not deficient in some aspects of their gradation, such that the effects of the deficiency may overwhelm or mask the effects of the RAPs. Tables 3-7 and 3-8 present the Superpave volumetric parameters and the DASR-IC parameters for FC-12.5 reference mixture. Table 3-9 presents the aggregate usage for the reference mixture and 20% RAP mixtures (two RAPs). The particle size distribution for three mixtures is shown in Figure 3-11.

Table 3-7 Superpave Volumetric Parameters: FC-12.5 Reference Mixture

Superpave Volumetric Parameters	P_b (%)	V_a (%)	VMA (%)	VFA (%)
	5.2	4.1	15.0	73

Table 3-8 DASR-IC Parameters: FC-12.5 Reference Mixture and RAP Mixtures

RAP Mixtures	DASR Porosity	DF	EFT	FAR
Reference Mixture	42.7	0.69	23	0.36
20% ATL RAP Mixture			22	
30% ATL RAP Mixture			21	
40% ATL RAP Mixture			20	
20% ATL RAP Mixture			23	
20% WHI RAP Mixture			25	
30% WHI RAP Mixture			25	
40% WHI RAP Mixture			23	
DASR-IC CRITERIONS	38-48	0.50-0.95	12.5-25	0.28-0.36

Table 3-9 Aggregate Usage for Reference and 20% RAP Blended Mixtures

Mixtures \ Aggregates	ATL RAP	WHI RAP	C43	C51	F20	334-LS
Reference Mixture	0%	0%	25%	10%	60%	5%
20% ATL RAP Mixture	20%	0%	20%	5%	53%	2%
20% WHI RAP Mixture	0%	20%	11%	2%	63%	4%

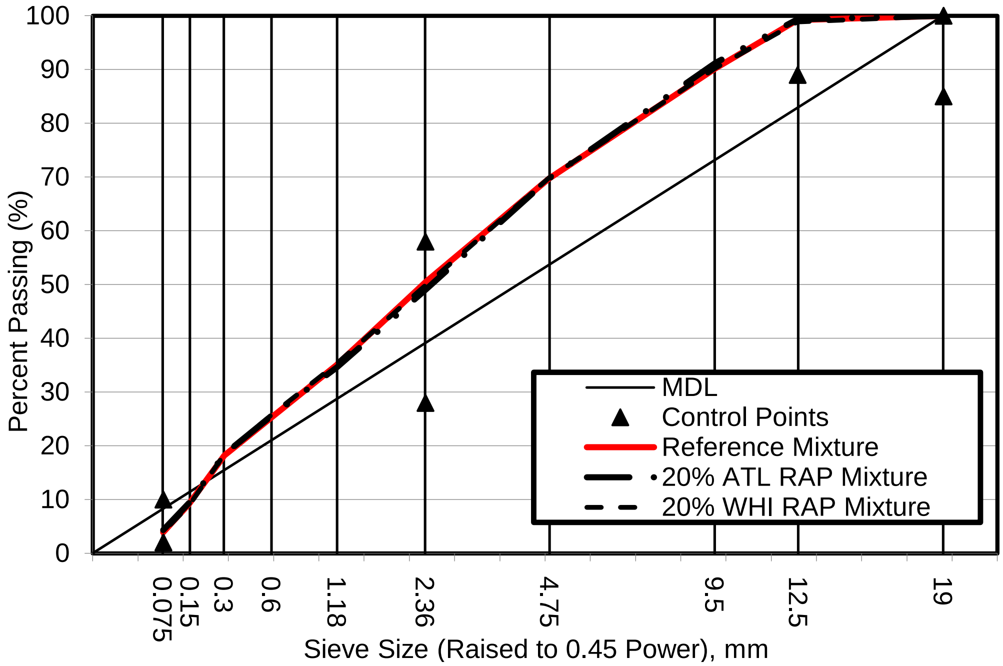

Figure 3-11 Reference and 20% RAP blended aggregate gradation

3.5.1.2 FC-12.5: High RAP content mixtures

Two tentative percentage of RAP content were evaluated in this stage of study, including 30% and 40% or higher. Table 3-10 shows the aggregate usage for 30% and 40% RAP mixtures. Figure 3-12 and 3-13 illustrate the blended gradations of high RAP mixtures. All RAP mixtures had identical blended aggregate gradations except for 40% RAP mixture between which and the reference mixture slight difference exists.

Table 3-10 Aggregate Usage for Reference, 30% RAP Blended Mixtures

Aggregates / Mixtures	ATL RAP	WHI RAP	C43	C51	F20	334-LS
30% ATL RAP Mixture	30%	0%	21%	2%	45%	2%
30% WHI RAP Mixture	0%	30%	4%	1%	62%	3%
40% ATL RAP Mixture	40%	0%	19%	2%	38%	1%
40% WHI RAP Mixture	0%	40%	0%	0%	57%	3%

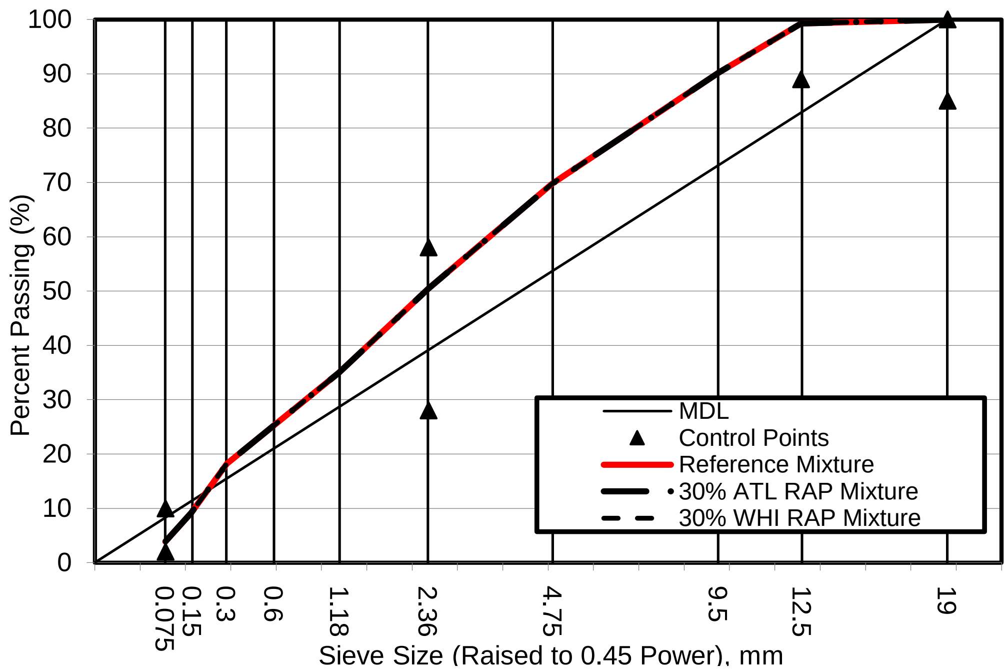

Figure 3-12 30% RAP blended gradation

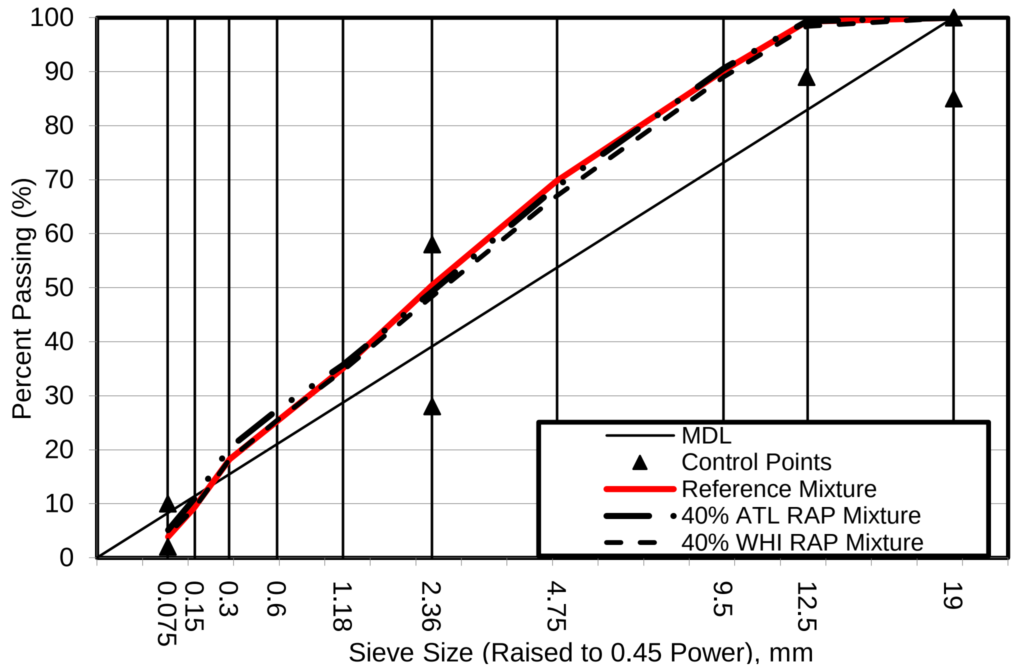

Figure 3-13 40% RAP blended gradation

3.6 Mixture Evaluation

It is now well recognized that top-down cracking is a major form of distress in hot mix asphalt mixtures, especially in the state of Florida. Relative cracking performance was evaluated for the reference and RAP mixtures by using and energy ratio (ER) parameter derived from the hot-mix-asphalt fracture mechanics (HMA-FM) model and measured fracture properties from Superpave IDT at 10 ºC. The general factors involved in the testing plan for FC-12.5 are shown in Figure 3-14, and described in the following paragraphs.

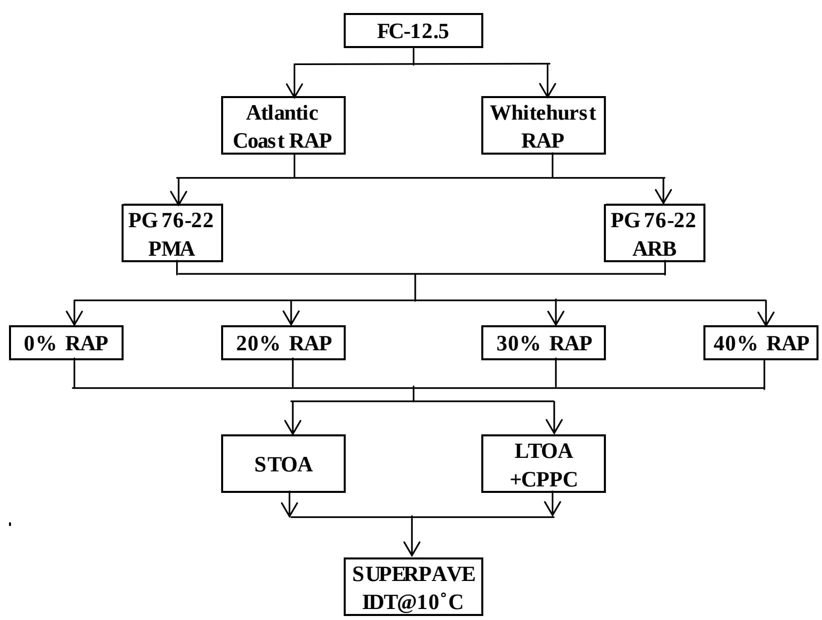

Figure 3-14 Overall mixture testing plan

3.6.1 Mixture Specimen Preparation

3.6.1.1 Batching and Mixing

The first step for specimen preparation was to batch 4500 g aggregates using the batching sheets included in Appendix B. Then, the batched aggregates (both virgin and RAP) and asphalt binder were heated in the oven at the mixing temperature (325°F) for approximately three hours. Next, the aggregates and binder were mixed in the bucket until the aggregates were well coated with the binder. The mixed samples were then spread in pans and kept in an oven at the mixing temperature for two hours for STOA conditioning. The mixtures were stirred after one hour to obtain a uniformly aged sample.

3.6.1.2 Compaction

After the STOA conditioning procedure, the mixed samples were compacted using the Superpave Gyratory Compactor (SGC) with a compaction stress of 600 kPa and a gyratory angle of 1.25° at the mixing temperature. Even though the mixtures were designed to have a 4% air void content at N_{design}, the gyratory pills were compacted in the SGC to obtain a 7% air void content at the proper number of gyrations, which simulates the initial air voids (and density) typically achieved in the field. After letting the gyratory pills cool down at the room temperature, the bulk specific gravity (G_{mb}) of each pill was measured in accordance with AASHTO T166 procedure to determine the percent air voids. The target air void content of the gyratory pill was approximately 7.8 % because the air void content of the specimens after slicing (described subsequently) is approximately 0.5–1.0 % lower as compared to that of the pills.

3.6.1.3 RAP mixture gradation and asphalt binder content verification

Due to the inherent variability of RAP materials and uncertainty of RAP aggregate true gradation, it is considerable to check actual blend gradation against the design blend, especially for high RAP content mixtures. Before conducting any conditioning and performance evaluating tests, one SGC specimen for each RAP mixture was randomly selected and burned in the ignition oven to reclaim the aggregate and to verify the asphalt binder content. Figure 3-15 shows the recovered aggregate gradation for various RAP mixtures and Table 3-11 presents the actual binder content and NCAT ignition oven reported results.

As expected, finer gradations of the recovered aggregate were obtained after the ignition oven test. Both ATL RAP mixtures and WHI RAP mixtures had identical recovered gradations and they were all slightly finer than the recovered reference mixture gradation. One potential explanation could be the breakup of RAP (limestone) aggregate during the ignition oven test. Clear difference between the actual and measured asphalt content was observed for WHI RAP mixtures, indicating the potential loss of burned aggregate.

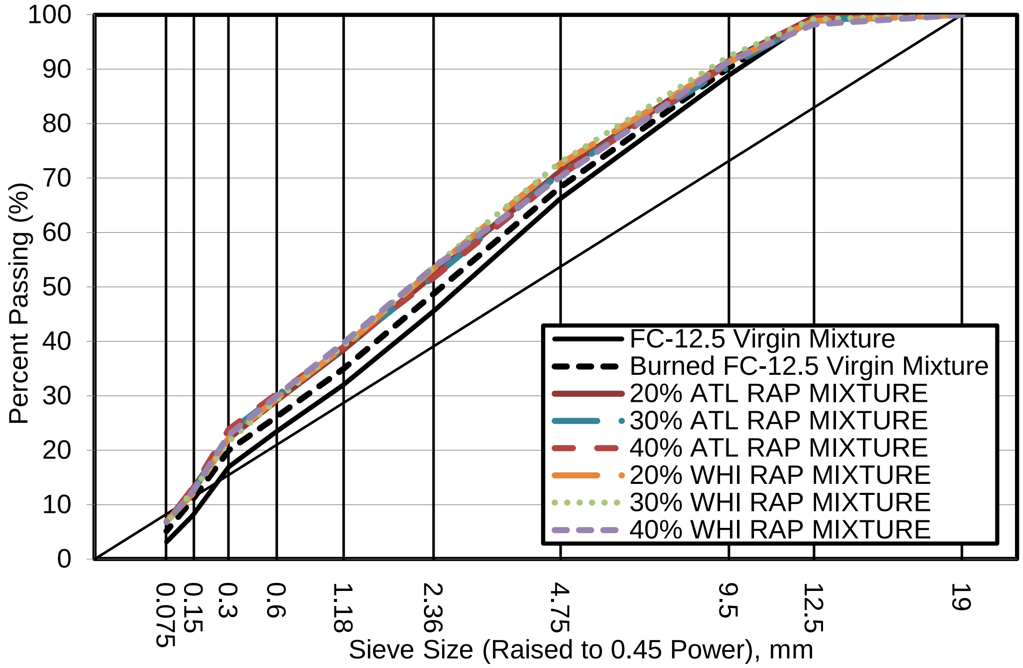

Figure 3-15 Ignition oven test results of RAP mixtures

Table 3-11 Asphalt Content of Randomly Selected SGC Specimens

NCAT Ignition Results	Actual Asphalt Content	Calibrated Asphalt Content(NCAT Ignition Oven)
FC-12.5 Virgin Mixture	5.50%	5.46%
20% ATL RAP MIXTURE	5.20%	5.35%
30% ATL RAP MIXTURE	6.00%	5.98%
40% ATL RAP MIXTURE	4.90%	4.85%
20% WHI RAP MIXTURE	6.50%	6.72%
30% WHI RAP MIXTURE	6.00%	6.30%
40% WHI RAP MIXTURE	5.80%	5.97%

3.6.1.4 Slicing and Gauge Point Attachment

Once the air void contents of compacted pills were properly checked and logged, all pills were sliced to obtain IDT test specimens of the desired thickness (approximately 1.5 inch). A masonry saw was used to slice specimens as shown in Figure 3-16(A). The, the sliced specimens were dried for 48 hours in a dehumidifier at room temperature before bulking. The bulk specific gravity (G_{mb}) of each IDT specimen was measured to make sure that the air void contents of the specimens was within the required range of 7.0% ± 0.5%. Specimen information can be found in Appendix C.

Gauge points were attached to both faces of the specimens using an epoxy adhesive, a steel template, and a vacuum pump setup (see Figure 3-16(B)). Two pairs of gauge points were placed on each face of the specimen at a distance of 19 mm (0.75 inch) from the center of the specimen along the vertical and horizontal axes, respectively.

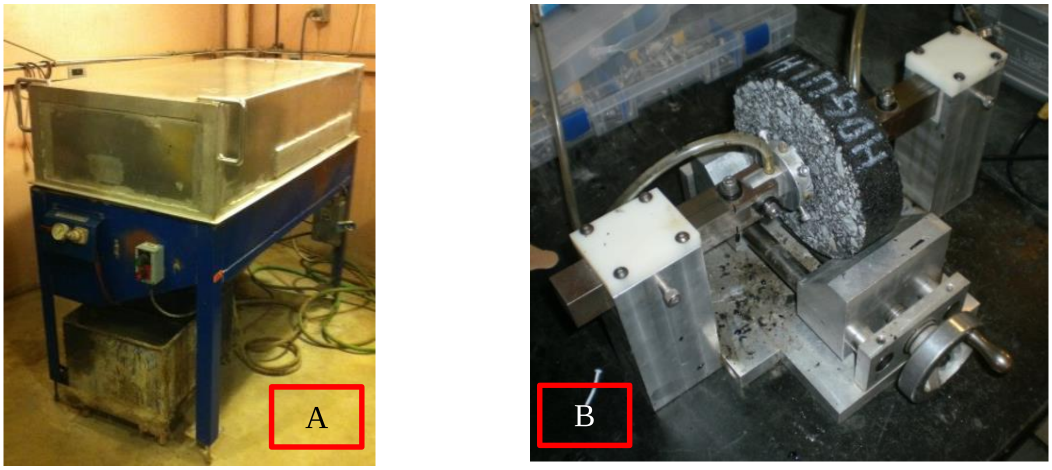

Figure 3-16 Laboratory equipment used for specimen preparation. A) Masonry saw. B) Vacuum pump setup for gauge points attachment.

3.6.2 Mixture Aging Conditionings

Mixtures were tested in both unconditioned (STOA only) and conditioned states. The conditioned state corresponds to the new conditioning procedure developed as part of a recently completed FDOT research effort (Roque et al, 2013), which involves heat oxidation conditioning (HOC: STOA followed by LTOA) followed by cyclic pore pressure conditioning (CPPC). This approach was determined to most effectively represent the long-term effects of temperature, moisture and traffic on changes in fracture properties of mixture in the field.

3.6.2.1 Long-Term Oven Aging (LTOA) Conditioning

To better simulate the effect of heat oxidation, after the STOA, specimens were subjected to LTOA, which involves heating a compacted specimen in a forced-draft oven at 185±5˚F for 5 days. To prevent the falling apart of smaller aggregate particles during the LTOA process, a wire mesh with openings of 0.125 inch and steel band clamps are used to contain the specimens. Great care is necessary to avoid applying too much pressure when attaching the band clamps. The specimens are placed on porous metal plates and then placed into the oven, as Figure 3-17 shows.

Figure 3-17 Specimens setup for LTOA conditioning

3.6.2.2 Cyclic Pore Pressure Conditioning (CPPC)

Asphalt pavement is continuously affected by water during its service life. The CPPC system was developed to effectively induce moisture damage in mixtures as similar and realistic as possible to what asphalt pavement experiences in the field (Roque et al, 2013).

The test specimens were vacuum-saturated at a pressure of 12.28±0.98 psi for 15 minutes and then sited submerged for 20 minutes at the normal pressure. The saturation process was completed after two cycles of vacuum plus normal pressure saturation. Later, saturated specimens were placed into an airtight, water-filled chamber. The triaxial chamber for conditioning allows for precise application of stress in three different directions, as Figure 3-18 shows. Deairated water was forced into the chamber to build up pressure. The pressure was transferred to every surface that water was in contact with. At room temperature (25˚C), a cyclic pore pressure of 5 psi to 25 psi was applied by a sine waveform with a 0.33 Hz frequency and a total of 5800 cycles (4.8 hours) was used. Specimens were placed in the water batch immediately after the CPPC to reach and maintain the desired test temperature (usually 10˚C for IDT).

Figure 3-18 Tabletop triaxial chamber (Roque et al, 2013)

3.6.3 Superpave Indirect Tensile (IDT) Testing

One set of Superpave IDT test, including resilient modulus, creep compliance and strength tests, were performed on each specimen of reference and RAP mixes to determine resilient modulus, creep compliance, strength, failure strain, and fracture energy density (FED) at 10˚C. These test results provided the properties to identify changes in key mixture properties as RAP contents change. The MTS and configuration of Superpave IDT test set-up are shown in Figure 3-19.

Figure 3-19 Superpave IDT tests

3.6.3.1 Resilient Modulus Test

Resilient modulus test is a nondestructive test used to determine the resilient modulus (M_R) of asphalt mixtures. The resilient modulus is defined as the ratio of the applied stress to the recoverable strain when repeated loads are applied. A repeated haversine waveform load is applied to the specimen for a 0.1 second followed by a rest period of 0.9 seconds. The load is selected to restrict the horizontal resilient deformations between 100 to 180 micro-inches to stay within the linear viscoelastic range.

Based on three dimensional finite element analyses, Roque and Buttlar (1992) developed following equations to calculate the resilient modulus and Poisson's ratio. Later, Roque et al. (1997) incorporated Equation 4 and 5 into the Superpave Indirect Tension Test at Low Temperatures (ITLT) computer program.

$$M_R = \frac{P \times GL}{\Delta H \times t \times D \times C_{cmpl}} \tag{4}$$

$$v = -0.01 + 1.480 \times (\frac{X}{Y})^2 - 0.778 \times (\frac{t}{D})^2 \times (\frac{X}{Y})^2 \tag{5}$$

Where,

M_R= Resilient modulus;
P= Maximum load;
GL= Gauge length;
ΔH= Horizontal deformation;
t= Thickness;
D= Diameter;
C_{cmpl}= $0.6345\times(X/Y)^{-1}-0.332$;
v= Poisson's ratio, and
(X/Y)= Ratio of horizontal to vertical deformation.

3.6.3.2 Creep Test

Creep compliance is defined as the ratio of the time-dependent strain over stress. Originally, the creep compliance curve was developed to predict thermally induced stress in asphalt pavement; it can also be used to evaluate the rate of damage accumulation of asphalt mixtures (Roque et al, 1997). Mixture parameters, D_0, D_1 and m-value can be obtained from the creep compliance curve.

The creep test is conducted in a load controlled mode by applying a static load in the form of a step function to the specimen and then holding it for 1000 seconds. The magnitude of the load is selected to maintain the accumulated horizontal deformations in the linear viscoelastic range, which is below the total horizontal deformation of 750 micro-inches. At 100 seconds, a horizontal deformation of 100 to 130 micro-inches is generally considered to be acceptable. The loading and deformation data are incorporated into the ITLT computer program to determine creep properties of the mixtures. Creep compliance and Poisson's ratio are computed by Equations 6 and 7.

$$D(t) = \frac{\Delta H \times t \times D \times C_{cmpl}}{P \times GL} \tag{6}$$

$$v = -0.1 + 1.480 \times (\frac{X}{Y})^2 - 0.778 \times (\frac{t}{D})^2 \times (\frac{X}{Y})^2 \tag{7}$$

Where,

D(t)= Creep compliance at time t (1/psi); and
others are the same as described previously.

3.6.3.3 Tensile Strength Test

Strength test is performed in a displacement-controlled mode by applying a constant rate of displacement of 50 mm/min until failure. Obtained from strength test, failure limits including tensile strength, failure strain and fracture energy can be used to estimate the cracking resistance of the asphalt mixtures. The maximum tensile strength is calculated using Equation 8.

$$S_t = \frac{2 \times P \times C_{SX}}{\pi \times t \times D} \tag{8}$$

Where,

S_t= Maximum indirect tensile strength;
P= Failure load at first crack;
C_{sx}= 0.948-0.01114(t/D)-0.2693(v)+1.436(t/D)(v)
t= thickness
D= diameter
v= Poisson's ratio

Fracture energy (FE), which is calculated as the area underneath the stress-strain curve until failure, is the total energy applied to the specimen until it fractures. Dissipated creep strain energy (DCSE) is the absorbed energy that damages the specimen, and the dissipated creep strain energy to failure ($DCSE_f$) is the absorbed energy to fracture. From resilient modulus test and strength test, following relationship can be developed, Equation 9. As shown in Figure 3-20, elastic energy (EE), FE and $DCSE_f$ can be determined by Equation 10, 11 and 12, respectively. The ITLT program also calculates FE automatically.

$$M_R = \frac{S_t}{\varepsilon_f - \varepsilon_o} \quad \rightarrow \quad \varepsilon_0 = \frac{M_R \epsilon_f - S_t}{M_R} \tag{9}$$

$$\text{Elastic Energy (EE)} = \frac{1}{2} S_t \left(\varepsilon_f - \varepsilon_0\right) \tag{10}$$

$$FE = \int_0^{\varepsilon_f} S(\varepsilon) d\varepsilon \tag{11}$$

$$DCSE_f = FE - EE \tag{12}$$

Where,

S_t= Tensile strength;
ϵ_f= Failure strain; and
Other parameters were defined previously.

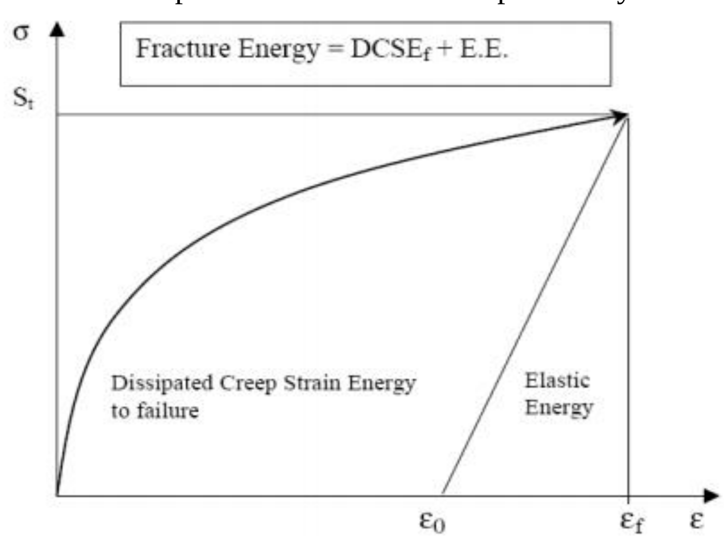

Figure 3-20 Determination of EE, FE, and $DCSE_f$

3.6.3.4 Energy Ratio (ER)

Roque et al. (2004) developed a parameter, energy ratio (ER), to account for the asphalt mixture's potential for top-down cracking. They defined the ER as the dissipated creep strain energy threshold of a mixture divided by the minimum dissipated creep strain energy required, can be determined on the basis of tensile properties obtained from one set of the Superpave IDT test (a modulus, creep, and strength test) at a temperature of 10˚C. ER allows the evaluation of cracking performance on different structures by incorporating the effects of mixture properties and pavement structural characteristics. In addition, the minimum ER criterion for a pavement can be adjusted based on the traffic level. The energy ratio is determined using Equation 13.

$$ER = \frac{DCSE_f}{DCSE_{min}} = \frac{a \times DCSE_f}{m^{2.98} \times D_1} \qquad (13)$$

Where,
$DCSE_f$= Dissipated creep strain energy to failure (kJ/m^3);
$DCSE_{min}$= Minimum dissipated creep strain energy for adequate cracking performance (kJ/m^3);
D_1 and m= Creep parameters;
a= $0.0299\sigma^{-3.1}\times(6.36\text{-St})+2.46\times10^{-8}$;
σ= Tensile stress of asphalt layer (psi); and
S_t= Tensile strength (MPa).

3.7 Summary

One reference mixture for FC-12.5 was identified and modified to include various percentages of RAP from two typical FDOT-approved source stockpiles. Assessment of the effects of RAP on performance were made at both the binder and mixture levels. Binder specimens were produced by blending recovered RAP binder with virgin binders. At least 14 binders were evaluated, corresponding to two virgin binders, two RAP sources, and four RAP contents (0%, 20%, 30%, and 40%). The Superpave binder testing methodologies were conducted to evaluate the resulting binder characteristics, as well as the MSCR test and BFE test. Relative cracking performance of 14 mixtures (one mixture gradations, two virgin binders, two RAP sources, four RAP percentages) was evaluated by using the energy ratio (ER) parameter derived from the hot-mix-asphalt fracture mechanics (HMA-FM) model based on measured fracture properties from Superpave IDT at 10 ºC. Mixtures were tested in both unconditioned (STOA only) and conditioned (LTOA+CPPC) states.

CHAPTER 4 BINDER EVALUATION

4.1 Introduction

Historically, state highway agencies limit RAP in HMA mixtures based on RAP percentage by weight of aggregate or by weight of total mix. However, the percentage of RAP binder blended with virgin binders used in this study, named binder replacement ratio, is different from the percentage of RAP mixture in mixtures, as it was calculated as the percentage of RAP binder divided by the mixture's total binder content. Before performing any binder tests, mixture designs were conducted for a total of seven mixtures, including virgin mixture, 20%, 30% and 40% Atlantic Coast RAP mixtures, 20%, 30% and 40% Whitehurst RAP mixtures. The total binder content for different RAP mixtures was determined as that resulting in 4% air voids at N_{design}. Only PG 76-22 PMA binder was used to determine the total binder contents and the same asphalt content was assumed for each mixture using the PG 76-22 ARB. Table 4-1 presents the mixture parameters and the binder replacement ratios. It was noted that VMA of the 40% ATL RAP mixture was slightly less than the Superpave specified minimum value (14.0%). Details regarding mix design can be found in Appendix D.

Table 4-1 Verified Mix Design Volumetric Parameters and RAP Binder Replacement Ratios

% RAP		N_{design}=75, Mixing and Compacting Temp. =325°F						
		Total Binder	Virgin Binder	RAP Binder	Air Voids	VMA (%)	VFA (%)	Binder Replacement Ratio
Reference	0%	5.2%	5.2%	0.0%	4.2%	15.3	72.5	0%
Atlantic RAP	20%	5.2%	4.2%	1.0%	4.3%	14.9	71.1	18%
	30%	5.0%	3.6%	1.4%	4.0%	14.2	71.8	29%
	40%	4.9%	3.0%	1.9%	3.9%	13.6	71.3	39%
Whitehurst RAP	20%	5.9%	5.0%	0.9%	3.9%	15.5	74.8	15%
	30%	5.9%	4.5%	1.4%	4.2%	15.7	73.2	23%
	40%	5.6%	3.8%	1.8%	4.0%	14.9	72.9	33%

Once the RAP binder replacement ratio was determined for each mix, Superpave binder tests, the multiple stress creep recovery (MSCR) test and the newly developed binder fracture energy (BFE) test were adopted to evaluate the effect of RAP on binder properties. Specimens were prepared by manually blending RAP binder with virgin binders at the corresponding binder replacement ratio. The blending temperature was 325 °F (163 °C). Two types of condition levels were involved, including RTFO and RTFO-plus-PAV aging. Table 4-2 summarizes the binder tests conditions and parameters applied in this study. Detailed binder test results can be found in Appendix E.

Table 4-2 Binder Tests Conditions and Parameters

Binder Tests	Aging Level	Testing Temperature (°C)	Parameters Measured	Specification (FDOT, 2015)
RV	Original Binder	135	Dynamic viscosity	Maximum 3.0 Pa·s
DSR		76	G*/sinδ	Maximum 1.0 kPa
			Phase angle (δ)	Maximum 75 °
MSCR	RTFO Residue	67	$J_{nr,3.2}$	"v"=1.0 kPa^{-1} max "E"=0.5 kPa^{-1} max
			%$Recovery_{3.2}$	$\%R_{3.2}>29.37(Jnr,3.2)^{-0.2633}$
DSR	PAV Residue	26.5	G*sinδ(10 rad/sec)	Maximum 5000 kPa
BBR		-12	m-value, @ 60 sec	Minimum 0.300
			S(Stiffness), @ 60sec	Maximum 300 Mpa
BFE		15	Fracture energy density	NA

4.2 Superpave Binder Tests

4.2.1 Brookfield Viscosity (BV) Test Results

The Rotational Viscometer test is used to determine the viscosity of asphalt binders in the high temperature range corresponding to manufacturing and construction. It measures the torque required to maintain a constant rotational speed (20 RPM) of a cylindrical spindle while submerged in asphalt binder at a constant temperature (typically 275 °F (135 °C)). For each blended binder, one specimen was tested. The Superpave specification limits a maximum viscosity of 3.0 Pa·s for all virgin binders.

Figure 4-1 shows the viscosity values for PG 76-22 PMA and blended binders, including 20%, 30% and 40% RAP (Atlantic Coast and Whitehurst RAP). It was observed that the addition RAP binder resulted in higher viscosity compared to virgin binder. As the percentage of RAP binder increased the viscosity increased, but even for 40% Whitehurst RAP blended binder, the viscosity was below 3.0 Pa·s.

Figure 4-2 shows the viscosity values for PG 76-22 ARB and blended binders, including 20%, 30% and 40% RAP (Atlantic Coast and Whitehurst RAP). It was observed that Atlantic Coast RAP did not affect the viscosity of PG 76-22 ARB, however, the viscosity of the 30% and 40% Whitehurst RAP binders were slightly above 3.0 Pa·s. This observation is reasonable considering that the PG 76-22 ARB itself has a viscosity value close to 3.0 Pa·s and the Whitehurst RAP is a heavily aged RAP material (above 500,000 poise).

Asphalt binder viscosity, measured at high temperature, is important material characteristic as it controls the ability of liquid asphalt binder to be pumped between storage facilities and into the HMA manufacturing plant. However, only virgin binder is pumped into the asphalt plant during the production of RAP mixtures. It should not be a great concern that 30% and 40% WHI RAP blended binder had slightly higher Brookfield viscosity values.

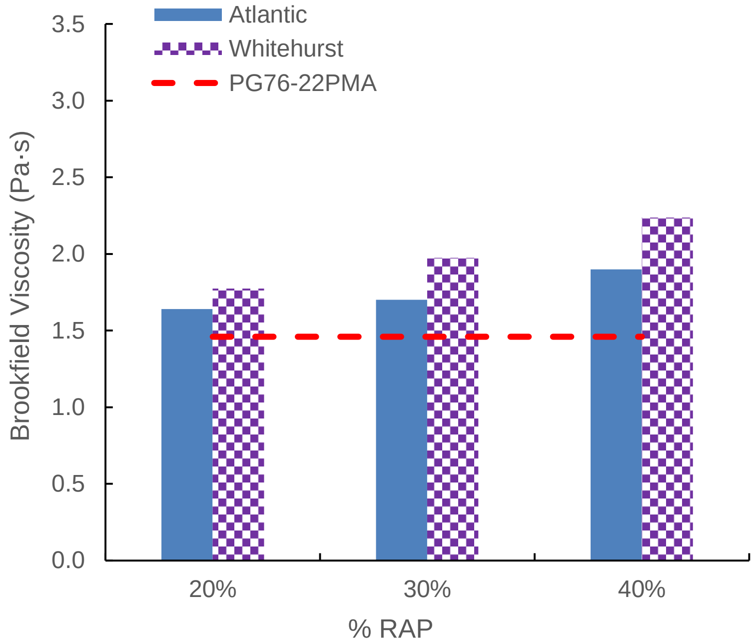

Figure 4-1 Brookfield viscosity: PG 76-22 PMA

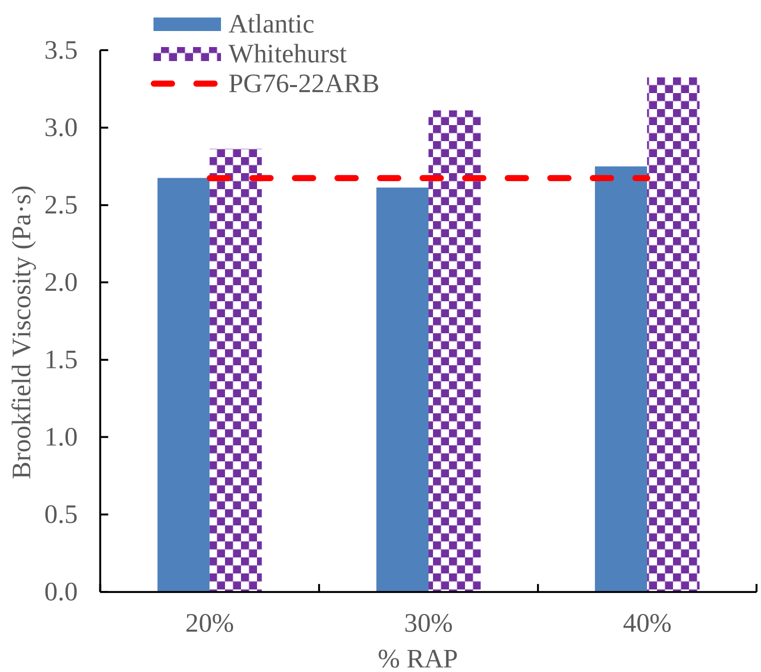

Figure 4-2 Brookfield viscosity: PG 76-22 ARB

4.2.2 Dynamic Shear Rheometer (DSR): Rutting

The DSR measures the complex shear modulus, G*, and phase angle, δ, of the binder. The complex shear modulus is a measure of total resistance of a binder to deform when exposed to repeated pulses of shear stress. The phase angle is an indicator of the relative amount of recoverable and non-recoverable deformation. When rutting is the primary concern, a minimum value for G*/sinδ, the elastic component of the complex shear modulus is specified. In this study, DSR tests were conducted only on virgin binders at high temperature and PAV-aged binders at intermediate temperature. Many state highway agencies, including FDOT, also specify the use of the multiple stress creep recovery (MSCR) test to evaluate RTFO-aged binders. For each blended binder type, two specimens were tested and an averaged value was used for analysis.

Figure 4-3 shows the G*/sinδ for PG 76-22 PMA and RAP blended binders. In terms of stiffness, the RAP binder affected the virgin binder in a positive way as the G*/Sinδ increased with RAP content. The same trend was observed for PG 76-22 ARB and RAP blended binders, as shown in Figure 4-4. All binders met the Superpave specified minimum requirement of 1.0 kPa, the Whitehurst RAP had high effect on G*/sinδ than the Atlantic Coast RAP. Again, Whitehurst RAP is a more aged material than Atlantic Coast RAP.

Figure 4-5 shows the phase angle for virgin binders and blended binders. The FDOT specifies a maximum phase angle of 75 ° for modified binders. All binders do not exceed the FDOT specified maximum value of 75°. It was observed that the addition of RAP increased the phase angle relative to virgin binder. However, this increase is small and very likely associated with data fitting approximations. Figure 4-6 shows the addition of RAP binder significantly increased the shear modulus (G*) of virgin binders and the effect was more pronounced for Whitehurst RAP than Atlantic Coast RAP.

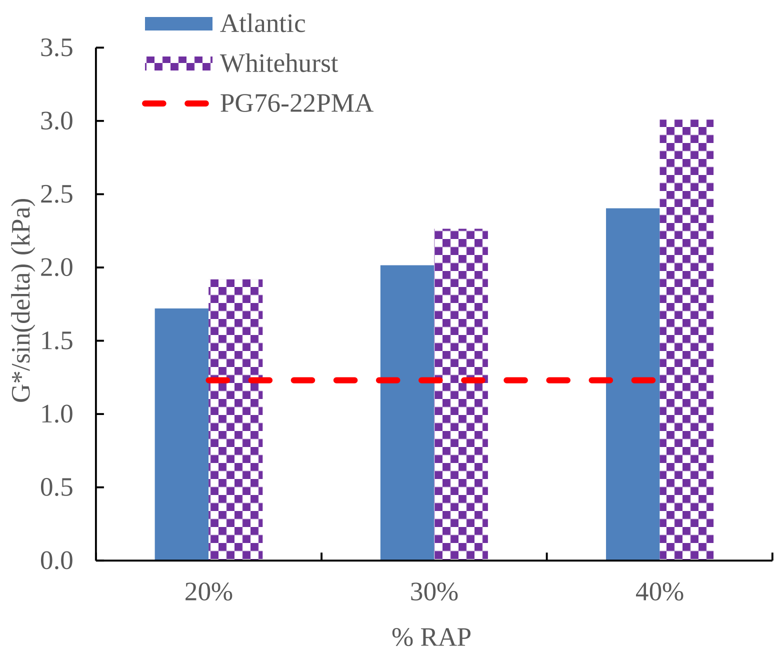

Figure 4-3 G*/sinδ for PG 76-22 PMA and blended binders

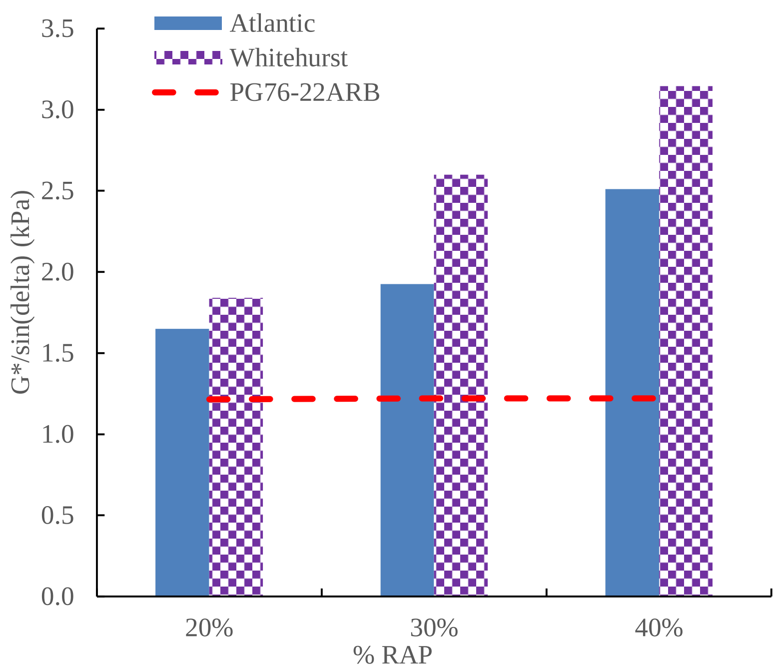

Figure 4-4 G*/sinδ for PG 76-22 ARB and blended binders

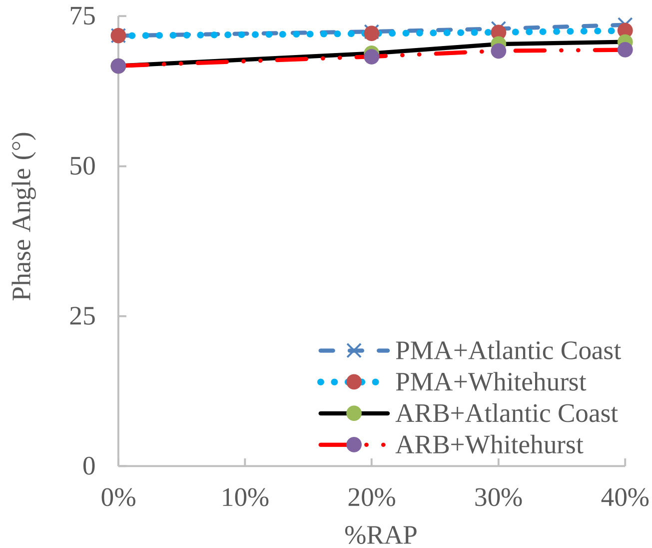

Figure 4-5 Phase angle for virgin and RAP blended binders

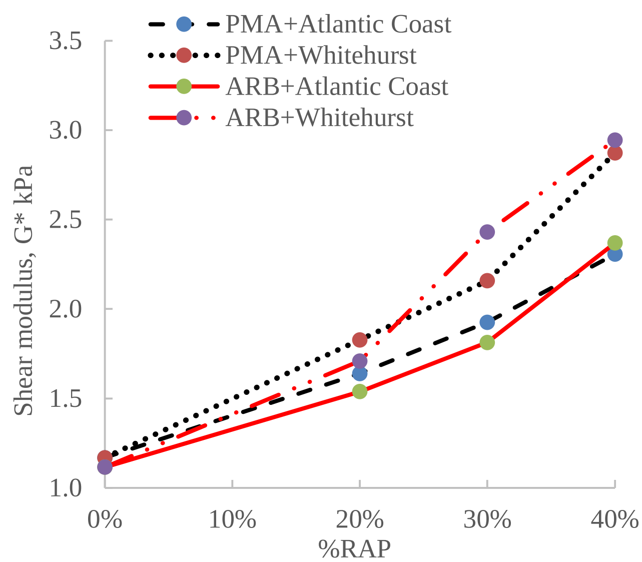

Figure 4-6 Shear modulus (G*) for virgin and RAP blended binders

4.2.3 Dynamic Shear Rheometer (DSR): Fatigue Cracking

To prevent fatigue cracking, an asphalt binder ideally should be elastic but not too stiff. In other words, instead of cracking, the asphalt binder should be able to dissipate energy by rebounding. If the asphalt binder is excessive stiff, it is prone to crack rather than deform-then-rebound. Therefore, when fatigue cracking is the primary concern, a maximum viscous portion of the complex shear modulus, G*sinδ, is established. For each type of binder, two PAV aged specimens were prepared and tested at 26.5 °C and an averaged value was used for analysis. Figure 4-7 shows the results for PG 76-22 PMA and the blended binders. It was observed that the addition of RAP binder increased the

G*Sinδ. In addition, the Whitehurst RAP tended to have more pronounced effects than the Atlantic Coast RAP. Same trend can be found for PG 76-22 ARB and the blended binders, as shown in Figure 4-8. It should be noted that all blended binders do not exceed the maximum requirement (5000 kPa) for virgin binder.

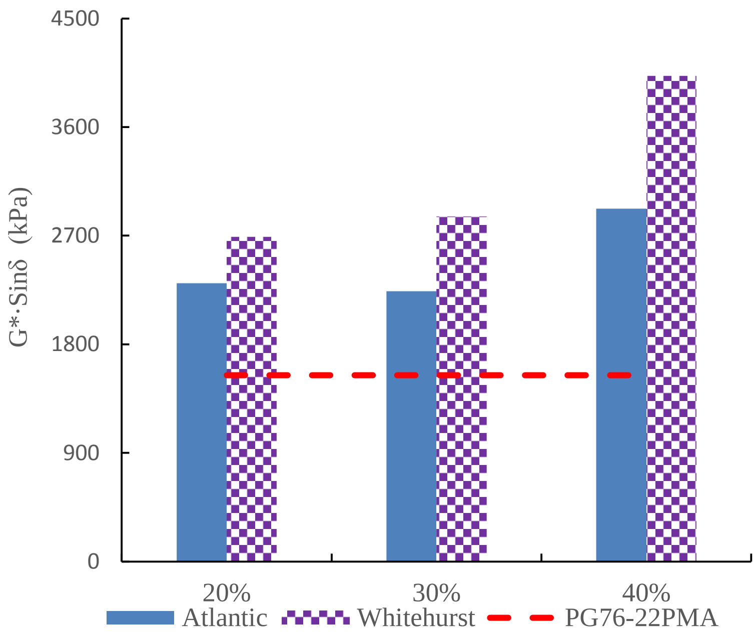

Figure 4-7 G*sinδ for PG 76-22 PMA and blended binders

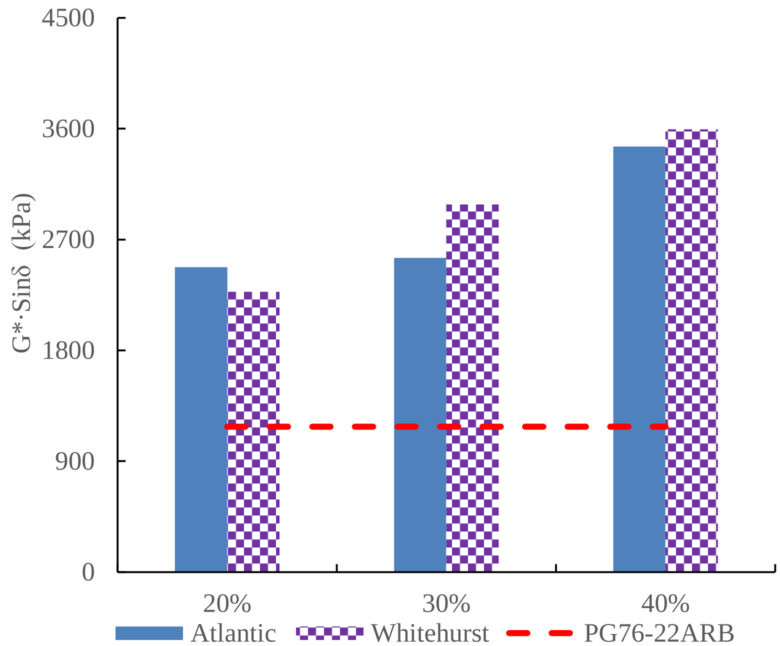

Figure 4-8 G*sinδ for PG 76-22 ARB and blended binders

4.2.4 Bending Beam Rheometer (DSR): Low-temperature Cracking

The Bending Beam Rheometer (BBR) is used to accurately evaluate binder properties at low temperature at which asphalt binders are too stiff to reliably measure rheological properties using the DSR equipment. Since low-temperature cracking occurs normally after the pavement has been in-service for some time, the BBR test addresses the low temperature properties using PAV-aged binder. Two parameters are measured: creep stiffness (S) and rate of stress relaxation (m) at 60 seconds. A maximum of 300 MPa and a minimum of 0.3 are specified for S (60) and m, respectively.

Figure 4-9 shows the stiffness of PG 76-22 PMA and blended binders, and Figure 4-10 shows the stiffness of PG 76-22 ARB and blended binders. Same trend can be found on both figures: as the percentage of RAP increased the stiffness increased. The effects were more pronounced on Whitehurst RAP as compared to the Atlantic Coast RAP. All binders do not exceed the FDOT specified maximum requirement of 300 MPa.

Figure 4-11 shows the stress relaxation value (m) of PG 76-22PMA and blended binders, and Figure 4-12 shows the stress relaxation value (m) of PG 76-22 ARB and blended binders. The same trend can be found on both figures: as the percentage of RAP increased the stiffness increased.

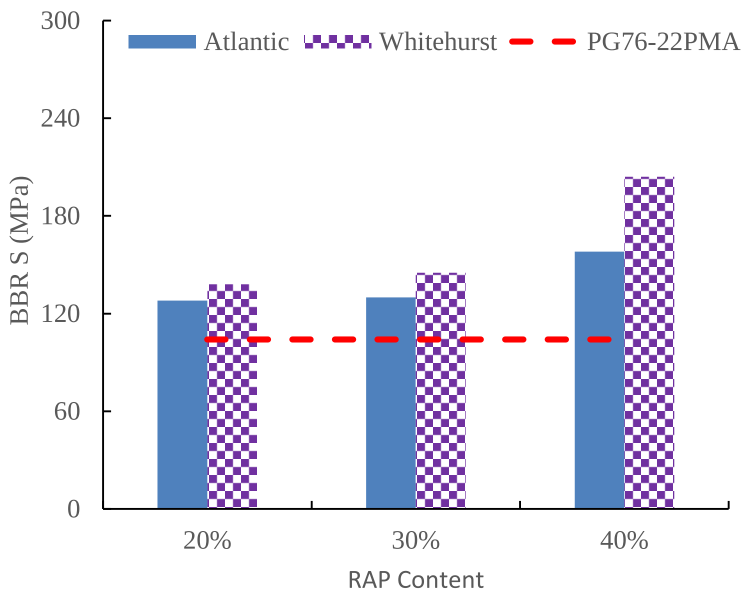

Figure 4-9 Stiffness for PG 76-22 PMA and blended binders

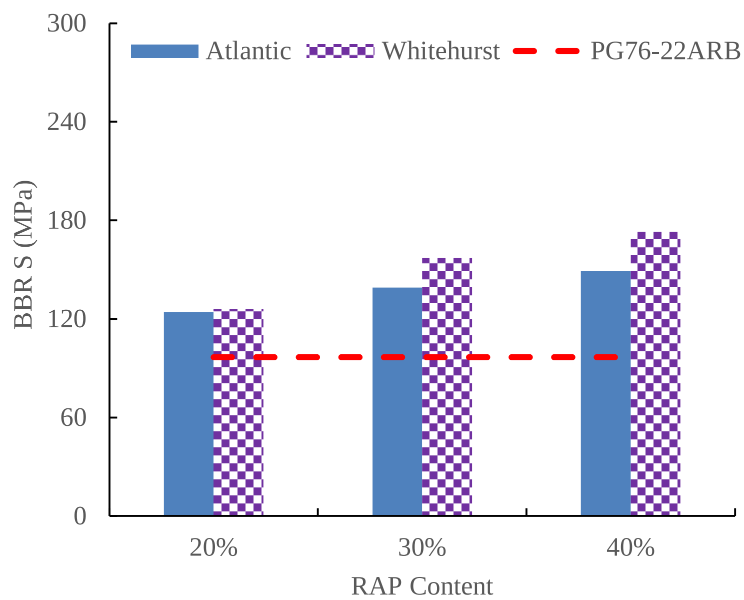

Figure 4-10 Stiffness for PG 76-22 ARB and blended binders

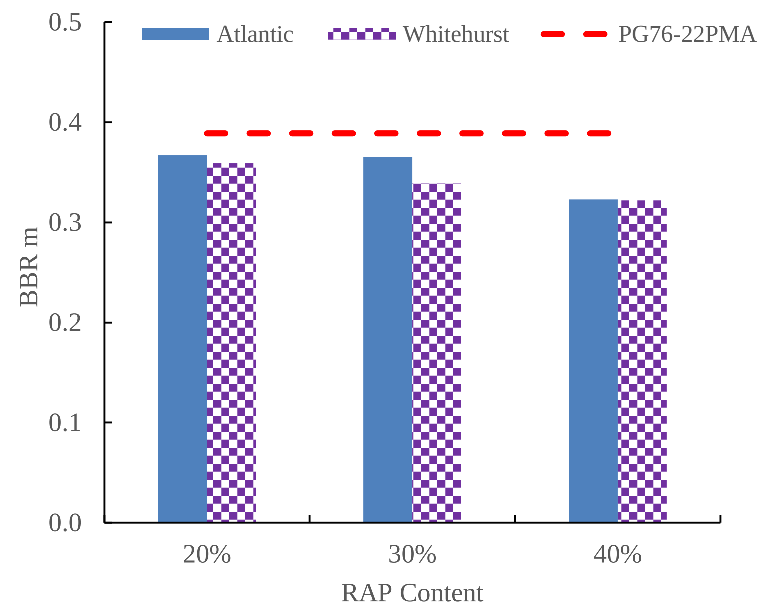

Figure 4-11 Stress relaxation “m” for PG 76-22 PMA and blended binders

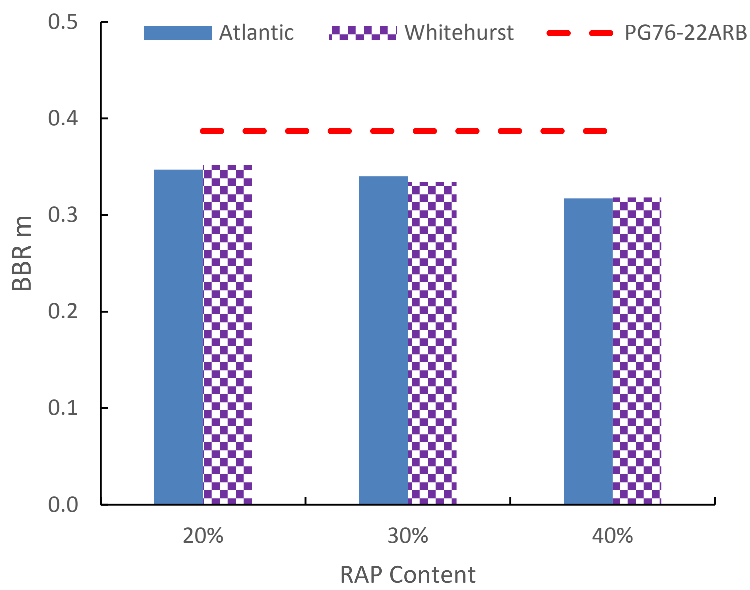

Figure 4-12 Stress relaxation "m" for PG 76-22 ARB and blended binders

4.3 Multiple Stress Creep Recovery Test: Rutting and Polymer Modification

The MSCR test was started with the application of a low stress (0.1 kPa) for 10 creep/recovery cycles then the stress wass increased to 3.2 kPa and repeated for an addition 10 cycles. Two parameters were calculated and evaluated: non-recoverable creep compliance for 10 cycles at a creep stress of 3.2 kPa ($J_{nr, 3.2}$) and %average recovery at a creep stress of 3.2 kPa. RTFO-aged specimens were prepared and tested at 67 °C. For each binder type, two specimens were tested and an average value was used for analysis.

Figure 4-13 shows the $J_{nr, 3.2}$ value for PG 76-22 PMA and blended binders. As the percentage of RAP increased, the non-recovery creep compliance decreased. The Whitehurst RAP had more pronounced effects than the Atlantic Coast RAP. The Atlantic Coast RAP did not affect the PG 76-22 ARB, as shown in Figure 4-14. For Whitehurst, a drop in non-recovery creep compliance was observed at 40% RAP content.

The %recovery parameter was used to characterize the elasticity of polymer-modified asphalt binder. The polymer modification curve adopted in AASHTO TP-70 was developed based on data from available PMA binders. Binders with %recovery above the polymer modification curve indicated good elastomeric behavior. From Figure 4-15, it was observed that all binders, including virgin binders and blended binders, were in the passing zone. It was observed that PG 76-22ARB had higher %recovery than PG 76-22PMA. Figure 16 was prepared to better illustrate the effects of RAP binder on the elastomeric behavior of virgin binders. For each binder, the minimum %recovery was calculated using a power function of $J_{nr, 3.2}$.

Figure 4-16 shows the effect of increasing RAP binder (Atlantic Coast and Whitehurst) contents on minimum %recovery requirement and actual %recovery for

PMA and ARB. Increasing RAP had a greater effect on minimum %recovery for PMA than for ARB, whereas the effect on actual %recovery was greater for ARB than for PMA. The figure also shows actual %recovery of ARB was not only higher than the PMA binder but also showed a greater difference between actual and minimum %recovery at all RAP binder contents.

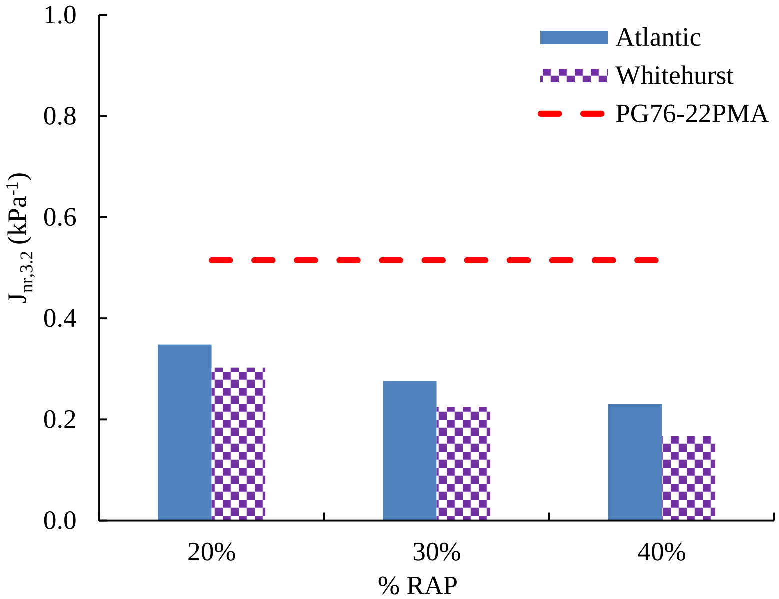

Figure 4-13 $J_{nr,\,3.2}$ for PG 76-22 PMA and blended binders

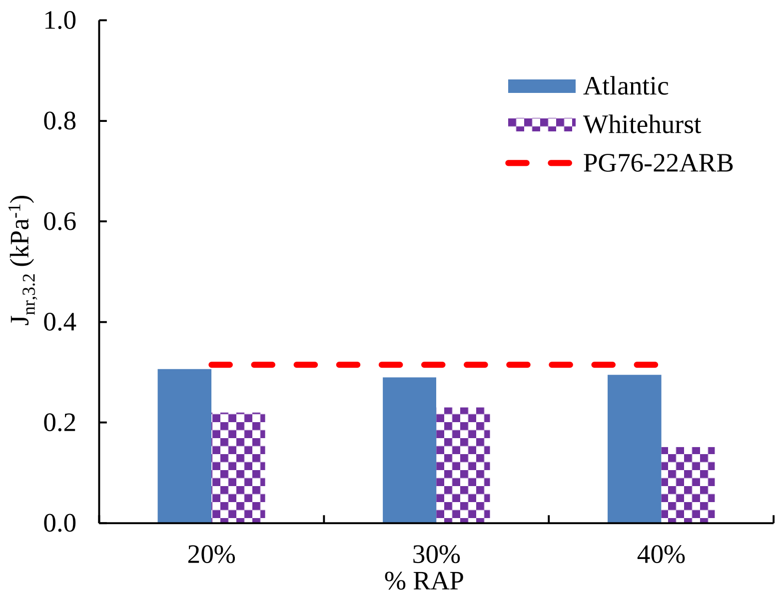

Figure 4-14 $J_{nr,\,3.2}$ for PG 76-22 ARB and blended binders

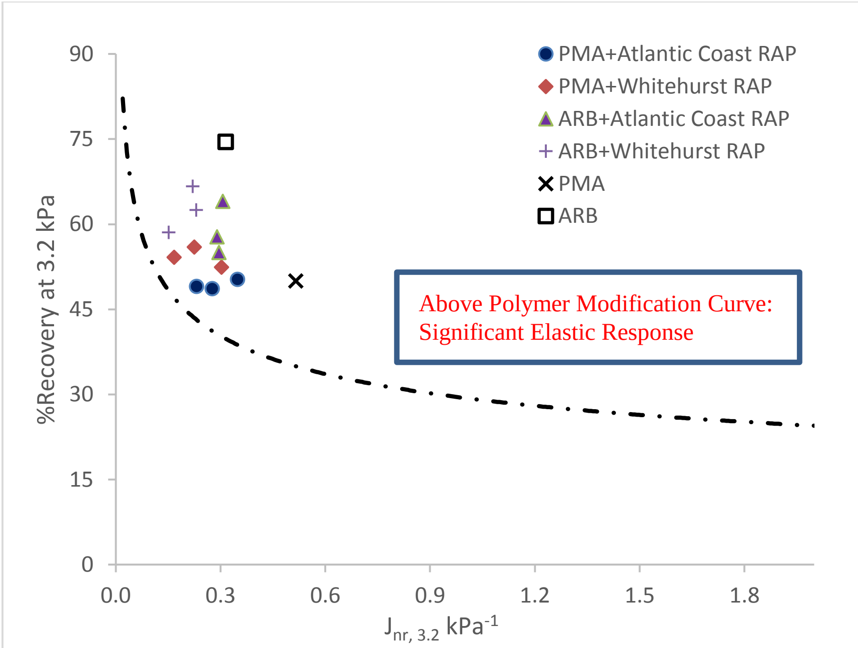

Figure 4-15 Illustration of measured %recovery and minimum requirements

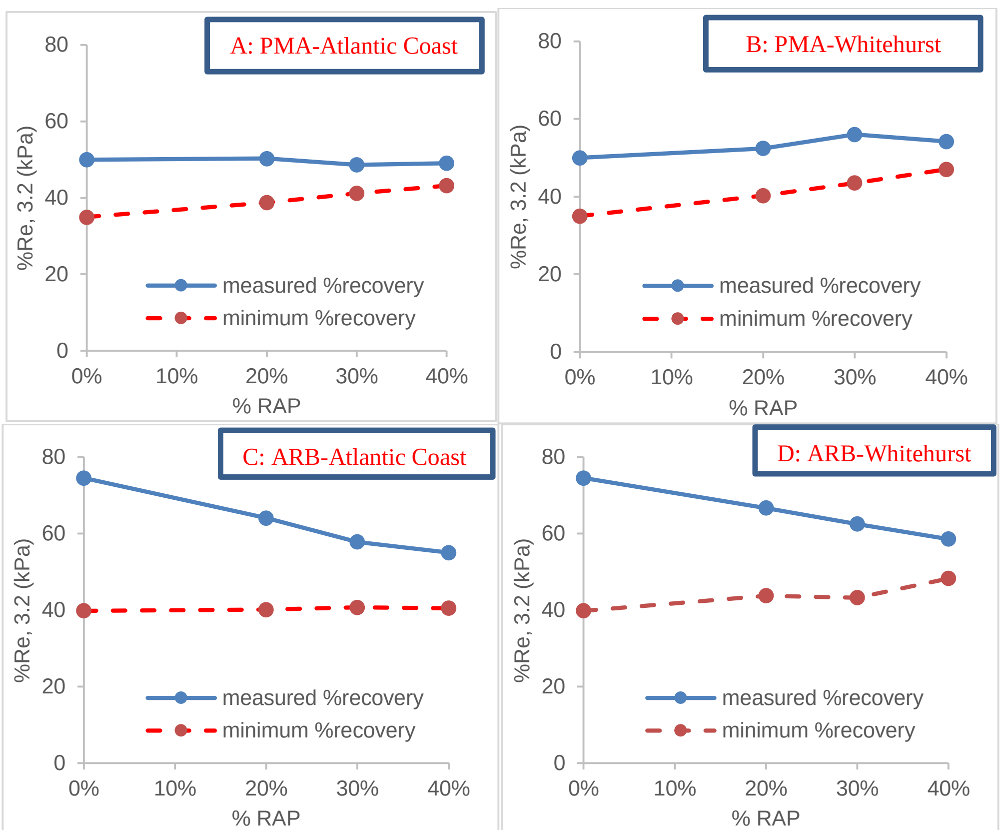

Figure 4-16 %Recovery and minimum requirements for blended binders

4.4 Binder Fracture Energy (BFE) Test: Cracking

The BFE test was developed to evaluate the cracking performance of asphalt binder at the intermediate temperature ranges. It is performed by pulling on two loading heads attached to an asphalt binder specimen at a constant displacement rate until failure occurs. Fracture energy density (FED) is defined as the area under the true stress-true strain curve up to the last true stress peak or inflection point depending on binder types. Previous research revealed that binder fracture energy density is a fundamental material property of asphalt binder as identical results were obtained for a given binder regardless of testing temperature (within the intermediate temperature range) and displacement rate. Table 4-3 summarizes the reference values of fracture energy density and characteristics of the true stress-true strain curve associated with different binders from previous research. In this study, the initial testing temperature was 15 °C and the displacement rate was 500 mm/min. For each type of binder, two successful testing results were obtained and an averaged value was used for comparison.

Table 4-3 Typical Fracture Energy Density Values of Different Binders and Corresponding Characteristics of the True Stress-True Strain Curves

Binder	% SBS	% Rubber	FE Density (psi)	First Stress Peak	Second Stress Peak	Inflection Point
Unmodified	0	0	200-300	Yes	No	No
Rubber-modified	0	5.0-13.0	400-500	Yes	No	Yes
SBS-modified	4.25	0	600-700	Yes(1)	Yes	No
	8.5	0	1600-1700	Yes	Yes	No

Note: (1) Some SBS binders do not exhibit a pronounced initial stress peak, but rather a continuously increasing stress to failure at high strain levels.

4.4.1 Fracture Energy Density (FED) Results

Figure 4-17 shows the binder fracture energy density of PG 76-22 PMA and blended binders. It was observed that the addition of RAP binder reduced the FED compared to the virgin PG 76-22 PMA binder. The Whitehurst RAP blended binders had higher FED than the Atlantic Coast RAP blended binders at all percentages. 40% Atlantic RAP blended binders had the lowest FED, however, the values were still higher than values obtained from previous research for unmodified binders (200-300 psi) and rubber modified binders (400-500 psi), and even above the range of 4.25% SBS-modified binder (600 to 700 psi).

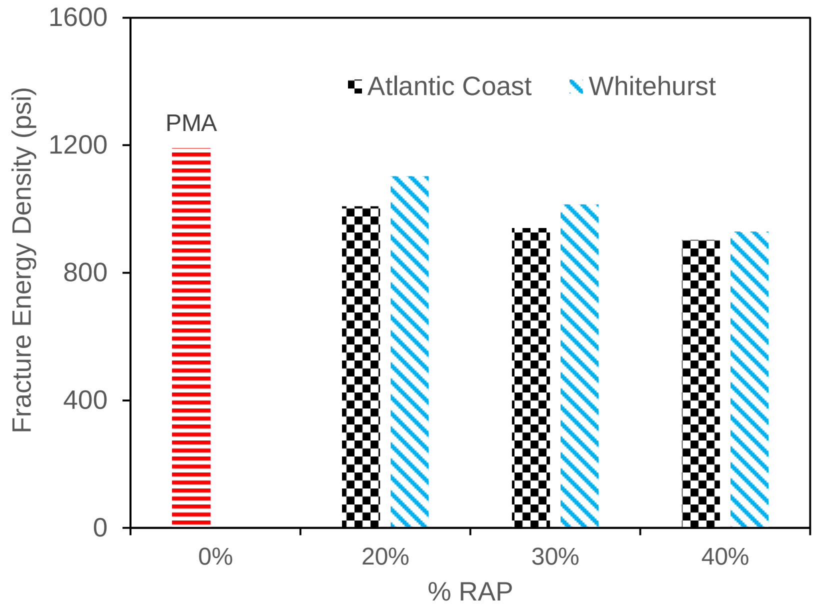

Figure 4-17 Binder fracture energy density for PG 76-22 PMA and blended binders

Figure 4-18 shows the binder fracture energy density of PG 76-22 ARB and blended binders. Unlike PG 76-22 PMA, the PG 76-22 ARB was less affected by RAP binder. Only at 40% Atlantic Coast RAP, the FED clearly dropped. All blended binders showed good FED results as they were all above 600 psi.

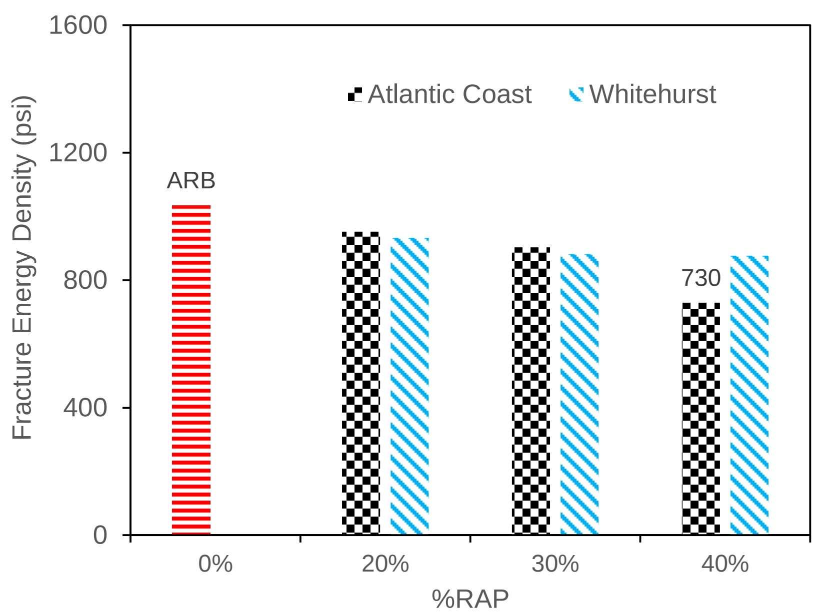

Figure 4-18 Binder fracture energy density for PG 76-22 ARB and blended binders

4.4.1.1 True Stress-True Strain Curve Results

Previous research (Roque et al, 2014 and Yan et al, 2015) revealed that each binder type has a unique true stress-true strain curve that can be used for identification purpose: unmodified binders typically present one single true stress peak, rubber-modified binders have an "inflection" after the first true stress peak, and SBS-modified binders have a second true stress peak.

Figure 4-19 shows the true stress-true strain curves for PG 76-22 PMA, 20%, 30% and 40% Atlantic RAP blended binders. On each figure, there were two specimens testing results presented. As the percentage of RAP increased, the second true stress peak became less pronounced. The same trend can be found in Figure 4-20, which shows the true stress-strain curves for PG 76-22 PMA and 20%, 30% and 40% Whitehurst RAP blended binders. This observation indicates that the addition of RAP binder potentially diluted the polymer modification.

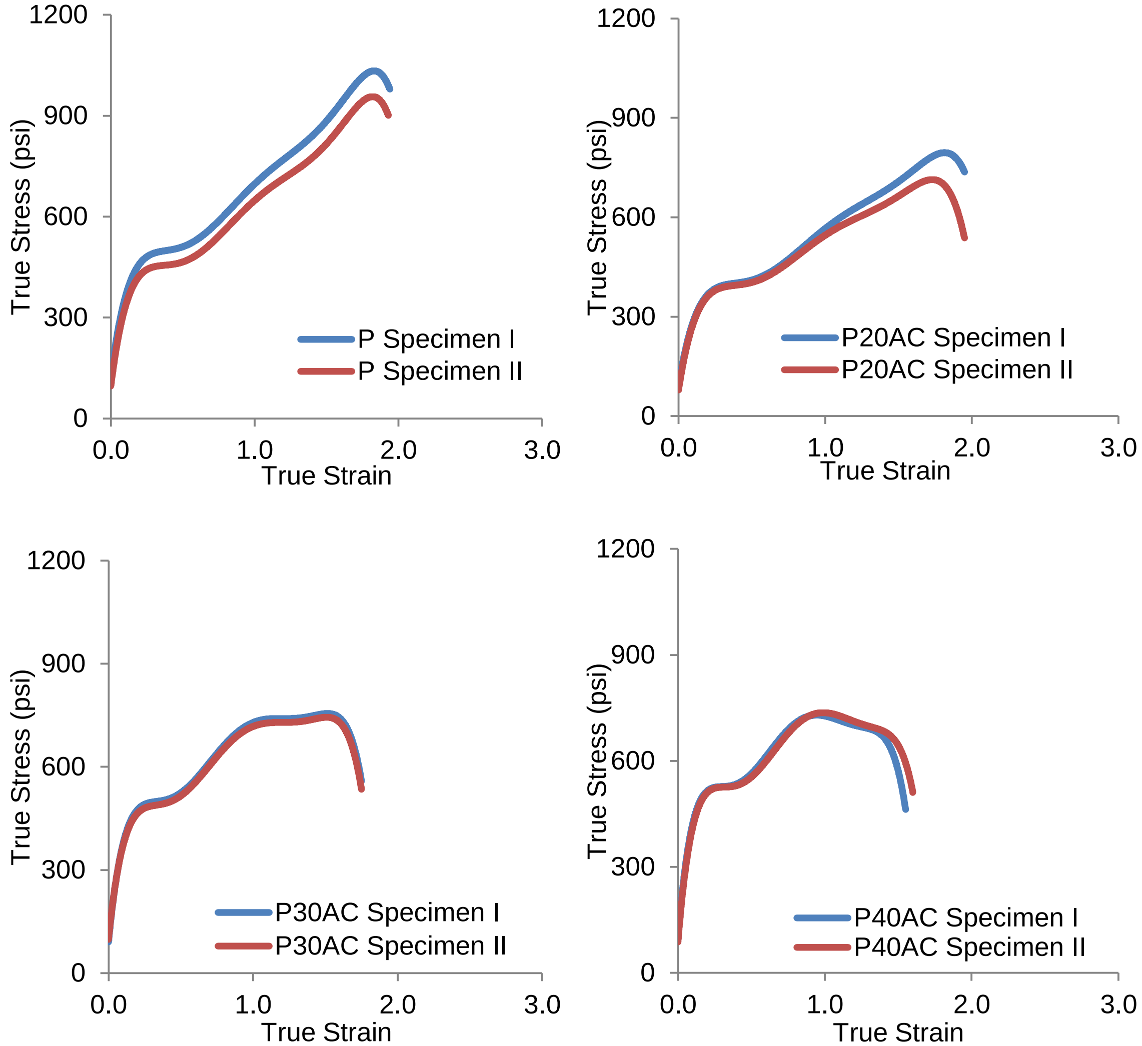

Figure 4-19 True stress-true strain curves for PG 76-22 PMA (P) and Atlantic Coast RAP (AC) blended binders

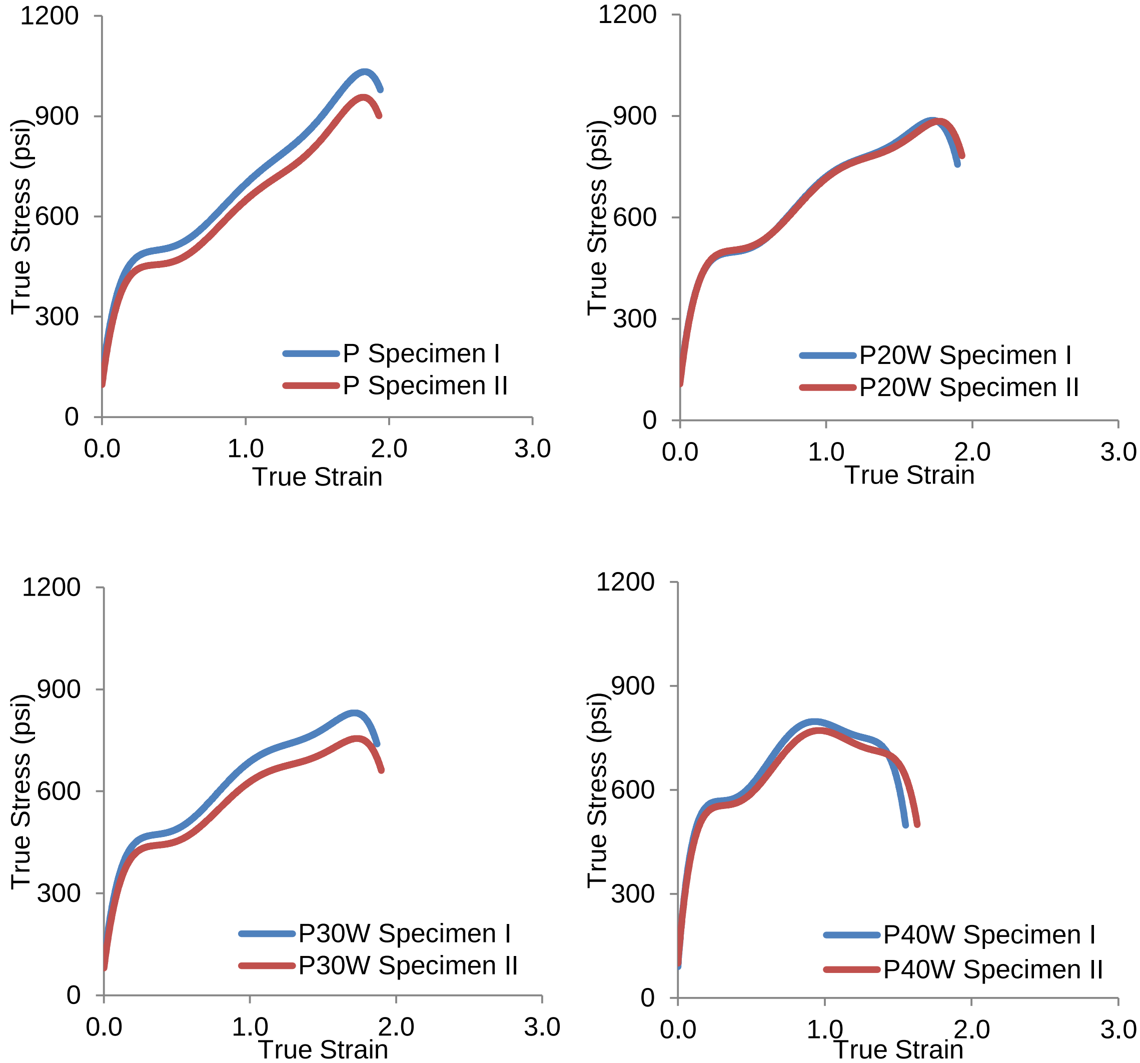

Figure 4-20 True stress-true strain curves for PG 76-22 PMA (P) and Whitehurst RAP (W) blended binders

Figures 4-21 and 4-22 show the true stress-true strain curves for PG 76-22 ARB, 20%, 30% and 40% Atlantic Coast and Whitehurst RAP blended binders, respectively. The PG 76-22 ARB has a clear second peak stress on the true stress-true strain curve indicating that it may have high polymer content. The RAP binders were found not to affect the overall shape of the true stress-true strain curves, but reduced the true stress as compared to the virgin PG 76-22 ARB binder.

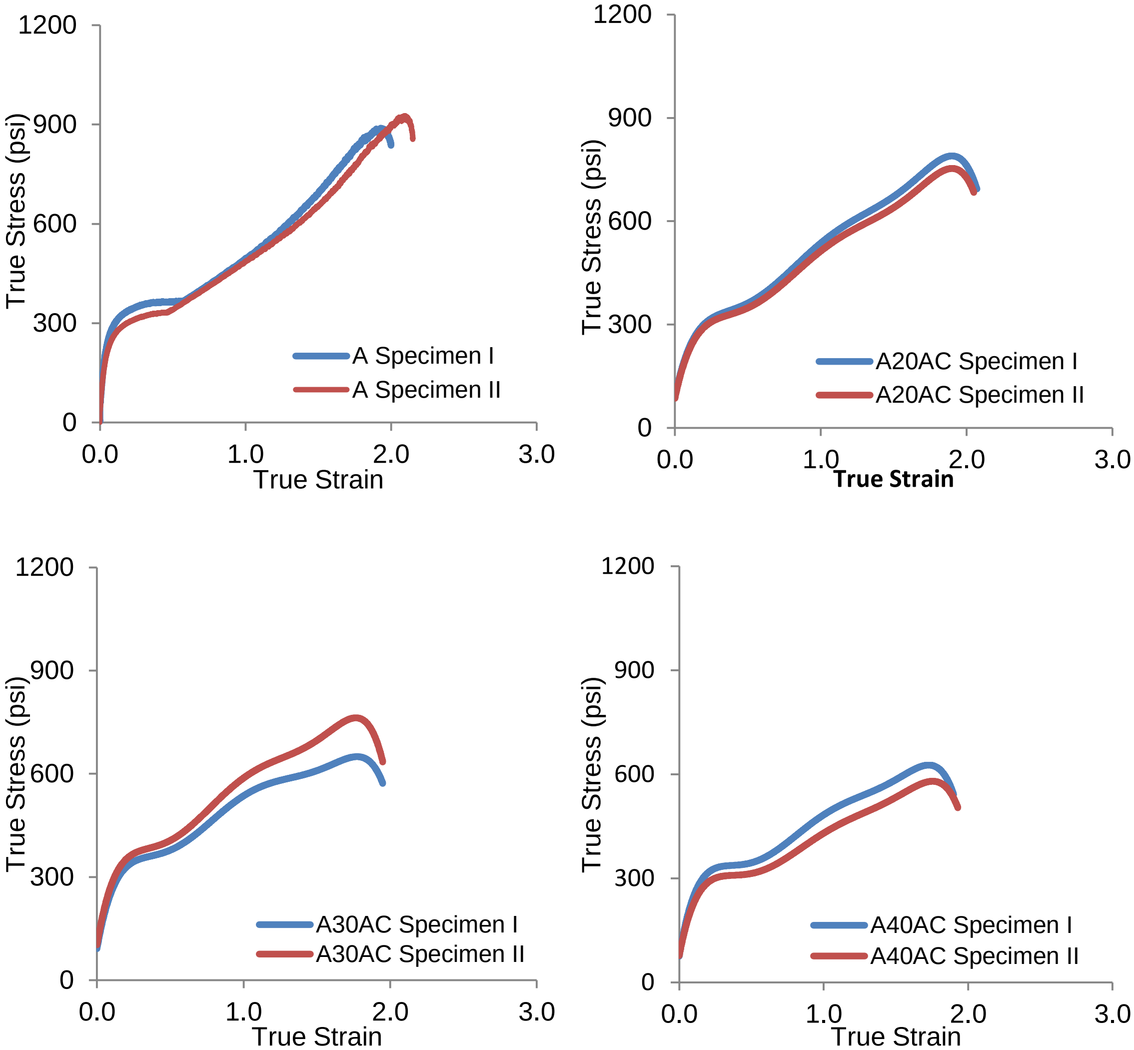

Figure 4-21 True stress-true strain curves for PG 76-22 ARB (A) and Atlantic Coast RAP (AC) blended binders

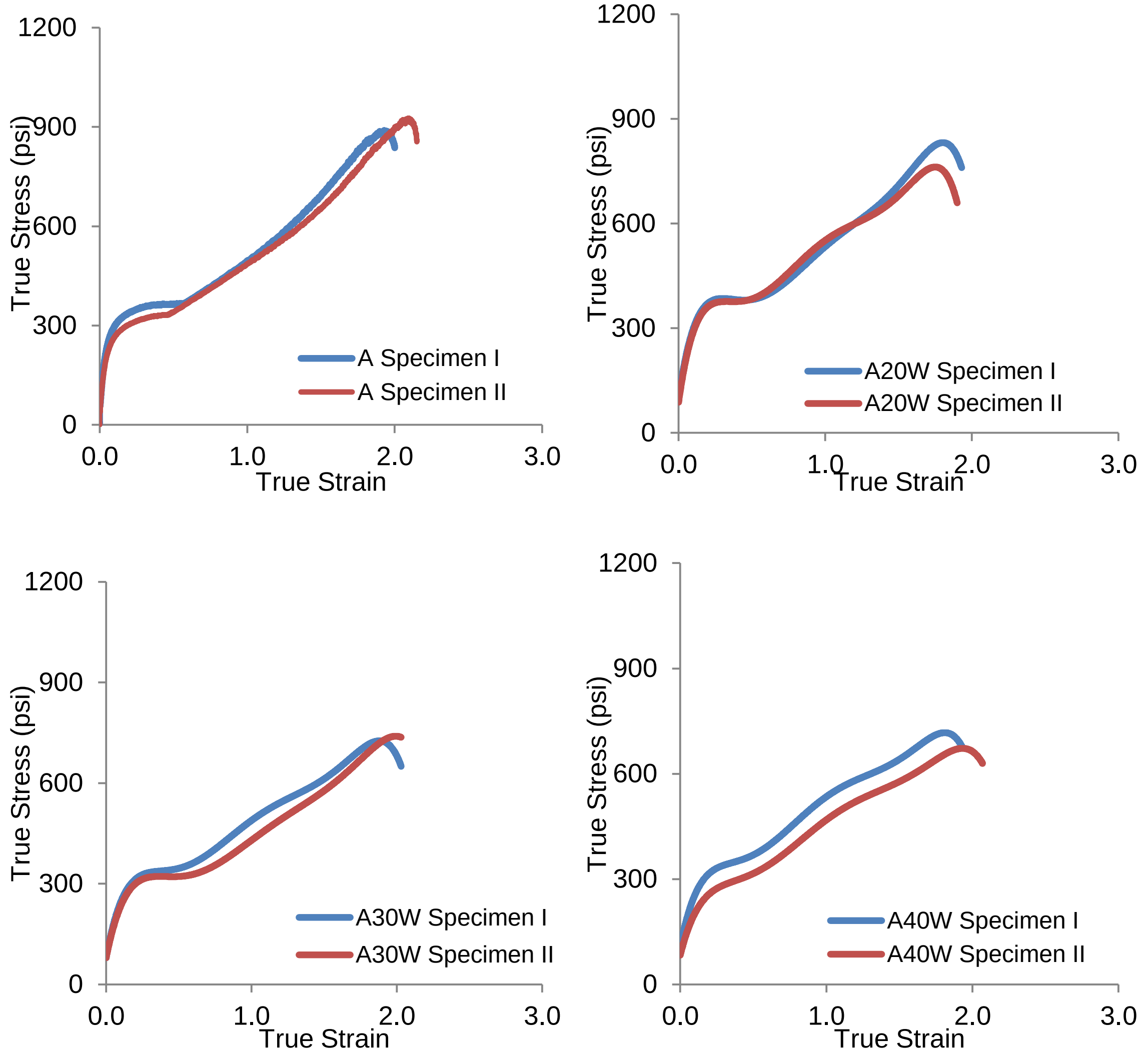

Figure 4-22 True stress-true strain curves for PG 76-22 ARB (A) and Whitehurst RAP (W) blended binders

4.4 Summary

To evaluate the effects of RAP on binder properties, laboratory blended binder specimens were prepared and tested using the Superpave binder tests, the multiple stress creep recovery (MSCR) test and the binder fracture energy (BFE) test.

All binders including the virgin binders and the blended binders met the Superpave low, intermediate and high temperature requirements for virgin modified binders. The addition of RAP binder increased the stiffness of the virgin binders. The WHI RAP had more pronounced effect on binder properties than the ATL RAP.

Based on the $J_{nr, 3.2}$ results obtained from the MSCR test, the addition of RAP binder enhanced the rutting resistance of virgin binders. Although RAP binders reduced the %Recovery of virgin binders, all blended binders, even at 40% RAP content, exhibited good elastomeric behavior.

Binder fracture energy (BFE) tests were conducted to evaluate the cracking resistance of asphalt binders at intermediate temperature. Both virgin binders, PG 76-22 PMA and ARB, exhibited excellent fracture energy density. The addition of RAP binders reduced the FED of the PG 76-22 PMA, but even 40% RAP blended binder retained FED above the reference value range of the 4.5% SBS-modified binder (approximately 600 to 700 psi from previous research). The addition of RAP binder did not notably reduce the FED of PG 76-22 ARB except for 40% ATL RAP blended binder. Again, the lowest retained FED was greater than the reference value of the rubber-modified binder (approximately 400 to 500 psi from previous research).

These binder testing results indicate that use of up to 40% RAP was potentially acceptable. Therefore, mixture test evaluation were performed using up to 40% RAP.

CHAPTER 5 MIXTURE TEST RESULTS

5.1 Introduction

A total of 28 mixture combinations was designed and evaluated to determine the maximum amount of RAP material allowable in friction courses without jeopardizing pavement performance. The experimental factors included two RAP sources, four RAP contents, two virgin binders, and two mixture conditioning levels. Fracture properties from Superpave IDT test at 10 °C and the energy ratio (ER) parameter derived from the hot-mix-asphalt mixture mechanics (HMA-FM) were used to evaluate the relative cracking performance of mixtures with various RAP contents. One complete set of Superpave IDT tests consisted of resilient modulus (Mr), creep compliance, and fracture tests. For each combination, three IDT specimens were tested, and the ITLT software was used to reduce and process the testing data. Detailed Superpave IDT testing data can be found in Appendix F.

Mixture properties determined from the analysis included resilient modulus (Mr), creep compliance rate, fracture energy density (FED), strength, dissipated creep strain energy (DCSE), and failure strain. Properties determined after STOA conditioning provided a quick glance at the general effects of experimental factors on mixture properties. Roque et al. (20049 determined that the combination of LTOA+CPPC conditioning most closely represents the effects of long-term changes in mixture properties observed in the field. They also determined that ER is a better predictor of cracking-related performance than any other single mixture property. Therefore, the determination of maximum allowable amount of RAP material was conducted based on mixture properties at LTOA+CPPC conditioning level using the ER parameter.

5.2 Mixtures Evaluation after STOA Conditioning

5.2.1 Introduction

Based on Superpave IDT testing results on STOA conditioned specimens, the following sections discuss the effect of RAP content and RAP characteristics on mixture properties. Comparisons were also made between same mixtures with different virgin binder. For clearer presentation, Atlantic RAP mixtures mixed with PG 76-22PMA and PG 76-22ARB were designated as ATL-PMA and ATL-ARB mixtures, respectively. Similarly, Whitehurst RAP mixtures mixed with PG 76-22PMA and PG 76-22ARB were designated as WHI-PMA and WHI-ARB mixtures, respectively.

5.2.2 Atlantic Coast (ATL) RAP Mixtures

Figures 5-1 and 5-2 show that tensile strength slightly increased and failure strain decreased as the RAP content increased. The overall effect of these trends was a reduction in FED as ATL RAP content increased, as shown in Figure 5-3. Interestingly, the clear reduction in failure strain and FE gradually slowed down when more than 20% of ATL RAP was introduced. In general, mixtures with PG 76-22ARB had lower tensile strength, higher failure strain, and slightly higher FED than mixtures with PG 76-22PMA.

Figure 5-4 depicts the resilient modulus increased as ATL RAP content increased indicating that addition of ATL RAP content stiffened the virgin mixtures. As shown in Figure 5-5, the creep compliance rate decreased as RAP content increased, which was expected as compliance is related to stiffness at longer loading time. It was also observed that mixtures with PG 76-22PMA consistently had lower creep compliance rate than mixtures with PG 76-22ARB.

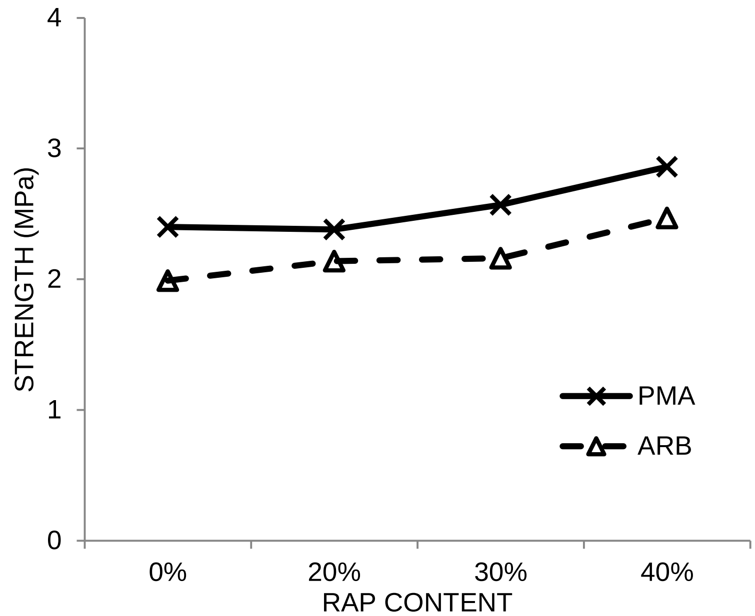

Figure 5-1 Strength of ATL-PMA and ATL-ARB mixtures after STOA conditioning

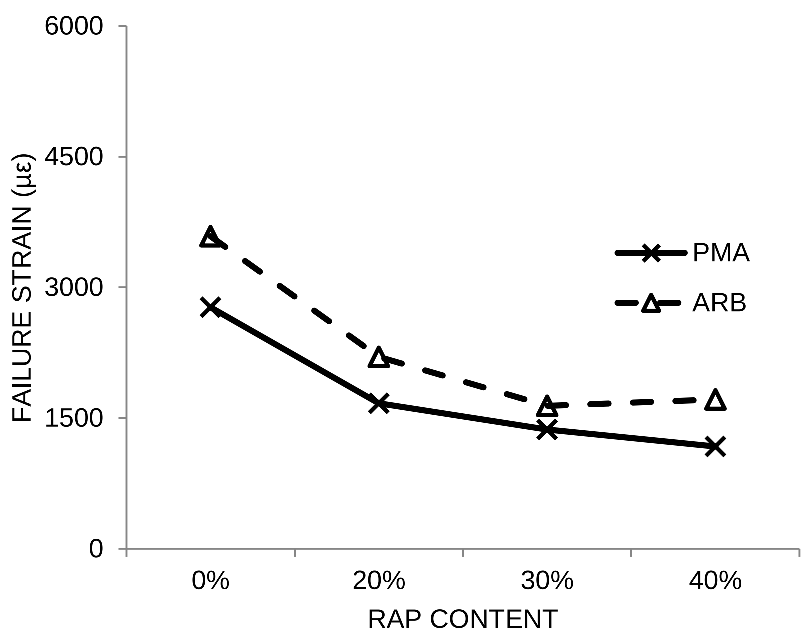

Figure 5-2 Failure strain of ATL-PMA and ATL-ARB mixtures after STOA conditioning

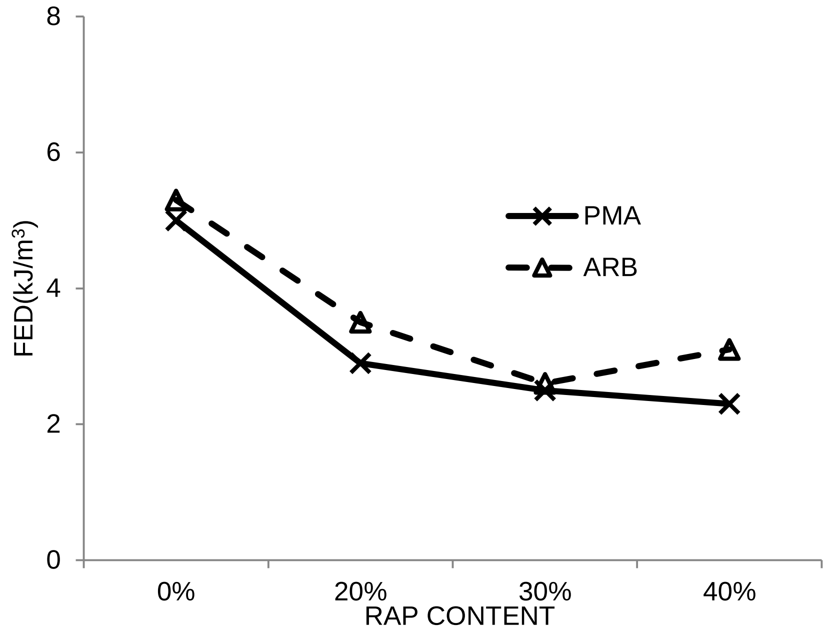

Figure 5-3 Fracture energy density of ATL-PMA and ATL-ARB mixtures after STOA conditioning

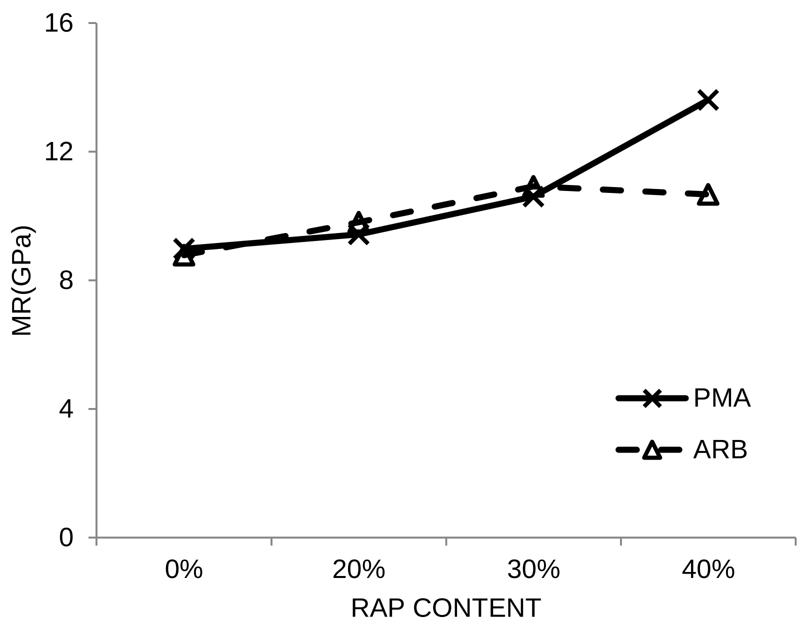

Figure 5-4 Resilient modulus of ATL-PMA and ATL-ARB mixtures after STOA conditioning

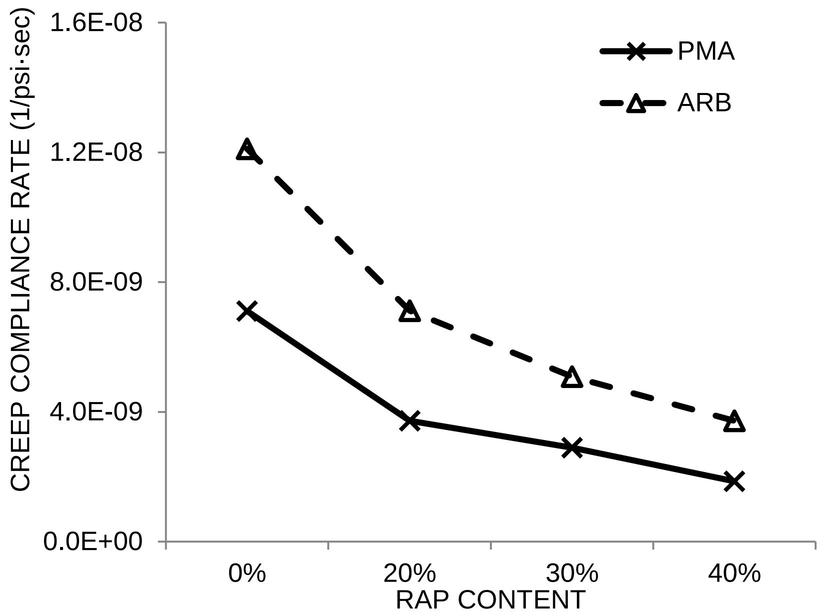

Figure 5-5 Creep compliance rate of ATL-PMA and ATL-ARB mixtures after STOA conditioning

5.2.3 Whitehurst (WHI) RAP Mixtures

Figure 5-6 depicts that the tensile strength of WHI RAP mixtures was minimally affected by RAP content. Figure 5-7 shows that failure strain decreased as the RAP content increased. As shown in Figure 5-8, the FED of RAP mixtures reduced as the RAP content increased. Note that failure strain and FED dropped for RAP content of 40%. Generally, mixtures with PG 76-22ARB had higher tensile strength, lower failure strain and lower FED than mixtures with PG 76-22PMA.

Figure 5-9 shows resilient modulus was relatively unaffected by RAP content up to 40% for WHI-ARB mixtures and RAP contents up to 30% for WHI-PMA mixtures, for which resilient modulus increased when RAP was increased to 40%. As expected, Figure 5-10 shows creep compliance rate of all WHI RAP mixtures generally decreased as the RAP content increased. Interestingly, 20% WHI RAP mixtures had comparable creep compliance rate to 30% WHI RAP mixtures, but a clear reduction occurred for 40% WHI RAP.

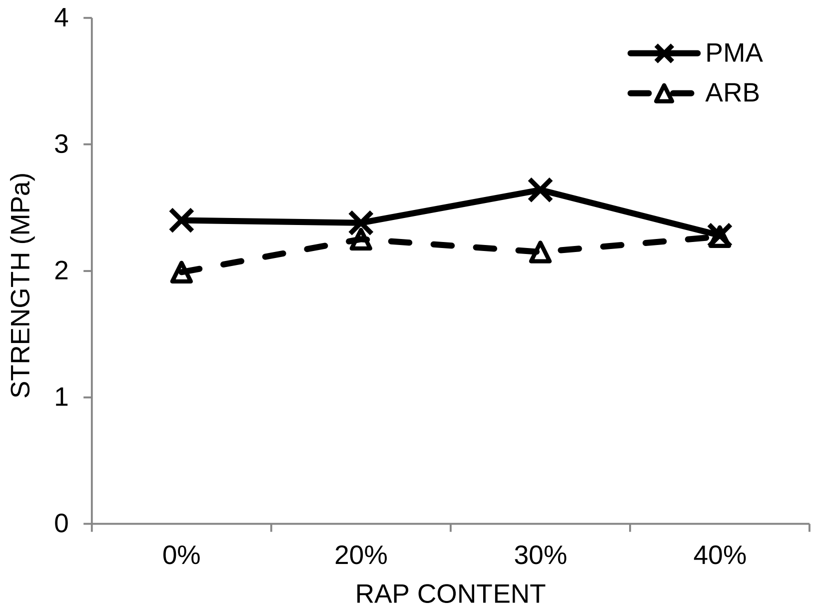

Figure 5-6 Strength of WHI-PMA and WHI-ARB mixtures after STOA conditioning

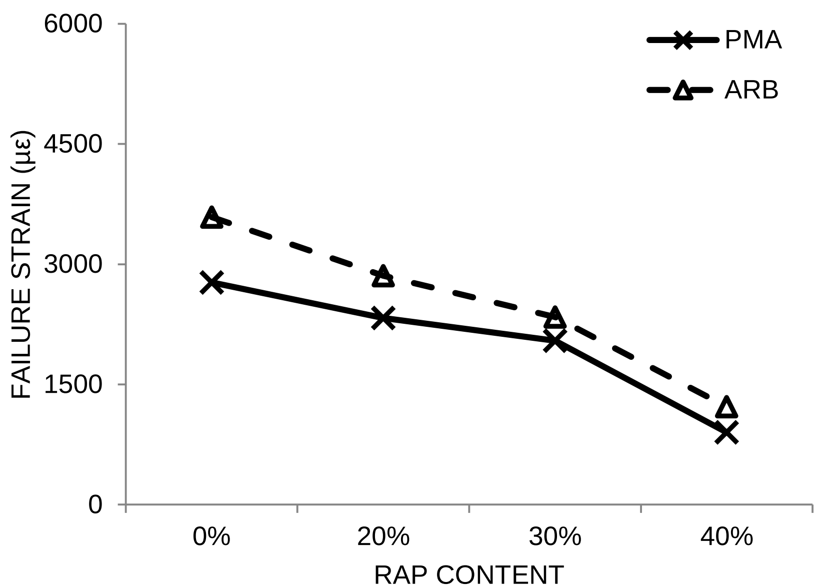

Figure 5-7 Failure strain of WHI-PMA and WHI-ARB mixtures after STOA conditioning

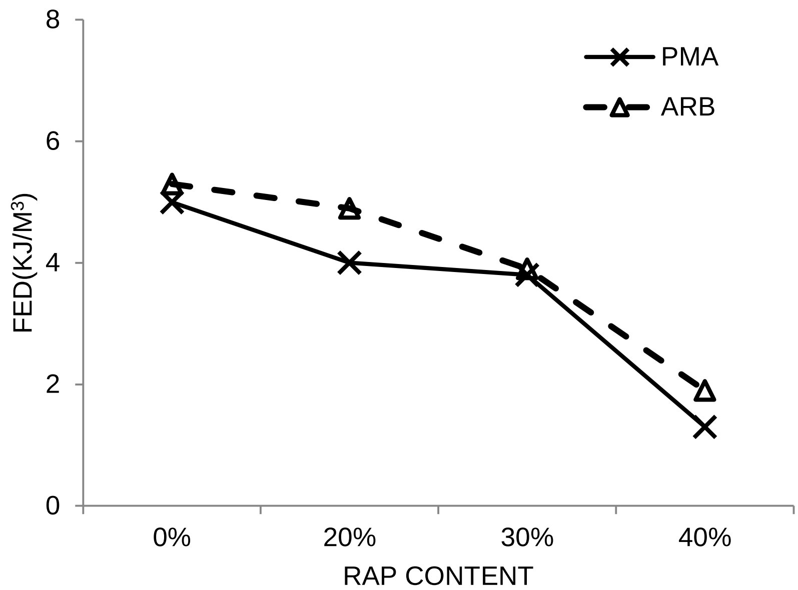

Figure 5-8 Fracture energy density of WHI-PMA and WHI-ARB mixtures after STOA conditioning

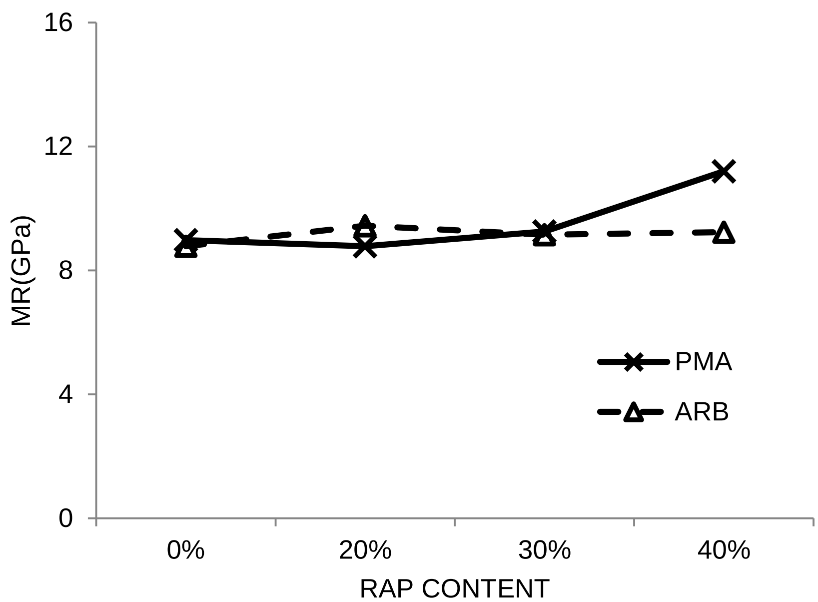

Figure 5-9 Resilient modulus of WHI-PMA and WHI-ARB mixtures after STOA conditioning

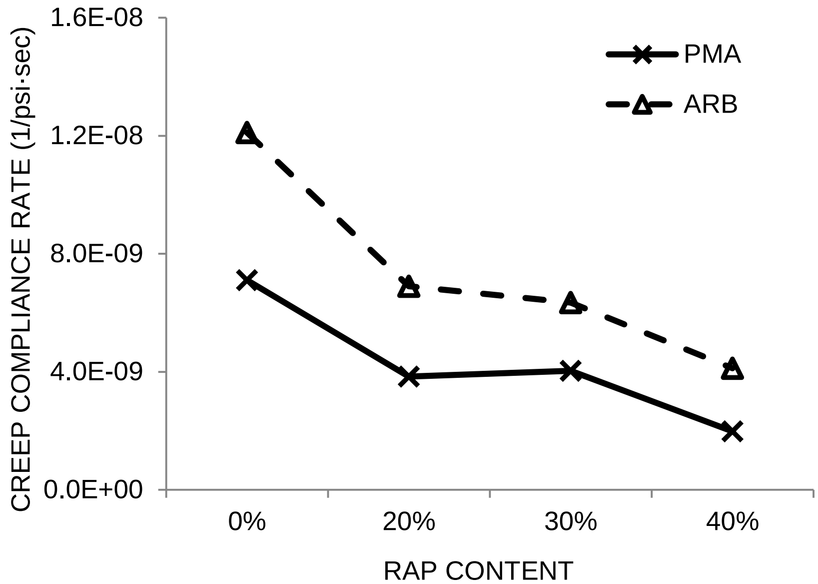

Figure 5-10 Creep compliance rate of WHI-PMA and WHI-ARB mixtures after STOA conditioning

5.2.4 Comparison between ATL RAP and WHI RAP Mixtures

Based on mixture properties obtained at STOA conditioning level, comparisons were made between ATL RAP and WHI RAP mixtures. Figure 5-11 presents a complete set of tensile strength data for all mixtures. PMA results were presented on the left side and ARB results on the right. Regardless of virgin binder type, ATL RAP mixtures generally had similar tensile strength to WHI RAP mixtures up to 30%RAP content. However, 40% ATL RAP mixtures yield higher tensile strength than 40% WHI RAP mixtures and the difference was more pronounced for PG 76-22PMA mixtures than for those with PG 76-22ARB.

Figures 5-12 and 5-13 illustrate how RAP gradation can have a dominant effect on failure strain and fracture energy. For both PMA and ARB binder, the coarser WHI RAP had higher failure strain and fracture energy for RAP contents up to 30%. As shown in Figure 5-14, WHI RAP was very coarse with 72% of its aggregate retained on the 4.75 mm sieve, while the ATL-RAP was much finer with 75% passing the 4.75 mm sieve. Consequently, the virgin portion of the WHI RAP mixture was relatively fine, while the virgin portion of the ATL RAP was relatively coarse. Since failure strain and fracture energy are primarily controlled by the finer portion of the mixture, mixtures with virgin finer aggregate (e.g., WHI RAP mixture) were expected to have higher failure strain and FED.

However, Figures 5-12 and 5-13 also show this trend was dramatically reversed at 40% RAP content where the failure strain and fracture energy of the WHI RAP mixture dropped below that of the ATL RAP mixture. It appears the amount of coarse weak limestone in the WHI RAP was enough to become the dominant factor in mixture failure strain and fracture energy. Figure 5-15 shows the limestone RAP aggregate in the WHI RAP makes up almost 100% of the RAP mixture aggregate retained on the 4.75 mm sieve. This effect appeared to overwhelm the positive effects of having virgin finer RAP observed in WHI RAP mixtures with RAP levels up to 30%.

The resilient modulus results presented in Figure 5-16 substantiate that the reduction in fracture energy observed at 40% RAP for the WHI RAP resulted primarily from the weakness of the limestone in the RAP. Since resilient modulus is a small strain response parameter, it is unaffected by strength or brittleness of rock and is primarily a reflection of the stiffness of the finer portion of the mixture. So, as expected, resilient modulus was lower for the WHI RAP mixtures because the finer portion of these mixtures was primarily virgin aggregate. This trend was observed even at the 40% RAP level.

Creep compliance, on the other hand, is a larger strain response parameter affected by all components of the mixture. Consequently, the effect of RAP level on creep compliance rate was almost the same for the ATL and WHI RAP mixtures (Figure 5-17). Explained in another way, whereas small strain response associated with resilient modulus was primarily affected by the finer portion of mixtures, creep compliance rate was also affected by the coarser portion. Therefore, the stiffer and coarser WHI RAP counterbalanced the effect of the lower stiffness of the virgin finer portion. Figure 5-17 also shows that PMA binder resulted in lower creep compliance rate than ARB binder. This observation is consistent with results of all previous research comparing PMA and ARB mixtures.

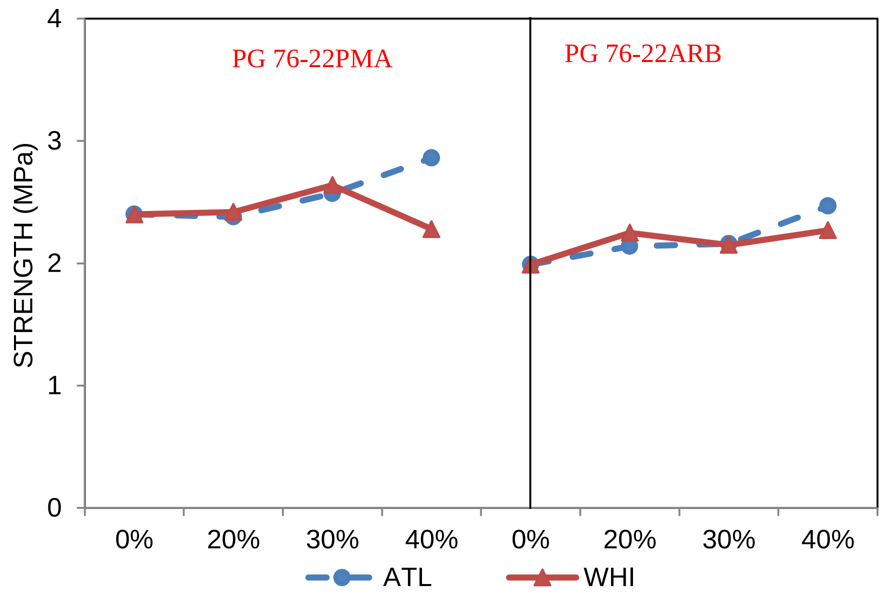

Figure 5-11 Strength of ATL and WHI RAP mixtures after STOA conditioning

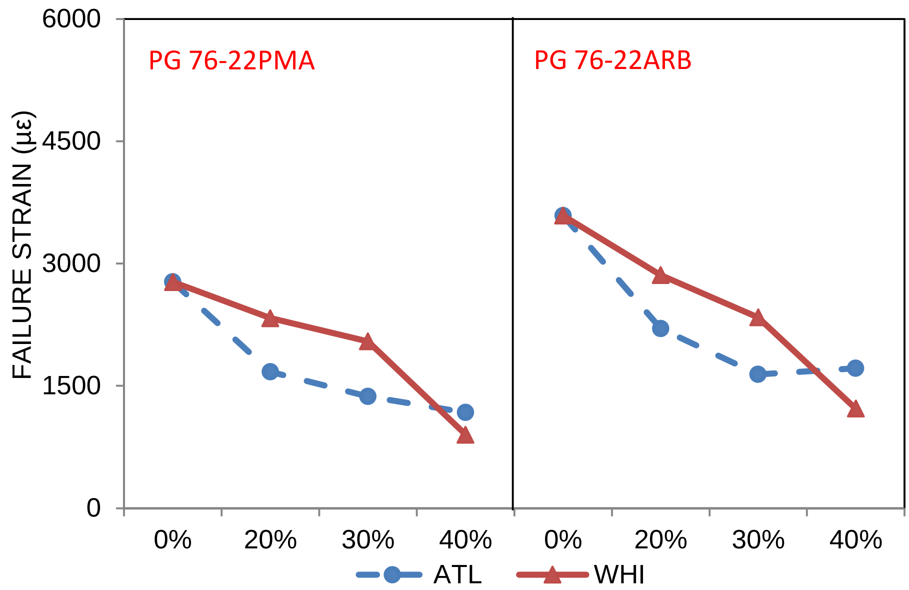

Figure 5-12 Failure strain of ATL and WHI RAP mixtures after STOA conditioning

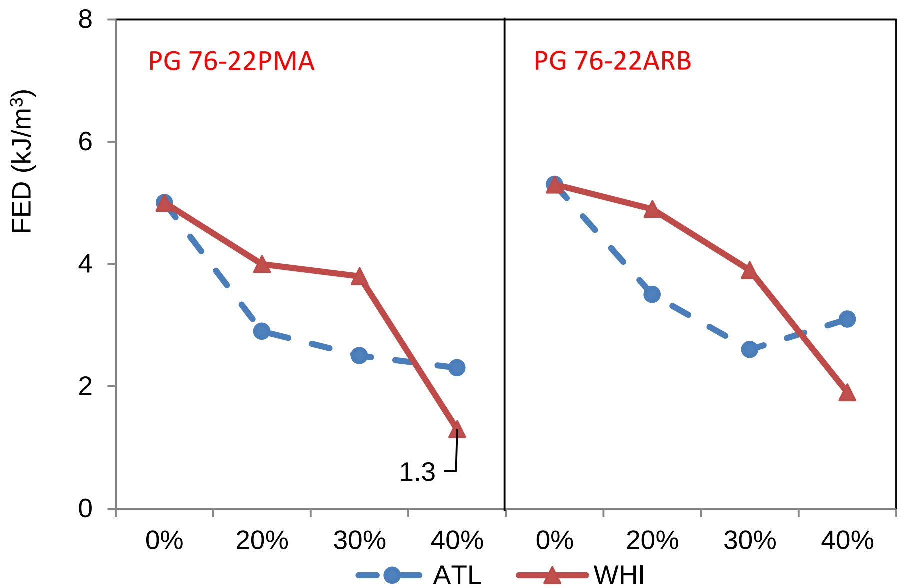

Figure 5-13 Fracture energy density of ATL and WHI RAP mixtures after STOA conditioning

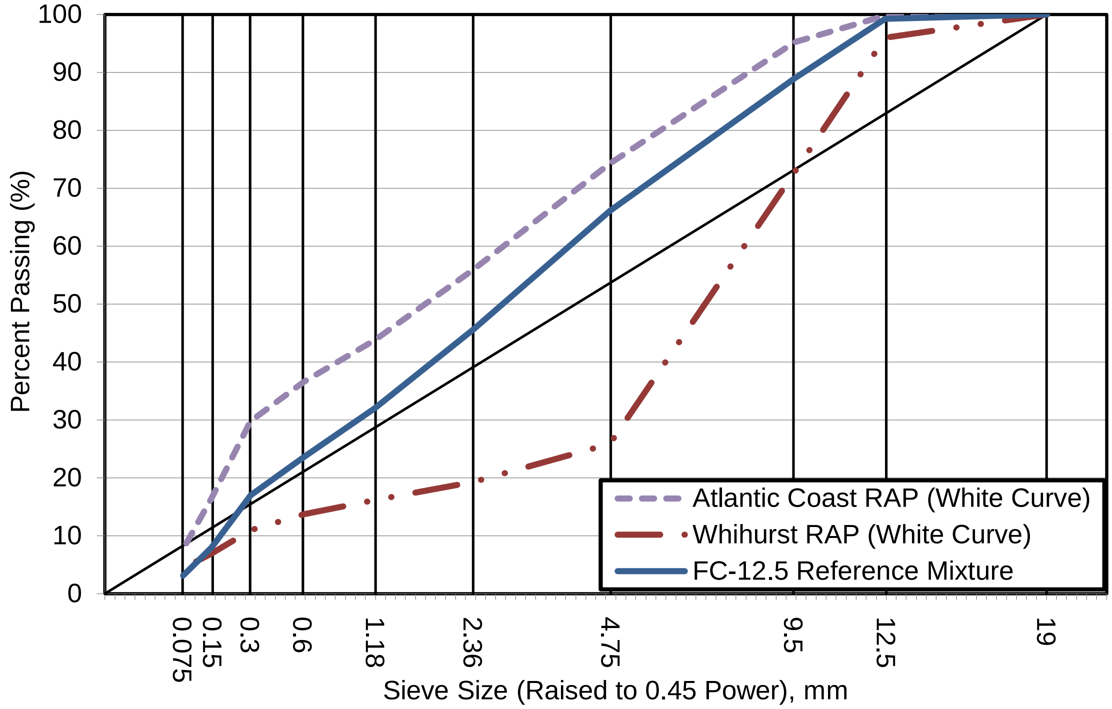

Figure 5-14 RAP “White curve” and reference mixture gradation

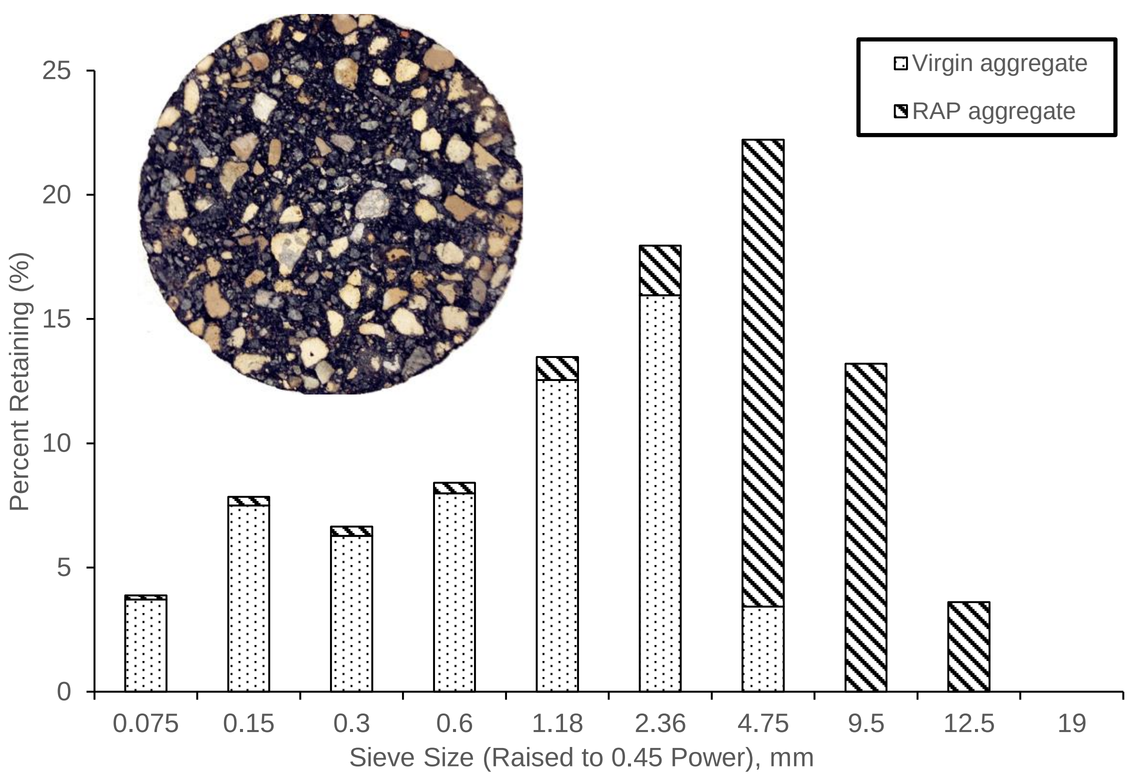

Figure 5-15 Aggregate component of 40% WHI RAP mixture

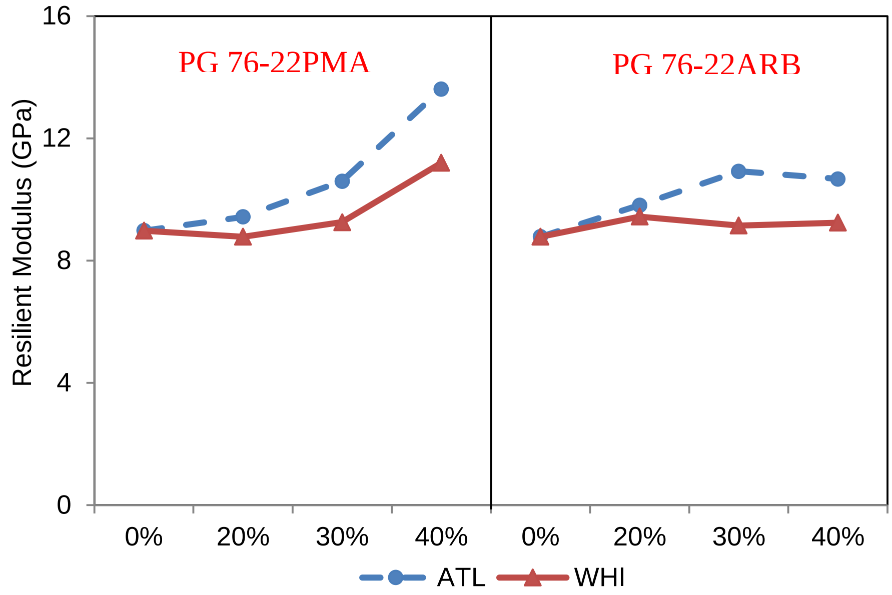

Figure 5-16 Resilient modulus of ATL and WHI RAP mixtures at STOA conditioning

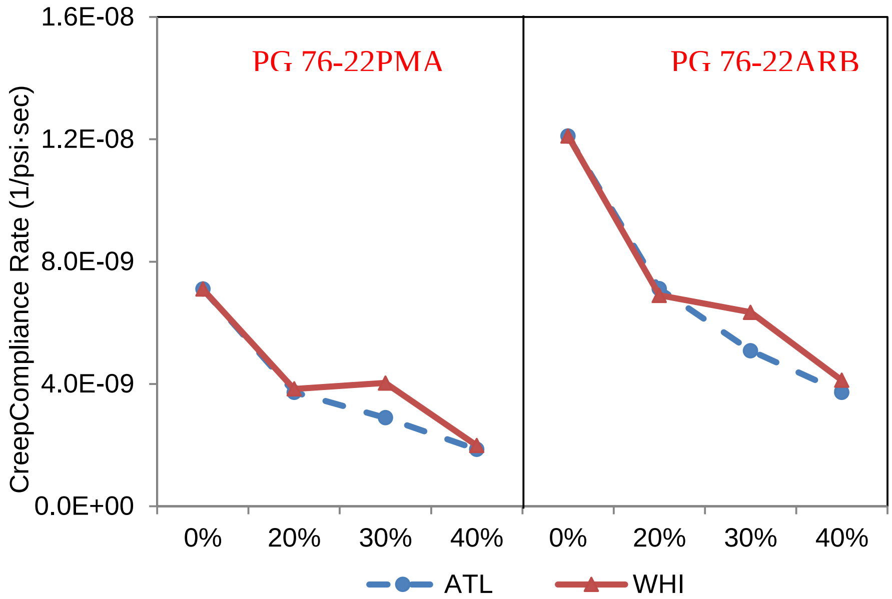

Figure 5-17 Creep Compliance Rate of ATL and WHI RAP mixtures after STOA conditioning

5.2.5 Closure

Based on mixture properties obtain after STOA conditioning, it was found that for both RAP sources evaluated, increased RAP content generally resulted in stronger (higher tensile strength) but more brittle (lower failure strain and lower FED) mixtures. It was noted that a marked reduction in FED occurred when 40% WHI RAP was introduced, which was attributed to the natural weakness of coarse limestone aggregate in this particular RAP source.

Effects of RAP gradation and virgin binder type were evident. Coarser WHI RAP generally resulted in higher FED (except at 40% RAP content where limestone aggregate weakness controlled FED) and lower resilient modulus than finer ATL RAP because the coarser RAP mixture required introduction of finer virgin aggregate that controls these two properties. RAP gradation effect was not observed in creep compliance rate results. PMA resulted in lower rate of damage (creep compliance) but lower FED than ARB. The PMA appears to result in a more integrated binder that better resists permanent deformation. It was hypothesized that the less integrated ARB binder has more asphalt that is free to blend with RAP binder, which resulted in the less brittle, higher FED mixture.

5.3 Mixture Evaluation after LTOA+CPPC Conditioning

5.3.1 Introduction

Based on a previous FDOT-sponsored study conducted at the University of Florida (Roque et al, 2013), it was found that the combination of oxidative aging and cyclic pore water pressure (i.e., LTOA+CPPC) is a viable approach to simulate mixture property changes to levels observed in the field. For this reason, properties determined after LTOA+CPPC conditioning procedure provided the clearest opportunity to evaluate the effects of RAP on mixture durability (i.e., changes in mixture fracture properties with time).

5.3.2 Atlantic Coast (ATL) RAP Mixtures

As shown in Figure 5-18, LTOA+CPPC increased the tensile strength of all RAP mixtures, except for 40% ATL-PMA mixture. Failure strain of all mixtures decreased after LTOA+CPPC (Figure 5-19). In general, the combined effect of LTOA+CPPC was a reduction in FED of all mixtures (Figure 5-20), which seems to indicates that all mixtures were stiffened (mainly by LTOA) and permanently damaged (by CPPC) during conditioning.

It is interesting that LTOA+CPPC induced relatively small reductions in failure strain and fracture energy for 20% and 30% ATL-ARB mixtures. As mentioned earlier, it was hypothesized that PG 76-22ARB was not as integrated as PG 76-22PMA binder, and therefore had more free asphalt that seemed to provide better blending between virgin and RAP binder.

After LTOA+CPPC, the tensile strength of RAP mixtures was essentially unaffected by the increased RAP content, whereas failure strain and FED were markedly reduced. Similar to STOA results, the use of PG 76-22ARB resulted in higher failure strain and higher FED than PG 76-22PMA. Once again, this was attributed to potentially better blending associated with ARB having more asphalt free to blend with RAP than

PMA. It was noted that FED at 40% ATL RAP was well above the stated minimum value of 0.75 kJ/m^3 (1.3 kJ/m^3 for PMA and 1.6 kJ/m^3 for ARB) recommended for satisfactory cracking performance.

Figure 5-21 once again shows that ARB appeared to have allowed better blending with RAP binder, thereby resulting in lower resilient modulus than PMA mixtures. As expected, resilient modulus generally increased with increasing RAP content for both binder types

Also as expected, creep compliance rate of all mixtures was reduced due to oxidative aging from LTOA (Figure 5-22) and was much lower for PMA than for ARB mixtures. Also, the effect of increasing RAP on creep compliance rate was less for PMA than for ARB mixtures. It was noted that the 40% ATL-PMA had the lowest creep rate value of 1.34E-9 (1/psi·sec) which is also the lowest value obtained from field cores in previous research by the UF research group.

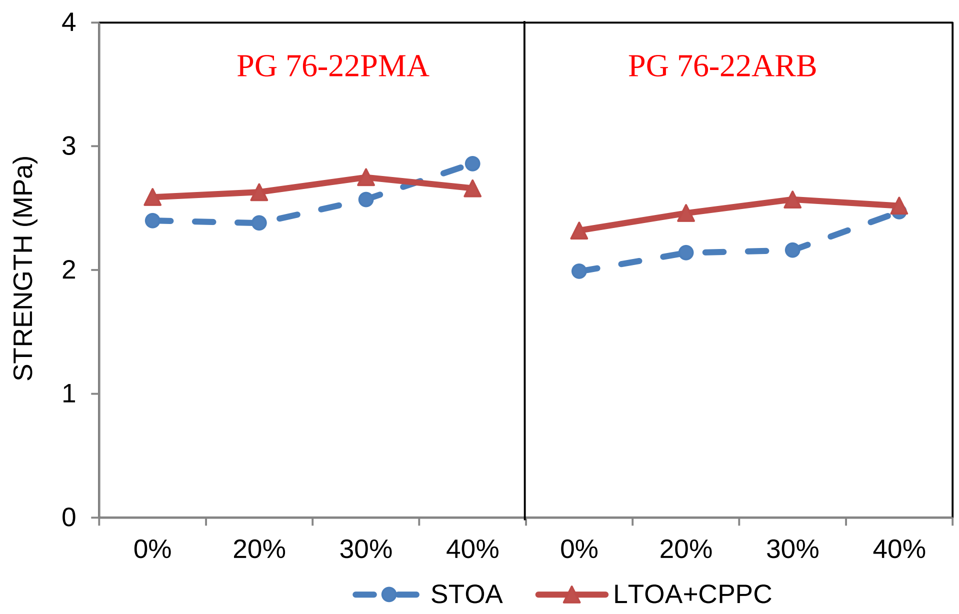

Figure 5-18 Strength of ATL RAP mixtures with two virgin binders at two conditioning levels

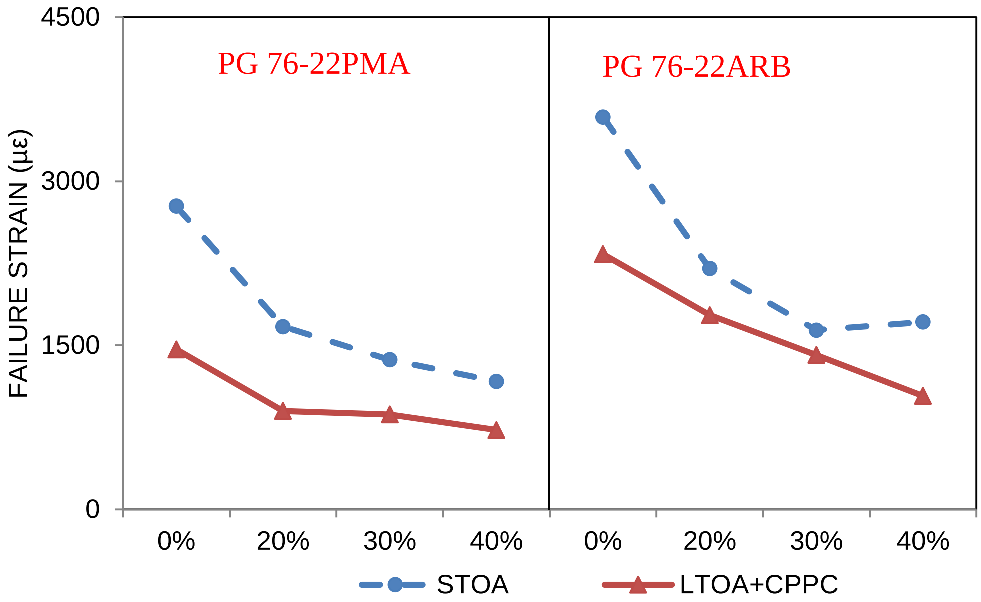

Figure 5-19 Failure strain of ATL RAP mixtures with two virgin binders at two conditioning levels

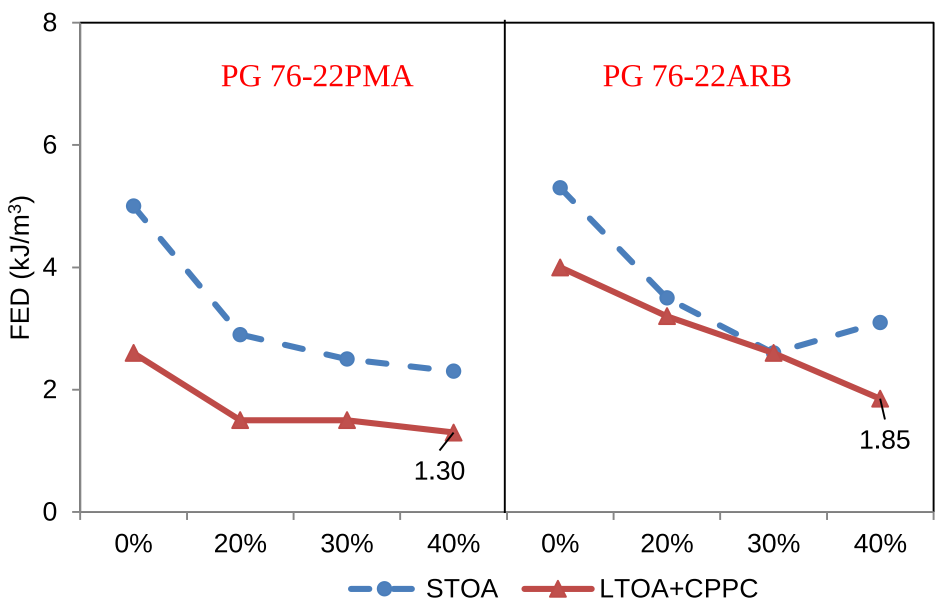

Figure 5-20 Fracture energy density of ATL RAP mixtures with two virgin binders at two conditioning levels

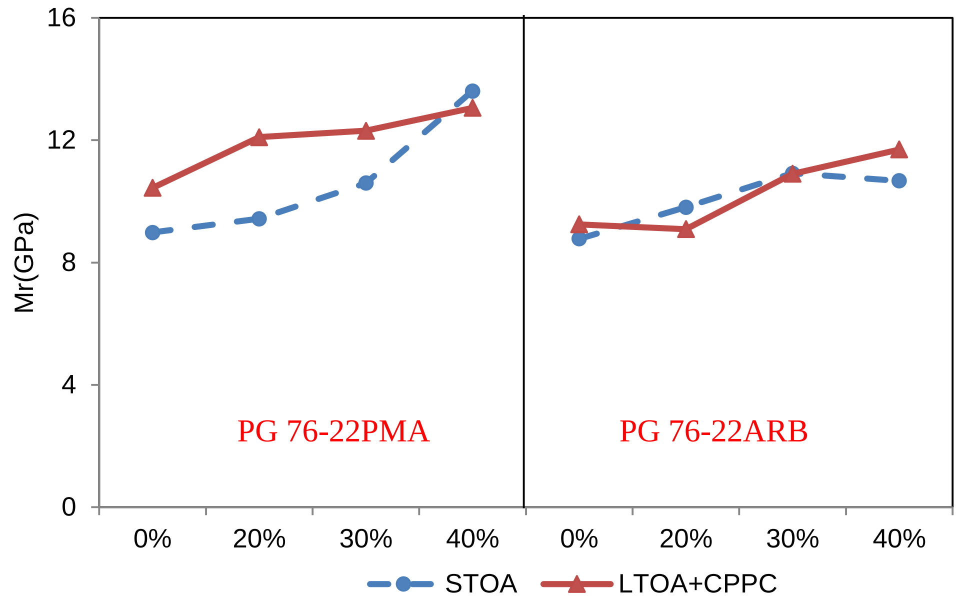

Figure 5-21 Resilient modulus of ATL RAP mixtures with two virgin binders at two conditioning levels

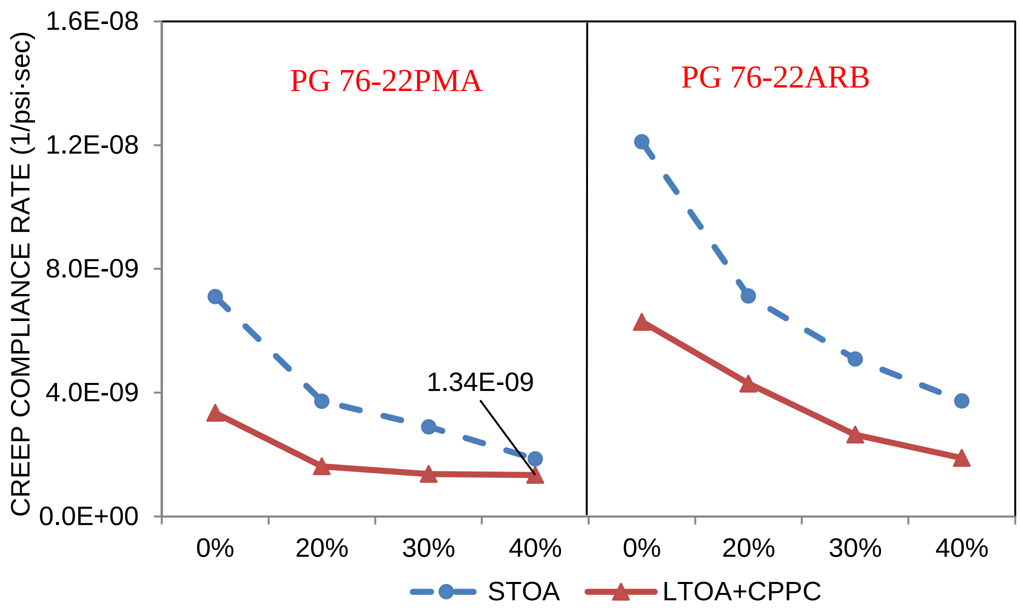

Figure 5-22 Creep compliance rate of ATL RAP mixtures with two virgin binders at two conditioning levels

5.3.3 Whitehurst (WHI) RAP Mixtures

Overall, figures 5-23 and 5-24 show that LTOA+CPPC generally increased tensile strength but reduced the failure strain of all mixtures. Figure 5-25 shows the overall effect was reductions in FED for all mixtures except for 40% WHI-PMA mixture, which exhibited almost the same FED at both conditioning levels.

Tensile strength of WHI RAP mixtures was less affected by the increased RAP contents, while the failure strain and FED clearly decreased as RAP content increased. Even though WHI-PMA and WHI-ARB mixtures exhibited a marked reduction at 40% RAP content; fracture energy density values were well above the stated minimum value of 0.75 kJ/m^3 (1.20 kJ/m^3 for PMA and 1.23 kJ/m^3 for ARB) recommended for satisfactory cracking performance. As explained in section 5.2.3, it appears that weakness of limestone in RAP became the factor that controlled FED once RAP content reached 40%. As for the LTOA+CPPC results, WHI-PMA mixtures had higher tensile strength, lower failure strain and lower FED than WHI-ARB mixtures. As explained for the similar STOA results, it appears ARB binder was better able to blend with RAP binder than PMA binder.

Figure 5-26 shows, resilient modulus of WHI-PMA mixtures exhibited a modest increase after LTOA+CPPC conditioning for PMA and almost no change for ARB mixtures. Clear increase in resilient modulus was observed between 30% and 40% WHI RAP contents. Once again, there seems to be a threshold of WHI RAP content above which the coarse WHI RAP aggregate had a dominant effect on mixture properties.

As expected, Figure 5-27 illustrates that the creep compliance rate of all WHI RAP mixtures was further reduced after the LTOA+CPPC conditioning and increasing RAP content resulted in lower creep compliance rate. Also, WHI-PMA mixtures showed lower creep compliance rate than WHI-ARB mixtures at each RAP content, indicating lower damage accumulation rate for PMA mixtures. It was noted that both 40% WHI-PMA and 40% WHI-ARB mixtures exhibited a low creep compliance rate than 1.34E-9 (1/ psi·sec), which is the lowest value obtained from field cores in previous research by the UF research group.

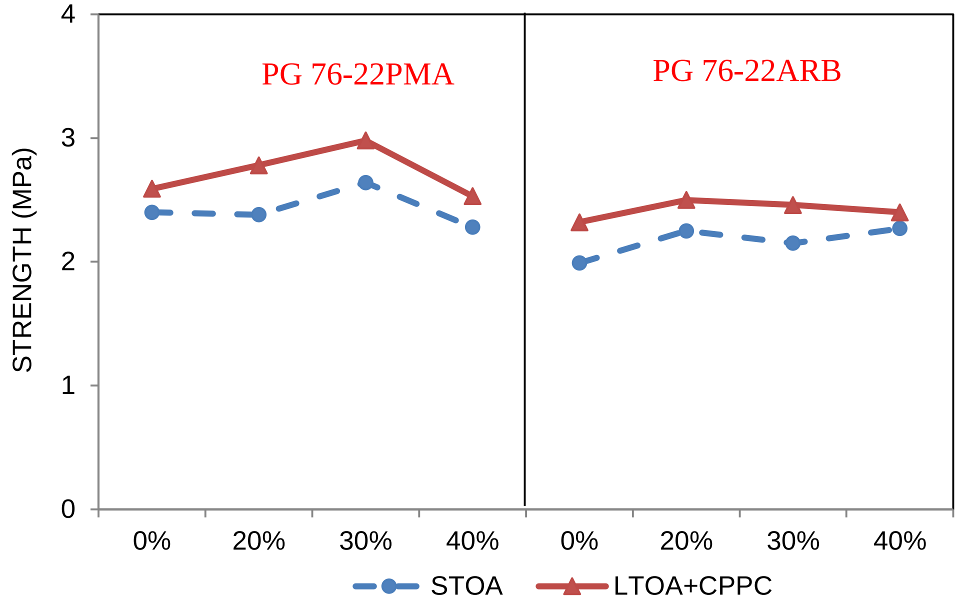

Figure 5-23 Strength of WHI RAP mixtures with two virgin binders at two conditioning levels

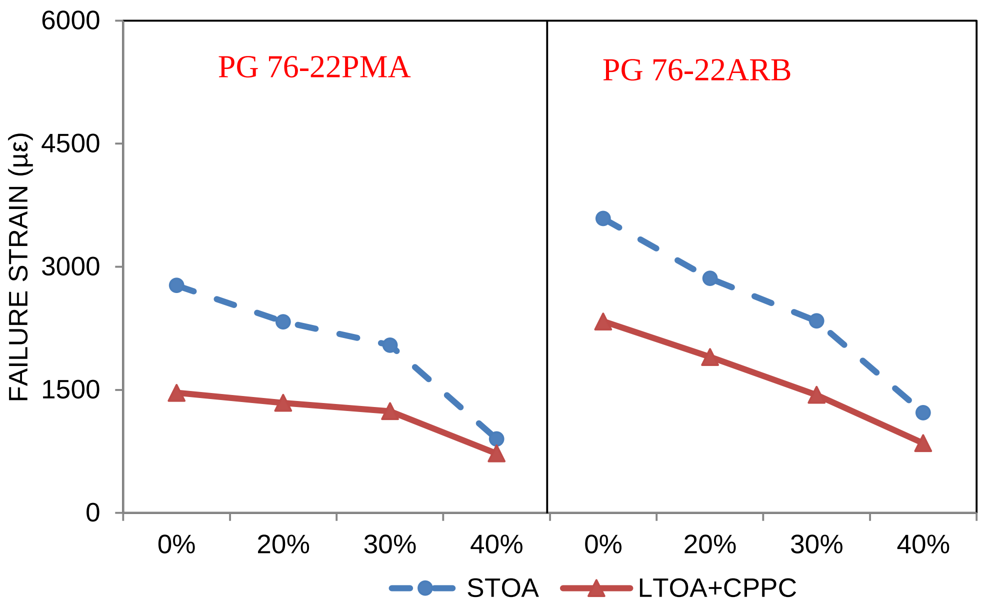

Figure 5-24 Failure strain of WHI RAP mixtures with two virgin binders at two conditioning levels

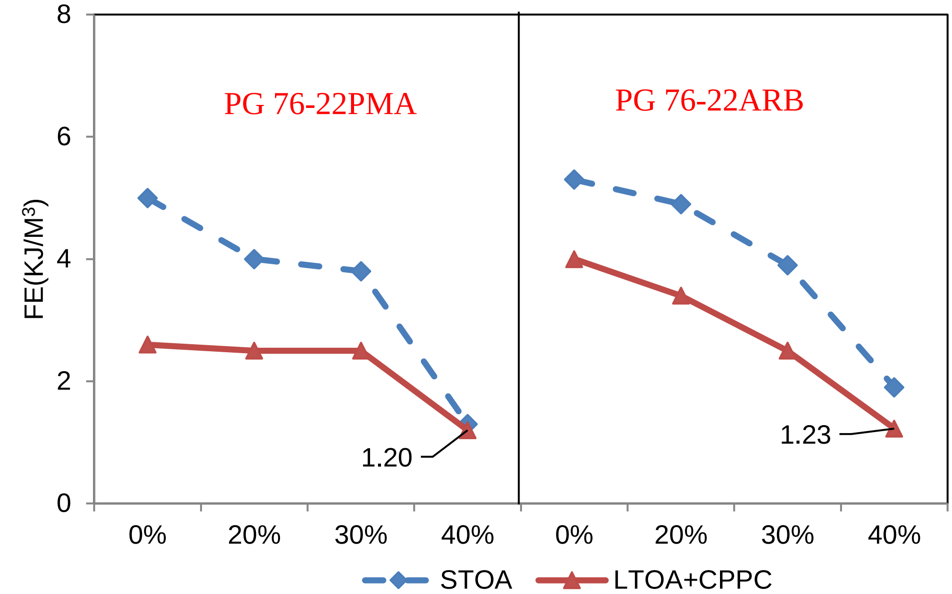

Figure 5-25 Fracture energy density of WHI RAP mixtures with two virgin binders at two conditioning levels

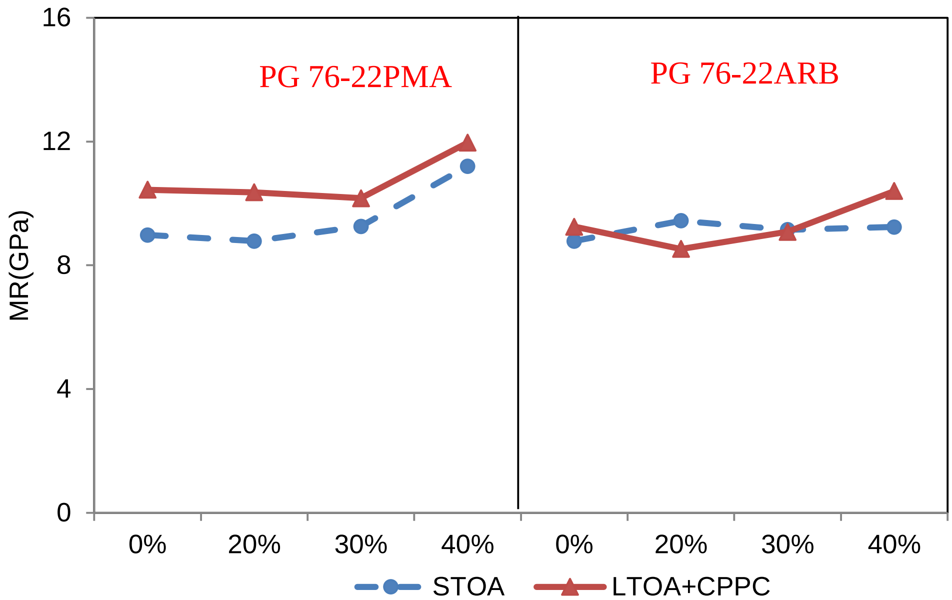

Figure 5-26 Resilient modulus of WHI RAP mixtures with two virgin binders at two conditioning levels

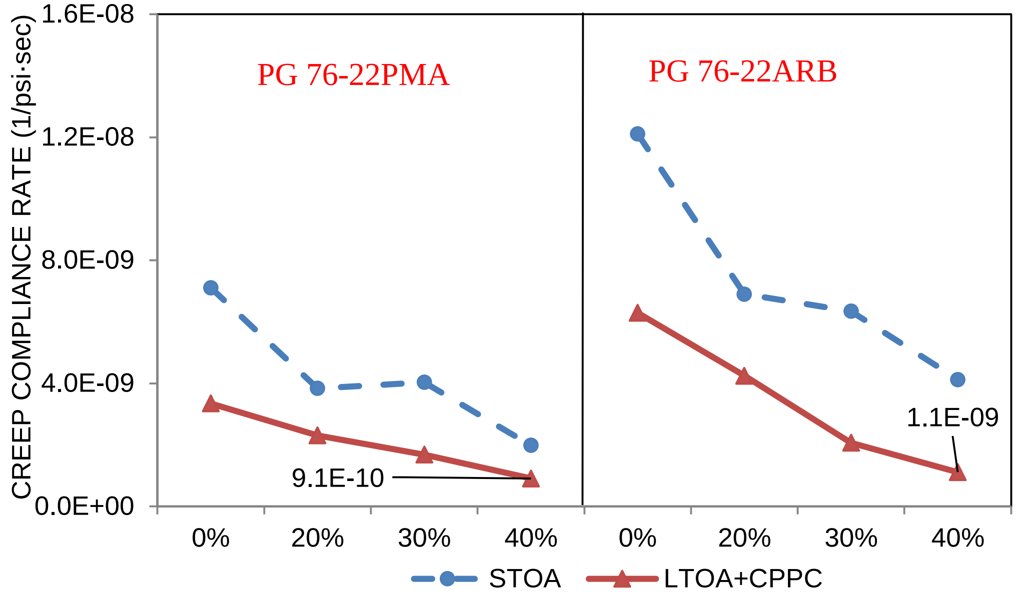

Figure 5-27 Creep compliance rate of WHI RAP mixtures with two virgin binders at two conditioning levels

5.3.4 Comparisons between ATL and WHI RAP mixtures

Figures 5-28, 5-29, and 5-30 illustrate that, when PG 76-22PMA was used, WHI RAP mixtures with 20% and 30% RAP content had higher tensile strength, higher failure strain, and higher FED than ATL RAP mixtures. Similar to STOA results, clear reductions in tensile strength, failure strain, and FED occurred when 40% WHI RAP was introduced. As described in section 5.2.4, this reduction was believed to be mainly caused by the weakness of coarse limestone aggregate.

However, when PG 76-22ARB was used, tensile strength, failure strain and FED were almost the same for the two RAP sources. As discussed in section 5.3.2, an explanation for the difference in results between the two binder types is that more of the ARB base binder than the PMA base binder may be available to blend with RAP binder. The effect is primarily seen in the ATL RAP mixtures, which exhibited lower FED with PMA binder because its gradation is finer than the WHI RAP and the finer portion of gradation has the strongest influence on failure limits (except for the weak coarse aggregate limestone effect at 40% WHI RAP).

As shown in Figure 5-31, ATL RAP mixtures had higher resilient modulus than WHI RAP mixtures regardless of virgin binder. This observation can be attributed to the difference in gradation between the RAP sources. The finer ATL RAP resulted in the higher resilient modulus mixtures because the finer portion of the gradation has the strongest influence on small strain response. Note this effect was so strong that the ATL RAP mixtures were stiffer even though the WHI RAP had the stiffer binder.

Figure 5-32 shows the effect of RAP gradation was not observed for the higher strain response associated with creep compliance rate, which is governed by all portions of the mixture. The figure clearly depicts that creep compliance rate decreased as RAP content increased.

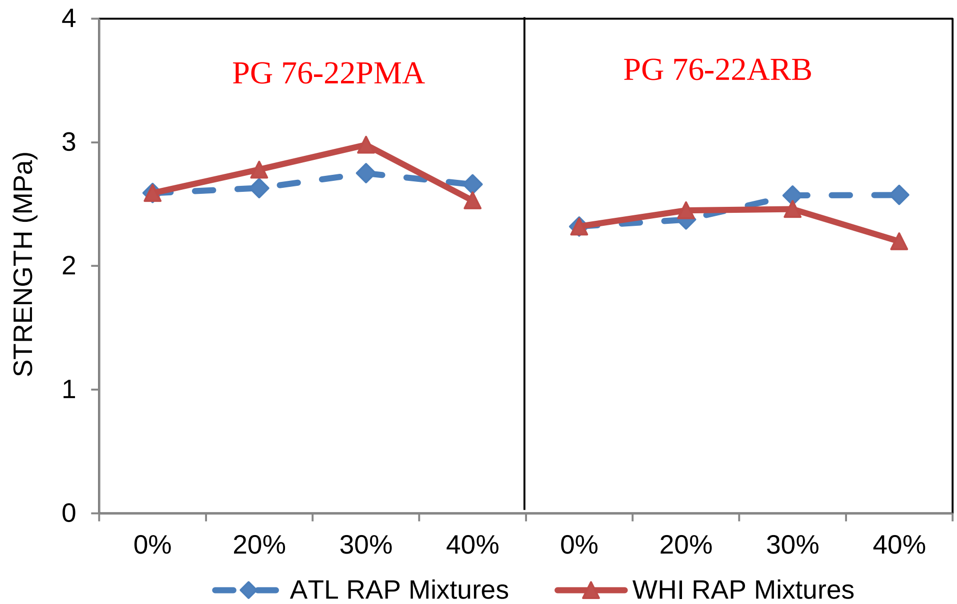

Figure 5-28 Strength of ATL and WHI RAP mixtures with two virgin binders after LTOA+CPPC conditioning

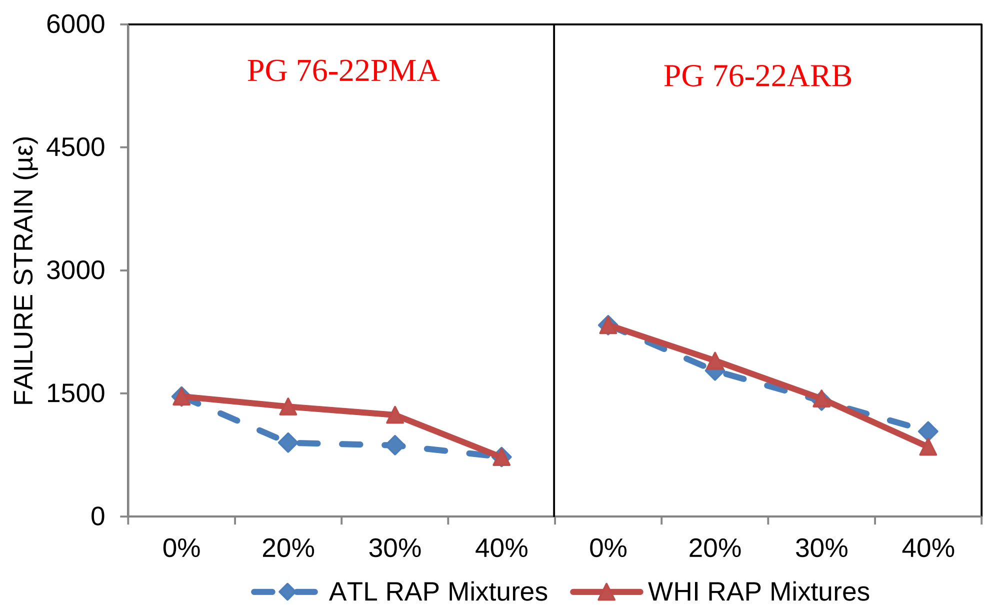

Figure 5-29 Failure strain of ATL and WHI RAP mixtures with two virgin binders after LTOA+CPPC conditioning

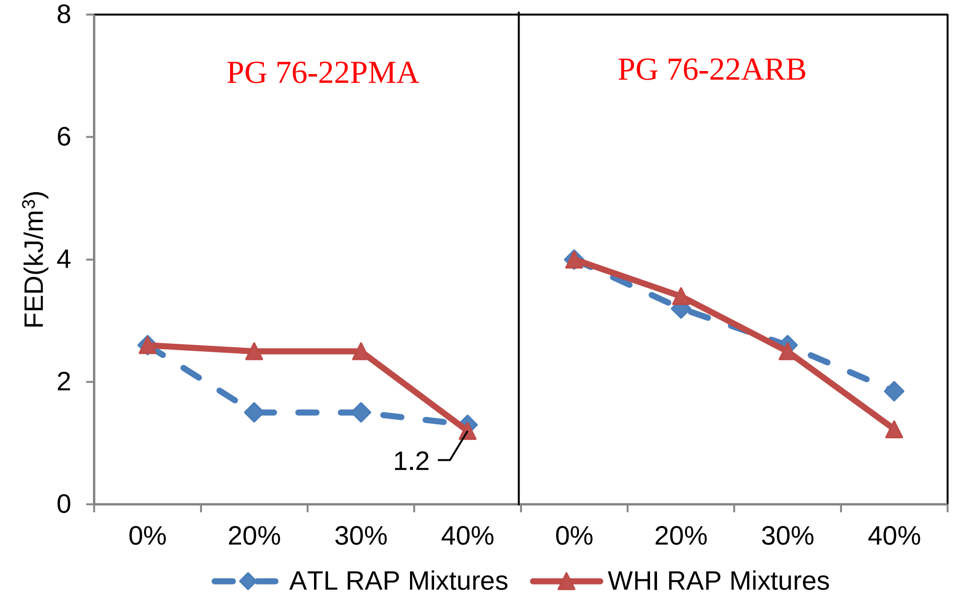

Figure 5-30 Fracture energy density of ATL and WHI RAP mixtures with two virgin binders after LTOA+CPPC conditioning

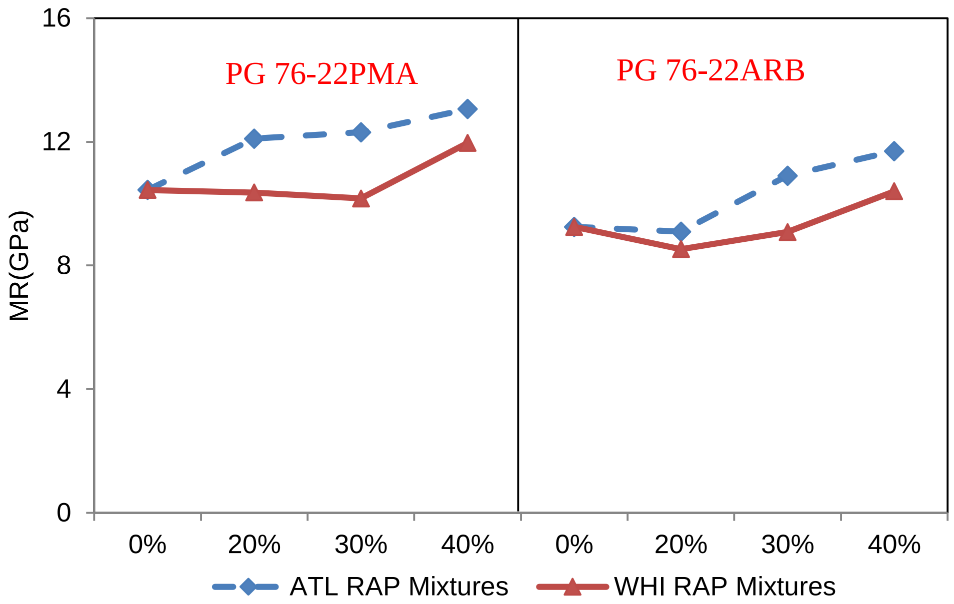

Figure 5-31 Resilient modulus of ATL and WHI RAP mixtures with two virgin binders after LTOA+CPPC conditioning

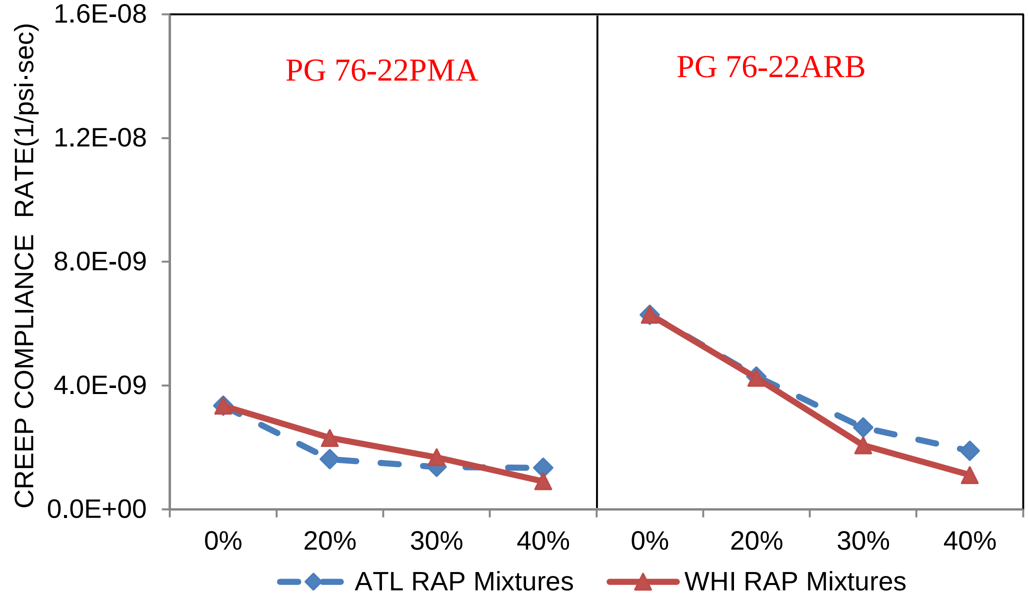

Figure 5-32 Creep compliance rate of ATL and WHI RAP mixtures two virgin binders after LTOA+CPPC conditioning

5.3.5 Closure

As expected LTOA+CPPC conditioning was found to stiffen RAP mixtures and induce permanent damage that reduced failure strain and FED. Overall, the effects of RAP source, RAP content and binder type were similar to those observed in STOA results.

5.4 Cracking Performance Evaluation

The overall effect of experimental factors on cracking performance was assessed through the energy ratio (ER) parameter determined from mixture properties after LTOA+CPPC conditioning. ER parameter was originally calibrated using properties measured on aged field cores, so appropriate use of ER requires determination of properties on mixtures conditioned to levels representing the combined effect of oxidative aging and moisture. Figure 5-33 presents a complete set of ER values for all mixtures.

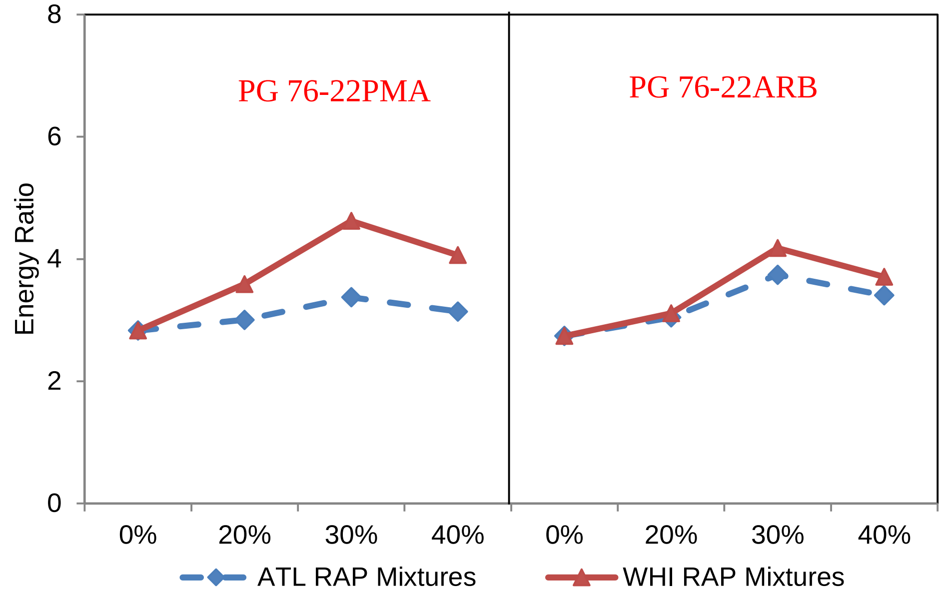

Figure 5-33 Energy ratio of ATL and WHI RAP mixtures with two virgin binders after LTOA+CPPC conditioning

Regardless of virgin binder type and RAP source, all RAP mixtures exhibited ER values well above 1.0, which is the minimum value proposed by the UF research group to ensure adequate cracking performance. For mixtures and RAP sources evaluated in this study, higher RAP content generally resulted higher ER values. However, the increasing trend was reversed between 30% and 40% RAP content, but the ER at 40% RAP was still well above 1.0 and greater than ER for 20% RAP mixtures.

It must be emphasized that all RAP mixtures evaluated not only met all Superpave design criteria, but also all DASR-IC gradation criteria. So satisfactory inclusion of up to 40% RAP was for well-designed mixtures with good gradation characteristics. Kim et al. (2007) clearly illustrated how gradation characteristics can make the difference as to whether a high RAP mixture is satisfactory or not. They showed how modifying gradation of a 45% RAP mixture resulted in both improved rutting and cracking performance as indicated by reduced APA rutting depth and increased ER value. So, it appears that RAP contents of up to 40% can be used while maintaining, and perhaps improving, cracking performance if good gradation characteristics are employed.

It must also be noted that these mixtures included PMA binder and ARB binder that had very good fracture resistance as measured by the binder fracture energy (BFE) test. Unmodified binder was not evaluated and would certainly result in stiffer more brittle mixtures with potentially unsatisfactory cracking performance.

WHI RAP mixtures had higher ER values than ATL RAP mixture regardless of virgin binder. This may be explained by the fact that WHI RAP had a coarser aggregate gradation such that most of the virgin aggregate and virgin binder constituted the fine portion of the WHI RAP mixtures, whereas ATL RAP had a finer gradation that was closer to the final blend resulting in homogeneously stiffened ATL RAP mixtures. The coarse RAP was more engaged at high strain level during the creep test such that it had more influence on creep compliance rate than FED. The trend may be partially attributed to the fact that WHI RAP mixtures had higher optimum asphalt content than ATL RAP mixtures.

It was observed that WHI-PMA mixtures had higher ER than WHI-ARB mixtures. Conversely, ATL-PMA mixtures had lower ER than ATL-ARB mixtures. With other volumetric parameters being the same, it seems the difference in trend was associated with the effects of PG 76-22ARB. As mentioned several times throughout this chapter, it appears the PG 76-22ARB had more free binder to blend with RAP than PMA binder. In addition the finer gradation of ATL RAP benefited more from the enhanced blending.

CHAPTER 6 CLOSURE

6.1 Summary and Findings

The overall goal of the study was to determine if FDOT's existing specification limits in the allowable amount of RAP material in asphalt concrete friction courses could be increased above 20% without jeopardizing pavement cracking performance. To achieve this objective, a laboratory experimental program was developed, including one FC-12.5 mixture, two RAP sources, two virgin binders (both modified), and four RAP proportions. Assessment of the effects of RAP on performance were made at both the binder and mixture levels. Binder tests, including Superpave binder tests, multiple stress creep recovery (MSCR) test and binder facture energy (BFE) test were conducted on laboratory blend binder as well as virgin binders. All mixtures were tested using the Superpave IDT test protocol and the mixture properties were determined using the ITLT software. The mixtures were subjected to two conditioning levels; STOA, and LTOA+CPPC. The main findings based on results of laboratory testing are listed below:

- As RAP content increased, the needs for virgin binder reduced. The reduction was more pronounced for fine gradation RAP than coarse gradation RAP. All RAP mixtures met the Superpave criteria and DASR-IC requirements, except VMA of 40% ATL RAP mixture was slightly low (13.6% to 14% required). Previous FDOT research (Roque et al, 2006) found it was not necessary to meet VMA requirements to have good mixture performance.

- All blended binders met the Superpave specifications for virgin binder, except that 30% and 40% WHI-ARB binder had slightly higher Brookfield viscosity values (3.1 and 3.3 to 3.0 Pa·s required).

- All blended binders exhibited good elastomeric behavior as %recovery values obtained from the MSCR test were above the minimum requirements. In addition, the RAP binder enhanced the rutting resistance of virgin binder as indicated by $J_{nr,\,3.2}$ results.

- The PMA and ARB binder used in this study exhibited excellent FED results. Although the addition of RAP binder reduced the FED of virgin binders, satisfactory results were obtained for blended binders as even the lowest FED value was still greater than FED values determined for PMA and ARB binder tested in previous research (Niu et al, 2014).

- For both RAP sources evaluated, increased RAP content generally resulted in stronger (higher tensile strength) but more brittle (lower failure strain and lower FED) mixtures. Such trends were observed at both STOA and LTOA+CPPC conditions.

- After LTOA+CPPC which simulates long term field conditioning, all RAP mixtures exhibited FED values above 0.75 kJ/m^3 and ER values well above 1.0, both of which are the minimum values proposed by the UF research group to ensure accepted cracking performance.

- Coarser gradation RAP (WHI) generally resulted in higher FED (except at 40% RAP content where limestone aggregate weakness controlled FED) and lower resilient modulus than finer gradation RAP (ATL) because the coarser RAP mixture required introduction of finer virgin aggregate and more virgin binder which control these two properties.

- The PMA appears to result in a more integrated binder that better resists permanent deformation. It was hypothesized that the less integrated ARB binder has more asphalt that is free to blend with RAP binder, which resulted in the less brittle, higher FED mixture.

- For mixtures and RAP sources evaluated in this study, higher RAP content generally resulted higher ER values. However, the increasing trend was reversed between 30% and 40% RAP content, but the ER at 40% RAP was still well above 1.0 and greater than ER for 20% RAP mixtures.

6.2 Conclusions

It was found that mixtures with up to 40% RAP content exhibited good relative cracking performance as indicated by the fracture properties and ER parameter. It is emphasized that all RAP mixtures evaluated not only met Superpave design criteria, but also DASR-IC requirement. So satisfactory inclusion of up to 40% RAP was for well-designed mixtures with good gradation characteristics and with modified asphalt binders. This study supports the continuous use of DASR-IC method and modified asphalt binders to ensure and/or improve mixture performance in the state of Florida.

LIST OF REFERENCES

Al-Qadi, I.L., S. H. Carpenter, G. Roberts, H. Ozer, and Q. Aurangzeb. *Determination of Usable Residual Asphalt Binder in RAP* (Illinois Department of Transportation Research Report ICT-09-031), Springfield, IL: IIIinois Department of Transportation. 2009.

Behnia B., E. V. Dave, S. Ahmen, W. G. Buttlar, and H. Reis. *Effects of Recycled Asphalt Pavement Amounts on Low-Temperature Cracking Performance of Asphalt Mixtures Using Acoustic Emissions,* In Transportation Research Record: Journal of the Transportation Research Board, No. 2208, TRB, National Research Council ,Washington, D.C., pp. 64-71, 2011.

Bukowski, J.R., *Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP)*, Memorandum, ETG Meeting, FHWA Superpave Mixtures Expert Task Group, San Antonio, TX, 1997.

Daniel, J. S., and A. Lachance. *Mechanistic and Volumetric Properties of Asphalt Mixtures with Recycled Asphalt Pavement*, In Transportation Research Record: Journal of the Transportation Research Board, No. *1929*, TRB, National Research Council, Washington, D.C., pp. 28-36, 2005.

Drakos, C. A., R. Roque, B. Birgisson, and M. Novak. *Identification of a Physical Model to Evaluate Rutting Performance of Asphalt Mixtures*, Journal of ASTM International, Volume 2, Issue 3, 2005.

Gardiner, M.S., and C. Wagner. *Use of Reclaimed Asphalt Pavement in Superpave Hot-Mix Asphalt Applications*, In Transportation Research Record: Journal of the Transportation Research Board, No. *1681*, TRB, National Research Council, Paper No. 99-0110. Washington, D.C., 2007.

Hansen, K.R., and D.E. Newcomb. *Asphalt Pavement Mix Production Survey, Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, Warm-mix Asphalt Usage: 2009-2010* (National Asphalt Pavement Association Final Report 2009-2010*)*, Lanham, MD: National Asphalt Pavement Association. 2011.

Huang, B., G. Li, D. Vukosavljevic, X. Shu, and B. K. Egan. *Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement*, In Transportation Research Record: Journal of the Transportation Research Board, No. *1929*, TRB, National Research Council, Washington, D.C., pp. 37-45, 2005.

Huang, B., X. Shu, and D. Vukosavljevic. *Laboratory Investigation of Cracking Resistance of Hot-Mix Asphalt Field Mixtures Containing Screened Reclaimed Asphalt Pavement*, Journal of Materials in Civil Engineering, ASCE, Volume 23, Special Issue, 2011.

Jones, C., *Survey of State RAP Use*, RAP ETG Meeting Presentation, Manchester, New Hampshire, 2009.

Kandhal, P.S., and K.Y. Foo. *Design Recycled Hot Mix Asphalt Mixture Using Superpave Technology* (National Center for Asphalt Technology Report No. 96-5), Auburn, AL: National Center for Asphalt Technology, 1997.

Kemp, G.R., and N. H. Predoehl. *A comparison of Field and Laboratory Environments on Asphalt Durability*, Proceedings of the Association of Asphalt Paving Technologists, Vol. 50, pp. 492-537, 1981.

Kim, S., Byron, T., Sholar, G.A, and Kim, J. *Evaluation of Use of High Percentage of Reclaimed Asphalt Pavement (RAP) for Superpave Mixtures* (Florida Department of Transportation Research Report FL/DOT/SMO/07-507). Gainesville, FL: State Materials Office. 2007.

Kim, S.; Scholar, G. A; Byron, T; and Kim, J. *Performance of Polymer-Modified Asphalt Mixture with Reclaimed Asphalt Pavement*. In Transportation Research Record: Journal of the Transportation Research Board, No. 2126, TRB, National Research Council, Washington, D.C., pp. 109-114, 2009.

Kim, M., L. N. Mohammad, and M. A. Elseifi. *Characterization of Fracture Properties of Asphalt Mixtures as Measured by Semicircular Bend Test and Indirect Tension Test*, In Transportation Research Record: Journal of the Transportation Research Board, No. *2296*, TRB, National Research Council, Washington, D.C., pp. 115-124, 2012.

Kowalski, K. J.; McDaniel, R. S, and Olek, J. *Influence of Reclaimed Asphalt Pavement (RAP) on Surface Friction*. Proceedings of the 89th Annual Meeting of the Transportation Research Board, Washington, D.C, 2010.

Kvasnak, A., R. West, J. Michael, L. Loria, E. Hajj, and N. Tran. *Bulk Specific Gravity of Reclaimed Asphalt Pavement Aggregate, Evaluating the Effect of Voids in Mineral Aggregate.* In Transportation Research Record: Journal of the Transportation Research Board, No. 2180, TRB, National Research Council, Washington, D.C., pp. 30-35, 2010.

Li, X., M. O. Marasteanu, R. C. Williams, and T. R. Clyne. *Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures*, In Transportation Research Record: Journal of the Transportation Research Board, No. 2051, TRB, National Research Council, Washington, D.C., pp. 90-97, 2008.

McDaniel, R., and R.M. Anderson. *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*, National Cooperative Highway Research Program (NCHRP) Report 452, TRB, Washington, D.C., 2001.

Maupin, G. W., S. D. Diefenderfer, and J. S. Gillespie. *Virginia's Higher Specification for Reclaimed Asphalt Pavement: Performance and Economic Evaluation*, In Transportation Research Record: Journal of the Transportation Research Board, No. 2126, TRB, National Research Council, Washington, D.C., pp. 142-150, 2009.

McDaniel, R., G. A. Huber, and V. Gallivan. *Conserving Resources and Quality with High RAP Content Mixes*, HMAT: Hot Mix Asphalt Technology, National Asphalt Pavement Association Volume 11, pp. 44-46, 2006.

Mohammad, L.N., I.I. Negulescu, Z. Wu, C. Daranga, W. H. Daly, and C. Abadie. *Investigation of the Use of Recycled Polymer-modified Asphalt Binder in Asphalt Concrete Pavements*. Journal of the Association of Asphalt Paving Technologists, Vol. 72, pp. 551-594, 2003.

Nash, T., G.A, Sholar., and J.A. Musselman. *Evaluation of High RAP asphalt Mixture Performance in Florida* (Florida Department of Transportation Research Report FL/DOT/SMO/11-545). Gainesville, FL: State Materials Office. 20011.

National Cooperative Highway Research Program (NCHRP). *NCHRP Research Results Digest 370: Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Studies*, Appendix B: Extraction and Recovery Procedures at TFGRC Asphalt Laboratories, TRB, National Research Council, Washington, D.C., 2012.

Niu, Tianying., R. Roque, and G. Lopp. *Development of a Binder Fracture Test to Determine Fracture Energy Properties*, Journal of the Association of Asphalt Paving Technologists, Volume 83, pp. 517-548, 2014.

Pappas, J., *Recycling Materials Survey*, RAP ETG Meeting Presentation, Irvine, California, 2011.

Roberts, F.L., P.S. Kandhal, E.R. Brown, D. Lee, and T.W. Kennedy. *Hot Mix Asphalt Materials, Mixture Design, and Construction (2nd.)*. Lanham, MD: Napa Education Foundation, 1996.

Roque, R., and W. G. Buttlar. *The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Mode*, Journal of the Association of Asphalt Paving Technologists, Vol. 61, pp. 304-332, 1992.

Roque, R., W. G. Buttlar, B. E. Ruth, Tia, M, Dickson, S. W. and B. Reid. *Evaluation of SHRP Indirect Tension Tester to Mitigate Cracking in Asphalt Pavements and Overlays* (Florida Department of Transportation Research Report for FDOT B-9885 Contract), Gainesville, FL: University of Florida. 1997.

Roque, R., B. Birgisson, C. A. Drakos, and B. Dietrich. *Development and Field Evaluation of Energy-Based Criteria for Top-Down Cracking Performance of Hot Mix Asphalt*, Journal of the Association of Asphalt Paving Technologists, Vol. 73, pp. 229-260, 2004.

Roque, R., S. Kim, and A. Guarin. *Mixture to Evaluate Gradations for Investigations in the Accelerated Pavement Testing Facility* (Florida Department of Transportation Research Report for FDOT 00056261 Contract), Gainesville, FL: University of Florida. 2006.

Roque, R., R. Simms, Y. Chen, C. Koh, and G. Lopp. *Development of a Test Method that will Allow Evaluation and Quantification of The Effects of Healing on Asphalt Mixture* (Florida Department of Transportation Research Report for FDOT *BDK* 75-977-26 Contract), Gainesville, FL: University of Florida. 2012.

Roque, R., M. Isola, S. Chun, J. Zou, C. Koh, and G., Lopp. *Effects of Laboratory Heating, Cyclic Pore Pressure, and Cyclic Loading on Fracture Properties of Asphalt Mixture* (Florida Department of Transportation Research Report for FDOT BDK 977-28 Contract), Gainesville, FL: University of Florida. 2013.

Roque. R., M. Isola, M. Bekoe, J. Zou, and G. Lopp. *Validation and Refinement of Mixture Volumetric Material Properties Identified in Superpave Monitoring Project II: Phase II* (Florida Department of Transportation Research Report for FDOT BDV31-977-18 Contract), Gainesville, FL: University of Florida. 2015.

Santucci, L., *Recycling Asphalt Pavements-A Strategy Revisited*, Pavement Research Center, Institute of Transportation Studies, University of California Berkeley, 2007

Shah, A., R.S. McDaniel, G.A. Huber, and V. L. Gallivan. *Investigation of Properties of Plant-Produced Reclaimed Asphalt Pavement Mixtures*, In Transportation Research Record: Journal of the Transportation Research Board, No.1998, TRB, National Research Council, Washington, D.C., pp.103-111, 2007.

Shirodkar, P., Y. Mehta, A. Nolan, K. Sonpal, A. Norton, C. Tomlinson, E. Dubois, P. Sullivan, and R. Sauber. *A Study to Determine the Degree of Partial Blending of Reclaimed Asphalt Pavement (RAP) Binder for High RAP Hot Mix Asphalt*, Construction and Building Materials, Volume 25, Issue 1, pp. 150-155, 2011.

Sholar, G.A., *Comparison of Rutting Test Results between Laboratory Tests and Heavy Vehicle Simulator Testing* (Florida Department of Transportation Research Report FL/DOT/SMO/10-534), Gainesville, FL: State Materials Office, 2010.

Florida Department of Transportation (FDOT). *Standard Specification for Road and Bridge Construction: Section 337 Asphalt Concrete Friction Courses*. Florida Department of Transportation, Tallahassee, FL. 2015.

Swamy, A. K., L. F. Mitchell, S. J. Hall, and J. S. Daniel. *Impact of RAP on the Volumetric, Stiffness, Strength, and Low-Temperature Properties of HMA*, Journal of Materials in Civil Engineering, ASCE, Volume 23, Special Issue, pp. 1490-1497, 2011.

Tran, B.T., and R.A. Hassan. *Performance of Hot-Mix Asphalt Containing Recycled Asphalt Pavement*, In Transportation Research Record: Journal of the Transportation Research Board, No.2205, TRB, National Research Council, Washington, D.C., pp. 121-129, 2011.

Watson, D.E., A.V. Nordcbeck, and J. Moore, D. Jared, and P. Wu. *Evaluation of the Use of Reclaimed Asphalt Pavement in Stone Matrix Asphalt Mixtures*, In Transportation Research Record: Journal of the Transportation Research Board, No. 2051, TRB, National Research Council, Washington, D.C., pp. 64-70, 2008.

West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner. *Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes: Laboratory and Accelerated Field Performance Testing at the National Center for Asphalt Technology Test Track*, In Transportation Research Record: Journal of the Transportation Research Board, No. 2126, TRB, National Research Council, Washington, D.C., pp. 100-108, 2009.

West, R.C., *Summary of NCAT Survey on RAP Management Practices and RAP Variability*, Auburn, AL: National Center for Asphalt Technology, 2008. http://www.morerap.us/files/rap-field-projects/summary-survey-rap-mgt-variablity.pdf, Accessed at 04/28/2015.

Yan. Y., C. Cocconcelli, R. Roque, T. Nash, J. Zou, D. Hernando, and G. Lopp. *Performance Evaluation of Alternative Polymer Modified Asphalt Binders*, Road Material and Pavement Design, EATA Issue, pp.1-15, 2015.

APPENDIX A RAP AGGREGATE AND BINDER RECOVERY

Table A-1 Ignition Oven Test Results: Atlantic Coast RAP

Sieve Size (mm)		ATLANTIC COAST RAP				AVERAGE VALUES
		Specimen 1	Specimen 2	Specimen 3	Specimen 4	
19	3/4"	100.0%	100.0%	100.0%	100.0%	100.0%
12.5	1/2"	99.7%	99.9%	99.8%	99.8%	99.8%
9.5	3/8"	96.0%	95.7%	95.5%	95.6%	95.7%
4.75	#4	74.6%	74.9%	74.7%	74.8%	74.8%
2.36	#8	58.4%	56.7%	57.5%	57.6%	57.5%
1.18	#16	47.7%	47.9%	47.0%	47.4%	47.5%
0.6	#30	40.5%	41.0%	39.7%	40.8%	40.5%
0.3	#50	33.2%	34.0%	32.7%	33.7%	33.4%
0.15	#100	16.7%	18.4%	17.3%	18.3%	17.7%
0.075	#200	7.79%	9.10%	8.58%	8.26%	8.44%
Binder Content		5.32%	5.42%	5.48%	5.45%	5.42%

Table A-2 Ignition Oven Test Results: Whitehurst RAP

Sieve Size (mm)		WHITEHURST RAP				AVERAGE VALUES
		Specimen 1	Specimen 2	Specimen 3	Specimen 4	
19	3/4"	100.0%	99.6%	100.0%	100.0%	99.9%
12.5	1/2"	96.4%	96.1%	96.8%	96.0%	96.3%
9.5	3/8"	73.8%	72.7%	72.9%	73.1%	73.1%
4.75	#4	27.0%	27.6%	27.1%	27.4%	27.3%
2.36	#8	20.7%	20.9%	21.2%	20.6%	20.8%
1.18	#16	17.7%	17.9%	17.5%	17.5%	17.7%
0.6	#30	15.3%	15.5%	15.6%	15.4%	15.5%
0.3	#50	12.3%	12.6%	12.1%	12.7%	12.4%
0.15	#100	7.9%	8.2%	8.0%	8.1%	8.1%
0.075	#200	4.92%	5.25%	5.40%	5.28%	5.21%
Binder Content		4.75%	4.78%	4.81%	4.83%	4.79%

Table A-3 Solvent Method Results: Atlantic Coast RAP

Sieve Size (mm)		ATLANTIC COAST RAP				AVERAGE VALUES
		Specimen 1	Specimen 2	Specimen 3	Specimen 4	
19	3/4"	100.0%	100.0%	100.0%	100.0%	100.0%
12.5	1/2"	99.4%	99.5%	99.6%	99.6%	99.5%
9.5	3/8"	94.4%	94.4%	92.3%	95.5%	94.2%
4.75	#4	74.2%	74.1%	72.5%	74.3%	73.8%
2.36	#8	56.5%	56.2%	55.9%	57.1%	56.4%
1.18	#16	46.0%	46.0%	45.9%	42.7%	45.2%
0.6	#30	38.7%	39.0%	39.2%	35.7%	38.1%
0.3	#50	31.7%	32.1%	32.5%	28.9%	31.3%
0.15	#100	18.1%	18.4%	19.3%	16.8%	18.2%
0.075	#200	8.52%	8.75%	9.01%	7.88%	8.54%
Binder Content		4.90%	5.15%	4.71%	4.58%	4.8%

Table A-4 Solvent Method Results: Whitehurst RAP

Sieve Size (mm)		WHITEHURST RAP				AVERAGE VALUES
		Specimen 1	Specimen 2	Specimen 3	Specimen 4	
19	3/4"	100.0%	100.0%	100.0%	100.0%	100.0%
12.5	1/2"	95.8%	97.0%	96.8%	95.3%	96.2%
9.5	3/8"	76.1%	76.8%	75.8%	74.1%	75.7%
4.75	#4	29.5%	28.0%	29.7%	27.3%	28.6%
2.36	#8	22.5%	21.2%	21.9%	20.9%	21.6%
1.18	#16	19.3%	18.1%	18.9%	18.1%	18.6%
0.6	#30	16.9%	15.7%	16.5%	15.9%	16.3%
0.3	#50	13.7%	12.8%	13.5%	13.0%	13.2%
0.15	#100	8.8%	8.2%	8.8%	8.5%	8.6%
0.075	#200	5.41%	5.12%	5.60%	5.28%	5.35%
Binder Content		4.33%	4.59%	4.69%	4.62%	4.6%

APPENDIX B BATCHING WEIGHTS FOR DESIGNED MIXTURES

Table B-1 Batching Sheet: FC-12.5 Reference Mixture

FC-12.5 Reference Mixture		Retained Weight (g)			
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit
29	1"	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0
12.5	1/2"	33.8	0.0	0.0	0.0
9.5	3/8"	461.3	0.0	0.0	0.0
4.75	#4	540.0	328.5	162.0	0.0
2.36	#8	56.3	108.0	756.0	0.0
1.18	#16	11.3	9.0	594.0	0.0
0.6	#30	0.0	0.0	378.0	0.0
0.3	#50	0.0	0.0	297.0	0.0
0.15	#100	0.0	0.0	270.0	135.0
0.075	#200	11.3	0.0	121.5	85.5
Pan		11.3	4.5	121.5	4.5
Sum Each Stockpile		1125.0	450.0	2700.0	225.0
Pb(%)	5.2	Gyration Number	75	SUM	4500.0

Table B-2 Batching Sheet: 20% ARL RAP Mixture

20% ATL RAP Mixture		Retained Weight (g)				
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit	ATL RAP
29	1"	0.0	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	27.0	0.0	0.0	0.0	9.5
9.5	3/8"	369.0	0.0	0.0	0.0	113.4
4.75	#4	432.0	164.3	143.1	0.0	274.2
2.36	#8	45.0	54.0	667.8	0.0	189.1
1.18	#16	9.0	4.5	524.7	0.0	111.5
0.6	#30	0.0	0.0	333.9	0.0	86.1
0.3	#50	0.0	0.0	262.4	0.0	76.9
0.15	#100	0.0	0.0	238.5	54.0	68.4
0.075	#200	9.0	0.0	107.3	34.2	14.3
Pan		9.0	2.3	107.3	1.8	2.0
Sum Each Stockpile		900.0	225.0	2385.0	90.0	945.4
Pb(%)	5.2	Gyration Number	75	SUM	4545.4	

Table B-3 Batching Sheet: 30% ARL RAP Mixture

30% ATL RAP Mixture		Retained Weight (g)				
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit	ATL RAP
29	1"	0.0	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	28.4	0.0	0.0	0.0	14.2
9.5	3/8"	387.5	0.0	0.0	0.0	170.2
4.75	#4	453.6	65.7	121.5	0.0	411.2
2.36	#8	47.3	21.6	567.0	0.0	283.6
1.18	#16	9.5	1.8	445.5	0.0	167.2
0.6	#30	0.0	0.0	283.5	0.0	129.2
0.3	#50	0.0	0.0	222.8	0.0	115.4
0.15	#100	0.0	0.0	202.5	54.0	102.6
0.075	#200	9.5	0.0	91.1	34.2	21.5
Pan		9.5	0.9	91.1	1.8	3.0
Sum Each Stockpile		945.0	90.0	2025.0	90.0	1418.1
Pb(%)	5.0	Gyration Number	75	SUM	4568.1	

Table B-4 Batching Sheet: 40% ATL RAP Mixture

40% ATL RAP Mixture		Retained Weight (g)				
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit	ATL RAP
29	1"	0.0	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	25.7	0.0	0.0	0.0	18.9
9.5	3/8"	350.6	0.0	0.0	0.0	226.9
4.75	#4	410.4	65.7	102.6	0.0	548.3
2.36	#8	42.8	21.6	478.8	0.0	378.2
1.18	#16	8.6	1.8	376.2	0.0	222.9
0.6	#30	0.0	0.0	239.4	0.0	172.3
0.3	#50	0.0	0.0	188.1	0.0	153.8
0.15	#100	0.0	0.0	171.0	27.0	136.8
0.075	#200	8.6	0.0	77.0	17.1	28.7
Pan		8.6	0.9	77.0	0.9	4.0
Sum Each Stockpile		855.0	90.0	1710.0	45.0	1890.8
Pb(%)	4.9	Gyration Number	75	SUM	4590.8	

Table B-5 Batching Sheet: 20% WHI RAP Mixture

20% WHI RAP Mixture		Retained Weight (g)				
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit	WHI RAP
29	1"	0.0	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	14.9	0.0	0.0	0.0	84.9
9.5	3/8"	203.0	0.0	0.0	0.0	311.3
4.75	#4	237.6	65.7	170.1	0.0	443.4
2.36	#8	24.8	21.6	793.8	0.0	47.2
1.18	#16	5.0	1.8	623.7	0.0	21.9
0.6	#30	0.0	0.0	396.9	0.0	10.3
0.3	#50	0.0	0.0	311.9	0.0	8.8
0.15	#100	0.0	0.0	283.5	108.0	8.2
0.075	#200	5.0	0.0	127.6	68.4	4.1
Pan		5.0	0.9	127.6	3.6	3.4
Sum Each Stockpile		495.0	90.0	2835.0	180.0	943.4
Pb(%)	5.9	Gyration Number	75	SUM	4543.4	

Table B-6 Batching Sheet: 30% WHI RAP Mixture

30% WHI RAP Mixture		Retained Weight (g)				
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit	WHI RAP
29	1"	0.0	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	5.4	0.0	0.0	0.0	127.4
9.5	3/8"	73.8	0.0	0.0	0.0	467.0
4.75	#4	86.4	32.9	167.4	0.0	665.1
2.36	#8	9.0	10.8	781.2	0.0	70.8
1.18	#16	1.8	0.9	613.8	0.0	32.8
0.6	#30	0.0	0.0	390.6	0.0	15.4
0.3	#50	0.0	0.0	306.9	0.0	13.2
0.15	#100	0.0	0.0	279.0	81.0	12.3
0.075	#200	1.8	0.0	125.6	51.3	6.1
Pan		1.8	0.5	125.6	2.7	5.1
Sum Each Stockpile		180.0	45.0	2790.0	135.0	1415.1
Pb(%)	5.9	Gyration Number	75	SUM	4565.1	

Table B-7 Batching Sheet: 40% WHI RAP Mixture

40% WHI RAP Mixture		Retained Weight (g)				
Sieve Size (mm)		C43/#7 Stone	C51/#89 Stone	F20/W-10 Stone	334-LS/Shad Pit	WHI RAP
29	1"	0.0	0.0	0.0	0.0	0.0
19	3/4"	0.0	0.0	0.0	0.0	0.0
12.5	1/2"	0.0	0.0	0.0	0.0	169.8
9.5	3/8"	0.0	0.0	0.0	0.0	622.6
4.75	#4	0.0	0.0	153.9	0.0	886.8
2.36	#8	0.0	0.0	718.2	0.0	94.3
1.18	#16	0.0	0.0	564.3	0.0	43.8
0.6	#30	0.0	0.0	359.1	0.0	20.6
0.3	#50	0.0	0.0	282.2	0.0	17.5
0.15	#100	0.0	0.0	256.5	81.0	16.4
0.075	#200	0.0	0.0	115.4	51.3	8.1
Pan		0.0	0.0	115.4	2.7	6.8
Sum Each Stockpile		0.0	0.0	2565.0	135.0	1886.8
Pb(%)	5.6	Gyration Number	75	SUM	4586.8	

APPENDIX C SUPERPAVE IDT SPECIMENS INFORMATION

Table C-1 ATL and WHI RAP mixtures with PG 76-22PMA after STOA Conditioning

PG 76-22PMA	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	%V	Average Thickness (in)
STOA-Virgin 01	1559.8	902.7	1562.5	2.364	2.529	6.5%	1.49
STOA-Virgin 02	1598.3	923.7	1601.5	2.358	2.529	6.8%	1.53
STOA-Virgin 03	1599.4	925.3	1602.7	2.361	2.529	6.6%	1.53
STOA-20%ATL 01	1647.0	947.0	1650.3	2.342	2.507	6.6%	1.59
STOA-20%ATL 02	1702.8	978.1	1705.7	2.340	2.507	6.7%	1.66
STOA-20%ATL 03	1592.5	914.2	1597.4	2.331	2.507	7.0%	1.54
STOA-20%WHI 01	1592.7	899.5	1595.9	2.287	2.467	7.3%	1.56
STOA-20%WHI 02	1639.8	928.0	1644.1	2.290	2.467	7.2%	1.60
STOA-20%WHI 03	1680.9	956.6	1684.3	2.310	2.467	6.4%	1.65
STOA-30%ATL 01	1523.8	875.1	1526.7	2.339	2.509	6.8%	1.47
STOA-30%ATL 02	1592.7	912.2	1598.3	2.321	2.509	7.5%	1.55
STOA-30%ATL 03	1549.1	890.0	1553.3	2.335	2.509	6.9%	1.50
STOA-30%WHI 01	1580.4	891.1	1583.4	2.283	2.449	6.8%	1.56
STOA-30%WHI 02	1536.6	866.7	1540.1	2.282	2.449	6.8%	1.50
STOA-30%WHI 03	1607.2	907.6	1610.1	2.288	2.449	6.6%	1.58
STOA-40%ATL 01	1585.2	913.0	1588.7	2.346	2.513	6.6%	1.51
STOA-40%ATL 02	1534.7	885.1	1537.4	2.353	2.513	6.4%	1.47
STOA-40%ATL 03	1607.8	927.1	1611.6	2.349	2.513	6.5%	1.55
STOA-40%WHI 01	1406.8	792.2	1411.8	2.270	2.445	7.1%	1.40
STOA-40%WHI 02	1441.9	811.7	1448.2	2.265	2.445	7.3%	1.43
STOA-40%WHI 03	1744.4	985.3	1748.5	2.286	2.445	6.5%	1.55

Table C-2 ATL and WHI RAP mixtures with PG 76-22ARB after STOA Conditioning

PG 76-22ARB	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	%V	Average Thickness (in)
STOA-Virgin 01	1668.9	967.3	1672.9	2.365	2.541	6.9%	1.59
STOA-Virgin 02	1562.5	905.9	1566.2	2.366	2.541	6.9%	1.48
STOA-Virgin 03	1686.7	981.2	1691.1	2.376	2.541	6.5%	1.59
STOA-20%ATL 01	1581.4	911.2	1583.4	2.353	2.518	6.6%	1.51
STOA-20%ATL 02	1568.5	899.6	1571.4	2.335	2.518	7.3%	1.51
STOA-20%ATL 03	1612.0	924.3	1615.5	2.332	2.518	7.4%	1.55
STOA-20%WHI 01	1628.8	926.9	1631.9	2.310	2.477	6.7%	1.58
STOA-20%WHI 02	1500.7	855.2	1503.6	2.314	2.477	6.6%	1.46
STOA-20%WHI 03	1638.6	933.6	1642.0	2.313	2.477	6.6%	1.59
STOA-30%ATL 01	1468.1	843.0	1471.1	2.337	2.516	7.1%	1.41
STOA-30%ATL 02	1573.8	903.8	1577.6	2.336	2.516	7.2%	1.51
STOA-30%ATL 03	1597.0	920.3	1601.0	2.346	2.516	6.8%	1.53
STOA-30%WHI 01	1526.8	865.6	1531.0	2.295	2.457	6.6%	1.50
STOA-30%WHI 02	1512.6	856.3	1516.6	2.291	2.457	6.8%	1.48
STOA-30%WHI 03	1548.0	876.5	1551.7	2.293	2.457	6.7%	1.52
STOA-40%ATL 01	1611.2	925.5	1615.6	2.335	2.517	7.2%	1.56
STOA-40%ATL 02	1639.4	939.3	1643.8	2.327	2.517	7.5%	1.58
STOA-40%ATL 03	1593.3	917.2	1597.6	2.342	2.517	7.0%	1.54
STOA-40%WHI 01	1532.9	864.2	1538.3	2.274	2.453	7.3%	1.50
STOA-40%WHI 02	1567.0	883.1	1570.9	2.278	2.453	7.1%	1.55
STOA-40%WHI 03	1458.1	819.7	1462.6	2.268	2.453	7.5%	1.45

Table C-3 ATL and WHI RAP mixtures with PG 76-22PMA after LTOA+CPPC Conditioning

PG 76-22PMA	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	%V	Average Thickness (in)
LTOA+CPPC-Virgin 01	1564.5	902.7	1567.7	2.353	2.529	7.0%	1.50
LTOA+CPPC-Virgin 02	1640.2	947.3	1643.0	2.358	2.529	6.8%	1.57
LTOA+CPPC-Virgin 03	1660.2	964.3	1666.2	2.365	2.529	6.5%	1.58
LTOA+CPPC-20%ATL 01	1566.6	902.0	1570.5	2.343	2.507	6.6%	1.50
LTOA+CPPC-20%ATL 02	1630.5	937.8	1633.0	2.345	2.507	6.5%	1.56
LTOA+CPPC-20%ATL 03	1560.4	898.3	1564.1	2.347	2.507	6.5%	1.50
LTOA+CPPC-20%WHI 01	1553.2	882.3	1556.6	2.303	2.467	6.6%	1.52
LTOA+CPPC-20%WHI 02	1486.6	844.5	1489.9	2.303	2.467	6.6%	1.46
LTOA+CPPC-20%WHI 03	1587.2	902.0	1591.8	2.301	2.467	6.7%	1.56
LTOA+CPPC-30%ATL 01	1680.8	967.0	1685.0	2.341	2.509	6.7%	1.60
LTOA+CPPC-30%ATL 02	1565.6	901.1	1569.1	2.344	2.509	6.6%	1.51
LTOA+CPPC-30%ATL 03	1548.1	889.0	1550.6	2.340	2.509	6.7%	1.48
LTOA+CPPC-30%WHI 01	1587.8	898.0	1591.7	2.289	2.449	6.5%	1.55
LTOA+CPPC-30%WHI 02	1534.8	867.8	1539.2	2.286	2.449	6.6%	1.51
LTOA+CPPC-30%WHI 03	1494.6	845.8	1498.7	2.289	2.449	6.5%	1.47
LTOA+CPPC-40%ATL 01	1573.0	905.2	1576.9	2.342	2.513	6.8%	1.50
LTOA+CPPC-40%ATL 02	1615.4	927.3	1620.3	2.331	2.513	7.2%	1.58
LTOA+CPPC-40%ATL 03	1596.2	920.5	1600.2	2.348	2.513	6.6%	1.55
LTOA+CPPC-40%WHI 01	1534.9	865.1	1539.1	2.277	2.445	6.9%	1.53
LTOA+CPPC-40%WHI 02	1512.1	851.0	1515.9	2.274	2.445	7.0%	1.49
LTOA+CPPC-40%WHI 03	1461.9	824.9	1468.0	2.273	2.445	7.0%	1.45

Table C-4 ATL and WHI RAP mixtures with PG 76-22ARB after LTOA+CPPC Conditioning

PG 76-22ARB	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	%V	Average Thickness (in)
LTOA+CPPC-Virgin 01	1648.3	958.4	1652.3	2.375	2.541	6.5%	1.56
LTOA+CPPC-Virgin 02	1563.5	908.2	1567.7	2.371	2.541	6.7%	1.50
LTOA+CPPC-Virgin 03	1528.9	887.7	1532.5	2.371	2.541	6.7%	1.45
LTOA+CPPC-20%ATL 01	1571.2	906.7	1575.6	2.349	2.518	6.7%	1.50
LTOA+CPPC-20%ATL 02	1591.6	914.0	1594.8	2.338	2.518	7.2%	1.53
LTOA+CPPC-20%ATL 03	1591.2	917.7	1596.7	2.343	2.518	6.9%	1.53
LTOA+CPPC-20%WHI 01	1595.1	918.1	1597.9	2.346	2.516	6.8%	1.53
LTOA+CPPC-20%WHI 02	1556.4	896.7	1559.9	2.347	2.516	6.8%	1.49
LTOA+CPPC-20%WHI 03	1550.6	891.2	1553.0	2.343	2.516	6.9%	1.50
LTOA+CPPC-30%ATL 01	1487.1	847.2	1490.8	2.311	2.477	6.7%	1.46
LTOA+CPPC-30%ATL 02	1564.2	891.7	1567.2	2.316	2.477	6.5%	1.52
LTOA+CPPC-30%ATL 03	1595.1	907.8	1597.4	2.313	2.477	6.6%	1.55
LTOA+CPPC-30%WHI 01	1571.8	888.8	1574.8	2.291	2.457	6.7%	1.54
LTOA+CPPC-30%WHI 02	1491.5	844.7	1495.1	2.293	2.457	6.7%	1.47
LTOA+CPPC-30%WHI 03	1504.0	850.4	1507.6	2.288	2.457	6.9%	1.47
LTOA+CPPC-40%ATL 01	1513.5	871.5	1516.9	2.345	2.517	6.8%	1.46
LTOA+CPPC-40%ATL 02	1594.6	918.8	1597.6	2.349	2.517	6.7%	1.53
LTOA+CPPC-40%ATL 03	1515.9	871.9	1520.3	2.338	2.517	7.1%	1.46
LTOA+CPPC-40%WHI 01	1462.2	825.2	1466.0	2.282	2.453	7.0%	1.43
LTOA+CPPC-40%WHI 02	1497.6	844.2	1500.4	2.282	2.453	7.0%	1.47
LTOA+CPPC-40%WHI 03	1593.1	897.1	1596.5	2.278	2.453	7.1%	1.57

APPENDIX D MIX DESIGNS

Table D-1 Mixture Design Parameters

% RAP		PG 76-22PMA				PG 76-22ARB
		Total Binder	G_{mm}	G_{mb}	Air Voids	G_{mm} used for IDT Specimen
Reference	0%	5.2%	2.529	2.424	4.2%	2.541
Atlantic RAP	20%	5.2%	2.507	2.399	4.3%	2.518
	30%	5.0%	2.509	2.409	4.0%	2.516
	40%	4.9%	2.513	2.415	3.9%	2.517
Whitehurst RAP	20%	5.9%	2.467	2.375	3.9%	2.477
	30%	5.9%	2.448	2.344	4.2%	2.457
	40%	5.6%	2.445	2.346	4.0%	2.453

Atlantic RAP Mixtures

20% Atlantic RAP Mixtures

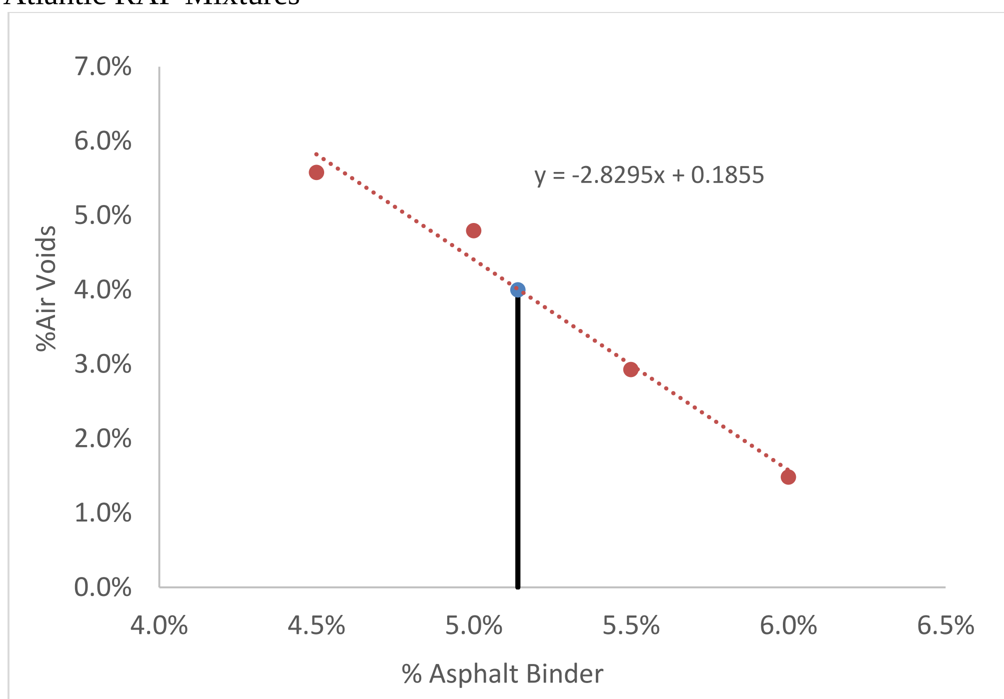

Figure D-1 %Asphalt binder vs. %Air voids

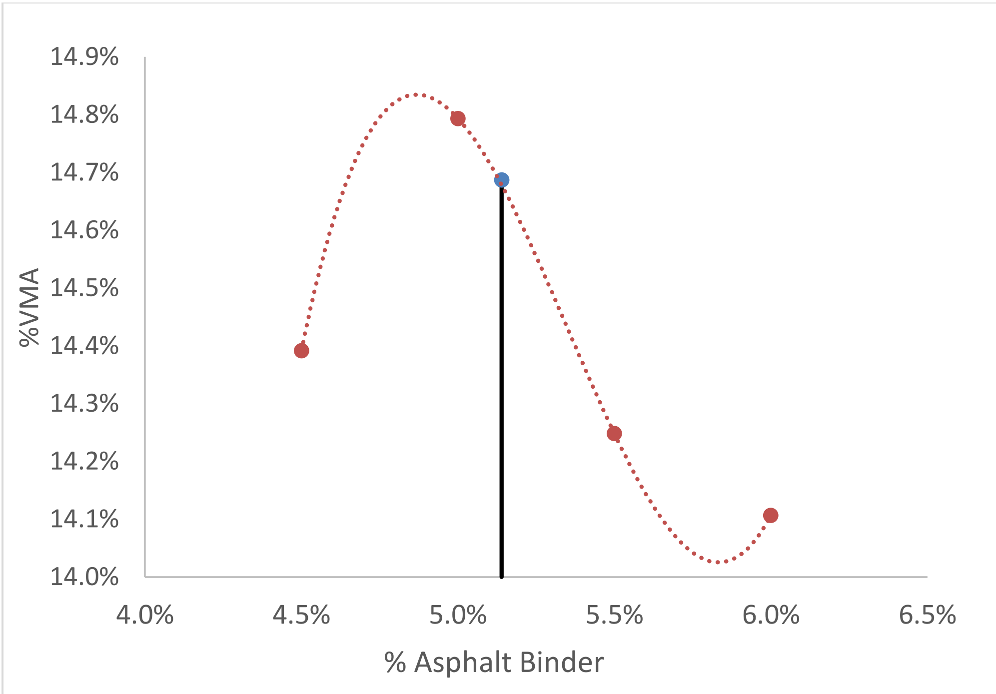

Figure D-2 % Asphalt binder vs. %VMA

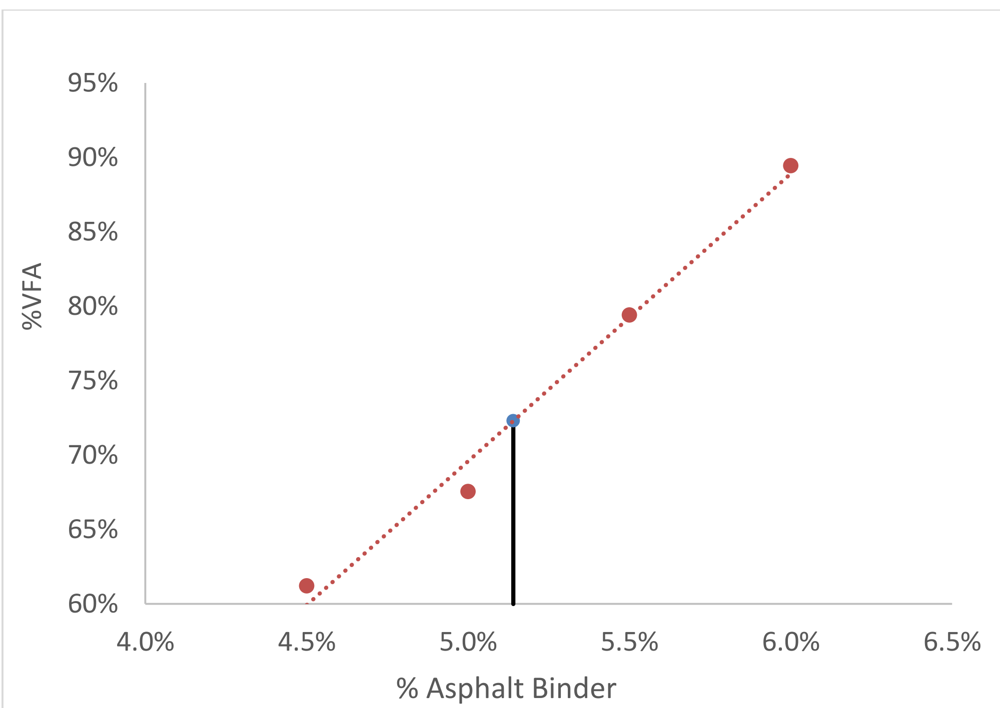

Figure D-3 %Asphalt binder vs. %VFA

30% Atlantic RAP Mixtures

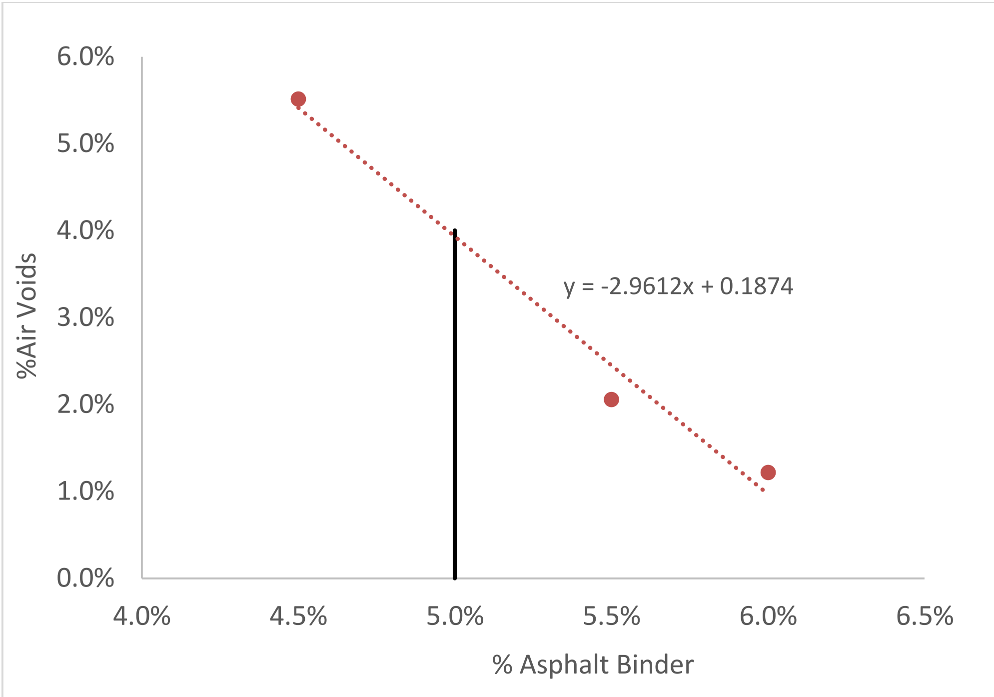

Figure D-4 %Asphalt binder vs. %Air voids

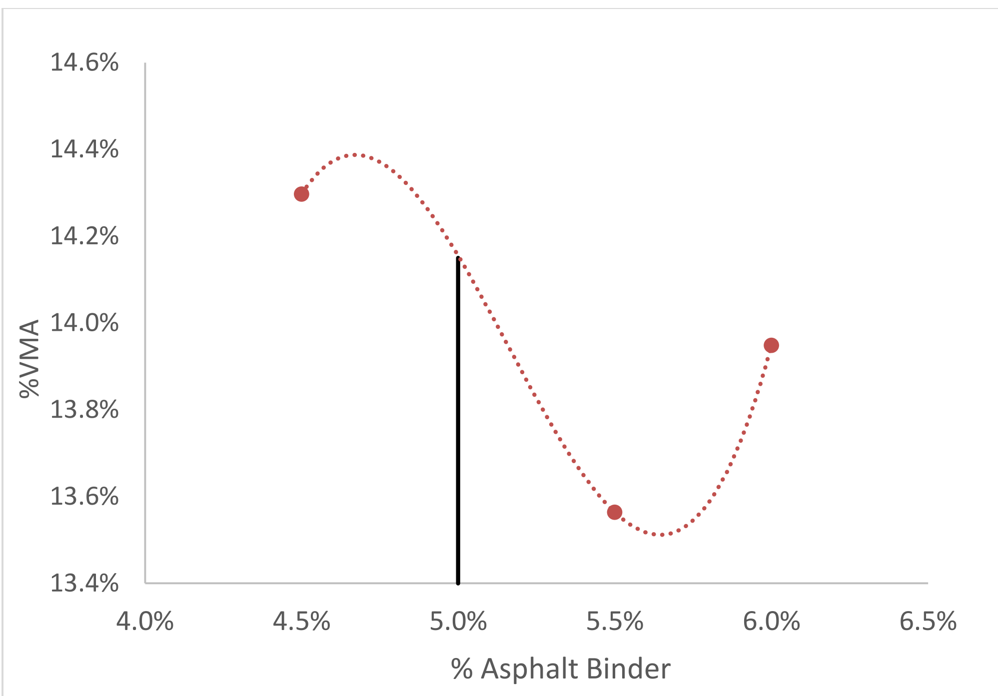

Figure D-5 %Asphalt binder vs. %VMA

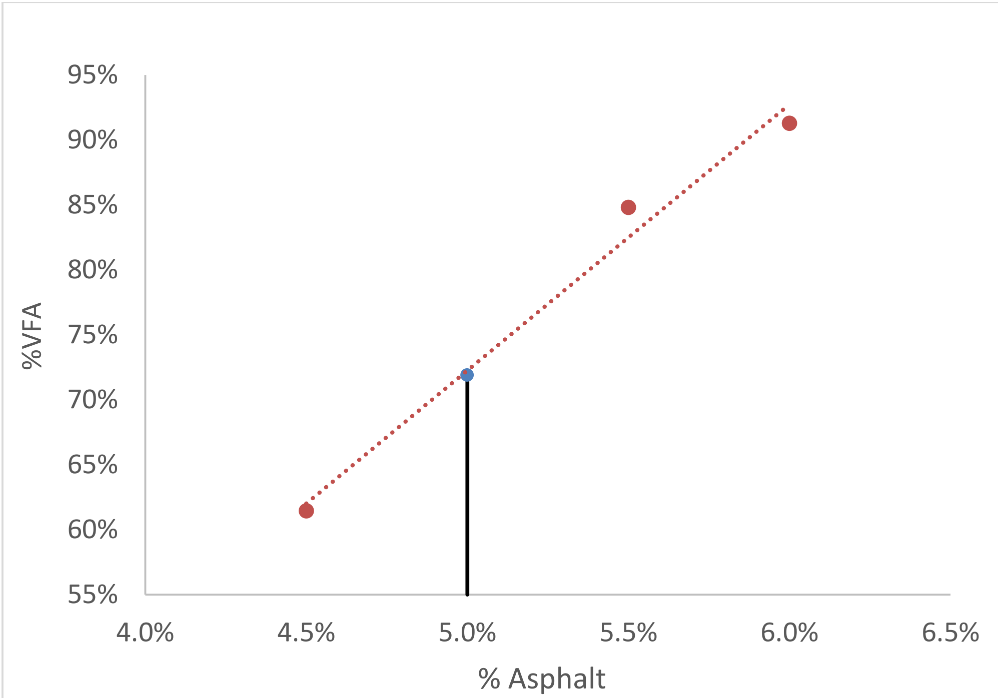

Figure D-6 %Asphalt binder vs. %VFA

40% Atlantic RAP Mixtures

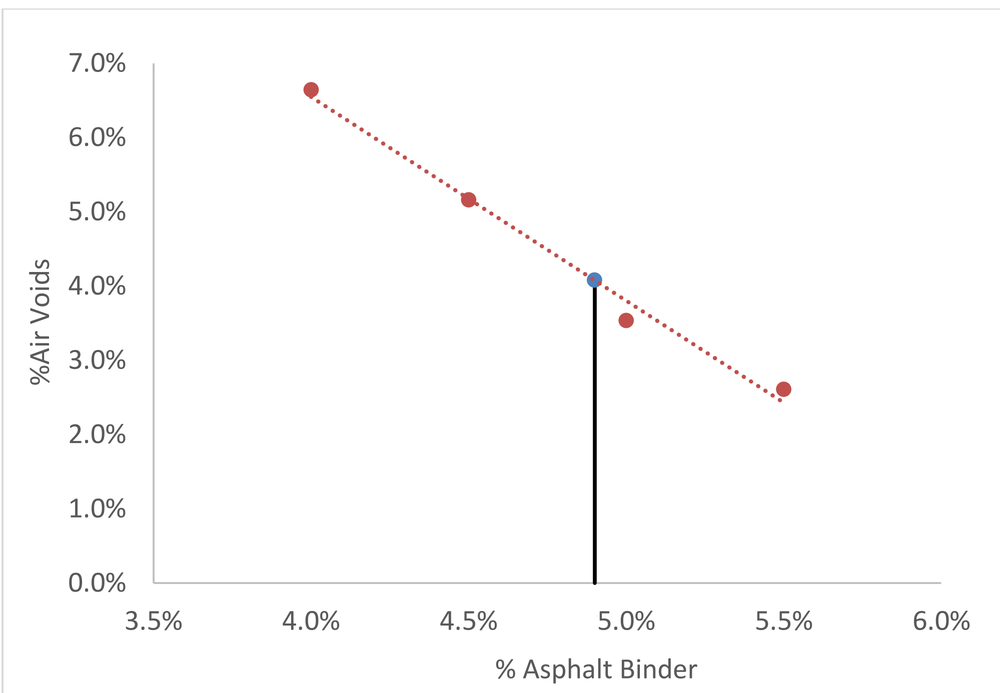

Figure D-7 %Asphalt binder vs. %Air voids

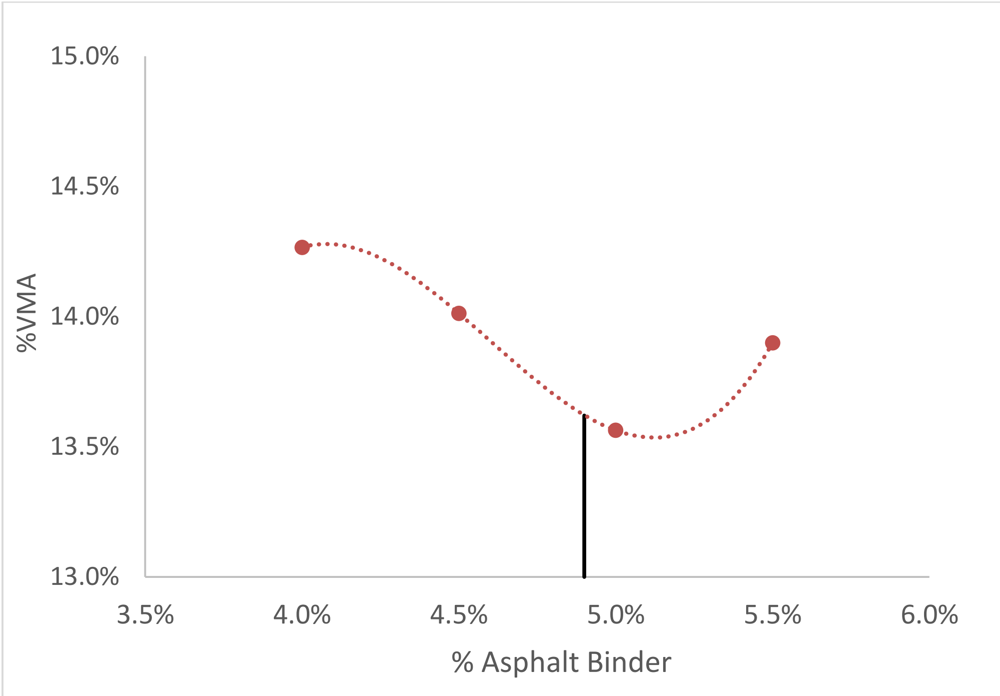

Figure D-8 %Asphalt binder vs. %VMA

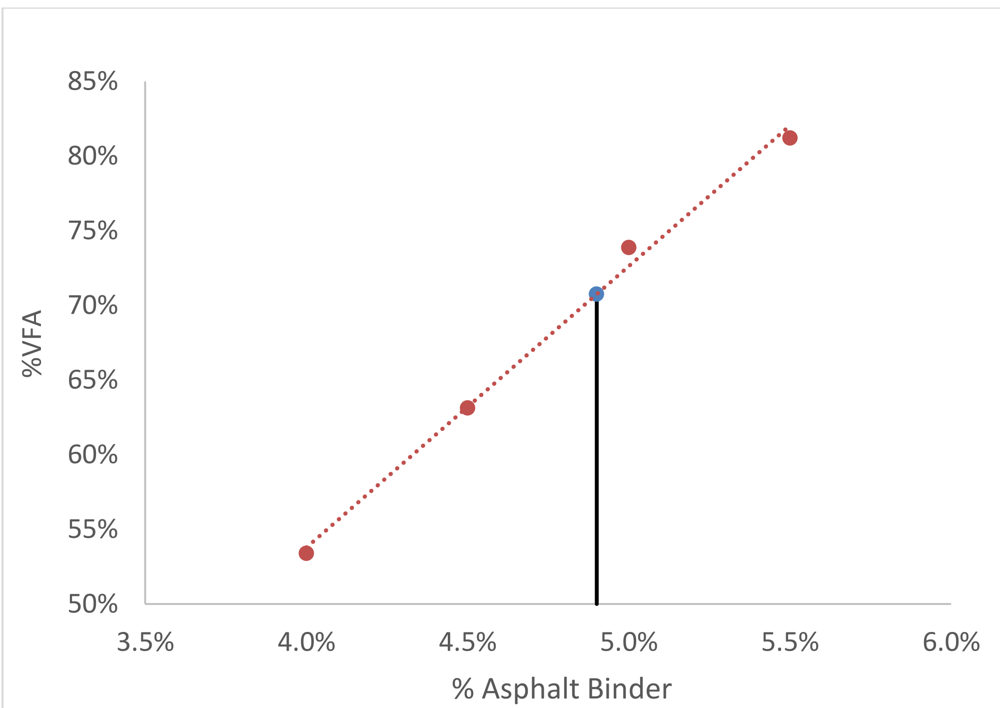

Figure D-9 %Asphalt binder vs. %VFA

Whitehurst RAP Mixtures
20% Whitehurst RAP Mixtures
Note: During the IDT specimen preparation process, it was found when 5.7% asphalt binder was added the SGC specimens actually had 4.7% and 4.8% air voids content. So, the asphalt binder content was revised to 5.9% to obtain 4% air voids

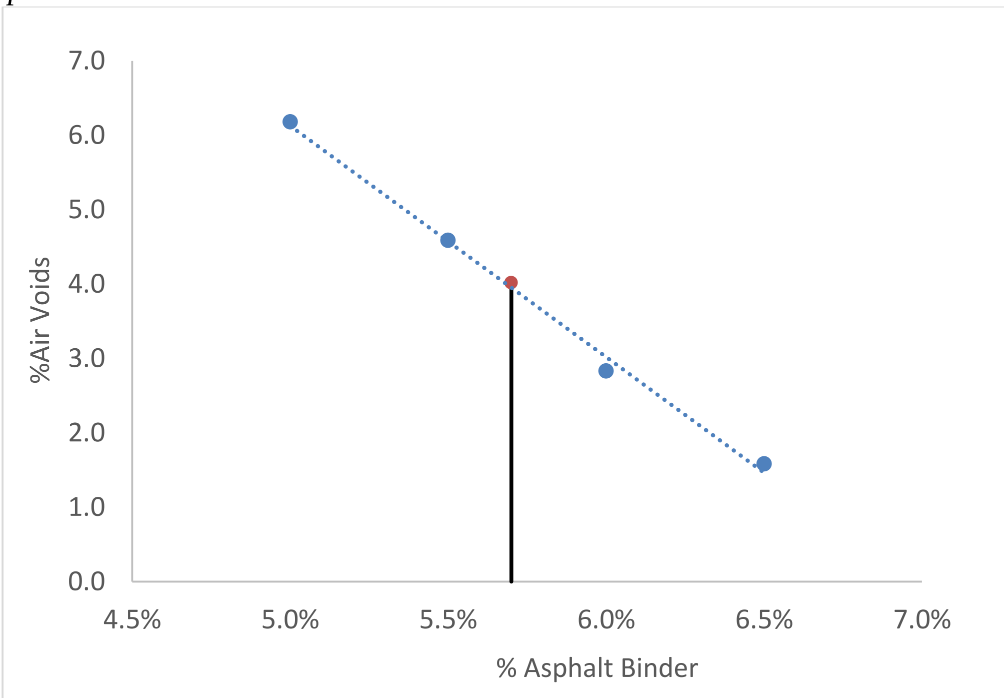

Figure D-10 %Asphalt binder vs. %Air voids

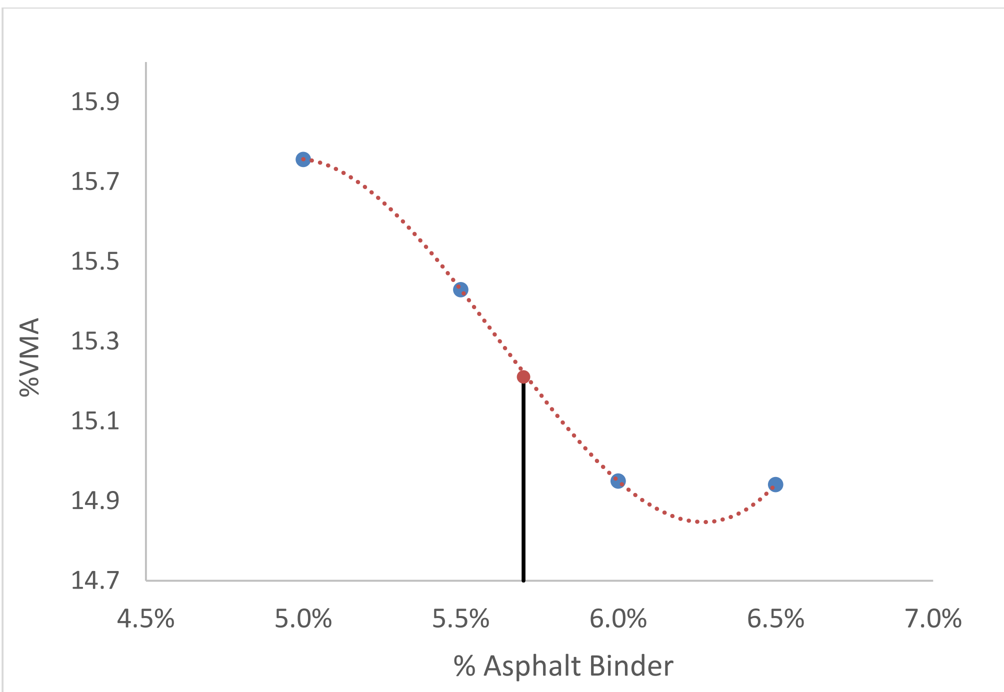

Figure D-11 %Asphalt binder vs. %VMA

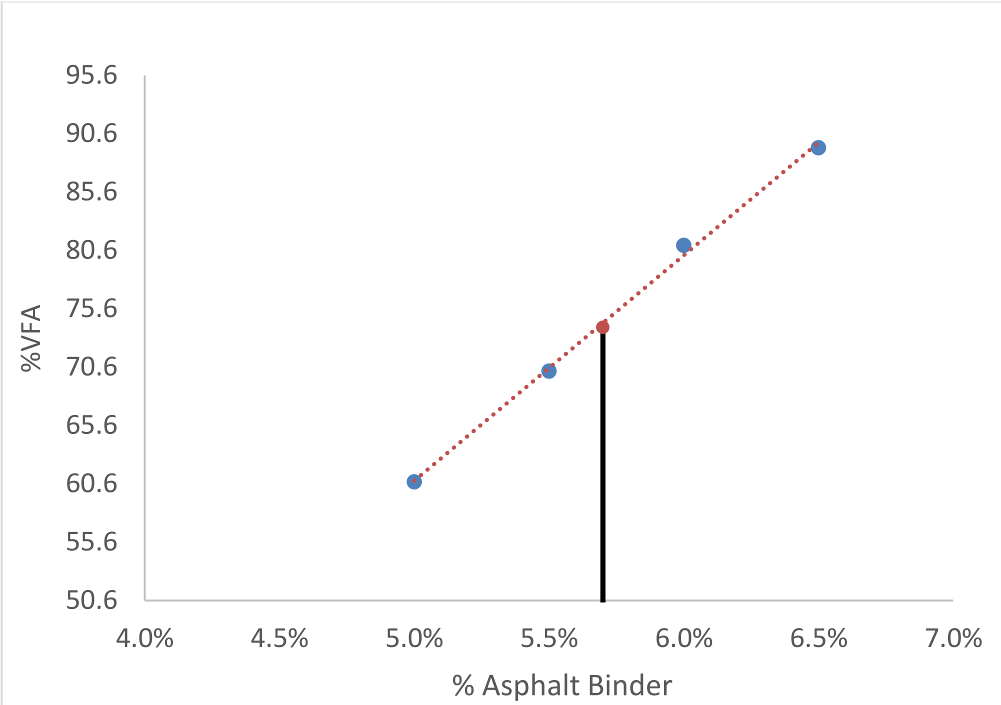

Figure D-12 %Asphalt binder vs. %VFA

30% Whitehurst RAP Mixtures

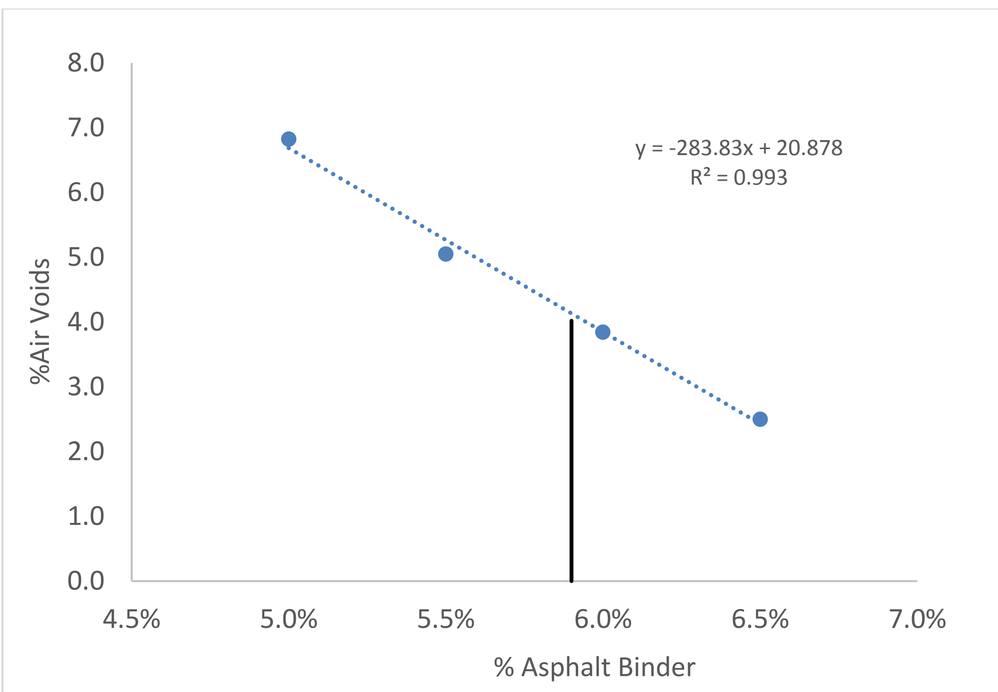

Figure D-13 %Asphalt binder vs. %Air voids

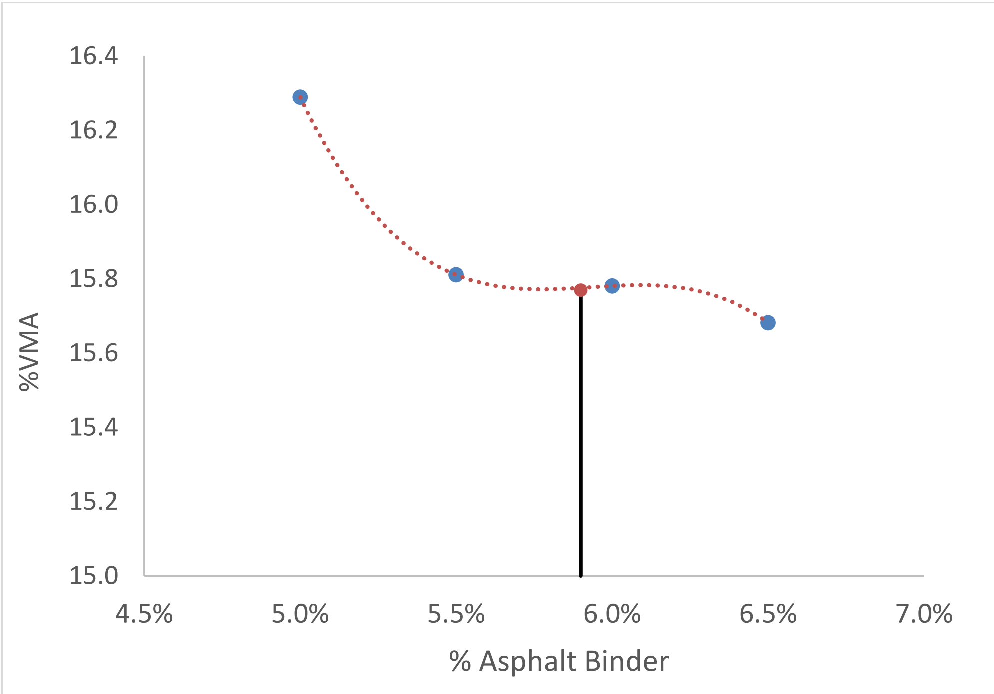

Figure D-14 %Asphalt binder vs. %VMA

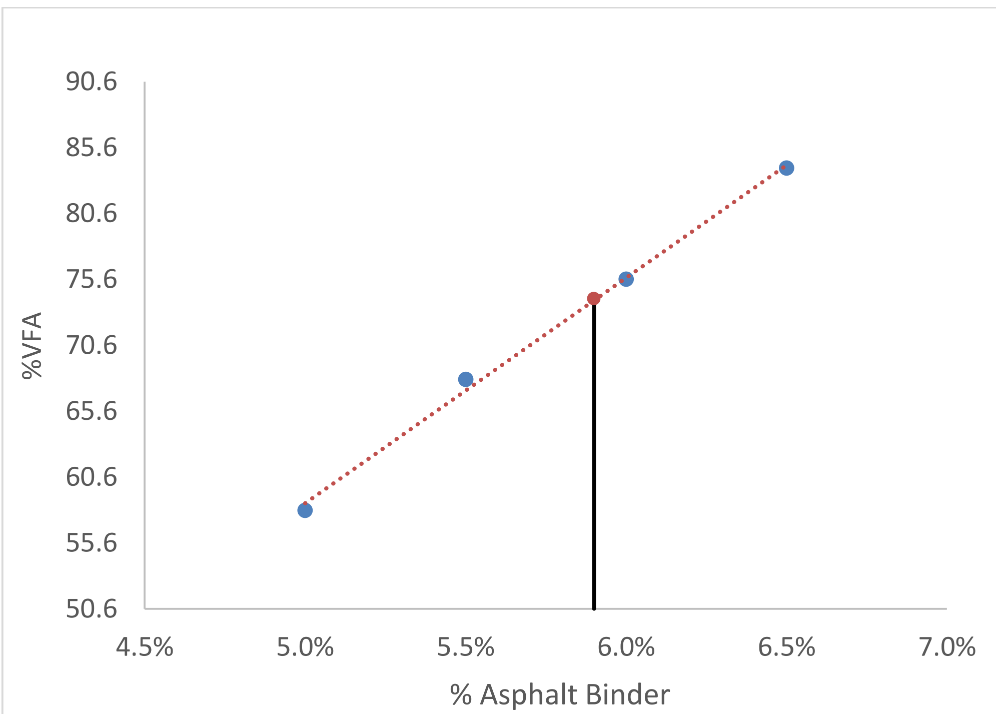

Figure D-15 %Asphalt binder vs. %VFA

40% Whitehurst RAP Mixtures

Note: During the IDT specimen preparation process, it was found when 5.8% asphalt binder was added the SGC specimen actually had 3.4% air voids content. So, the asphalt binder content was revised to 5.6% to obtain 4% air voids

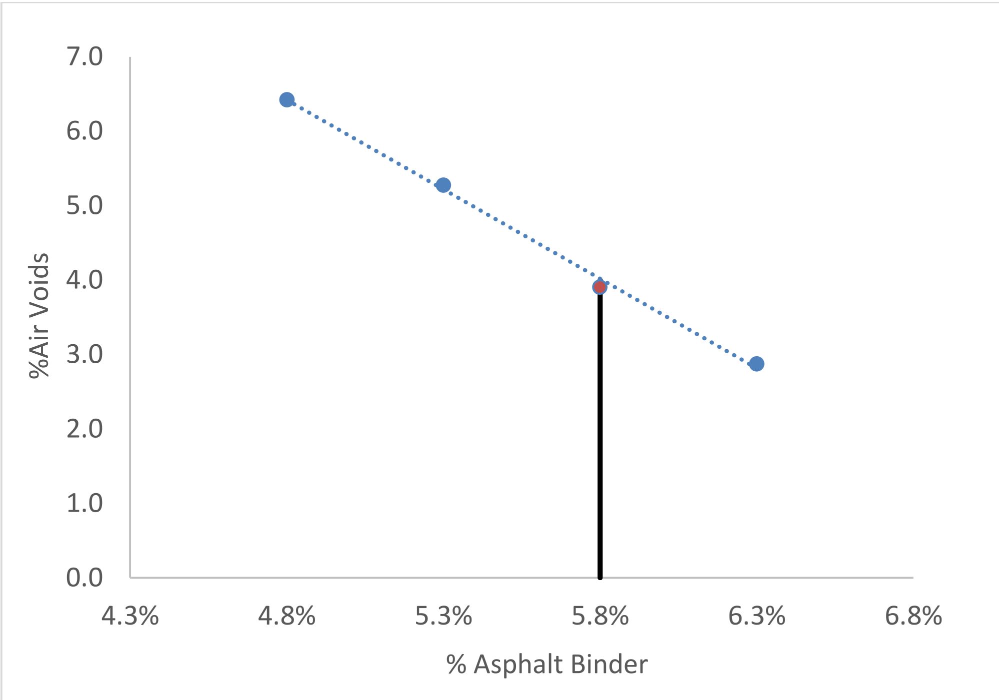

Figure D-16 %Asphalt binder vs. %Air voids

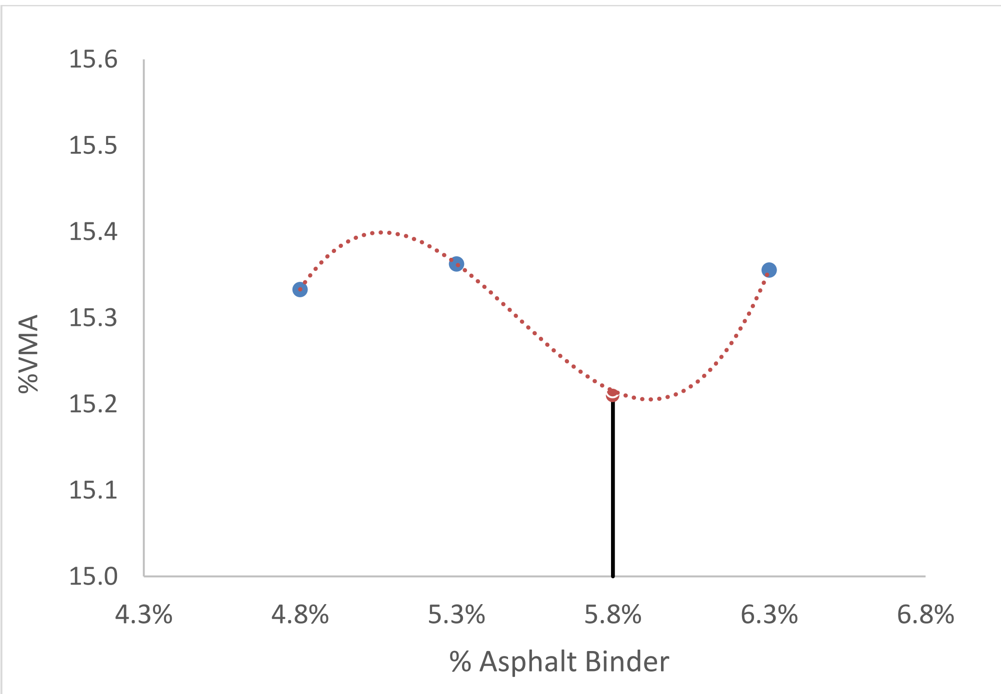

Figure D-17 %Asphalt binder vs. %VMA

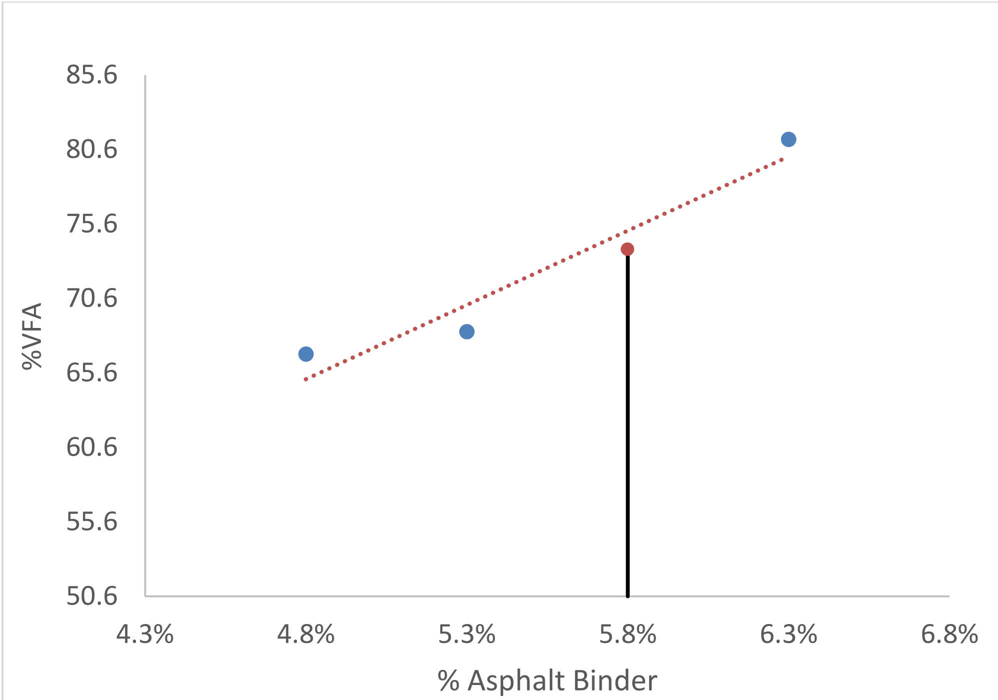

Figure D-18 %Asphalt binder vs. %VMA

APPENDIX E BINDER TESTING RESULTS

Table E-1 BV and DSR Tests Results: PG 76-22PMA (Original)

Original Binder		PG76-22 PMA						
		0%	Atlantic Coast RAP			Whitehurst RAP		
			20%	30%	40%	20%	30%	40%
BV (Pa·s)		1.46	1.64	1.70	1.90	1.78	1.98	2.24
DSR(G/sin (delta)) (kPa)	Specimen I	1.26	1.70	2.00	2.40	2.26	2.25	3.06
	Specimen II	1.20	1.74	2.03	2.41	1.88	2.28	2.96

Table E-2 BV and DSR Tests Results: PG 76-22ARB (Original)

Original Binder		PG76-22 ARB						
		0%	Atlantic Coast RAP			Whitehurst RAP		
			20%	30%	40%	20%	30%	40%
BV (Pa·s)		2.68	2.68	2.61	2.75	2.86	3.11	3.33
DSR(G*/sin (delta)) (kPa)	Specimen I	1.24	1.66	1.90	2.54	1.89	2.65	3.18
	Specimen II	1.19	1.64	1.95	2.48	1.79	2.55	3.11

Table E-3 DSR Phase Angle Results

Phase Angle, δ(°)		PG76-22PMA			PG76-22ARB		
		Specimen I	Specimen II	Average	Specimen I	Specimen II	Average
Atlantic Coast RAP	0%	71.8	71.7	71.8	66.8	66.6	66.7
	20%	72.4	72.4	72.4	68.8	68.8	68.8
	30%	73.0	72.8	72.9	70.4	70.3	70.4
	40%	73.6	73.5	73.6	70.7	70.7	70.7
Whitehurst RAP	0%	71.8	71.7	71.8	66.8	66.6	66.7
	20%	72.0	72.2	72.1	68.2	68.3	68.3
	30%	72.3	72.3	72.3	69.2	69.2	69.2
	40%	72.6	72.6	72.6	69.3	69.5	69.4

Table E-4 MSCR Test Results: PG 76-22 PMA (RTO-aged)

RTFO Binder			PG76-22 PMA						
			0%	Atlantic Coast RAP			Whitehurst RAP		
				20%	30%	40%	20%	30%	40%
MSCR	$J_{nr,3.2}$	Specimen I	0.41	0.34	0.27	0.23	0.30	0.12	0.17
		Specimen II	0.40	0.36	0.28	0.23	0.30	0.13	0.16
	%Re	Specimen I	55.48	50.57	48.78	49.32	52.34	56.12	53.20
		Specimen II	56.66	49.97	48.52	48.82	52.46	55.85	55.10

Table E-5 MSCR Test Results: PG 76-22 ARB (RTO-aged)

RTFO Binder			PG76-22 ARB						
			0%	Atlantic Coast RAP			Whitehurst RAP		
				20%	30%	40%	20%	30%	40%
MSCR	$J_{nr,3.2}$	Specimen I	0.31	0.30	0.30	0.28	0.22	0.23	0.15
		Specimen II	0.32	0.31	0.28	0.31	0.22	0.23	0.15
	%Re	Specimen I	74.30	63.98	57.88	56.62	66.78	62.40	58.63
		Specimen II	74.70	64.12	57.69	53.35	66.64	62.40	58.48

Table E-6 BBR Test Results: PG 76-22 PMA (PAV-aged)

PAV Binder		PG76-22 PMA						
		0%	Atlantic Coast RAP			Whitehurst RAP		
			20%	30%	40%	20%	30%	40%
DSRG*sin(delta) (kPa)	Specimen I	1520	2330	2280	2900	2630	2710	4060
	Specimen II	1570	2280	2200	2950	2750	3010	3990
BBR	m	0.39	0.37	0.37	0.32	0.36	0.34	0.32
	s	104	128	130	158	138	145	204

Table E-7 BBR Test Results: PG 76-22 ARB (PAV-aged)

PAV Binder		PG76-22 PMA						
		0%	Atlantic Coast RAP			Whitehurst RAP		
			20%	30%	40%	20%	30%	40%
DSRG*sin(delta) (kPa)	Specimen I	1180	2600	2580	3330	2270	3230	3600
	Specimen II	1180	2350	2520	3580	2280	2740	3590
BBR	m	0.39	0.35	0.34	0.32	0.35	0.33	0.32
	s	97	124	139	149	126	157	173

Table E-8 BFE Test Results

Binder Fracture Energy Density (psi)						
Binder Types	PG 76-22PMA			PG 76-22ARB		
	Specimen I	Specimen II	Averaged	Specimen I	Specimen II	Averaged
0%	1240	1143	1192	990	1080	1035
ATLANTIC 20%	981	883	932	954	951	952
ATLANTIC 30%	841	805	823	855	952	903
ATLANTIC 40%	611	636	623	761	697	729
WHITEHURST 20%	1065	1141	1103	900	966	933
WHITEHURST 30%	1059	969	1014	871	893	882
WHITEHURST 40%	631	620	625	893	861	877

APPENDIX F SUPERPAVE IDT TESTING RESULTS

Table F-1 Superpave IDT Results for RAP mixtures with PMA (STOA)

Mixture Type	m-value	D_1 (1/psi)	St (Mpa)	MR (Gpa)	FED (kJ/m^3)	DCSEf (kJ/m^3)	Creep Compliance Rate (1/psi·sec)	Failure Strain (με)
Virgin	0.432	8.3E-07	2.4	9.0	5.0	4.7	7.1E-09	2773
20%ATL	0.390	6.5E-07	2.4	9.4	2.9	2.6	3.7E-09	1671
30%ATL	0.420	3.8E-07	2.6	10.6	2.5	2.2	2.9E-09	1369
40%ATL	0.421	2.4E-07	2.9	13.6	2.3	2.0	1.9E-09	1172
Virgin	0.432	8.3E-07	2.4	9.0	5.0	4.7	7.1E-09	2773
20%WHI	0.386	6.9E-07	2.4	8.8	4.0	3.7	3.8E-09	2330
30%WHI	0.411	5.7E-07	2.6	9.3	3.8	3.4	4.0E-09	2046
40%WHI	0.366	4.3E-07	2.3	11.2	1.3	1.1	2.0E-09	902

Table F-2 Superpave IDT Results for RAP mixtures with ARB (STOA)

Mixture Type	m-value	D_1 (1/psi)	St (Mpa)	MR (Gpa)	FED (kJ/m^3)	DCSEf (kJ/m^3)	Creep Compliance Rate (1/psi·sec)	Failure Strain (με)
Virgin	0.504	7.4E-07	2.0	8.8	5.3	5.1	1.2E-08	3587
20%ATL	0.463	6.3E-07	2.1	9.8	3.5	3.3	7.1E-09	2202
30%ATL	0.473	4.1E-07	2.2	10.9	2.6	2.4	5.1E-09	1639
40%ATL	0.444	3.9E-07	2.5	10.7	3.1	2.8	3.7E-09	1714
Virgin	0.504	7.4E-07	2.0	8.8	5.3	5.1	1.2E-08	3587
20%WHI	0.466	5.9E-07	2.3	9.4	4.9	4.6	6.9E-09	2858
30%WHI	0.460	5.8E-07	2.2	9.2	3.9	3.6	6.3E-09	2341
40%WHI	0.388	7.3E-07	2.3	9.2	1.9	1.6	4.1E-09	1222

Table F-3 Superpave IDT Results for RAP mixtures with PMA (LTOA+CPPC)

Mixture Type	m-value	D_1 (1/psi)	St (Mpa)	MR (Gpa)	FED (kJ/m^3)	DCSEf (kJ/m^3)	Creep Compliance Rate (1/psi·sec)	Failure Strain (με)	ER
Virgin	0.362	7.6E-07	2.6	10.4	2.6	2.3	3.3E-09	1464	2.83
20%ATL	0.337	4.7E-07	2.6	12.1	1.5	1.2	1.6E-09	901	3.00
30%ATL	0.314	5.0E-07	2.8	12.3	1.5	1.2	1.4E-09	869	3.37
40%ATL	0.357	3.2E-07	2.7	13.1	1.3	1.0	1.3E-09	727	3.14
Virgin	0.407	9.3E-07	2.3	9.3	4.0	3.7	6.3E-09	2334	2.74
20%WHI	0.397	7.0E-07	2.4	9.1	3.2	2.9	4.3E-09	1777	3.05
30%WHI	0.383	4.9E-07	2.6	10.9	2.6	2.3	2.6E-09	1412	3.74
40%WHI	0.353	4.7E-07	2.6	11.7	1.9	1.6	1.9E-09	1039	3.41

Table F-4 Superpave IDT Results for RAP mixtures with ARB (LTOA+CPPC)

Mixture Type	m-value	D_1 (1/psi)	St (Mpa)	MR (Gpa)	FED (kJ/m^3)	DCSEf (kJ/m^3)	Creep Compliance Rate (1/psi·sec)	Failure Strain (με)	ER
Virgin	0.362	7.6E-07	2.6	10.4	2.6	2.3	3.3E-09	1464	2.83
20%ATL	0.325	7.5E-07	2.8	10.4	2.5	2.1	2.3E-09	1342	3.59
30%ATL	0.318	5.9E-07	3.0	10.2	2.5	2.1	1.7E-09	1240	4.63
40%ATL	0.275	4.9E-07	2.5	12.0	1.2	0.9	9.1E-10	725	4.06
Virgin	0.407	9.3E-07	2.3	9.3	4.0	3.7	6.3E-09	2334	2.74
20%WHI	0.378	8.3E-07	2.5	8.5	3.4	3.0	4.2E-09	1900	3.11
30%WHI	0.301	8.6E-07	2.5	9.1	2.5	2.2	2.1E-09	1438	4.18
40%WHI	0.260	7.1E-07	2.2	10.4	1.2	1.0	1.1E-09	850	3.71