Evaluating the Contribution of Asphalt Binder from Recycled Asphalt Shingles in Asphalt Concrete

by

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Abstract

The use of Recycled Asphalt Shingles (RAS) to replace a portion of the virgin asphalt binder in asphalt mixtures has been increasing over the past several years due to environmental and economic motivations. Yet, since shingle asphalts are much stiffer than paving asphalts, there are concerns that the shingle asphalt may not be completely activated as a binding material which could result in under asphalted mixtures, or that the composite binder created by the blended shingle asphalt and virgin asphalt may not have suitable characteristics to resist cracking under load and environmental conditions in pavements.

This research studied RAS using three approaches. First, the effects of the individual components of RAS on asphalt mixtures were studied by separating the shingle asphalt and shingle aggregates and fibers. These were used separately to replace a portion of a control virgin mixture and compared to a similar 5% RAS mixture. Second, the effect of mixing temperature on RAS containing asphalt mixtures was studied by mixing and compacting a 5% RAS mixture at temperatures ranging from 250°F to 350°F. Third, the mixtures described above were compared to the properties of plant-mixed laboratory-compacted mixtures.

It was found that the shingle aggregates and fibers do not appear to significantly affect the cracking resistance of the mixture. The shingle asphalt may increase the stiffness and lower the cracking resistance of RAS containing mixtures. Also, increasing the mixing temperature increases the stiffness of the mixture. This increased stiffness may be caused by increased activation of shingle asphalt in RAS containing mixtures, and increasing the mixing time and/or

storage time may additionally increase the percentage of activated shingle asphalt. Finally, further aging or increased mixing temperatures of laboratory produced RAS containing mixtures may be needed to better match to plant produced properties.

Table of Contents

List of Tables

List of Figures

I. Introduction

Since the 1980s, a small number of asphalt concrete producers have used recycled asphalt shingles (RAS) as a component in asphalt paving mixtures to replace a portion of the virgin asphalt binder and the fine aggregate material. In 2007, the United States Environmental Protection Agency (EPA) began to target construction and demolition (C&D) debris as a part of its Resource Conservation Challenge (RCC). Tipping fees at landfills were increased for C&D debris as an incentive to reduce, reuse and recycle (EPA 2003). The annual tonnage of asphalt shingles disposed into U.S. landfills each year has been estimated to be 10 million tons of post-consumer shingles and one million tons of manufacturer's waste shingles (Sandler 2003). According to an estimate by the EPA, asphalt shingles account for about eight percent of all building-related debris and one to ten percent of all C&D debris generated annually (Sandler 2003). With shingle waste tipping fees escalating to over $60 per ton, roofing contractors and shingle manufacturers have been searching for more economical ways to dispose of waste shingles (Brunswick County NC 2015; California Waste Services 2016; Dane County Department of Public Works 2015; Halifax C & D Recycling Ltd. n.d.).

In response to the RCC and the rising cost of asphalt binder through much of the past 10 years, recycling of shingles in asphalt concrete has been increasing in popularity and more state highway agencies are allowing its use. In 2007, 15 state highway agencies allowed the use of RAS in hot mix asphalt (HMA), 11 of these states had adopted specifications for routine use of RAS. Eight of the 11 states allowed only the use of manufacturer's waste RAS (MWRAS) (CMRA 2007). By 2013, 23 state highway agencies had adopted specifications for routine use. Ten of the 23 states allowed either post-consumer RAS (PCRAS) or MWRAS (J. R. Willis 2013). A 2014 National Asphalt Pavement Association (NAPA) survey estimated that from

2009 to 2014 the amount of RAS used in HMA increased from 702,000 tons to nearly 2.0 million tons in the United States (Hansen and Copeland 2015).

A number of experts in the asphalt pavement community have concerns about how to account for the quantity and quality of asphalt from RAS. Asphalt used in the manufacture of shingles is commonly air-blown to significantly increase the asphalt's viscosity. PCRAS shingles removed from roofs are further oxidized from years of direct ultra-violet radiation. Incomplete activation and blending of the shingle asphalt (low asphalt content) can cause the paving mixture to be difficult to place and more susceptible to cracking and raveling. Also, under-estimating the amount of activation and blending of the shingle asphalt, or not compensating for the increased stiffness of the shingle asphalt, can increase the paving mixtures stiffness beyond its ability to relax strains. Potential saving gained by using recycled shingles can be quickly negated by a decrease in pavement life.

A. Objective

The objective of this research was to evaluate the activation of shingle asphalt and assess the contribution of the individual components within RAS on the properties and performance of asphalt concrete mixtures.

B. Scope

To meet the above objective, several laboratory experiments were conducted using asphalt mixtures containing 5% RAS by weight of total aggregate blend. In the first experiment, the effect of mixing temperature on the activation of shingle asphalt was investigated by evaluating a mixture at six different mixing temperatures ranging from 225°F to 350°F. Using the same compactive effort for all samples, the level of shingle asphalt activation was evaluated using volumetric properties. The mixing temperatures of 250°F, 300°F, and 350°F were chosen for further evaluation of mixture properties.

In the second experiment, the components of RAS were separated and added individually to a control mixture. Solvent extraction and rotary-evaporator recovery was used to separate the RAS into shingle asphalt and shingle aggregates and fibers. The separated components were then added individually to the control mix. The four mixtures evaluated in the second experiment:

(1) the mixture from the first experiment containing 5% whole RAS

(2) a control mixture containing all virgin materials

(3) the control mixture with all virgin aggregates and a portion of the total asphalt binder provided by shingle asphalt

(4) the control mixture with all virgin binder and a portion of the aggregate blend containing shingle aggregate and fibers.

The effects of the shingle asphalt and the shingle aggregate and fibers were evaluated by comparing the volumetric properties and results of selected laboratory performance tests conducted on the four mixtures above.

In addition, performance tests were also conducted on three plant-mixed lab-compacted (PMLC) mixtures that were placed on Lee County Road 159 (LR 159) in 2012 as part of a pavement preservation study. The three mixtures from this experiment were:

(1) a 5% RAS mixture

(2) an all-virgin material control mixture

(3) a 50% fine fractionated Recycled Asphalt Pavement (RAP) mixture

The performance tests conducted on the mixtures in this study included dynamic modulus, a modified version of the Texas Overlay Test, Indirect Tension Creep Compliance Test, and the Energy Ratio method developed in Florida as an indicator of top-down cracking.

C. Organization of Thesis

This thesis has been organized into five chapters. Chapter I is the introduction and an overview of the objectives and scope of this paper. Chapter II is the background and literature review. This chapter reviews the components of RAS and their individual properties and reviews previous research investigating how RAS affects the composite asphalt binder properties, asphalt mixture properties, and pavement performance. Chapter III describes the research methodology used to meet the objectives mentioned in Chapter I. Chapter IV details the testing results and discussion of the results. Finally, Chapter V comprises of the conclusions of this thesis.

II. Background and Literature Review

To better understand the characteristics of asphalt shingles and their effects on asphalt mixtures, a background and literature review was conducted. The information in this chapter is organized into five sections:

a. A review of the material components that make up shingles
b. A review of current methods of estimating the degree of shingle asphalt activation
c. A review of research investigating how shingle asphalt affects the properties of the composite asphalt binder.
d. A review of research on how RAS affects asphalt mixture testing properties
e. A review of research projects with field evaluations of RAS containing mixtures.

A. Composition of Asphalt Shingles

Asphalt, mineral filler, fine aggregate granules and a fiber mat make up the basic components of asphalt shingles. Table 1 lists typical proportions of components for manufactured fiberglass shingles as percentage by weight.

Table 1: Percent by Weight of Shingle Components (CMRA 2007)

32% to 42%	Mineral Filler (limestone or Fly Ash)
28% to 42%	Granules (painted rocks and coal slag)
16% to 25%	Asphalt
3% to 6%	Back Dust (limestone or silica sand)
2% to 15%	Mat (fiberglass, paper, and cotton rags)
0.2% to 2%	Adhesives (modified asphalt based)

The exact proportion of components will vary from Table 1, especially when using PCRAS. This can be due to the loss of granules from weathering, variations in manufacturer's design, and/or the presence of deleterious materials. Therefore, when using RAS, it is important to determine the composition before proceeding with a mix design.

a. Fiber Mat, Granules and Mineral Filler

The fiber mat, granules and mineral filler material make up 70-80% of the shingle, by weight. When considering the recycling of shingles, this large portion may not be as valuable as the asphalt, but it cannot be ignored. If used in any asphalt pavement applications, this portion needs to be accounted for in the total aggregate gradation.

The fibers are the smallest portion of the shingle by weight and are typically either fiberglass or organic. Organic fiber mat shingles have higher asphalt contents. Organic fiber mats are first soaked in a bituminous saturant and then coated with a filled asphalt on both sides. Filled asphalt is a viscous mastic created by blending the asphalt and mineral filler and provides added weight and waterproofing to the moisture susceptible organic fiber shingles. Also, the asphalt soaked organic mat is more durable, providing better performance in areas with thermal cycling. Fiberglass matting for shingles was introduced in the 1960's. The lighter fiberglass mat required less filled asphalt and took advantage of the self-sealing tab shingles innovation to provide similar wind resistance as organic fiber shingles. Fiberglass shingles also had the advantage of a "Class A" fire resistance rating over the "Class C" organic shingles (McNulty 2000). By 2001, 95% of the shingles produced were fiberglass shingles (Dixon 2013).

Aggregate granules are adhered to the surface of the shingles. The granules serve to protect the shingle. Without the granules, the sun would quickly oxidize the shingle asphalt, leading to premature cracking and loss of water proofing ability. The size distribution of the granules must allow for consistent application to the surface of the shingle and cover the highest amount of surface area as possible (McNulty 2000). Table 2 gives a typical size distribution for roofing granules from 3M. Also, the granules are colored and coated in a strong ceramic coating to provide an aesthetic quality to the shingles, desired by consumers, but also to make the granules non-porous. This prevents the absorption of water and the growth of mold or algae on the shingle surface. Additional coatings can also be applied to provide additional protection against algae or for reflecting solar energy (3M 2016). The roofing granules are also coated with a light oil to help them better adhere to the asphalt surface, since the granules are non-porous (3M 2014).

Table 2: 3M Grade 11 Roofing Granules Size Distribution (3M 2014)

Sieve Size		**% Retained**	
ASTM[1] #	**mm**	**Specification**	**Typical Range**
8	2.36	0.0 - 0.1	-
12	1.7	4.0 - 10.0	-
16	1.18	-	30 – 50
20	0.85	-	20 – 40
30	0.6	-	10 – 30
40	0.425	-	1 – 10
- 40	- 0.425	0.0 - 2.0	-
- 100	- 0.150	< 0.2	-

[1] American Society of Testing and Materials (ASTM)

Mineral filler is typically the largest component by weight. Fillers can vary in size distribution, chemical composition, and percentage used in shingles. Fillers are used to increase the viscosity of the asphalt, preventing the asphalt from flowing off the shingle during manufacturing and while in service. Fillers also add durability to the shingle by decreasing the asphalt's coefficient of thermal expansion, increasing resistance to thermal cycling (McNulty

2000). The size distribution of fillers is widely variable and can range from ASTM #20 mesh to #325 mesh depending on source (Minerals Technologies 2016). Typical percentages of filler in roofing asphalt are 60-70% by weight of the filled asphalt, but the actual level must be determined through testing of the filled asphalt and will vary depending on the filler source used (McNulty 2000).

b. Asbestos

There is a potential for asbestos to be present in older PCRAS. Asbestos was used in many products and industrial applications, including roofing shingles before it was known to cause diseases in humans. Asbestos is a naturally occurring mineral fiber that has numerous desirable characteristics including good tensile strength, flexibility, resistance to corrosion and fire, and is a great insulator. Asbestos is mined from the earth, but when crushed, it breaks down into microscopic fibers instead of small angular particles. These crushed fibers are typically mixed with other materials to produce an asbestos containing material (ACM). ACMs are not hazardous to human health, but when ACMs breakdown, they release the dangerous microscopic asbestos fibers into the air. Asbestos fibers are extremely light and may remain suspended in air for a long time or travel long distances. Once these airborne fibers are inhaled or ingested by humans they may never leave the human body. Each exposure increases the risk of developing an asbestos related disease, and many asbestos related diseases will not develop until years after exposure (EPA 2011).

There is limited information available about the use of asbestos in asphalt shingles, but asbestos is known to have been extensively used in various other roofing and insulating products and applications. An extensive case study, by Townsend, Powell, & Xu in 2007 found that asbestos was positively identified in 1.5% of the 27,694 RAS samples tested. It was noted that many of these positive identifications were the result of other ACM roofing materials contaminating the shingle stockpiles. Table 3 lists several manufacturers who have reported using asbestos in their products and the years the product was manufactured (Townsend, Powell and Xu 2007).

Table 3: Asbestos Containing Roofing Products (Townsend, Powell and Xu 2007)

Manufacturer	Years Manufactured	Product
Barber Asphalt Corporation	N/A	Asphalt-asbestos roof felt
Carey Manufacturing Company	N/A	Asphalt-asbestos shingles, asbestos finish felt, mastic
The Celotex Corporation	1906 – 1984	Asphalt roof coating and other miscellaneous materials
Fibreboard Corporation	1920 – 1968	Roof paint, roll roofing with asbestos-containing base sheets, caulking compounds, plastic cements, taping and finishing compounds
General Aniline and Film Corporation	N/A	Roofing Asphalt
Johns-Manville Corporation	1891 – 1983	Asphalt-asbestos shingles, rag-felt shingles, fibrous roof coating, shingle tab cement, roof putty
Kaylite Company	N/A	Asbestos surface coating for shingles
National Gypsum Company	1941 – 1981	Roofing and shingles
Monroe Company	N/A	Asbestos surface coating for shingles
Rhone-Poulenc Ag Company	1930 – 1976	Adhesives, coatings, sealants, and mastics
United States Gypsum Company	1930 – 1977	Paper and felt

c. Deleterious materials

Almost all PCRAS will contain deleterious materials. Typical deleterious materials found in shingles are roofing nails, plastic caps, paper or plastic shingle backing, felt roofing mats, and wood. MWRAS should not contain any construction or demolition waste materials, but may contain plastic packaging used to package the shingles for sale. If possible, all deleterious materials should be removed prior to grinding RAS, but the removal of deleterious materials is almost exclusively done by hand. To reduce this workload, many recycling centers offer reduced tipping fees if roofing contractors take special care to separate the shingles from other roofing debris (CMRA 2007; Brunswick County NC 2015; Dane County Department of Public Works 2015; Halifax C & D Recycling Ltd. n.d.).

d. Shingle Asphalt

The asphalt in RAS is its most economically desired component. It is highly valuable as a replacement or supplement to virgin asphalt binder. When first investigating MWRAS in 2008, and PCRAS in 2010, the Virginia Department of Transportation (VDOT) estimated $2.69-$3.40 per ton of HMA cost savings (Maupin 2008, Maupin 2010). Many state agencies and researchers are concerned that the stiffer asphalt from RAS will increase susceptibility to low-temperature, top-down and fatigue cracking in HMA. Asphalt used for shingle manufacturing is typically air-blown to greatly increase its viscosity so that the shingles will not deform when used on a steep roof and exposed to hot ambient temperatures. *ASTM D312-00: Standard Specification for Asphalt Used in Roofing* details the testing requirements for roofing asphalts. Table 4 compares the physical requirements for ASTM D312 roofing asphalt to *ASTM D946-15: Standard Specification for Penetration-Graded Asphalt Binder for Use in Pavement Construction.* As shown in Table 4, the stiffest ASTM D946 penetration graded asphalt (40-50 Pen Grade) meets the specifications of the softest roofing asphalt (Type I). Lower softening point, higher penetration, and higher ductility requirements make the roofing asphalts unsuitable for paving applications.

Table 4: Physical Properties of ASTM D312 Roofing Asphalt Compared to ASTM D946 Paving Asphalt (ASTM D312 2006, ASTM D946 2015)

Property	Roofing Asphalts (ASTM D312)				Paving Asphalts (ASTM D946)	
	Type I	Type II	Type III	Type IV	40-50 Pen Grade	85-100 Pen Grade
Softening Point	135 - 151°F	158 - 176°F	185 - 205°F	210 - 225°F	>120°F	>108°F
Flash Point	> 500°F	> 500°F	> 500°F	> 500°F	>450°F	>450°F
Penetration						
at 32 °F (dmm)	> 3	> 6	> 6	> 6	-	-
at 77 °F (dmm)	18 - 60	18 - 40	15 - 35	12 - 25	40-50	85-100
at 115 °F (dmm)	90 - 180	< 100	< 90	< 75	-	-
Ductility at 77°F	> 10 cm	> 3 cm	> 2.5 cm	> 2.5 cm	> 100 cm	> 100[3] cm
Solubility in TCE[1]	> 99%	> 99%	> 99%	> 99%	> 99%	> 99%

[1]Trichloroethylene (TCE) [2] > 75 cm after aging in thin-film oven

ASTM D7654-10: Standard Specification for Asphalt Used in Roofing Measured by Dynamic Shear Rheometer, a newer roofing asphalt specification, makes uses of the Dynamic Shear Rheometer (DSR) to test the viscosity of the asphalt. Table 5 compares ASTM D7654 roofing asphalts to *ASTM D3381: Standard Specification for Viscosity-Graded Asphalt Cement for Use in Pavement Construction* Viscosity Graded asphalts. It can be seen by Table 5 the ASTM D3381 viscosity graded paving asphalts are much softer than the ASTM D7654 roofing asphalts. The viscosity of the roofing asphalts are 100 times greater than the viscosity of the paving grade asphalts, and mineral filler is used to further increase the viscosity of the roofing asphalts. This higher viscosity makes the asphalt stiffer at both higher and lower temperatures, preventing the asphalt from flowing off the shingle during hot days.

Table 5: Physical Properties of ASTM D7654 Roofing Asphalt Compared to ASTM D3381 Paving Asphalt (ASTM D7654 2010, ASTM D3381 2013)

Property	Roofing Asphalts (ASTM D7654)		Paving Asphalts (ASTM D3381)		
	Type III	Type IV	AC-10 Visc. Grade	AC-20 Visc. Grade	AC-30 Visc. Grade
Viscosity (Pa. s)	> 6,700[1]	> 13,000[1]	80-120[2]	160-240[2]	240-360[2]
Flash Point	> 500°F	> 500°F	> 425°F	> 450°F	> 450°F
Penetration					
at 32 °F	> 6 dmm	> 6 dmm	-	-	-
at 77 °F	15 - 35 dmm	12 - 25 dmm	> 70 dmm	> 40 dmm	> 30 dmm
at 115 °F	< 90 dmm	< 75 dmm	-	-	-
Solubility in TCE	> 99%	> 99%	> 99%	> 99%	> 99%

[1] DSR Viscosity @ 158 °F [2] Absolute Viscosity @ 140 °F

PCRAS asphalt is stiffer than the asphalt in MWRAS due to oxidation from years of direct sunlight. This is why some state highway agencies only allow MWRAS in HMA (CMRA 2007). Typical high-temperature performance grades (PGs) of asphalt recovered from MWRAS range from 130°C to 150°C. For PCRAS, the high temperature PG can be as high as 175°C or more. For comparison, the high-temperature PG for paving asphalts typically are in the range of 58°C to 76°C. Current standard methods are not adequate to determine the low-temperature PG of shingle asphalt. Testing results are highly variable and not reliable, with typical results ranging from -10°C to greater than 0°C (Willis and Turner 2016). Typical asphalt contents for MWRAS are 17-23%, and PCRAS has been reported to have asphalt contents as high as 35%. Asphalt contents as high as 30% are typically encountered with organic mat shingles or when felt paper used as extra water proofing below the shingles was not separated from the shingles (McGraw, et al. 2007, Zhou, Li, et al. 2013).

B. Shingle Asphalt Activation

When RAS is used in HMA, a portion of the shingle asphalt is assumed to contribute to the total binder content of the mixture. The percentage of shingle asphalt that is thought to blend with the virgin asphalt and contribute to the total binder content is commonly referred to as the percent activated. However, there is no reliable method to determine the actual percentage of activated shingle asphalt in asphalt mixtures. Since the total binder content of a mixture is used to calculate many of the key volumetric properties used as criteria for mix design and quality assurance testing of plant produced mixtures, an incorrect assumption of the amount of activated shingle asphalt can lead to mixes with deficient or excess asphalt. Also, because shingle asphalt is much stiffer than conventional paving asphalt, it is important to determine the percentage of shingle asphalt that is blending with the virgin asphalt so that the characteristics of the composite asphalt can be estimated. If the composite binder is too stiff the mixture will be likely have a decline in resistance to various forms of cracking, or if it is too soft it may be more susceptible to permanent deformation

The former American Association of State and Highway Transportation Officials (AASHTO) provisional publication *AASHTO PP 53-09 Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in New Hot Mix Asphalt (HMA)* proposed an approach for estimating the percentage of activation for the shingle asphalt. This method required the design of two mixtures: 1) a mixture with RAS and 2) the same mixture without RAS. Both mixtures were designed according to AASHTO M323-13 to determine the optimum virgin asphalt contents. The difference in the optimum virgin asphalt contents for the two mixtures was said to represent the activated shingle asphalt replacing the virgin asphalt binder. Equation 1 was used to calculate the asphalt binder availability factor, or the percentage of shingle asphalt that was activated (AASHTO PP 53-09 2012).

$$\boldsymbol{F_c = \frac{P_{bv} - P_{bvr}}{(P_{sr})(P_{br})}} \qquad \textbf{Equation 1}$$

$\mathbf{F_c}$ is the estimated asphalt binder availability factor, percent;

$\mathbf{P_{bv}}$ is the design virgin asphalt binder content of a mix without RAS, percent;

$\mathbf{P_{bvr}}$ is the design virgin asphalt binder content of the same mix with RAS, percent;

$\mathbf{P_{sr}}$ is the percentage of RAS in the mix, decimal;

$\mathbf{P_{br}}$ is the percentage of shingle asphalt in the RAS, decimal;

AASHTO PP 53-09 stated that F_c (calculated in Equation 1) represents the percentage of the shingle asphalt activated within the mixture, but would likely underestimate the true value. Therefore, AASHTO PP 53-09 used Equation 2 to get the true value for F_c as an average of F_c and 100 percent activation (AASHTO PP 53-09 2012).

$$\boldsymbol{F = 100\left(\frac{1 + F_c}{2}\right)} \qquad \textbf{Equation 2}$$

$\mathbf{F}$ is the shingle asphalt binder availability factor, percent;

$\mathbf{F_c}$ is the estimated asphalt binder availability factor, decimal;

AASHTO PP 53-09 was unclear as to the extent the two mixtures needed to be designed, what asphalt contents were used in the equations, why the first equation underestimated the amount of activation, and when a variable was to be used as a percentage or as a decimal. At the Construction and Demolition Recycling Association (CDRA) Asphalt Shingle Recycling Forum, in 2013, Gerry Huber of the Heritage Research Group gave a presentation detailing the problems with the method and how it could be improved. Mr. Huber pointed out that the VMA of a mixture may change with the addition of the RAS due to the fine aggregate in RAS, and that this change in the VMA would cause the required asphalt content of the mixture to change. Therefore, he suggested that the "Asphalt Binder Availability" has little to do with the asphalt binder properties and is highly dependent on the asphalt content of the RAS. He showed this by designing a virgin control mixture and then added RAS to the mixture in three forms: 1) regular RAS, 2) RAS that had 50% of the asphalt extracted from it, and 3) RAS aggregate that had 100% of the asphalt extracted from it. He held the total binder content the same as the virgin control mixture, and adjusted the virgin binder content to account for the addition of the shingle asphalt. Table 6 shows that the addition of the RAS increased the VMA and air voids for each of the mixes containing RAS (Huber 2013).

Table 6: Volumetric Properties of Mixtures Containing Varying Levels of Extracted RAS (Huber 2013)

	Mix Design Material Blend			
	Virgin Blend	100% Extracted RAS	50% Extracted RAS	0% Extracted RAS
% AC Virgin	5.8	5.8	5.0	4.3
% RAS AC	0.0	0.0	0.8	1.5
%AC, Total	5.8	5.8	5.8	5.8
VMA, %	15.5	17.4	17.3	17.5
Air Voids, %	4.0	7.0	6.8	6.8

The calculations in AASHTO PP 53-09 were based on an assumption that the total optimum binder content of the mixtures were the same, and the differences between the virgin binder contents represented the amount of activated shingle asphalt. However, the increase in the optimum binder content caused by the increase in the VMA was offset by the addition of shingle asphalt. Therefore, Huber concluded that whenever the percent of shingle asphalt exceeds the change in the optimum binder content caused by the change in VMA, the virgin binder content of the mixture will decrease (Huber 2013).

More recently, AASHTO published an update to AASHTO PP 53-09, as *AASHTO PP 78-14: Design Considerations When Using Reclaimed Asphalt Shingles (RAS) in Asphalt Mixtures,* which removed the design requirements and calculation of the availability factor from the standard. Equation 3 was added for calculating the percentage of shingle asphalt (or combined RAP and shingle asphalt) of the total binder content of the mixture. This percentage is used to adjust the virgin asphalt binder grade. The asphalt binder availability factor (F) was used in the calculation, and Note 6 in the specification states, F is assumed to range from 0.70 and 0.85, but more research is needed. Table 7 shows the recommended adjustments for the virgin binder grade in AASHTO PP 78-14 (2014). This methodology is much quicker and simpler to calculate, and it is more practical for mix designers, but it is not a definitive answer to the problem. The availability factor is just an estimate and the use of a softer virgin binder is not guaranteed to provide better performance without knowing exactly how the shingle asphalt will affect the mixture properties.

Table 7: Binder Grade Adjustment Guidelines for RAS Mixtures (AASHTO PP 78-14 2014)

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

$$P_{bst} = \left[\frac{F(P_s)(P_{bs}) + (P_r)(P_{br})}{P_b}\right]100 \qquad \textbf{Equation 3}$$

P_{bst} = percentage of RAS and/or RAP binder in the design asphalt binder content;

F = RAS asphalt binder availability factor, expressed as a decimal;

P_s = percentage of RAS in the asphalt mixture, expressed as a decimal;

P_{bs} = percentage of asphalt binder in the RAS, expressed as a decimal;

P_r = percentage of RAP in the asphalt mixture, expressed as a decimal;

P_{br} = percentage of asphalt binder in the RAP, expressed as a decimal;

P_{bst} = design asphalt binder content in the asphalt mixture, expressed as a decimal;

C. Research on How RAS Affects the Composite Asphalt Binder Properties

Shingle asphalt is very stiff compared to conventional paving grade asphalt and is challenging to adequately characterize using standard test methods. As mentioned above, if the percentage of activated shingle asphalt can be determined, or even estimated, it is important to know how that percentage will affect the final blended grade of the asphalt in the HMA mixture. Therefore, several studies were performed to determine the properties of the composite asphalt.

Bonaquist (2011) conducted a study for the Wisconsin Highway Research Program on the resultant PG of binder blends containing shingle asphalt. After investigating the use of linear blending charts from AASHTO M323 for estimating blended PG of mixtures containing RAP, he extended the notion that the use of blending charts could be extended to RAS mixtures and even RAP and RAS mixtures. A procedure for creating blending charts with RAP/RAS blends was created and included as an appendix to the report. This research also developed a method for extrapolating the continuous grade of the shingle asphalt from a blend of 30% shingle asphalt and 70% virgin PG binder with a known continuous grade (R. Bonaquist 2011). This method is important because typical PG tests were not designed for asphalt as stiff as shingle asphalt, and therefore testing results of pure shingle asphalt can be highly variable and even impossible for many labs.

A paper by Abbas et al. (2013) examined the properties of asphalt blended with 0%, 5%, 7%, and 10% shingle asphalt. This research showed that higher percentages of shingle asphalt increased the stiffness of the blended asphalt as observed in the results for rotational viscosity, high-temperature DSR, MSCR, and BBR testing. The increase in the viscosity of the asphalt blends indicates that higher mixing and compaction temperatures may need to be used to achieve good coating and workability. They also concluded that the increased stiffness in the high-temperature DSR and MSCR tests indicated increased resistance to rutting. The 7% and 10% blends met the MSCR specifications for Very Heavy traffic binders. BBR testing indicated an increased susceptibility to low-temperature thermal cracking; however, the intermediate temperature DSR results indicated no change in the resistance to fatigue cracking as shingle asphalt increased. Given that the fatigue results were contrary to many observations of field performance, they recommended that a new test for fatigue cracking be developed (Abbas et al. 2013).

Zhao et al. (2013) examined the chemical composition of lab designed mixtures using Gel Permeation Chromatography (GPC) and compared the results to G* tested by DSR. For this experiment, they designed seven mixtures for analysis (Table 8). Immediately after mixing, they separated the coated large, medium, and fine aggregates. By analyzing the binder from each aggregate size separately they were able to compare the percentage of large molecular size (LMS) particles as an indication of blending. They found that increasing the percentage of RAS increased the percent of LMS particles and a strong correlation between the LMS percentage and the G* for the blended asphalts. They also found that the LMS particles in the large and medium size aggregates increased with the mixing time and the percent of LMS particles in the small sized aggregates remained about the same. This indicated increased blending occurred in the asphalt coating the large and medium size particles during the longer mixing times, prior to separation. They noted that the most efficient blending was observed in the 5% RAS mixture which could indicate that for over 5% RAS the percentage of shingle asphalt to virgin asphalt is too high to allow for adequate blending (Zhao et al., 2013).

Table 8: Differentiation between Mixtures 1 through 7 (Zhao et al., 2013)

Mixture	Mixing Time	RAS Content (%)
1	2 min	2.5
2	2 min	5
3	2 min	7.5
4	2 min	10
5	30 sec	5
6	1 min	5
7	3 min	5

Kriz et al. (2014) investigated binder blending that occurs for mixtures containing RAP. RAP and RAS are similar materials that are introduced into the asphalt mixture using the same methods. Therefore, the principles of Kriz's research on diffusion of RAP and virgin binders may translate to mixtures containing RAS. For diffusion to occur, the RAP binder must first come in contact with the virgin binder during the mechanical mixing process, and then it is believed that the two binders begin to diffuse. Kriz showed that the rate of diffusion is dependent on temperature. For stiffer recycled asphalts (RAS or stiff RAP), either the temperature must be increased to increase the rate of diffusion, or more storage time must be allowed at standard temperatures to allow for the diffusion to occur prior to placement (Kriz et al., 2014).

D. Research on How RAS Affects Asphalt Mixture Properties

Foo et al. (1999) investigated the use of RAS in conventional HMA and SMA mixtures. Three mixtures were modified with 0%, 5%, and 10% MWRAS by weight of the aggregates for a total of nine mixtures. The mixtures were tested using Indirect Tensile Testing for cracking resistance, and Dynamic Creep and the Asphalt Pavement Analyzer (APA) for rutting resistance. Generally, the indirect tensile strength of the mixtures decreased and the permanent deformation decreased with increasing percentage of shingles. They concluded that shingles could be used effectively in both HMA and SMA mixtures. They also mentioned that shingles can be used at 5% to increase the stiffness and rutting resistance similarly to increasing the binder grade, but at the cost of lowering the fatigue and low temperature cracking resistance. They recommend the use of an appropriate lower performance graded virgin binder to offset the lower fatigue and low temperature cracking resistance (Foo et al., 1999).

Mallick et al. (2000) tested a mixture modified with increasing amounts of RAS (0%, 3%, 5%, 7%). This study compared the results of the volumetric properties, indirect tensile strength at 4°C and the APA rut depth to determine the mixture and economic benefits of using shingles. The volumetric properties were not significantly affected by the addition of shingles. The APA rut depths decreased significantly with increasing shingle percentage, indicating an increased resistance to rutting for shingle mixtures. The indirect tensile strength increased with increasing shingle percentages but the increase was not significant. Mallick et al. (2000) recommended the use of 5% shingles due to the economic savings and comparable mixture properties to 3% shingles.

Johnson et al. (2010) reported on testing performed for the Minnesota Department of Transportation to evaluate their new specification requiring a minimum of 70% new binder of the mixture's total binder. The study examined the durability of HMA with RAS, including using a "softer grade" of virgin binder to offset the stiffer shingle asphalt, and also studied differences between lab and plant produced HMA containing RAS. Dynamic Modulus (E*) testing showed an increase in mix stiffness with increasing percentages of recycled materials. APA testing showed a decrease in rut depths with increasing percentages of recycled materials. The mixtures containing RAP and shingles had high TSR values and met moisture susceptibility standards for Minnesota. No differences between MWRAS and PCRAS were observed in E* for the mixtures containing 3% RAS, but a visual increase in stiffness was observed between the mixtures containing 5% MWRAS and 5% PCRAS.   The use of a softer binder to offset the recycled asphalt was shown to effect E* and APA results. Using a virgin asphalt with a lower low-temperature grade resulted in lower E* values at all temperatures and higher rutting in the APA test. Using crack counts, crack lengths, and measured rutting for six field projects, the researchers were able to generally relate more cracking in the field with lower virgin binder ratios (when other factors did not interfere). They recommend the continued use of the 70% virgin binder ratio specification and mentioned the improved mixture properties and observed field performance from using a "softer grade" binder with mixtures containing recycled materials (Johnson, et al. 2010).

Mogawer et al. (2011) investigated mixtures containing RAS, high percentages of RAP, and WMA modifiers separately as well as combinations of the materials. The six mixtures were tested for E*, Texas Overlay Tester (OT) cycles to failure, Asphalt Concrete Cracking Device (ACCD) thermal cracking temperature, and Hamburg Wheel Tracking Device (HWTD) rutting/stripping resistance. The E* test results showed that the inclusion of 40% RAP and 35% RAP + 5% RAS had a significant increase in the stiffness of the mixture and decreased cracking resistance. The mixture with only 5% RAS did not hot have a significant change in the stiffness, but this was likely due to the lower percentage of recycled asphalt to total binder. The results from the OT cycles to failure agree with the E* results. The 40% RAP and 35% RAP + 5% RAS mixtures had much lower cycles to failure than the mixtures with less recycled asphalt (see Table 9). The ACCD cracking temperature test results showed no significant change in the low temperature cracking resistance with the inclusion of RAP, RAS or the combination (see Table 9). Lastly, the HWTD showed improved resistance to rutting and stripping over the control mixture. The inclusion of WMA showed a lower stripping resistance, but it was hypothesized that the lower temperatures did not allow the shingle asphalt to activate (Mogawer et al. 2011).

Table 9: Testing Results for Overlay Test, Asphalt Concrete Cracking Device, and Hamburg Wheel Tracking Device (Mogawer et al. 2011)

Mixture	Average OT Cycles to Failure	Standard Deviation of OT Results	ACCD Cracking Temperature °C	Stripping Inflection Point from HWTD
Control	1004	278	-38.5	16,800
40% RAP	3	1	-37	None
5% RAS	308	102	-38.8	None
35% RAP + 5% RAS	22	5	-37	None
Control + 1% WMA	936	373	-39.3	6200
40% RAP + 1% WMA	143	91	-39.8	None
5% RAS + 1% WMA	297	124	-40.5	9,800
35% RAP + 5% RAS + 1% WMA	63	29	-39.3	None

In a case study of Ontario Canada's use of RAS in HMA, Yang et al. (2013) tested six mixtures for E*, resilient modulus (tested using IDT @ 25°C), thermal stress restrained specimen test (TSRST), and flexural bending beam fatigue. These 6 mixtures had different amounts of RAS and RAP as well as different grades of virgin asphalt binder (Table 10).

Table 10: HMA Mix Designs Used in Study (Yang, et al. 2013)

Mixture ID	Mix Type	Percent RAP	Percent RAS	PG of Virgin AC	Total AC	Virgin AC	Recycled AC
Mix 1	Hot Laid 3	13.5	1.5	PG 58-28	5.0	4.0	1.03
Mix 2	Superpave 12.5	17	3	PG 52-34	5.1	3.3	1.83
Mix 3	Superpave 12.5	0	6	PG 52-40	5.2	3.3	1.93
Mix 4	Superpave 12.5	12	3	PG 52-34	5.2	3.6	1.62
Mix 5	Superpave 19	25	3	PG 52-34	4.9	2.9	2.01
Mix 6	Superpave 19	0	6	PG 52-40	4.9	3.3	1.62

E* testing showed Mix 1 had lower modulus values at the high frequencies (lower temperatures) than mixtures 2, 3 and 4. Mixtures 2, 3, and 4 used a softer grade binder than Mix 1 and therefore should have lower E* values at the high frequencies (lower temperatures), but mixtures 2, 3 and 4 have higher percentages of RAS, which could indicate the percent of recycled asphalt in the mixture had a greater impact on the stiffness of the mixtures than the softer binder. Mixtures 5 and 6 performed similarly, but Mix 6 was less stiff at intermediate temperatures. Resilient modulus testing was performed at 25°C. Mix 1 had a significantly higher resilient modulus than the other mixtures. This result is contrary to the dynamic modulus results, which showed Mix 1 with a lower stiffness at the high frequencies (lower temperatures) regardless of the higher asphalt binder grade. Mix 3 had a lower asphalt binder grade than Mix 4, but had a slightly higher resilient modulus value due to the higher recycle content. The results of the TSRST indicated a greater significance on the virgin asphalt binder grade. Mix 3 had the lowest thermal fracture temperature and the lowest asphalt binder grade, and Mix 1 had the highest thermal fracture temperature and the highest asphalt binder grade. Yet, Mix 6 had the same PG 52-40 asphalt binder as Mix 3 and had the second lowest thermal fracture temperature. Yang attributed the variation in these results to the effects of other mix properties. Statistically, no significant difference was evident among the TSRST results for all of the mixtures. The flexural bending beam fatigue test results showed that Mix 2 and Mix 4 had the highest cycles to failure. Mixes 5 and 6 had the lowest cycles to failure. Yang mentioned the difficulty in achieving the correct air voids for Mixes 5 and 6, and suggested that this had a large impact on the cycles to failure for this test. They concluded that the addition of RAS had a significant negative impact on the fatigue life of the mixtures (Yang, et al. 2013).

Nam et al. (2014) studied the effects of an incremental increases in the percentage of RAS and increases in binder content on Marshall Stability, moisture resistance, and rutting resistance of asphalt mixtures. The mixture with 3.77% virgin binder content and 6% shingles had the highest Marshall Stability and stiffness; the mixture with 5.77% virgin binder content and 0% shingles had the lowest Marshall stability. The 3.77% virgin binder content mixture was shown to be very moisture susceptible by the tensile strength ratio. The mixtures with 4.77% virgin binder content and 3% or 6% shingles passed the minimum criteria for TSR with 0.81 and 0.87 respectively. The mixture with 4.77% virgin binder content and no shingles did not pass the TSR minimum criteria. Samples with 4.77% virgin binder content and 0%, 3%, and 5% shingles were tested for rutting resistance using an Asphalt Pavement Analyzer (APA) and showed that the inclusion of shingles reduced the rutting of the mixture (Nam et al. 2014).

E. Research on how RAS Affects Pavement Performance

A significant amount of research is available on the performance of asphalt mixtures containing RAS dating back as early as the 1980s. Generally, the results are mixed, with some pavements performing very well and others failing within the first few years. Therefore, it seems that the successful use of RAS in asphalt pavements may come down to following best practice guidelines. Several organizations have published guidelines on recommendations for best practices in using RAS, (CMRA 2007; J. R. Willis 2013; Zhou et al. 2012; Hansen 2009), but when studying previous research, it is not clear whether or not these best practices were used during production and placement.

Watson et al. (1998) studied the effect of MWRAS on the aging of surface mixtures in Georgia. He concluded that the surface mixture with RAS seemed to visually age more than the control mixtures, but both showed comparable performance after two years (Watson et al. 1998).

Williams et al. (2011) studied the combination of RAS and fractionated RAP (FRAP) at Iowa State. They evaluated eight mix designs with varying percentages of recycled FRAP and RAS. Their work included laboratory and plant produced mixes for comparison. When comparing plant and laboratory produced samples, they noted that AASHTO mixing and curing procedures may need to be adjusted for mixtures containing RAS, due to consistent differences noticed in the test results. The E* at high temperatures indicated significant increases in the stiffness of the mixtures up to 40% combined recycled materials. Mixtures with 40% or higher combined recycled materials did not show any significant differences in E* values.

Flow number test results showed the mixes to be resistant to rutting, with Mix 8 (25% FRAP 0% RAS) having the highest strain percentage of 1.92%. The fatigue resistance of the mixtures was tested using the beam fatigue test and determining the K1 and K2 coefficients.

Table 11: Mixtures Used to Evaluate FRAP/RAS Combination (Williams, et al. 2011)

Mix ID	Mix Type	FRAP (%)	RAS (%)	Field Sample	Lab Sample
1	Base Course	25	5	X	X
2	Base Course	35	5	X	X
3	Base Course	45	5	X	X
4	Base Course	50	0	X	N/A
5	Binder Course	35	5	N/A	X
6	Binder Course	40	0	X	X
7	Surface Course	20	5	X	X
8	Surface Course	25	0	X	N/A

K2 coefficient was used to compare fatigue resistance as it is an indication of the rate of damage accumulation. Results did not indicate any clear trends, but only two mixtures had K2 values below the minimum suggested criteria of 3.5 (Mix 2 field sample only, Mix 3 both field and lab samples). Intermediate temperature E* values confirmed this result with no statistical difference among all of the mixes. Low temperature cracking was tested using the DCT test. Resistance to low temperature cracking decreased with increasing recycled percentage. Using a DCT fracture energy criteria of 350 J/m^2 as an adequate level of low temperature cracking resistance, all of the mixes with less than 40% total recycled materials were acceptable. Some of the mixes with 40% or more total recycled materials had between 350-400J/m2, but generally, the trend was decreasing with increasing percentage of recycled materials. Low temperature E* were not significantly different between the mixtures. It was hypothesized that the shingle fibers added to the ductility of the asphalt and therefore help with the low temperature cracking properties. This was also seen when comparing the DCT results of mixtures with and without RAS. None of the mixtures showed significant susceptibility to freeze thaw as shown by the TSR results. All mixtures had TSR values greater than 0.79 (Williams, et al. 2011).

Wang et al. (2014) studied the use of RAS in OGFC mixtures for rutting resistance and moisture susceptibility. An OGFC mixture with PG 64-22 and one with PG 76-22 asphalt binder were tested with and without RAS for rutting resistance using the Asphalt Pavement Analyzer (APA). The PG 64-22 mixture without RAS quickly failed. Whereas the PG 64-22 mixture with RAS had similar rutting results as the PG 76-22 mixture without RAS. The PG 76-22 mixture with RAS had the lowest APA rutting results. E* testing was performed on the PG 76-22 mixture with and without RAS at 4°C, 25°C, and 45°C. The mixture with RAS was consistently stiffer than the mixture without RAS. The mixture without RAS had a TSR of 0.81 and the mixture with RAS had a TSR of 0.69, but one of the conditioned samples with RAS had much higher air voids than the rest of the samples (25% compared to 21%) and a much lower tensile strength. When the outlier was removed, the TSR of the mixture with RAS was 0.83, which indicates the addition of RAS did not have a significant impact on the moisture susceptibility. A test section of RAS OGFC was placed in North Carolina. After 2 years 7 months the section did not show any significant signs of deterioration other than clogging of the voids (Wang et al. 2014).

Cascione et al. (2015) reported on the field and laboratory performance of RAS mixtures from seven state agencies. The mixtures were designed to evaluate multiple properties of RAS as well as evaluate the use of RAS with Ground Tire Rubber (GTR) and Warm Mix Asphalt (WMA) technologies. Flow number and E* testing of the mixtures showed that the addition of RAS or RAS and RAP improved the rutting resistance, and this was confirmed by the field projects, as “no measureable amount of wheel path deformation” was observed over multiple years of evaluation. The four-point bending beam test was used to analyze the fatigue resistance of the mixtures, and the results showed that the mixtures with RAS had similar results to the mixtures without RAS. This was also consistent with the field trials, as most of the mixtures with RAS performed as well or better than the mixtures without RAS, in terms of fatigue cracking. Low temperature cracking was evaluated using the semi-circular bend test. For most projects there were no significant differences in the fracture energies of mixtures with or without RAS. Results for one state showed a significant increase in the low temperature cracking resistance with the addition of RAS, but results from another state had a significant decrease in the low temperature cracking resistance with the addition of 15% RAP to a 5% RAS mixture. Evaluation of the field trials in Missouri found that a mix with coarse ground RAS exhibited more transverse cracking than a similar mix with fine ground RAS, two winters after construction. The mixtures containing RAS were observed to have slightly more cracking than the mixtures without RAS in Missouri and Colorado, one winter after construction. In contrast, the mixtures with RAS were observed to have similar or less cracking than the mixtures without RAS in Iowa and Indiana, two and three winters after construction respectively. In Minnesota, a mixture with MWRAS displayed "slightly more cracking" than a mix with PCRAS, four winters after construction. The authors caution against drawing conclusions from results of the field evaluations since the extent of cracking prior to being overlaid was highly variable for the field projects (Cascione et al. 2015).

Wu et al. (2015) performed a study on field cores obtained from a Washington State project with four sections, two sections with 15% RAP and two sections with 3% RAS and 15% RAP. The study compared extracted binder testing for rutting, fatigue and thermal cracking resistance to mixture test results for the same distresses.

Table 12: Quality Acceptance Summary of Four Sections (Wu, et al. 2015)

Section	RAP/RAS	Asphalt Content (%)	Baghouse Fines Content (%)	Air Void Content (%)
1	15% RAP	5.6	6.5	2.3
2	3% RAS + 15% RAP	5.6	7	3.3
3	3% RAS + 15% RAP	6.4	7	1
4	15% RAP	5.4	5.9	3.3

They found that the inclusion of RAS had little to no effect on the PG of the recovered asphalts, but it did contribute to the significantly reduced non-recoverable compliance (Jnr) and increased percentage of recovery (R3.2), which corresponds with better rutting resistance. The binder test for fatigue and thermal cracking resistance was the monotonic binder fatigue test at 20°C and 5°C respectively, which was reported to correlate well with field performance (Wen and Bhusal 2013). The recovered binders containing RAS showed comparable fatigue resistance, but showed lower thermal cracking resistance due to the lower failure strains at 5°C. (Wu, et al. 2015) For mixture testing, the HWTD was used to evaluate rutting resistance. Results showed that the mixtures containing RAS had better rutting resistance. The low frequency (high temperature) E* and the IDT creep compliance values were higher for the mixtures containing RAS, also indicating increased rut resistance. Fatigue and thermal cracking resistance were tested using the IDT test and measuring the fracture work density, vertical deformation, and horizontal fracture strain (Wen 2013). This testing showed no significant difference in the mixtures with or without RAS for both fatigue and thermal cracking resistance. The mixture test results and binder test results were consistent with each other (better rutting resistance and no difference in fatigue resistance), except for the thermal cracking resistance. The binder testing indicated a reduction in the thermal cracking resistance and the mixture testing showed no significant difference in the thermal cracking with the addition of RAS. The authors explained this conflict in that the binder behavior was negatively affected by the shingle asphalt, but the mixture thermal cracking resistance was improved by the RAS fibers (Wu, et al. 2015).

F. Summary of Literature Review

Shingle asphalt is much stiffer than conventional paving grade asphalt. The shingle asphalt is air-blown (oxidized) prior to the production of shingles, and then further oxidized by the years of exposure to direct sunlight. Therefore, the use shingles in asphalt mixtures is typically associated with increased stiffness in the mixture caused by the activation and blending of the shingle asphalt. This increased stiffness has been shown to increase the rutting resistance of the asphalt mixture, but it has also been shown to decrease the mixture’s resistance to fatigue and low temperature cracking. One solution typically recommended is to choose a softer grade of virgin binder to off-set the high stiffness RAS binder, such that the final composite binder is approximately equal to the binder grade appropriate for the project climate. However, if activation of the shingle asphalt does not occur, the softer binder could negatively affect the rutting resistance of the mixture and/or result in a low effective binder content for the mixture, reducing the mixture’s durability. Therefore, the activation of the shingle asphalt needs to occur in order for the designer to property design a mixture that will performing well. Kris et al. (2014) showed that the rate of diffusion (for RAP asphalt) was dependent on temperature. A higher mixing and storage temperature may be needed to increase the diffusion rate for shingle asphalts, or increased conditioning time at standard temperatures (longer storage time in silos) may be needed to increase the amount of diffusion.

III. Research Methodology

This chapter summarizes the development of the experimental plan, volumetric analysis, and performance testing of mixtures to evaluate the effect of mixing temperature on the activation of shingle asphalt and to assess the contribution of the individual shingle components on HMA performance. This chapter also summarizes the evaluations used to quantify the activation of shingle asphalt.

A. Development of Mixtures

In 2012, NCAT began a pavement preservation experiment on a local county road (Lee County Road 159). Lee County Road 159 dead ends into a quarry and asphalt plant, and traffic on the road is primarily closely monitored truck traffic. This allows for analysis of traffic data on the performance of each preservation technique throughout the duration of the experiment. The road was segmented into twenty-five 100 ft. sections, and each section was treated with a different pavement preservation technique. Crack sealing, chip seals, micro-surfacing, fog seals and thin-lift asphalt overlays were all included in the preservation experiment. A thin-lift overlay mixture with 100% virgin materials was constructed in Section 19 and a 5% RAS thin-lift overlay mixture constructed in Section 24 were chosen as the designs to target and modify for the purposes of this research. (NCAT 2013)

a. Mix Designs

Four mix designs were developed for the purposes of this research. The first two mix designs replicated, as close as possible, the 5% RAS 4.75 mm NMAS (nominal maximum aggregate size) thin-lift overlay and the virgin 4.75 mm NMAS thin-lift overlay used in the NCAT pavement preservation experiment. These two mixtures were reproduced at NCAT's laboratories using the same aggregate materials and PCRAS stockpiles. The 5% RAS mixture was designed as 5% RAS by weight of the aggregate. The quality control data of the thin-lift overlay mixtures were used as targets for the aggregate gradations of the laboratory produced mixtures. These two mixtures were designed at a mixing temperature of 325°F, and will be identified as Mixture 5S (-/5|-/16)[1] and Virgin (-/-|-/-). Table 13 shows the average particle size distributions for the aggregate stockpiles, as determined by *AASHTO T 27: Sieve Analysis of Fine and Coarse Aggregates*, and the reclaimed aggregate particle size distribution, reclaimed asphalt content and the reclaimed fiber content of the RAS stockpile. The asphalt content of the RAS was determined from multiple samples using solvent extraction, *ASTM D 2172: Quantitative Extraction of Bitumen from Bituminous Paving Mixtures*. The G_{sb} of the RAS was determined according to AASHTO PP 53-09. AASHTO PP 53-09 recommends determining the G_{se} of RAS using *AASHTO T209: Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Hot Mix Asphalt (HMA).* AASHTO PP 53-09 notes that shingle granules are not very absorptive, and, therefore, G_{sb} and G_{se} should be relatively equal. The fiber content of the RAS was determined during the sieve analysis of the post-extraction aggregates by removing clumps of fiber from the sieves and weighing them separately.

Table 14 compares the quality control aggregate gradations and mix formulas from the two plant produced mixtures to the aggregate gradations and mix formulas of the two laboratory produced mixtures. Slight variations were made to the mix formulas to match the quality control aggregate gradations of the two plant produced mixtures.

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[1] (A / B | X / Y) notation is used to better illustrate the percentage of recycled materials in each mixture. A is the percentage of RAP in the mixture by weight of aggregate, B is the percentage of RAS in the mixture by weight of aggregate, X is the percentage of RAP asphalt of the mixture's total asphalt binder content, and Y is the percentage of shingle asphalt of the mixture's total asphalt binder content. Mixture 5S (-/5|-/16) has 5% RAS and the shingle asphalt is 16% of the mixture's total asphalt binder content.

Table 13: Aggregate Particle Size Distributions

Sieve Size		Calera LS 820s	Shorter Sand	EAP Bag-House Fines	Hydrated Lime	PCRAS (Aggregate)	PCRAS (As-Is)
English	Metric						
3/8"	9.5	100.0	100.0	100.0	100.0	100.0	99.3
#4	4.75	96.7	99.5	100.0	100.0	99.3	81.7
#8	2.36	68.6	91.8	100.0	100.0	97.7	70.7
#16	1.18	42.6	72.3	100.0	100.0	82.9	52.1
#30	0.6	28.4	42.0	100.0	100.0	59.5	31.3
#50	0.3	19.3	14.3	99.7	99.8	49.1	19.6
#100	0.15	13.7	4.0	98.5	98.3	39.4	9.8
#200	0.075	10.1	1.0	93.6	97.1	27.4	2.6
				Asphalt Content		18%	
				Fiber Content		(2%)[2]	

Table 14: Comparison of Laboratory and Plant Mixture Gradations

Sieve Size (mm)	Mixture 5S (-/5|-/16)	5% RAS Plant QC	Virgin (-/-|-/-)	Virgin Plant QC	50% RAP Plant QC
9.5	100.0	100	100.0	100	100
4.75	97.7	98	97.4	98	96
2.36	77.6	76	74.7	72	74
1.18	54.7	55	50.6	50	56
0.6	35.5	34	32.5	31	39
0.3	20.9	19	18.8	16	24
0.15	13.8	13	12.1	11	16
0.075	9.95	10.3	8.71	8.4	11.4
Calera Limestone	63%	64%	74%	69%	34%
Shorter Sand	30%	30%	25%	30%	15%
Hydrated Lime	1%	1%	1%	1%	1%
Bag House Fines	1%	0%	0%	0%	0%
Oxford PCRAS	5%	5%	0%	0%	0%
Fine Fractionated RAP	0%	0%	0%	0%	50%
Binder Content	6.3%	(6.3%)[3]	6.4%	6.3%	5.8%

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[2] Approximately 2%x` by weight, approximately 5%-10% by volume

[3] QC data states 6.0%, but further testing, using the NCAT ignition oven, demonstrated 6.3% to be actual

The final two mixtures were designed to evaluate the effects of the components of RAS on the properties of HMA. The ***shingle asphalt*** and the ***shingle aggregates and fiber*** were separated using chemical extraction (*ASTM D 2172: Quantitative Extraction of Bitumen from Bituminous Paving Mixtures*) and rotary-evaporation recovery (*ASTM D 5404: Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator*). The shingle aggregates and fibers, Figure 1, were extracted from the shingle asphalt using trichloroethylene (TCE). Then, 5% shingle aggregates and fibers were used to replace the 5% RAS (by weight of aggregates) in Mixture 5S (-/5|-/16), this mixture will be identified as Mixture 5A (-/5|-/-)[4]. The bulk specific gravity (G_{sb}) of the aggregate and fibers was assumed to be the same as the RAS. The G_{sb} of the RAS as assumed to be equal to the G_{se}, and this was calculated by testing the G_{mm} and the asphalt content of the RAS, as mentioned above. The shingle aggregate and fibers is a small percentage of the mixture and therefore potential errors in the G_{sb} were determined to be negligible.

Figure 1: Extracted Shingle Aggregates and Fibers

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[4] Mixture 5A (-/5|-/-) has 5% shingle aggregates and fiber but no shingle asphalt in the mixture

The extracted shingle asphalt was recovered from the TCE using rotary-evaporation. The shingle asphalt was tested and graded as an RTFO aged binder according to *AASHTO M320-10: Standard Specification for Performance-Graded Asphalt Binder*. The high temperature grade was determined to be 148°C and the low temperature grade was estimated to be +2°C, resulting in a PG 148+2. Many extractions were performed and the average asphalt content of the PCRAS was 18%. The extracted shingle asphalt was poured onto a cookie sheet and allowed to cool before being broken into small pieces and an ASTM #4 sieve was used to ensure all the pieces were smaller than the ASTM #4 sieve openings (Figure 2). The room temperature shingle asphalt pieces were added to the Virgin (-/-|-/-) mixture during mixing to replace a portion of virgin asphalt binder. This mixture will be identified as Mixture 16B (-/-|-/16)[5]. 16% recycled shingle asphalt was chosen to match the amount of recycled asphalt in Mixture 5S (-/5|-/16), assuming 100% activation.

Figure 2: Extracted Shingle Asphalt at Room Temperature

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[5] Mixture 16B (-/-|-/16) has no RAS in the mixture, but replaces 16% of the virgin asphalt binder with shingle asphalt.

Table 15 shows the aggregate gradations and mix formulas for the four mixtures that were produced. All mixtures were designed according to *AASHTO M323-13: Superpave Volumetric Mix Design* and *AASHTO R35: Superpave Volumetric Design for Hot Mix Asphalt (HMA)* for 3-10 million ESALs and a N_{design} of 75 gyrations. The virgin asphalt binder used for these mixtures was a PG 64-22, and the optimum binder content was determined at a mixing temperature of 325°F and a compaction temperature of 300°F. 100% activation was assumed when designing the mixtures with shingle asphalt. Table 16 shows the volumetric properties of each mixture determined during the design phase.

Table 15: Aggregate Gradations of Mixtures

Sieve Size (mm)	Mixture 5S (-/5|-/16)	Mixture 5A (-/5|-/-)	Virgin (-/-|-/-)	Mixture 16B (-/-|-/16)
9.5	100.0	100.0	100.0	100.0
4.75	97.7	97.7	97.4	97.7
2.36	77.6	77.6	74.7	76.6
1.18	54.7	54.7	50.6	53.2
0.6	35.5	35.5	32.5	34.2
0.3	20.9	20.9	18.8	19.4
0.15	13.8	13.8	12.1	12.4
0.075	10.0	10.0	8.7	9.0
Calera Limestone	63%	63%	74%	66%
Shorter Sand	30%	30%	25%	32%
Hydrated Lime	1%	1%	1%	1.1%
Bag House Fines	1%	1%	0%	1,1%
Oxford PC RAS	5%	(5%)[6]	0%	(16%)[7]
Binder Content	6.3%	6.2%	6.4%	6.4%

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[6] Extracted shingle aggregates and fibers were used in place of whole asphalt shingles

[7] Recovered shingle asphalt was used to replace 16% of the total virgin binder content

Table 16: Design Volumetric Properties of 4.75 mm Mixtures

Property	Superpave Criteria	Mixture 5S (-/5|-/16)	Mixture 5A (-/5|-/-)	Virgin (-/-|-/-)	Mixture 16B (-/-|-/16)
Pb	-	6.3	6.2	6.4	6.4
Va	4.0 - 6.0	4.1	4.0	4.7[8]	4.3
VMA	> 16.0	16.3	15.6	16.3	16.0
VFA	66 – 77	74.8	74.0	71.0	72.9
DP	1.5 - 2.0	1.88	2.01	1.72	1.78
Gmm	-	2.461	2.475	2.472	2.473
Gmb	-	2.360	2.375	2.355	2.366

B. Volumetric Analysis of Mixtures

The volumetric properties of each mixture were compared. The hypothesis was that there would be little difference in the volumetric properties between Mixture 5S (-/5|-/16) and Mixture 5A (-/-|-/16), or between Virgin (-/-|-/-) and Mixture 16B (-/-|-/16). This hypothesis assumes that the shingle asphalt would be 100% activated and the stiffer shingle asphalt would not affect the volumetric design. Any differences in the volumetric properties of these two sets of mixtures could be attributed to either incomplete activation of the shingle asphalt or the stiffness of the shingle asphalt. Also, there could be volumetric differences between Mixture 5S (-/5|-/16) and Mixture 5A (-/-|-/16) caused by the shingle aggregates and fibers not being held together by the shingle asphalt.

The effect of mixing temperature on the activation of shingle asphalt was also analyzed by examining differences in the volumetric properties of mixtures. Mixture 5S (-/5|-/16) was mixed at six temperatures ranging from 225°F to 350°F (Table 17). The mixing temperature was

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[8] Matched to the quality control air voids of the thin lift overlay control mixture

controlled by superheating the aggregates and allowing them to cool to 15-20°F above the desired mixing temperature before adding the 5% RAS and virgin binder. The RAS was added at ambient temperature (77°F) and blended with the aggregates prior to adding the virgin asphalt binder. The virgin asphalt binder was heated to 300°F.

Table 17: Mixture 5S (-/5|-/16) Mixing Temperatures

Aggregate Temperature (°F)	Shingle Temperature (°F)	Virgin Binder Temperature (°F)	Desired Mixing Temperature (°F)
425	77	300	350
400	77	300	325
375	77	300	300
350	77	300	275
325	77	300	250
300	77	300	225

The temperature of the mix was measured throughout the mixing process using a handheld infrared thermometer. The mixing temperature of each sample was recorded as the midpoint temperature measured during the mixing process. The samples were aged for two hours according to *AASHTO R 30-02: Mixture Conditioning of Hot Mix Asphalt (HMA)* at 25°F below the respective mixing temperature. The compactive effort was 75 gyrations. Five replicates were produced for each mixing temperature.

The hypothesis was that increasing the mixing and compaction temperatures would cause more shingle asphalt to be activated. Therefore, as more shingle asphalt is activated, the shingle asphalt will fill the voids of the mixture and the G_{mb} will increase. This hypothesis assumes the maximum specific gravity of the mixture would not be affected by mixing temperature. Two maximum specific gravity samples were prepared at 320°F and 250°F to verify that there was no change due to changes in mixing temperature, and as shown in Table 18, the results were within the acceptable precision range of AASHTO T209.

Table 18: Comparison of G_{mm} with Different Mixing Temperatures

G_{mm} of Mixture 5S mixed at 320°F		G_{mm} of Mixture 5S mixed at 250°F	
Sample 1	Sample 2	Sample 1	Sample 2
2.468	2.461	2.462	2.456
Standard Deviation		Precision (1s)	Actual
		0.0051	0.0049
Acceptable Range of Two Results		Precision (d2s)	Actual
		0.014	0.012

a. Estimating the Activation of Shingle Asphalt

The activation of shingle asphalt was investigated and estimated using several different methods. The two main questions concerning activation are: does the shingle asphalt soften and blend with the virgin asphalt, and how much of the shingle asphalt is activated and contributes to the total asphalt content of the mixture? Investigation into the first question of activation was performed two ways. The first method was to replace the virgin asphalt with a clear asphalt. There are several manufacturers of clear asphalt, which is a vegetable oil based adhesive with similar properties to crude oil based asphalt. Clear asphalts can be produced at different grades much like asphalt. Table 19 shows the specifications for a penetration grade 70/100 clear binder. It can be used to improve lighting conditions in tunnels or used with coloring pigments to make aesthetic changes in the pavement surface or to identify lanes for pedestrians, bicyclists or other special vehicles (Bocci, et al. 2012). One question with using the clear asphalt for this test was; does the clear asphalt represent the same interaction between paving grade asphalt and RAS? This question would be very difficult to answer without an extensive study into the chemistry of the clear asphalt; therefore, the results should be considered as possibly influenced by the use of the clear asphalt.

Table 19: Sealoflex Clear Binder Properties (Limited 2010)

Penetration at 25°C	ASTM D5	70-100 dmm
Softening Point	ASTM D36	50-56 °C
Elastic Recovery	ASTM D6084	≥ 70%
Viscosity at 135°C	ASTM D4402	400-600 mPa-s
Flash Point	ASTM D92	> 230 °C

The asphalt mixture with 5% RAS was mixed and compacted at 300°F. It was hypothesized that the shingle asphalt would activate and begin to blend with the clear adhesive, turning it black or darker than a control mix with the clear binder but no RAS.

The second investigation involved mixing aggregate and RAS without any additional asphalt. The hypothesis was the shingle asphalt would activate and begin to coat the aggregate and provide visual cues that activation was occurring. Visual cues thought to indicate the activation of the shingle asphalt may have included: transfer of asphalt from the shingles to the larger aggregate particles, conglomeration of non-shingle particles and shingle particles, or discoloration of the non-shingle particles.

After these investigations into whether or not the activation was occurring, the next step was to estimate the amount of activation. The method outlined in the former AASHTO specification AASHTO PP 53-09 was used to estimate the amount of activated shingle asphalt (Section II.B). Taking Gerry Huber’s recommendations into consideration, Mixture 5S (-/5|-/16) and Mixture 5A (-/5|-/-) were used as the two samples for the calculation because both have the same aggregate gradation and therefore the VMA of the two mixtures should be very similar. It is hypothesized that the shingle asphalt in Mixture 5S (-/5|-/16) would replace a portion of the virgin binder content of Mixture 5A (-/5|-/-). Also, the calculations for AASHTO PP 78-14 and selection of binder grade were performed assuming 100% activation and assuming 85% activation.

C. Mixture Performance Testing

Mixture performance testing was conducted to further evaluate activation of the shingle asphalt and to assess the effect of the shingle components on the performance properties of the mixtures. E*, Texas Overlay, IDT Creep Compliance and Strength, and Energy Ratio testing were used to provide a better understanding the effect of mixing temperature on the activation of shingle asphalt and the effect each shingle component had on mixture's laboratory performance. Nine mixtures were chosen for performance testing and the results were organized into three groups for comparisons:

Table 20: Grouping of Mixtures for Analysis of Mixture Properties

Mixtures	Group #1 - Shingle Components	Group #2 - Mixing Temperature	Group #3 - Comparison to PMLC
Mixture 5S mixed at 250°F (-/5|-/16)		X	
Mixture 5S mixed at 300°F (-/5|-/16)	X	X	
Mixture 5S mixed at 350°F (-/5|-/16)	X	X	X
Virgin (-/-|-/-)	X		X
Mixture 5A (-/5|-/-)	X		
Mixture 16B (-/-|-/16)	X		
Mixture 5S PMLC (-/5|-/16)		X	X
Virgin PMLC (-/-|-/-)			X
Mixture 50R PMLC (50/-|55/-) [9]			X

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[9] 50% Fine Fractionated RAP assumed to have 6% asphalt equaling 55% of total asphalt being RAP binder

PMLC is the abbreviation for Plant-Mixed Lab-Compacted. These mixtures were produced as part of the 2012 NCAT pavement preservation experiment on Lee County Road 159. These mixes were sampled at the plant and were stored in buckets for laboratory compaction and testing. The buckets of each mixture were reheated at 320°F for 3-4 hours and 4 to 6 specimens were separated out into smaller pans. The smaller pans were then placed back into the oven at 320°F until they reached the compaction temperature of 300°F. These mixtures were included as a comparison between plant produced and laboratory produced mixtures.

The laboratory produced mixtures were short-term aged for mechanical property testing for four hours according *AASHTO R 30-02: Mixture Conditioning of Hot Mix Asphalt (HMA)*. Long term aging was excluded from the scope of this research because the pavement preservation project was only 2 years old at the time of testing and a preliminary comparison of laboratory results and field evaluation was desired.

The three groups were selected to test the various hypotheses of this research. Group #1 was selected to investigate the effect of each shingle component separately. The hypothesis for Group #1 was that the addition of the shingle asphalt would cause an increase in the stiffness of the mixture, and the shingle fibers would increase the cracking resistance of the mixture. Group #2 was selected to test the effect of mixing temperature on the performance properties of Mixture 5S (-/5|-/16) and compare those results to the plant produced Mixture 5S PMLC (-/5|-/16). The hypothesis for Group #2 was that increasing the mixing temperature may increase the stiffness of the mixture. This increase in stiffness may be caused by increased activation and blending of the shingle asphalt at the higher temperatures, or it may also be caused by increased aging from the higher temperatures. It was also hypothesized that the plant mixture would be stiffer, possibly due to increased activation of the shingle asphalt assisted by the more thorough mixing conditions, but also due to increased aging of the mixture from the harsher mixing conditions. Group #3 was selected to compare the plant produced mixtures to the matched laboratory produced mixtures. It was hypothesized the plant produced mixtures would be stiffer than the laboratory produced mixtures due to more thorough mixing and increased aging from plant production.

a. Dynamic Modulus

Dynamic Modulus (E*) of each mixture was conducted using an IPC Global Asphalt Mixture Performance Tester (AMPT) in accordance with *AASHTO TP 79-09: Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)* and *AASHTO PP 61-10: Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT).* Three specimens of each mixture were prepared according to *AASHTO PP 60-09: Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)* (150mm height x 100mm diameter and 7.0 ± 0.5% air voids). The virgin asphalt used was a PG 64-22; therefore, in accordance with Table 2 of *AASHTO PP 61-10: Developing Dynamic Modulus Master Curves for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)*, each specimen was tested at temperatures of 4°C, 20°C and 40°C and frequencies of 10, 1, 0.1, and 0.01[10] Hz. After testing, the results were analyzed using Mastersolver Version 2.3, developed as part of NCHRP 09-29 by Ray Bonaquist (R. Bonaquist 2009), and 20°C was chosen as the reference temperature. The E* master curves for each mixture were compared side by side for changes in the shape or value. The hypothesis for this performance test was that the stiffer shingle asphalt would cause a mixture stiffness (higher E*). Therefore, it was predicted

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[10] Frequency of 0.01 Hz was only tested at the 40°C temperature

that Mixture 5S PMLC (-/5|-/16), Mixture 5S 350°F (-/5|-/16), and Mixture 16B (-/-|-/16) would have the highest E* values, and the mixtures with little to no recycled asphalt would have lower E* values.

b. Texas Overlay

Reflective cracking resistance was assessed using a modified version of the overlay testing procedure developed by the Texas Department of Transportation (TxDOT 248-F). The test parameters for the OT were determined by conducting preliminary testing using Mixture 5S PMLC (-/5|-/16) at various maximum opening displacements (MOD). These test results were expected to be qualitative and therefore a MOD was chosen that gave an average cycles to failure greater than 500 and less than 5000 cycles. A MOD of 0.381 mm was determined to be appropriate for this research, and a loading frequency of 1 Hz was used instead of the standard 0.1 Hz. Research by Ma (2014) at NCAT evaluated the loading frequency of the Overlay Test at smaller MODs for use with mixtures containing recycled materials. Ma ran tests at three different MODs (0.381 mm, 0.318 mm, and 0.254 mm), and two frequencies (1 Hz and 0.1 Hz). His analysis concluded that either frequency can be used without significantly affecting the variance of the results, but only one frequency should be used for the evaluation of mixtures within a project. Ma also included an analysis of overlay testing analysis methods. He analyzed several mixtures using the standard 93% load reduction method (TxDOT 248-F), a "normalized-load × cycle" (NLC) method (developed based on ASTM D7460's "normalized-stiffness x cycle" for bending beam fatigue analysis), and a visual Thru-crack method (video recording was used to determine the number of cycles for the crack to propagate completely through the specimen). The NLC method was shown to better represent the Thru-crack propagation and was less variable than the 93% load reduction method. Therefore, both the 93% load reduction method and the NLC method were used for the analysis of the results (Ma 2014).

The OT specimens were tested at 25°C in controlled displacement mode with a saw-tooth loading waveform according to TxDOT 248-F. The standard 93% load reduction was used as a termination point for testing.

In addition to using this test to assess the effect of shingle asphalt on cracking resistance of mixtures, it was also used to identify how the addition of shingle aggregate and fibers affected the mixture’s reflection cracking resistance. The hypothesis was that increased mixture stiffness would decreased the mixture’s resistance to high strains. Lower cycles to failure compared to the virgin mixture, may indicate activation and blending of the shingle asphalt. Also, the addition of shingle aggregate and fibers was hypothesized to cause an increase in cracking resistance compared to the virgin mixture.

c. IDT Creep Compliance

Resistance to low-temperature cracking was evaluated by testing the creep compliance and tensile strength of each mixture according to *AASHTO T 322-07: Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*. Four specimens of each mixture were fabricated no less than 32 mm thick x 150 mm diameter and 7.0 ± 0.5% air voids. One specimen was used as the “loading specimen” for determining the appropriate load to apply, and all conditioning and loading criteria were performed on all specimens according to *AASHTO T 322-07: Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*. The analysis of IDT creep compliance testing requires three testing temperatures, but the addition of shingle asphalt was shown to increase the stiffness of asphalt mixtures through the E* testing. Therefore, four testing temperatures (-20°C, -10°C, 0°C, and 10°C) were used to reduce the potential for inconclusive data at the lower temperatures. The results of this testing indicated less variable results when analyzing the [-10°C, 0°C, and 10°C] data set; therefore, the IDT strength test was performed at the midpoint temperature for this data set (0°C).

The IDT data were analyzed using the LTSTRESS spreadsheet developed by Don Christenson (Christenson 2013). Creep compliance master curves, estimated thermal stress models, and the critical low temperature cracking temperatures were compared between mixtures. The critical low temperature cracking temperatures are determined as the minimum temperature at which the asphalt mixture is flexible enough relieve the accumulating thermal stresses due to thermal shrinkage. Below this critical temperature, it is expected that the pavement will begin to develop thermal cracking. It was hypothesized that a decrease in the creep compliance of the RAS containing mixtures may indicate activation and blending of the shingle asphalt.

d. Energy Ratio

The Energy Ratio (ER) method was used to evaluate the mixtures' resistance to top-down cracking. The ER method, developed in Florida, uses a combination of indirect tension tests at 10°C to determine the resilient modulus, creep compliance and the indirect tensile strength for each mixture. One loading specimen and three replicate specimens were fabricated. Each specimen had a thickness of no less than 38mm x 150mm diameter and 7.0 ± 0.5% air voids. The resilient modulus and creep compliance were initially tested for each specimen, and the data quality was checked for accuracy before proceeding with the destructive indirect tensile strength test. For resilient modulus, a predetermined pulse load was applied for 0.1 seconds that resulted in a horizontal strain between 100 and 200 microstrain (με). The specimen was allowed to rest for 0.9 seconds before another load was applied. The resilient modulus was determined using the stress-strain curves (Figure 3(a)). The creep compliance load was then applied using a constant load-controlled mode. This load is typically around 10% of the target load used for resilient modulus and results in a horizontal strain of 100 με after 100 seconds. The creep compliance power function shown in Figure 3(b) was fitted to the data for each specimen. After the data quality was checked for the first two tests, the indirect tensile strength test was performed by loading each specimen at a fixed rate of 2 in/min until failure. Figure 3(c) shows how the dissipated creep strain energy (DCSE) at failure was calculated using the indirect tensile strength stress-strain failure curve (Roque, et al. 1997).

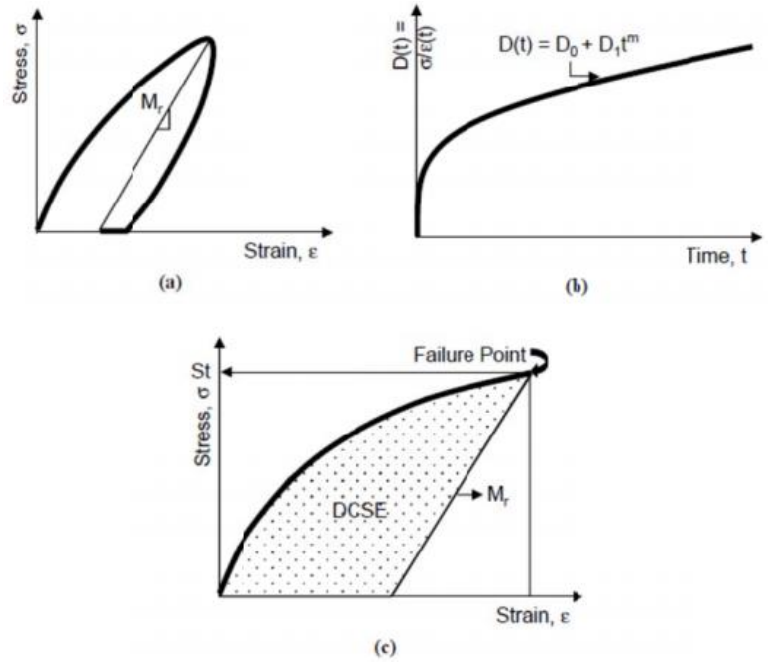

Figure 3: Stress-Strain Graphs for the Calculation of Energy Ratio from (a) Resilient Modulus, (b) Creep Compliance, and (c) Indirect Tensile Strength Testing (Timm, et al. 2009)

The ER was calculated as the ratio between the DCSE at failure of each mixture and the minimum DCSE required for the mixture to have adequate cracking resistance. $DCSE_{min}$ was calculated, as shown in Equation 5, using the curve fitting parameters from the mixture creep compliance and the tensile strength of the mixture. Suggested criteria indicating increased resistance to top-down cracking are listed in Table 21. These criteria were developed empirically using cracked and uncracked field sections throughout Florida and adjustments are recommended for different climates (Roque, et al. 2004). The hypothesis for ER testing was that activation of shingle asphalt would cause the mixtures to become more susceptible to top-down cracking. Therefore, the mixtures with activated shingle asphalt were expected to have lower ERs than the mixtures with all virgin asphalt.

$$\boldsymbol{ER = \frac{DCSE_f}{DCSE_{min}}} \qquad \textbf{Equation 4}$$

$$\boldsymbol{DCSE_{min} = \frac{m^{2.98}\, D_1}{[(0.0299)\, \sigma^{-3.1}\, (6.36 - S_t) + 2.46 * 10^{-8}]}} \qquad \textbf{Equation 5}$$

DCSE$_f$ is the dissipated creep strain energy at failure

DCSE$_{min}$ is the minimum dissipated creep strain energy threshold

σ is the tensile stress at the bottom of the asphalt layer, typically assumed 150 psi

D$_1$ and ***m*** are the power funtions from the creep compliance testing.

S$_t$ is the tensile strength of each mixture.

Table 21: Criteria for Top-Down Cracking Resistance (Roque, et al. 2004)

Minimum DCSE$_f$	0.75 KJ/m^3
Traffic ESALS/year x 1000	**Minimum Energy Ratio**
Less than 250	1
Less than 500	1.3
Less than 1000	1.95

IV. Results and Discussion

A. Analysis of Volumetric Properties

The pavement preservation experiment 4.75 mm NMAS mixtures were used as the target mixtures for this research. The aggregate size distribution and volumetric properties quality control (QC) data from production were used for matching the mixtures. The QC data are shown along with the data from the matched laboratory designs (Table 22). The percentage of the mixture that is virgin binder, not accounting for any activated shingle asphalt, is shown as the virgin binder content (VBC). The total binder content (TBC) is the total percentage of the mixture that is asphalt, assuming 100% activation of recycled asphalt.

The plant produced virgin mixture and the laboratory produced virgin mixture both had 4.7% air voids at 75 gyrations, but ASTM 323-12 allows for 4.0-6.0% design air voids for 4.75mm NMAS designs, due to the low permeability of 4.75mm NMAS mixtures. *AASHTO T-308: Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method* was used to determine the binder content of the plant produced mixtures, stored from the pavement preservation experiment. The 5% RAS 4.75 mm NMAS mixture and the matched Mixture 5S 325°F (-/5|-/16) had very similar volumetric properties, except the TBC. The 5% RAS 4.75mm NMAS QC data listed the TBC at 6.0%, but AASHTO T-308 testing showed the mixture to have a 6.3% TBC. It is possible deleterious materials were burnt off and caused a higher binder content, but 6.3% matches the design binder content of the laboratory produced Mixture 5S 325°F (-/5|-/16). The plant produced Virgin 4.75mm NMAS mixture and lab produced Virgin Mixture (-/-|-/-) were also very similar in volumetric properties. The plant produced mixture had a slightly lower TBC. Assuming, 100% activation of the shingle asphalt, the total binder contents for Mixture 5A (-/5|-/-) and Mixture 5S 325°F (-/5|-/16) were within 0.1%. The G_{mm} of Mixture 5A (-/5|-/-) was higher than Mixture 5S 325°F (-/5|-/16). This could be caused by the extracted shingle aggregates and fibers because they are no longer conglomerated together and are free to fill smaller holes in the aggregate structure. Also, this could indicate the G_{sb} of the aggregates and fines needs to be further evaluated when separated from the shingles.

Table 22: 4.75mm Quality-Control Data Compared to the Matched Laboratory Designs

	Plant Produced QC Data		Laboratory Produced Mixtures			
	5% RAS 4.75 NMAS (-/5|-/16)	**Virgin 4.75 NMAS (-/-|-/-)**	**Mixture 5S 325°F (-/5|-/16)**	**Mixture 5A (-/5|-/-)**	**Virgin (-/-|-/-)**	**Mixture 16B (-/-|-/16)**
TBC	6.0[11]	6.2	6.3	6.2	6.4	6.4
VBC	5.0[12]	6.2	5.2	6.2	6.4	5.4
Pbe	5.6	5.8	5.3	5.0	5.1	5.0
Gmm	2.455	2.449	2.461	2.475	2.472	2.473
Avg. Gmb	2.365	2.335	2.360	2.375	2.355	2.366
Avg. Va	3.7	4.7	4.1	4.0	4.7	4.3
Avg. Gsb	2.663	2.665	2.638	2.638	2.635	2.635
Avg. VMA	16.5	17.8	16.2	15.6	16.3	16.0
Avg. VFA	78	74	75	74	71	73
D to B	1.8	1.4	1.9	2.0	1.7	1.8

Mixture 16B (-/-|-/16) and Virgin Mixture (-/-|-/-) had the same total binder content, and nearly the same G_{mm}. The G_{mm} for these mixtures more closely matches the G_{mm} of Mixture 5A

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[11] The binder content was later proven to be 6.3% using the NCAT ignition oven (AASHTO T-308)

[12] Estimated using known RAS properties

(-/5|-/-), which may also indicate the conglomerated shingle aggregates, fibers, and asphalt are not being adequately separated and allowed to blend with the rest of the mixture.

a. Analysis of the Effect of Temperature on the Activation of Shingle asphalt

The results from mixing Mixture 5S (-/5|-/16) at six different temperatures are shown below in Figure 4. The plot shows a trend of increasing G_{mb} with higher mixing temperatures, which might have been caused by increasing activation and blending of the shingle asphalt. The increasing activation and blending of the shingle asphalt would increase the effective binder content and reduced the air-voids within the mixture. An analysis of variance (ANOVA) showed that temperature had a high influence on the compaction of these specimens (p=0.000).

The data was analyzed using the Tukey method of grouping with a 95% confidence interval. The results shown in Figure 4 demonstrate the groupings according to the Tukey analysis. The midrange temperatures were placed into group B, and the highest and lowest temperatures were placed in groups A and C respectively.

According to the hypothesis, these groupings should indicate three levels of activation of the recycled asphalt, little to no activation at the lowest temperature, minor activation at the mid-range temperatures, and more complete activation at the highest temperature. However, NCHRP 9-39 also studied the effect of temperature on compaction results and concluded that temperature has a highly significant effect on the compaction of mixtures, even without recycled materials. Mixture 5S (-/5|-/16) containing 5% RAS had a similar impact from increasing temperature, and therefore, there is not clear evidence that the shingle asphalt is being activated by the higher temperatures. Comparison of the NCHRP 9-39 data to the results of this research did not yield any conclusive results due to differences in binders and mixtures (West, et al. 2010).

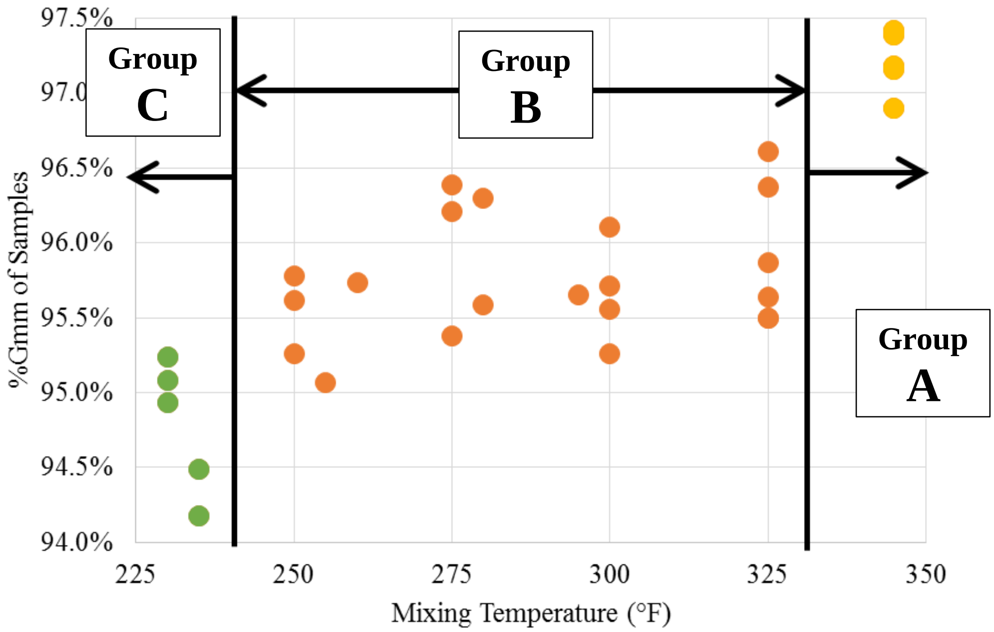
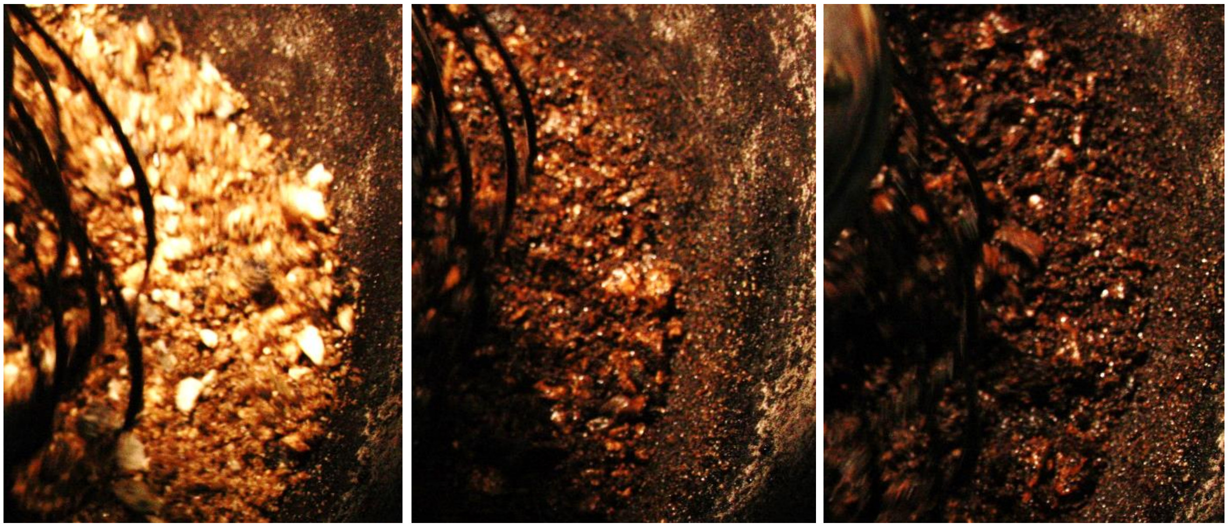


Figure 4: Compaction Results from Increasing Mixing Temperatures for Mixture 5S

b. Quantifying the Activation of Shingle asphalt

Two small experiments were conducted to investigate the activation of shingle asphalt. The first test was performed by mixing the 5% RAS mixture with a clear asphalt at 300°F. The use of the clear asphalt showed the activation of the shingle asphalt during the mixing process. The mixing bowl and whisk were thoroughly cleaned prior to mixing, and two samples without RAS were mixed for comparison. The samples without RAS had a light tan color after mixing, closely resembling the color of the sand used in the mixture. During the mixing of the sample with RAS, a slow change in color of the mixture was visually observed. The pictures below, taken during mixing with a planetary mixer, show the clear asphalt turn darker and darker through the mixing process.



(a) (b) (c)

Figure 5: 5% RAS Mixture with Clear Asphalt (a) Initial Coating of Aggregate (b) One Minute after Mixing, (c) End of Mixing

Figure 5(a) was taken just as the clear asphalt coated a majority of the particles, Figure 5(b) was taken about midway through the mixing process, and Figure 5(c) was taken near the end of the mixing process (about 2 minutes). The darker color of the mixture is believed to be caused by the activation of the shingle asphalt and blending with the clear asphalt. The darker color was very consistent throughout the mixture, indicating that the shingle asphalt blended fairly well with the clear asphalt during the mixing process. This is thought to represent the blending process when actual asphalt is used. Concerns with using RAS is that incomplete activation or blending could cause mixtures to be “dry” (asphalt content is lower than optimum) or if the shingle asphalt is not uniformly dispersed it could cause areas of localized stiff asphalt. Localization would cause these areas of the mixtures to be very susceptible to early cracking. The clear asphalt mixture test seems to indicate that shingle asphalt will activate and will blend with virgin binder during the mixing process, but further evaluation is needed to confirm whether the clear asphalt interacts with RAS in the same manner as conventional asphalts.

The second activation experiment consisted of mixing a 5% RAS mixture at 300 °F without any virgin asphalt. After mixing for two minutes and then cooling the material, a sieve analysis was performed to separate the different particle sizes of the mixture for closer inspection. As shown in Figure 6 (a), there was little to no asphalt coating any of the aggregate and intact shingle pieces were evident and coated with fine aggregate. Figure 6 (b) shows the larger particles of the mixture after being washed according to *AASHTO T 11: Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing* to remove the very fine mineral matter. This indicates that the larger shingle pieces were not activated enough to cause any of the aggregate (large or small) to stick to the shingle pieces, as would be expected.

Additionally, a replicate mixture was mixed in the same manner and then placed in an oven for 2 hours at 275°F to simulate aging according to AASHTO R 30. After this short-term conditioning period, the overall color of the aggregate changed and some of the large shingle pieces showed dark spots where the asphalt was activated enough to absorb the fine aggregates (Figure 6 (c)). The change in color was more notable in the fine aggregates as shown in Figure 7 (a) and (b). This change in color during the conditioning process indicates the occurrence of activation after mixing and during storage time of mixtures.

The results from these two experiments seem to contradict each other. Mixing a RAS mixture with clear asphalt showed the shingle asphalt activating during the mixing process, but the dry mixing showed the shingle asphalt was only activated during the conditioning process. Due to the very stiff nature of shingle asphalt, it is possible that mixing temperature alone is not enough to activate much of the shingle asphalt, but because asphalt is a visco-elastic material an extended storage time of the asphalt mixture in the silos may be able to achieve additional activation after the mixing process. An additional explanation is that the virgin asphalt binder may significantly contribute to the activation and blending of the shingle asphalt during the mixing process.


(a) (b) (c)

Figure 6: Dry Mixing of Aggregates and RAS (a) ASTM #4 Retained Aggregates after Dry Mixing (b) Washed ASTM #4 Retained Aggregates after Dry Mixing (c) ASTM #4 Retained Aggregates after Dry Mixing and Aging


(a) (b)

Figure 7: Dry Mixing of Aggregates and RAS (a) Passing ASTM #16 Aggregates after Dry Mixing (b) Passing ASTM #16 Aggregates after Dry Mixing and Aging

The procedure for estimating the asphalt binder availability factor (F_c) from AASTHO PP 53-09 was used to estimate the amount of shingle asphalt activation occurs in Mixture 5S (-/5|-/16). Taking the recommendation of Gerry Huber (Huber 2013), Mixture 5A (-/5|-/-) was used as the mixture without shingle asphalt. Mixture 5A (-/5|-/-) contained the shingle aggregate and fibers, whereas Mixture 5S (-/5|-/16) included the whole RAS. Therefore, the aggregate gradation of Mixture 5A (-/5|-/-) should be identical to Mixture 5S (-/5|-/16), except with no recycled asphalt. Equation 1 and 2 were used to determine F for Mixture 5S (-/5|-/16). For comparison, F was also determined using the Virgin Mixture (-/-|-/-) and Mixture 5S (-/5|-/16).

The method is not clear if the total binder content or the virgin binder content is to be used, but it was assumed that the virgin binder content was intended to be used. Therefore:

P_{bv} = 6.2% VBC for Mixture 5A (-/5|-/-)

P_{bvr} = 5.2% VBC for Mixture 5S (-/5|-/16)

P_{sr} = 5.7% or 0.057 RAS in Mixture 5S (-/5|-/16) (5% by weight of aggregate)

P_{br} **=** 18% or 0.18 shingle asphalt in the RAS

$$F_c = \frac{P_{bv} - P_{bvr}}{(P_{sr})(P_{br})} = \frac{\mathbf{6.2 - 5.2}}{(\mathbf{0.057})(\mathbf{0.18})} = \mathbf{97.5} \qquad \textbf{Equation 1}$$

$$F = 100\left(\frac{1 + F_c}{2}\right) = 100\left(\frac{1 + \mathbf{0.975}}{2}\right) = \mathbf{98.8} \qquad \textbf{Equation 2}$$

F was also determined using the Virgin Mixture (-/-|-/-) and Mixture 5S (-/5|-/16).

P_{bv} = 6.4% VBC for Virgin Mixture (-/-|-/-)

P_{bvr} = 5.2% VBC for Mixture 5S (-/5|-/16)

P_{sr} = 5.7% or 0.057 RAS in Mixture 5S (-/5|-/16) (5% by weight of aggregate)

P_{br} **=** 18% or 0.18 shingle asphalt in the RAS

$$F_c = \frac{P_{bv} - P_{bvr}}{(P_{sr})(P_{br})} = \frac{\mathbf{6.4 - 5.2}}{\mathbf{(0.057)(0.18)}} = \mathbf{117.0} \qquad \textbf{Equation 1}$$

$$F = 100\left(\frac{1 + F_c}{2}\right) = 100\left(\frac{1 + \mathbf{1.17}}{2}\right) = \mathbf{108.5} \qquad \textbf{Equation 2}$$

According to AASHTO PP 53-09, 99% of the shingle asphalt was activated in Mixture 5S (-/5|-/16) when compared to Mixture 5A (-/5|-/-). This is higher than the recommended range of 0.7 to 0.85 in AASHTO PP 78-14, and it was already shown that Mixture 5A (-/5|-/-) and Mixture 5S were not volumetrically the exact same. Therefore, it may be incorrect to assume the optimum binder content of Mixture 5A represents the optimum binder content of Mixture 5S, but it may be safe to assume that the Virgin Mixture does not adequately represent the optimum binder content of Mixture 5S, due to the availability factor of 108%.

The AASHTO PP 78-14 calculation of the percentage of RAS asphalt in the design asphalt binder content of Mixture 5S (-/5|-/16) was performed assuming 100% activation and assuming 85% activation. Note 6 mentions the assumed range for the shingle asphalt binder availability factor is 0.70-0.85 (or 70%-80% activation of the shingle asphalt). The virgin binder used for this mixture was a PG 64-22, and according to the Table 1 from AASHTO PP 78-14, if the percentage of RAS asphalt in the design binder content is above 15%, the binder grade should be bumped to a PG 58-28.

Assuming 100% activation:

$$\boldsymbol{P_{bst}} = \left[\frac{\boldsymbol{F(P_s)(P_{bs}) + (P_r)(P_{br})}}{\boldsymbol{P_b}}\right]\mathbf{100} = \left[\frac{\mathbf{1.0\ (0.057)(0.18) + (0)(0)}}{\mathbf{0.063}}\right]\mathbf{100} = \ \mathbf{16.3}\%$$

Assuming 85% activation:

$$\boldsymbol{P_{bst}} = \left[\frac{\boldsymbol{F(P_s)(P_{bs}) + (P_r)(P_{br})}}{\boldsymbol{P_b}}\right]\boldsymbol{100} = \left[\frac{\boldsymbol{0.85\ (0.057)(0.18) + (0)(0)}}{\boldsymbol{0.063}}\right]\boldsymbol{100 =\ 13.8}\%$$

According to the above calculations, if 100% of the shingle asphalt was assumed to be activated, the grade of the virgin binder should be bumped to a PG 58-28, but if 85% activation is assumed, no grade bump is required. This shows the importance of knowing how the shingles will react in an asphalt mixture. If the stiffness of the mixture is significantly increased, the use of the softer “grade bumped” binder may off-set the increased stiffness. Yet, if the mixture stiffness does not increase, the use of the softer “grade bumped” binder may be too soft for the climate

B. Analysis of Mixture Performance Testing

The results from the mixture performance testing are presented and discussed in this section. The measured E* results, measured OT cycles to failure results, IDT creep compliance results from LTSTRESS, and the testing results used to calculate ER are all included in Appendix A.

a. Dynamic Modulus (E*)

Table 23 shows the Tukey Analysis of Group #1’s E* data, and Figure 8 shows the E* master curves for the mixtures in Group #1. The analysis of these results showed the E* values for the Virgin Mixture (-/-|-/-), Mixture 5A (-/5|-/-), and Mixture 5S 300°F (-/5|-/16) mixtures were never statistically different from each other; therefore, it may be concluded that any shingle asphalt activation in Mixture 5S 300°F (-/5|-/16) was not enough to contribute to the stiffness of the mixture (this was further evaluated with Group #2). Also, Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16) had significantly higher E* values compared to Virgin Mixture (-

/-|-/-) and Mixture 5A (-/5|-/-) at the higher temperatures/lower frequencies. It has been shown in previous studies (Foo, Hanson, & Lynn, 1999; Mallick, Teto, & Mogawer, 2000; Kriz, et al., 2014) that increasing the blend percentage of shingle asphalt, increasingly stiffens the composite binder; therefore, the increased stiffness in Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16) may be due to increased activation and blending of the shingle asphalt.

Table 23: Tukey Analysis of Dynamic Modulus Values for Group #1

	4°F/0.1 Hz	4°F/1 Hz	4°F/10 Hz
Mix. 5S 350°F	A	A	A
Mix. 16B	A B	A	A
Mix. 5A	A B C	A B	A B
Virgin Mix.	B C	A B	A B
Mix. 5S 300°F	C	B	B

	20°F/0.1 Hz	20°F/1 Hz	20°F/10 Hz
Mix. 5S 350°F	A	A	A
Mix. 16B	A	A B	A B
Mix. 5A	B	B	A B
Virgin Mix.	B	B	A B
Mix. 5S 300°F	B	B	B

	40°F/0.01 Hz	40°F/0.1 Hz	40°F/1 Hz	40°F/10 Hz
Mix. 5S 350°F	A	A	A	A
Mix. 16B	B	B	B	B
Mix. 5A	C	C	C	B C
Virgin Mix.	C	C	C	B C
Mix. 5S 300°F	C	C	C	C

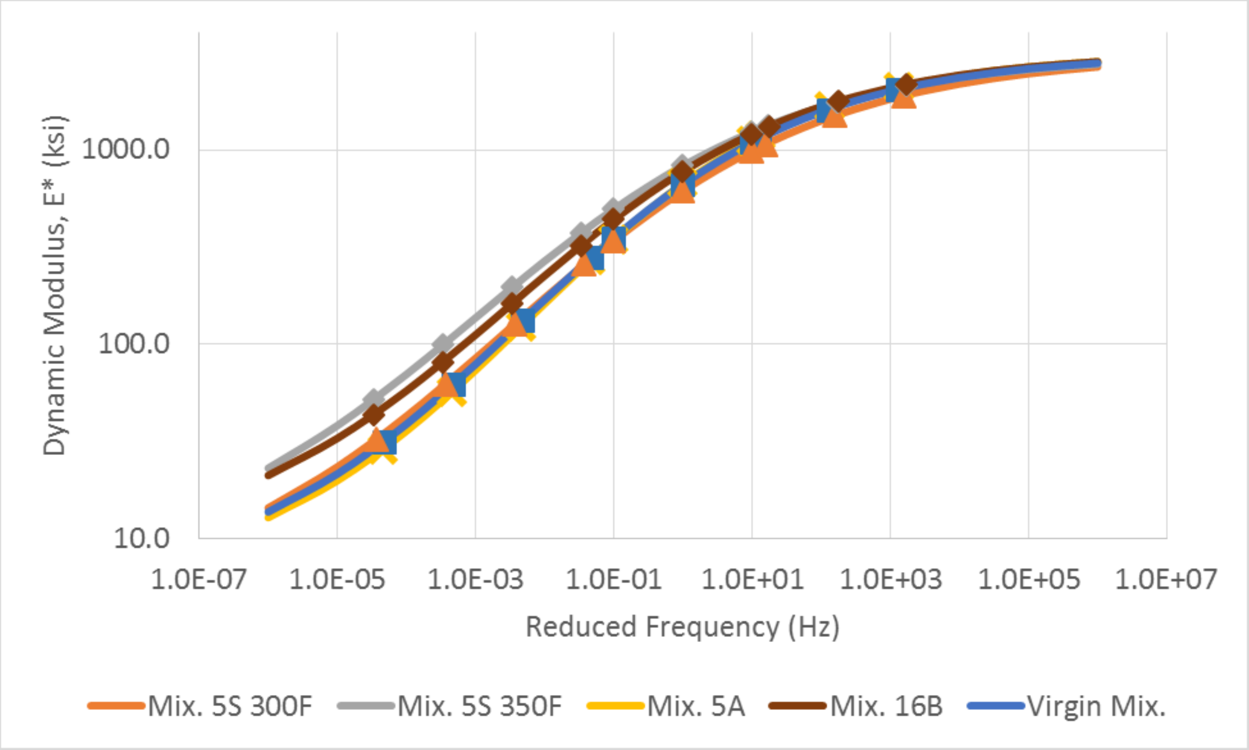


Figure 8: RAS Component Effects on Dynamic Modulus

Table 24 shows the Tukey Analysis of Group #2's E* data, and Figure 9 shows the E* master curves for the mixtures in Group #2. Analysis of the results for this group shows that increasing the mixing temperature significantly increases the E* of the mixture. This could be due to the increased activation and blending of the shingle asphalt caused by the increased mixing and compaction temperatures, or it could be due to the aging of the asphalt caused by the increased mixing and compaction temperature. It should also be noted that in Group #1, Mixture 5S 300°F (-/5|-/16) was not significantly different from the Virgin Mixture (-/-|-/-). Mixture 5S PMLC (-/5|-/16) (produced at 325°F) and Mixture 5S 350°F (-/5|-/16) were not significantly different except at the highest temperature and 10 Hz frequency. This could indicate a higher mixing temperature is required for laboratory produced mixtures to simulate the conditions of plant produced mixtures.

Table 24: Tukey Analysis of the Dynamic Modulus Values for Group #2

	4°F/0.1 Hz	4°F/1 Hz	4°F/10 Hz	
Mix. 5S PMLC	A	A	A	
Mix. 5S 350°F	A	A	A B	
Mix. 5S 300°F	B	B	C	
Mix. 5S 250°F	B	B	B C	
	20°F/0.1 Hz	20°F/1 Hz	20°F/10 Hz	
Mix. 5S PMLC	A	A	A	
Mix. 5S 350°F	A	A	A	
Mix. 5S 300°F	B	B	B	
Mix. 5S 250°F	C	B	B	
	40°F/0.01 Hz	40°F/0.1 Hz	40°F/1 Hz	40°F/10 Hz
Mix. 5S PMLC	A	A	A	A
Mix. 5S 350°F	A	A	A	B
Mix. 5S 300°F	B	B	B	C
Mix. 5S 250°F	C	C	C	D

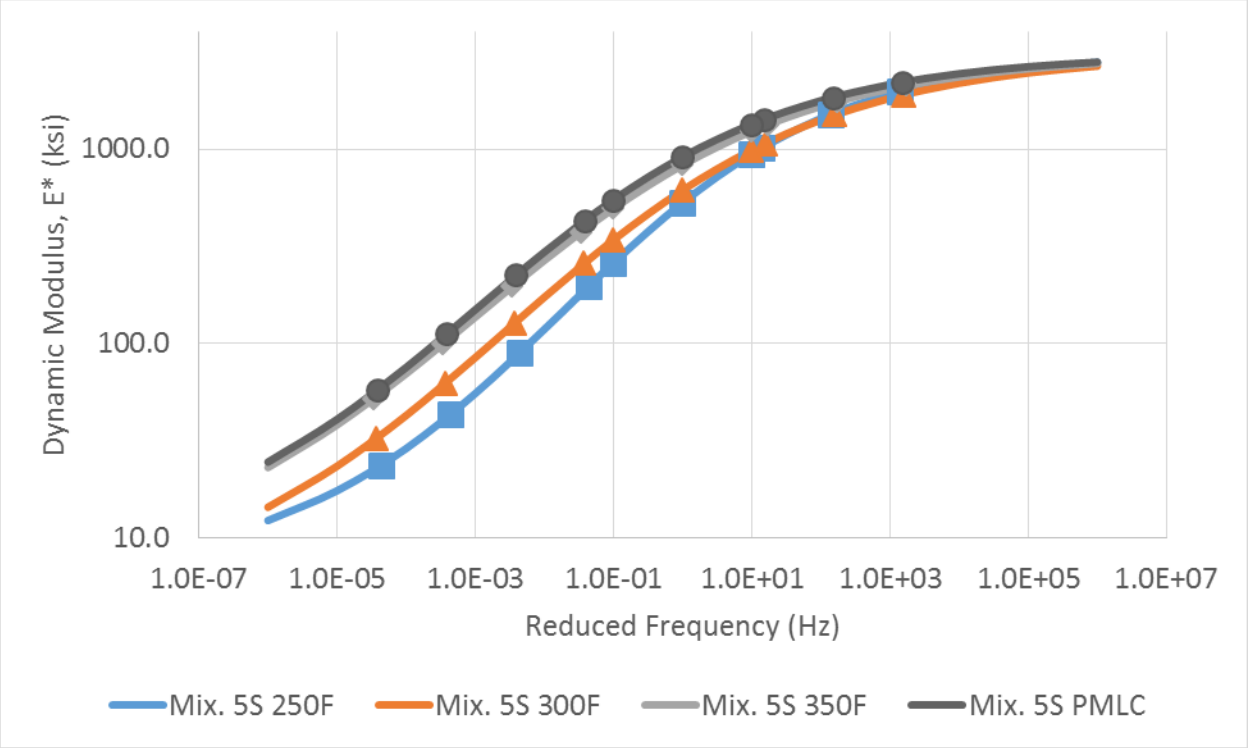


Figure 9: Temperature Effects on the Dynamic Modulus of Mixtures Containing RAS

Table 25 shows the Tukey Analysis of Group #3’s E* data, and Figure 10 shows the E* master curves for the mixtures in Group #3. The analysis of this group showed that the Mixture 5S 350°F (-/5|-/16) closely represents Mixture 5S PMLC (-/5|-/16). Also, Virgin Mixture (-/-|-/-) closely matches the Virgin PMLC (-/-|-/-) mixture except at the highest test temperature. These are important comparisons for relating the laboratory performance testing results to the field performance on Lee Road 159. Mixture 50R PMLC (50/-|55/-) was significantly stiffer than the other mixtures. This was likely due to the high percentage of recycled asphalt replacing the virgin binder in the mixture and its lower total binder content.

Table 25: Tukey Analysis of the Dynamic Modulus Values of Group #3

	4°F/0.1 Hz	4°F/1 Hz	4°F/10 Hz	
Mix. 50R PMLC	A	A	A	
Mix. 5S PMLC	B	B	B	
Mix. 5S 350°F	B C	B C	B	
Virgin Mix.	C D	B C	B	
Virgin PMLC	D	C	B	
	20°F/0.1 Hz	20°F/1 Hz	20°F/10 Hz	
Mix. 50R PMLC	A	A	A	
Mix. 5S PMLC	B	B	B	
Mix. 5S 350°F	B	B C	B	
Virgin Mix.	C	C	B	
Virgin PMLC	C	C	B	
	40°F/0.01 Hz	40°F/0.1 Hz	40°F/1 Hz	40°F/10 Hz
Mix. 50R PMLC	A	A	A	A
Mix. 5S PMLC	B	B	B	B
Mix. 5S 350°F	B	B	B	B
Virgin Mix.	C	C	C	C
Virgin PMLC	D	D	D	D

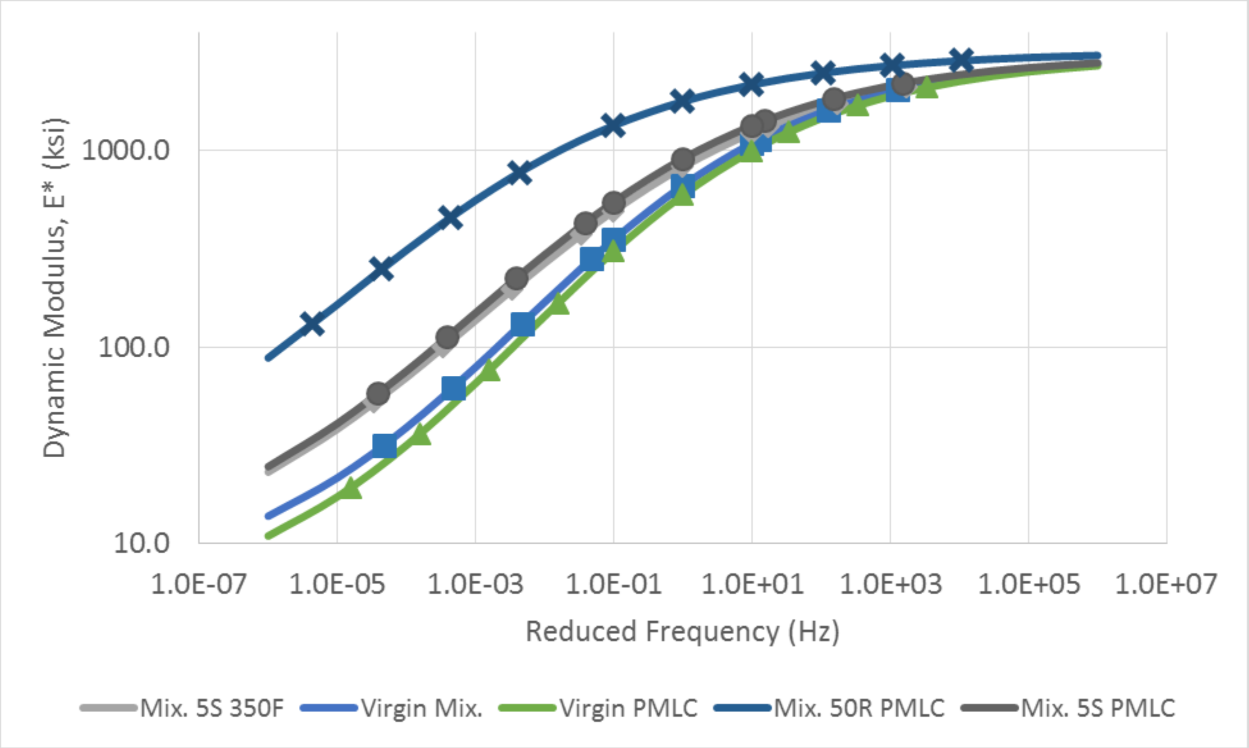


Figure 10: Dynamic Modulus Curves for Group #3

The dynamic modulus data indicated an increased stiffness in Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16), which may indicate an increased activation and blending of the shingle asphalt in those mixtures. Mixture 5A (-/5|-/-), Virgin Mixture (-/-|-/-), and Mixture 5S 300°F (-/5|-/16) were not significantly different. Mixture 5S 250°F (-/5|-/16) had a decreased stiffness at the high temperatures/low frequencies. The laboratory produced mixtures were not significantly different from the matched PMLC mixtures. A higher mixing temperature or additional aging may be need to adequately match the E* data of laboratory produced mixtures to plant produced mixtures.

b. Texas Overlay Tester

The number of cycles to failure using the AMPT Overlay Test was determined two ways. First was the traditional 93% load reduction (93%LR) method, and second was the normalized load x cycle (NLC) method. Each of these two methods were analyzed separately and the results were compared for further evaluation of the normalized load x cycles as a viable method of analysis. Table 26 gives the Tukey Analysis of each group individually and a combined group. Figure 11 compares the cycles to failure for each group using bar charts.

Figure 11 (a) compares the mixtures in the Group #1. Mixture 5A (-/5|-/-) had the highest number of cycles to failure in this group, but it's OT results were not significantly different than the Virgin mixture (-/-|-/-) nor Mixture 5S 300°F (-/5|-/16) for both the 93%LR and NLC evaluation methods. Therefore, the hypothesis that the shingle fine aggregates and fibers would increase the cracking resistance could not be verified. Also, this statistical grouping indicates that the shingle asphalt in Mixture 5S 300°F (-/5|-/16) may not have activated or blended enough to affect the cracking resistance of the mixture. Yet, the shingle asphalt was likely contributing to the mixture in some way because a decrease in the effective binder content would likely decrease the cracking resistance of the mixture. OT cycles to failure for Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16) were significantly lower than Mixture 5A (-/5|-/-). This may support the hypothesis that the recycled shingle asphalt contributes to a lower resistance to high strains, but the cycles to failure for Mixture 16B (-/-|-/16) was not significantly lower than for Virgin Mixture (-/-|-/-).

Analysis of the mixtures in Group #2 (Figure 11 (b)) gives similar results as the E* testing. A statistically significant difference was seen between Group A (Mixture 5S 250°F (-/5|-/16) and Mixture 5S 300°F (-/5|-/16)) and Group B (Mixtures 5S 350°F (-/5|-/16) and Mixture 5S PMLC (-/5|-/16)). This supports the hypothesis that increased mixing temperatures increases mixture stiffness and decreases tolerance to high strains. It is possible increased activation and blending of the shingle asphalt may have caused the decreased OT results, but increased aging of the mixture caused by higher temperatures could have also affected these results.

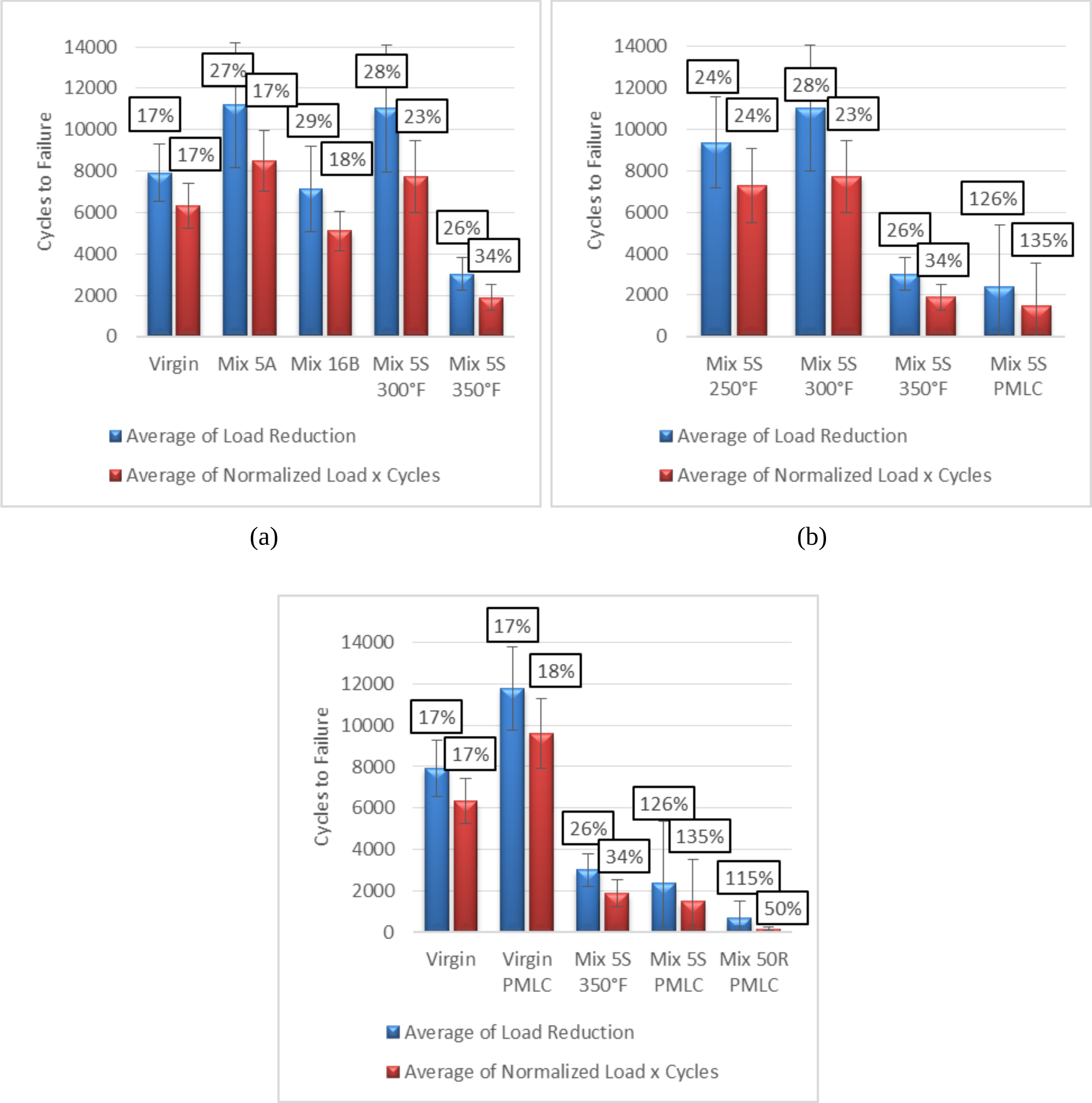
Figure 11 (c) compares OT results for the mixtures in Group #3. These results show a significant difference between the laboratory produced Virgin Mixture (-/-|-/-) and Virgin PMLC (-/-|-/-). Also, the Tukey analysis showed that Mixture 5S PMLC (-/5|-/16), Mixture 5S 350°F (-/5|-/16), and Mixture 50R (50/-|55/-) are not significantly different, even though there is a large difference in the means. This was found to be caused by the high coefficient of variance for these mixtures.

Table 26: Tukey Analysis of the Overlay Tester Cycles to Failure Results

Group #1	NLC	93%LR	Group #3	NLC	93%LR
Mix 5A	A	A	Virgin PMLC	A	A
Mix 5S 300°F	A B	A	Virgin	B	B
Virgin	A B	A	Mix 5S 350°F	C	C
Mix 16B	B	A B	Mix 5S PMLC	C	C
Mix 5S 350°F	C	B	Mix 50R PMLC	C	C

Group #2	NLC	93%LR
Mix 5S 250°F	A	A
Mix 5S 300°F	A	A
Mix 5S 350°F	B	B
Mix 5S PMLC	B	B

All Mixtures	NLC	93%LR
Virgin PMLC	A	A
Mix 5A	A	A
Mix 5S 300°F	A B	A
Mix 5S 250°F	A B	A
Virgin	A B	A B
Mix 16B	B C	A B C
Mix 5S 350°F	C D	B C D
Mix 5S PMLC	D	C D
Mix 50R PMLC	D	D



(a) (b)

(c)

Figure 11: Overlay Testing Results (a) Group #1 – Shingle Components (b) Group #2 – Mixing Temperature (c) Group #3 – Comparison to PMLC

The hypothesis that the shingle fine aggregates and fibers would increase the cracking resistance could not be verified because Mixture 5A (-/5|-/-) was not significantly different from Virgin Mixture (-/-|-/-). The shingle asphalt in Mixture 5S 300°F (-/5|-/16) and Mixture 5S

250°F (-/5|-/16) may not have activated or blended enough to affect the cracking resistance of the mixture but the mixtures were not adversely affected by a lack of effective asphalt. The activation and blending of shingle asphalt may affect the cracking resistance of the mixture. OT cycles to failure for Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16) were significantly lower than Mixture 5A (-/5|-/-). There was a significant difference between the laboratory produced Virgin Mixture (-/-|-/-) and Virgin PMLC (-/-|-/-), but there was not a significant difference between Mixture 5S PMLC (-/5|-/16), Mixture 5S 350°F (-/5|-/16), and Mixture 50R (50/-|55/-).

c. Indirect Tension Testing

Creep compliance testing was performed at temperatures -20°C, -10°C, 0°C, and 10°C. These data were analyzed in two sets [-20°C, -10°C, and 0°C] and [-10°C, 0°C, and 10°C] for comparison. The base virgin asphalt was a PG 64-22, and according to AASHTO T 322-07 the creep compliance analysis should be performed using -20°C, -10°C, and 0°C. Analyses were also conducted using tests at -10°C, 0°C, and 10°C because a majority of the mixtures contain aged asphalt which has been shown to affect mixture results for low temperature properties (R. Bonaquist 2011; Abbas, et al. 2013; Zhao, et al. 2013).

After analyzing both data sets, the [-10°C, 0°C, and 10°C] set was shown to have a lower standard error than the [-20°C, -10°C, and 0°C] data set. Therefore, the IDT Strength testing was performed at 0°C, and only the [-10°C, 0°C, and 10°C] data set was used for comparisons between mixtures. It should also be noted that the Mixture 50R PMLC (50/-|55/-) and the Virgin PMLC (-/-|-/-) mixture were only tested at -20°C, -10°C, and 0°C and the IDT Strength testing was performed at -10°C. Therefore, Mixture 50R PMLC and Virgin PMLC were analyzed using the data from -20°C, -10°C, and 0°C but with a reference temperature of -10°C, and they are excluded from the comparison of Mixture IDT Tensile Strength. Changing the reference temperature to accurately calculate the reduced time was achieved by changing one cell to the reference temperature in the LTSTRESS workbook used to analyze the IDT data (Christenson, 2013).

The data for IDT Tensile Strength is shown in Figure 12. The values shown are the average mixture tensile strength values from the LTSTRESS workbook and have been corrected and adjusted using a field strength calibration factor of 0.63. For statistical analysis, the mixture tensile strength was determined for each specimen, using the same correction and adjustment technique.

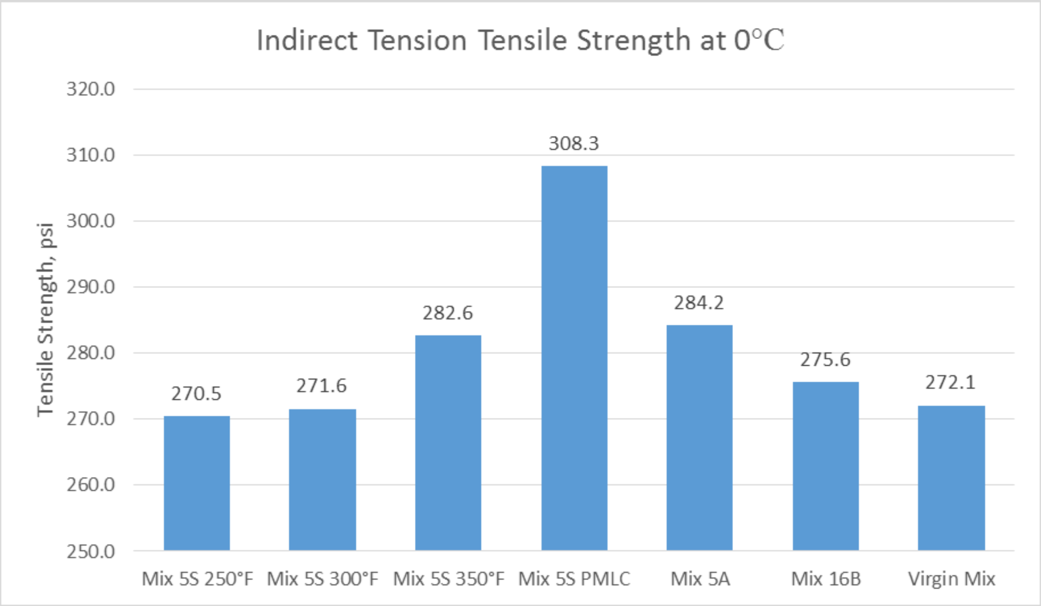


Figure 12: IDT Strength

The estimated critical pavement temperature for low temperature thermal stress cracking in the pavement is shown in Table 27. The critical temperature was determined using the LTSTRESS workbook, but when the critical temperatures were plotted, the temperatures did not line up with the thermal stress curves. After further investigation, it was determined that the calculation of the critical temperature assumed that the thermal stress curve was linear between

100 and 1000 psi when plotted as semi-logarithmic (x-log(y)). While this was a close approximation, the semi-logarithmic curve was concave down, and, therefore, the estimation of the critical temperature was an over-estimation. In order to get a more accurate calculation of the critical stress, the thermal stress curve was assumed to be a quadratic polynomial function, and quadratic regression was used to determine the best fit equation for the curve between 100 and 1000 psi. The sum of squares due to error (SSE) and the total sum of squares (SST) were calculated for each point with a stress between 100 and 1000 psi, and Microsoft Excel's Solver function was used to maximize the R^2 value. This resulted in more accurate calculations of the critical temperature based on the thermal stress curve.

Table 27: IDT Critical Temperature Results

Mixture	IDT Strength (psi)	LTSTRESS Critical Temperature (°C)	Quadratic Regression Critical Temperature (°C)
Virgin PMLC	383.6	-19.1	-18.4
Mix 5S 250°F	270.5	-17.8	-17.3
Virgin Mix	272.1	-18.0	-17.3
Mix 5S 300°F	271.6	-16.6	-15.5
Mix 5A	284.2	-15.3	-15.0
Mix 16B	275.6	-15.6	-15.0
Mix 5S PMLC	308.3	-14.4	-13.3
Mix 5S 350°F	282.6	-13.7	-12.7
Mix 50R PMLC	422.1	-13.6	-12.3

As shown in Table 27, there is no correlation between the IDT strength and the critical temperature. The shift of the thermal stress curve has a greater impact on the critical temperature than changes in the strength. Virgin PMLC (-/-|-/-), the laboratory produced Virgin Mixture (-/-|-/-), and Mixture 5S 250°F (-/5|-/16) had critical temperatures of about -17C, meaning they are the most resistant to thermal stresses. Mixture 5S 300°F (-/5|-/16), Mixture 5A (-/5|-/-), and Mixture 16B (-/-|-/16) had critical temperatures of about -15C, meaning they are less resistant to thermal stresses. This could be caused by minor activation and blending of shingle asphalt, but Mixture 5A (-/5|-/-) does not contain any shingle asphalt. Mixtures 5S PMLC (-/5|-/16), Mixture 5S 350°F (-/5|-/15), and Mixture 50R PMLC (50/-|55/-) had critical temperatures of about -13C, meaning they are the least resistant to thermal stresses. These mixtures were also shown to have higher E* values than the other mixtures, and to be significantly less tolerant of high strains (OT results). The shift in the thermal stress curves may have been caused by increased activation and blending of the shingle asphalt (RAP asphalt for Mixture 50R (50/-|55/-)), but as shown with Mixture 5A (-/5|-/-), there may be other factors affecting the shift in the thermal stress curves.

The LTSTRESS analysis of the creep compliance master curve yields only one combined result, which eliminates the possibility of a statistical analysis. Therefore, it is difficult to determine if differences between the results are statistically significant. Visual and numerical analysis were used for the comparison of increases and decreases in the creep compliance. For each group, the creep compliance master curves are shown, as well as a bar graph of the creep compliance at certain loading times, for easier comparison of mixtures. The loading times of 31600 seconds, 1000 seconds, and 31.6 seconds were chosen to as the approximate mid-point of the data at each temperature tested, 10°C, 0°C, and -10°C respectively.

Group #1 shows a very close grouping of the creep compliance master curves (Figure 13) indicating little variation in the creep compliance between mixtures. This is further shown by the bar chart in Figure 14. Little differences are seen in the compliance values at the two lower temperatures. At the highest test temperature (+10°C), the creep compliance values for Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16) are somewhat lower than the other mixes in the group, possibly indicating activation and blending of the shingle asphalt and consequently a stiffer composite binder. At the lower temperatures, the small differences in compliance values for the group could indicate that the activated shingle asphalt does not significantly affect the low temperature cracking properties of the mixture.

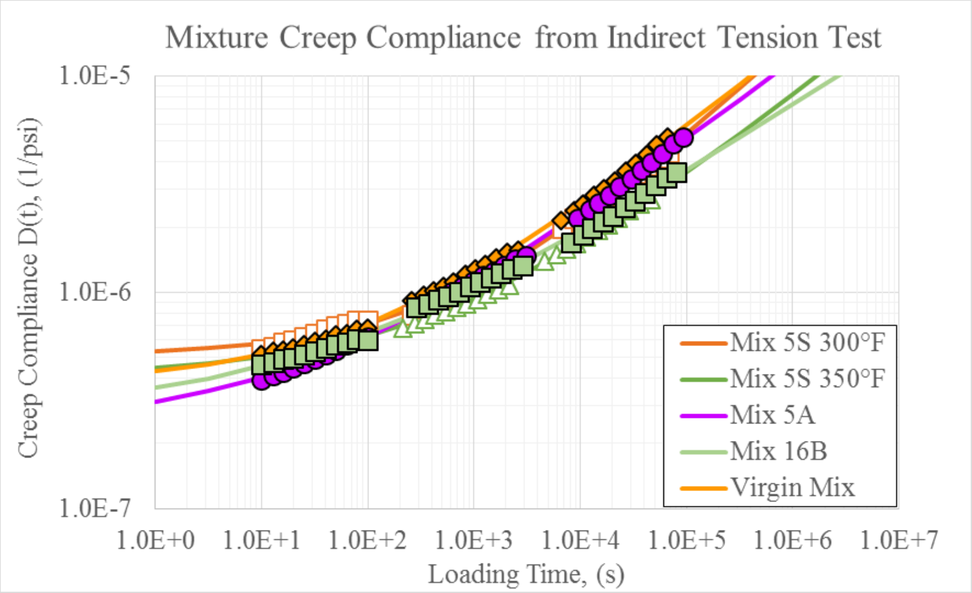


Figure 13: Group #1 Creep Compliance Master Curves

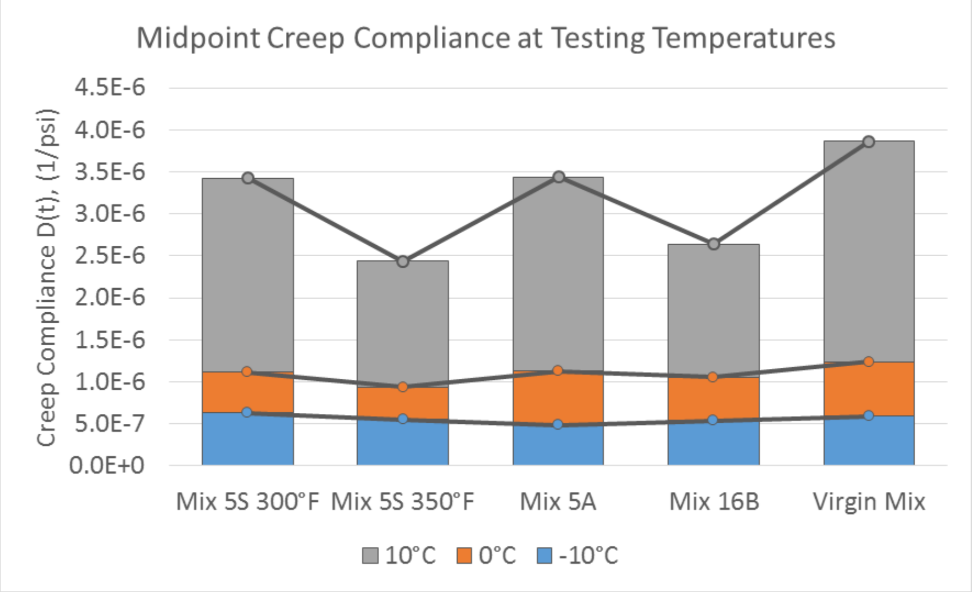


Figure 14: Group #1 Creep Compliance Midpoint Values

Figure 15 and Figure 16 show the data for Group #2. There is a clear decrease in the creep compliance with increased mixing temperature, and Mixture 5S PMLC (-/5|-/16) has an even lower creep compliance than the laboratory produced mixtures. The decrease in creep compliance could be due to increased activation of the stiffer shingle asphalt. This is consistent with the results seen in the E* and overlay testing. Yet, data from NCHRP Report 648 also showed a reduction in the creep compliance results for higher mixing and compaction temperatures for virgin mixtures. Therefore, the reduction in creep compliance may be impacted by aging of the virgin binder at the higher mixing temperatures. Further testing may be necessary comparing the impact of mixing temperature on virgin binder and composite binders (West, et al. 2010).

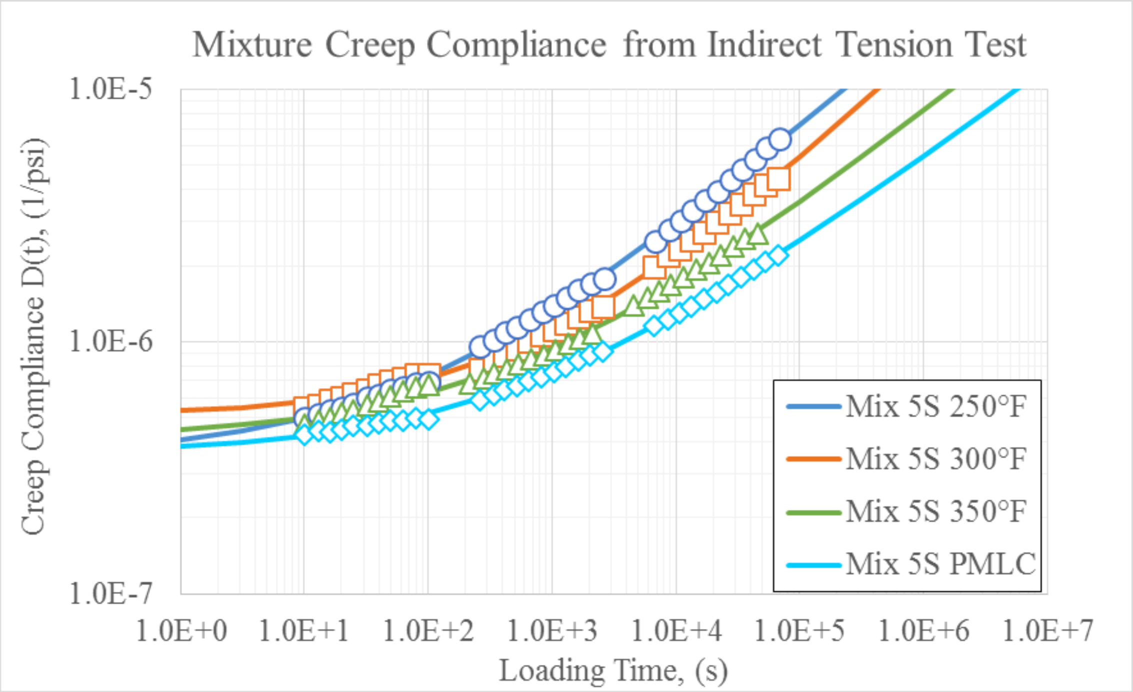


Figure 15: Group #2 Creep Compliance Master Curves

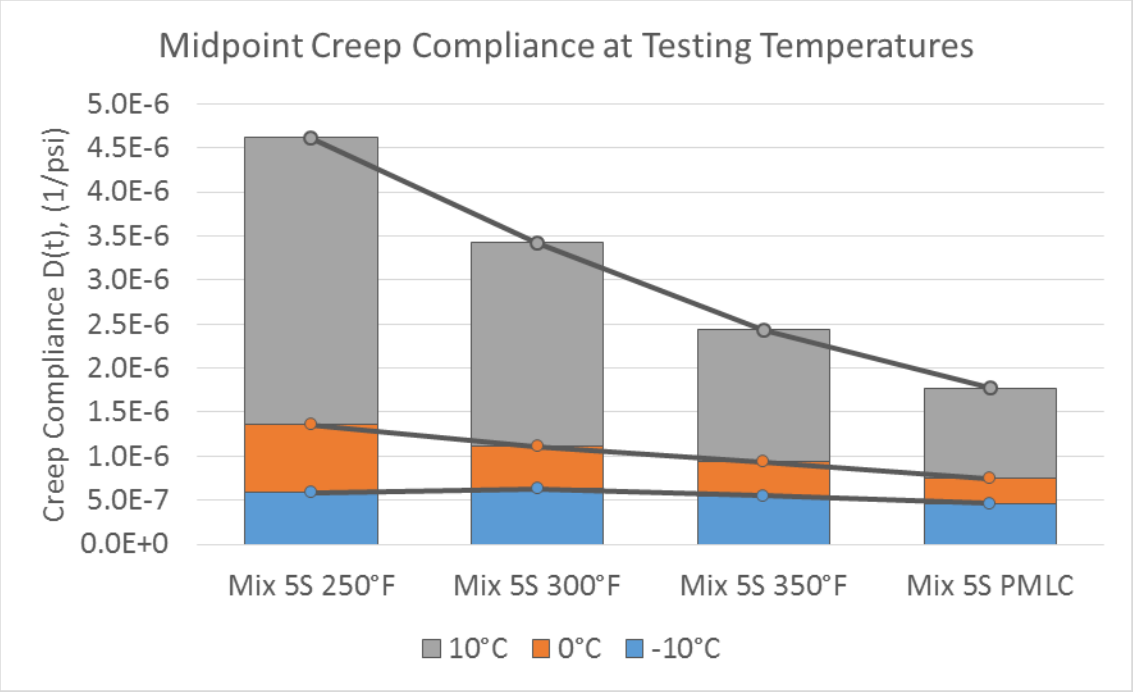


Figure 16: Group #2 Creep Compliance Midpoint Values

Figure 17 and Figure 18 show the data for Group #3. Mixture 5S PMLC (-/5|-/16) is shown to have a lower creep compliance than Mixture 5S 350°F (-/5|-/16). The Virgin PMLC (-/-|-/-) mixture is shown to have a lower creep compliance than the laboratory produced Virgin Mixture (-/-|-/-). The lower creep compliance of the PMLC mixtures could indicate more aging during plant production. Mixture 50R PMLC (50/-|55/-) was shown to have the lowest creep compliance. This was consistent with the higher stiffness seen in the E* and overlay testing results.

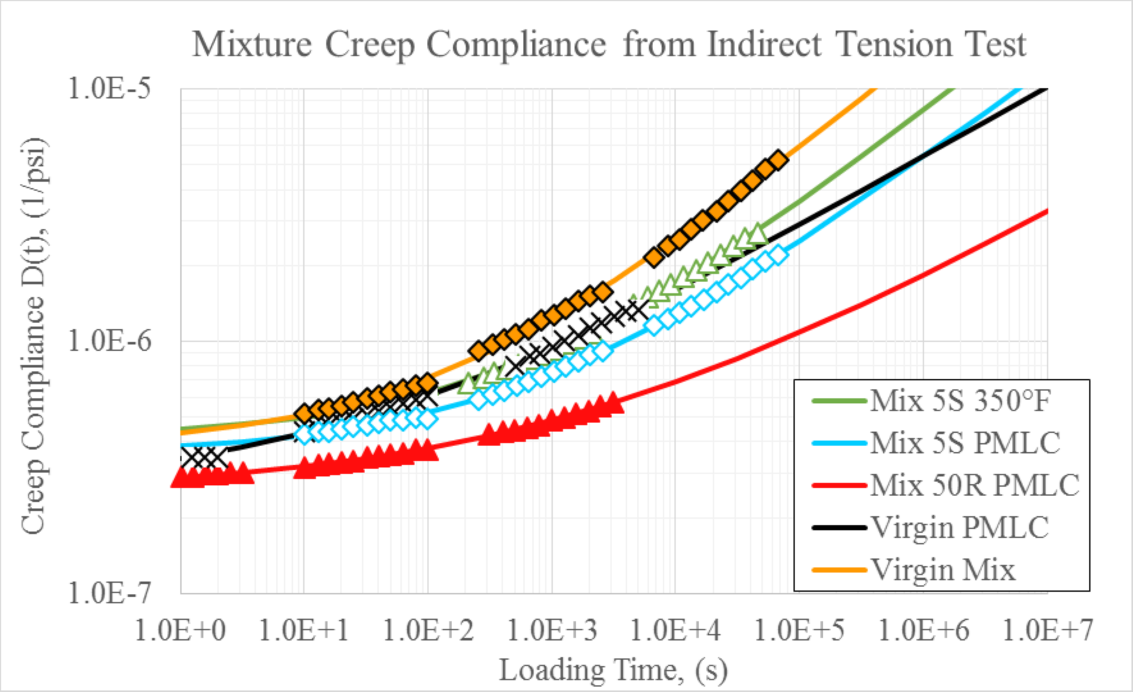


Figure 17: Group #3 Creep Compliance Master Curves

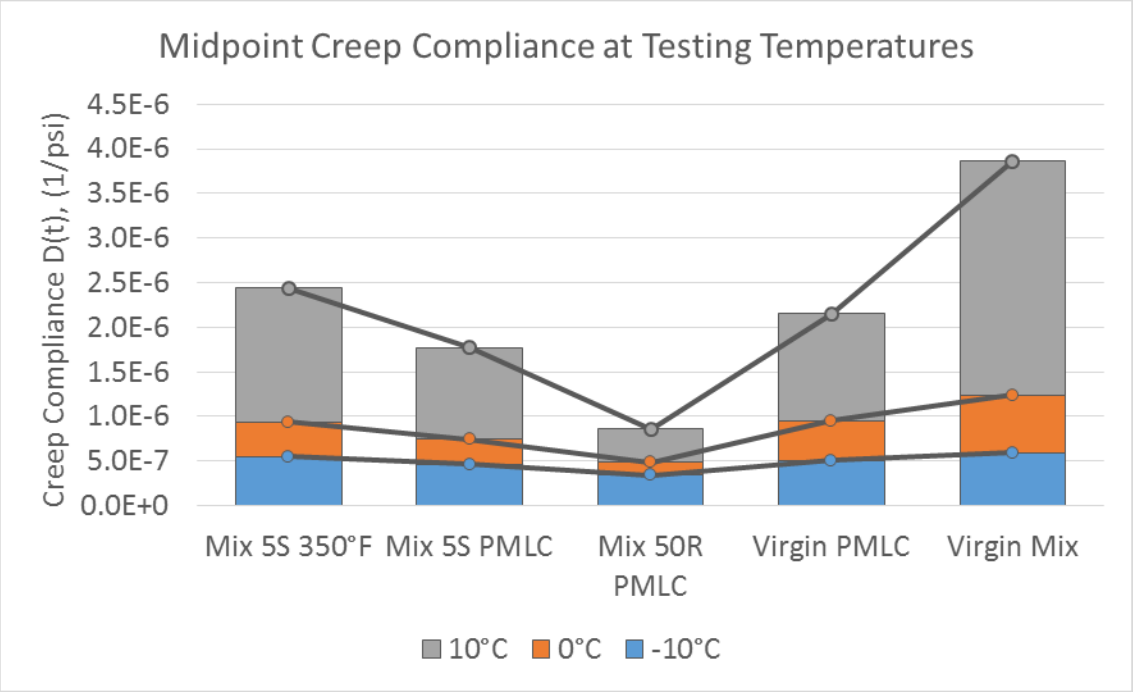


Figure 18: Group #3 Creep Compliance Midpoint Values

Little difference was observed between the tensile strengths of the mixtures, but three groupings of the mixtures were observed for the critical temperatures. The virgin mixtures and low temperature mixtures had the lowest critical temperature, and the stiffer mixtures, as shown by E* and OT results, had higher critical temperatures. The shifting in the thermal stress curves may have been caused by increased activation and blending of the shingle asphalt. Yet, there may be other factors affecting the shift in the thermal stress curves because Mixture 5A (-/5|-/-) had a higher critical temperature than the virgin mixtures.

The creep compliance values for Mixture 5S 350°F (-/5|-/16) and Mixture 16B (-/-|-/16) are somewhat lower than the other mixes in Group #1, possibly indicating activation and blending of the shingle asphalt. Increasing the mixing temperature decreased the creep compliance, which could be due to increased activation and blending of the shingle asphalt. Yet, data from NCHRP 9-39 also showed a reduction in the creep compliance results for higher mixing and compaction temperatures for virgin mixtures. The PMLC mixtures both had lower creep compliance results compared to their laboratory produced matches. This could indicate more aging during plant production.

d. Energy Ratio Findings

The Energy Ratio and related properties were determined using the software program Indirect Tension Test at Low Temperatures (ITLT) developed by the University of Florida and the Florida Department of Transportation. ITLT uses three replicate specimens for analysis and returns a single cumulative result for each property of the mixture. The cumulative results are shown in the following bar graphs. The three groups are shown by the different colored bars. Mixtures that appear in more than one group are included separately with each group.

The Dissipated Creep Strain Energy at Failure (DCSE$_f$) result for each mixture is shown in Figure 19. The data of Group #1 showed similar results for Virgin Mixture (-/-|-/-), Mixture 5S 300°F (-/5|-/16), and Mixture 16B (-/-|-/16). Mixture 5S 350°F (-/5|-/16) had a lower DCSE$_f$, which could indicate increased stiffness, and this may be caused by an increased activation and blending of the shingle asphalt. Mixture 5A (-/5|-/-) has a higher DCSE$_f$, indicating the shingle fibers may contribute to the cracking resistance of the mixture. The data from Group #2 showed a decreasing trend of DCSE$_f$ with increasing mixing temperature, and Mixture 5S PMLC (-/5|-/16) had the lowest DCSE$_f$. This indicates increased stiffness in the mixtures, which may be caused by increased activation and blending of the shingle asphalt with increasing mixing temperature, but the increased stiffness could also be due to additional aging caused by the higher temperatures. Also, more thorough mixing conditions during plant mixing may also cause increased stiffness, which could also be caused by increased activation and blending of the shingle asphalt or increased aging of the mixture. The DCSE$_f$ of the Virgin Mixture (-/-|-/-) and the Virgin PMLC (-/-|-/-) mixture in Group #3 were not similar. Virgin PMLC's DCSE$_f$ was much higher than the laboratory produced Virgin Mixture (-/-|-/-). As mentioned with Group #2, Mixture 5S PMLC (-/5|-/16) had a slightly lower DCSE$_f$ than Mixture 5S 350°F (-/5|-/16), but the results were similar.

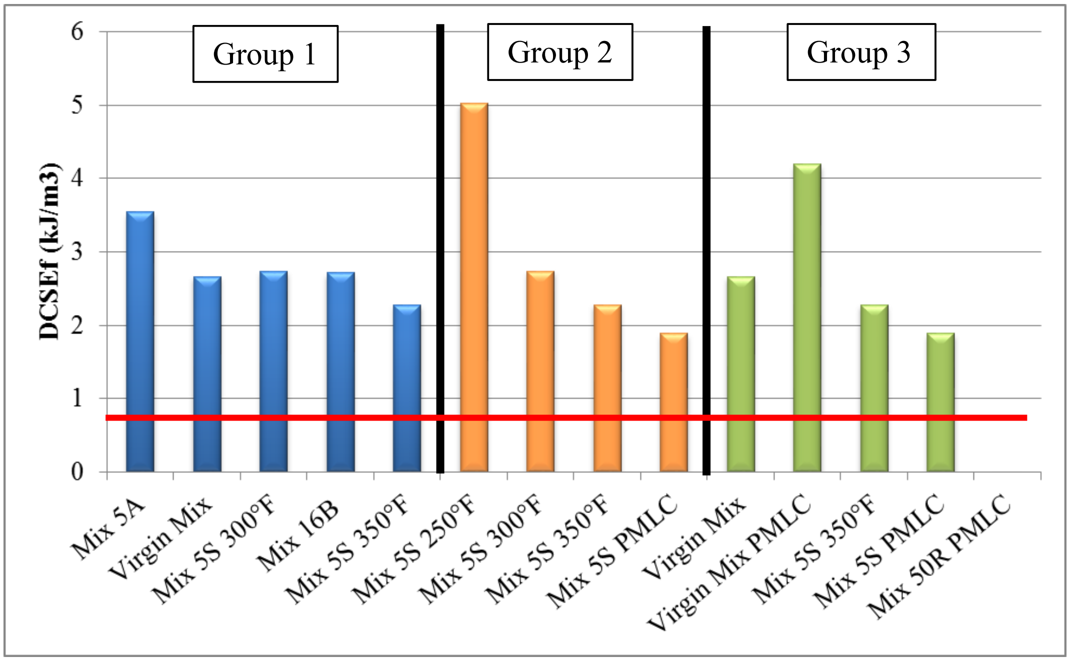


Figure 19: Dissipated Creep Strain Energy at Failure (kJ/m^3)

All the mixtures except Mixture 50R PMLC (50/-|55/-) met the criteria of DCSE$_f$ >0.75 kJ/m^3. Mixture 50R PMLC (50/-|55/-) had a negative value for DCSE$_f$. DCSE$_f$ was calculated using the resilient modulus and the Fracture Energy as shown in Figure 3(c) Indirect Tensile Strength Testing, and the Fracture Energy of Mixture 50R PMLC (50/-|55/-) was 0.0 kJ/m^3 for two of the samples and 0.1 kJ/m^3 for one of the samples tested. The Fracture Energy for the other mixtures ranged from 2.2 to 5.3 kJ/m^3. Mixture 50R PMLC (50/-|55/-) has been shown to be much stiffer than the other mixtures from the E* results (Figure 10), and IDT creep compliance results (Figure 17 and Figure 18). Figure 20 shows the difference between the strength testing's force-strain curves of Mixture 5S 250°F (-/5|-/16) and Mixture 50R PMLC (50/-|55/-). It is believed that because Mixture 50R PMLC (50/-|55/-) is incredibly stiff, the measurable fracture energy was too low or the stiffness caused an error in the testing or the analysis of this mixture.

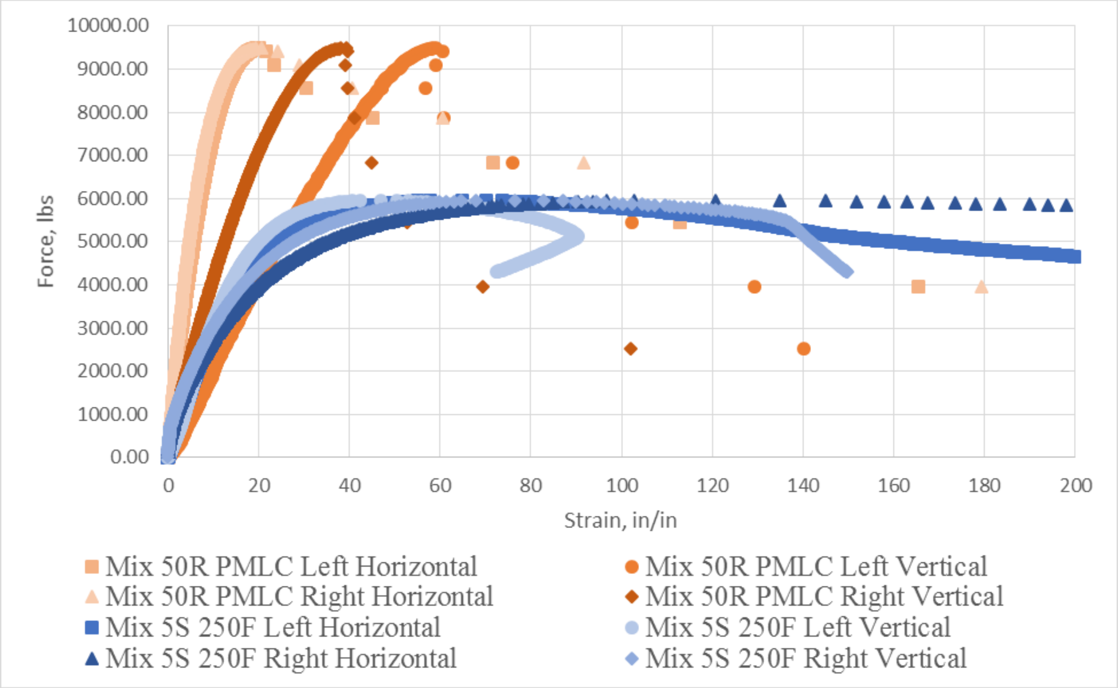


Figure 20: Comparison of Strength Testing Force-Strain Plots

The Creep Compliance Rate result for each mixture is shown in Figure 21. The results show a clear divide between the mixtures that have been shown to be stiffer (Mixture 16B (-/-|-/16), Mixture 5S 350°F (-/5|-/16), Mixture 5S PMLC (-/5|-/16), and Mixture 50R PMLC (50/-|55/-)) and the mixtures that were not significantly different from the virgin mixture (Mixture 5A (-/5|-/-), Mixture 5S 250°F (-/5|-/16), Mixture 5S 300°F (-/5|-/16), Virgin Mixture (-/-|-/-), and Virgin PMLC Mixture (-/-|-/-)). The mixtures with lower creep compliance results are likely stiffer due to increased activation and blending of the shingle asphalt, but other factors could be affecting the creep compliance results.

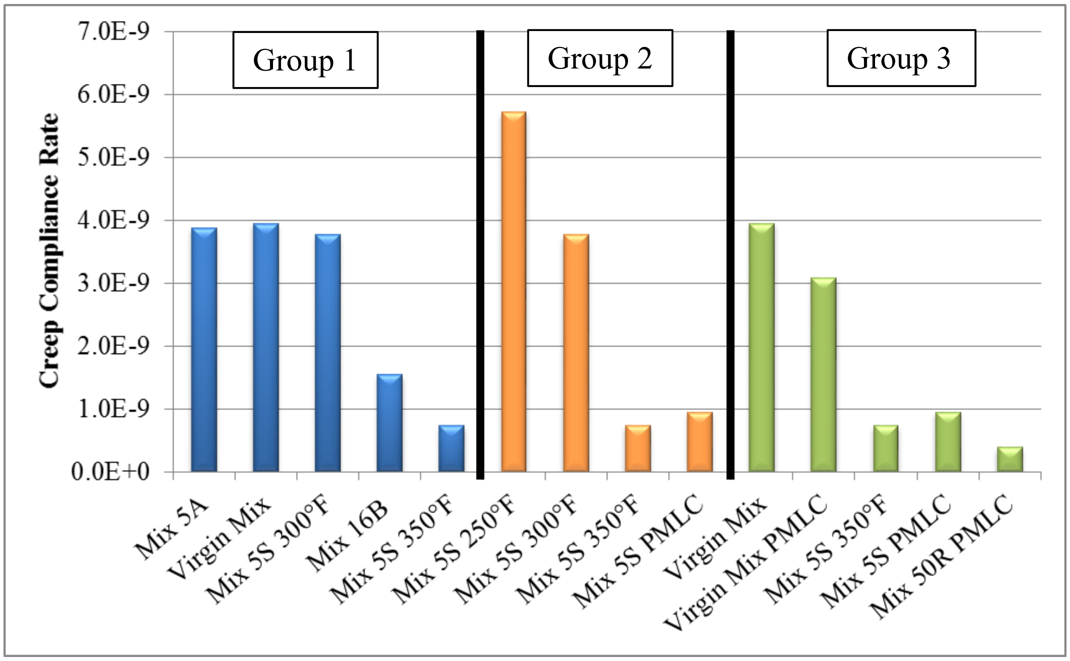


Figure 21: Creep Compliance Rate

The Energy Ratio result for each mixture is shown in Figure 22. In Group #1, Mixture 16B (-/-|-/16) and Mixture 5S 350°F (-/5|-/16) had the highest ER. This may indicate that these two mixtures will be less susceptible to top-down cracking. Mixture 5A (-/5|-/-) had a slightly higher ER than Virgin Mix (-/-|-/-) and Mixture 5S 300°F (-/5|-/16), indicating the shingle fibers may have an impact on the top-down cracking resistance of the mixture. In Group #2, Mixture 5S 250°F (-/5|-/16) and Mixture 5S 300°F (-/5|-/16) had ERs that were much lower than Mixture 5S 350°F (-/5|-/16) and Mixture 5S PMLC (-/5|-/16). This may indicate an increased top-down cracking resistance with increased mixing temperature. In Group #3, the Virgin PMLC Mixture (-/-|-/-) had a higher ER than the laboratory produced Virgin Mix (-/-|-/-). Mixture 5S 350°F (-/5|-/16) had a higher ER than Mixture 5S PMLC (-/5|-/16), but both were higher than the Virgin mixtures. Mixture 50R PMLC (50/-|55/-) had a negative Energy Ratio due to the negative DCSE$_f$ result.

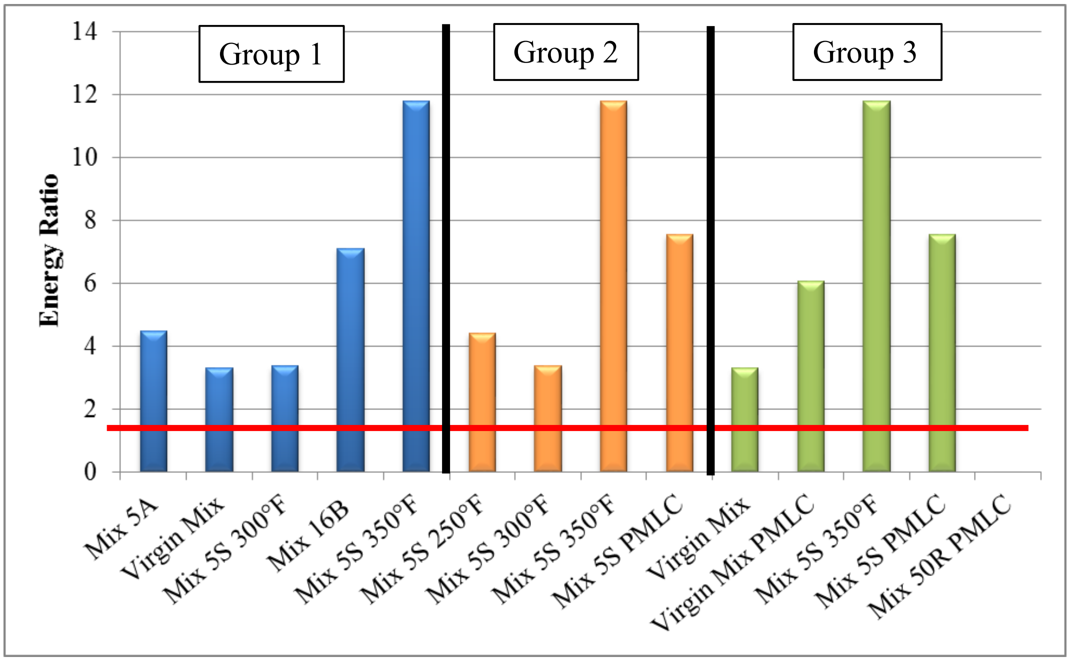


Figure 22: Energy Ratio

These results for ER are opposite from what was expected. The creep compliance rates of the stiffer mixtures were much lower than the mixtures that were not significantly different from the virgin mixture. Increased stiffness of mixtures is desired when heavier loads are considered, to prevent rutting, but flexibility is generally desired when cracking resistance is the primary concern. Although ER is meant to indicate if mixtures are prone to top-down cracking, very stiff mixtures can meet the ER criteria. The reason these very stiff mixtures resulted in such high ER values was because the $DCSE_{min}$ was a function of the creep compliance parameters and $DCSE_{min}$ was in the denominator of the ER equation. As the creep compliance decreases (stiffness/brittleness of the mixture increases) the ER increases. It is possible a specification criteria for a minimum $DCSE_{min}$ may help prevent these very high ER values from occurring.

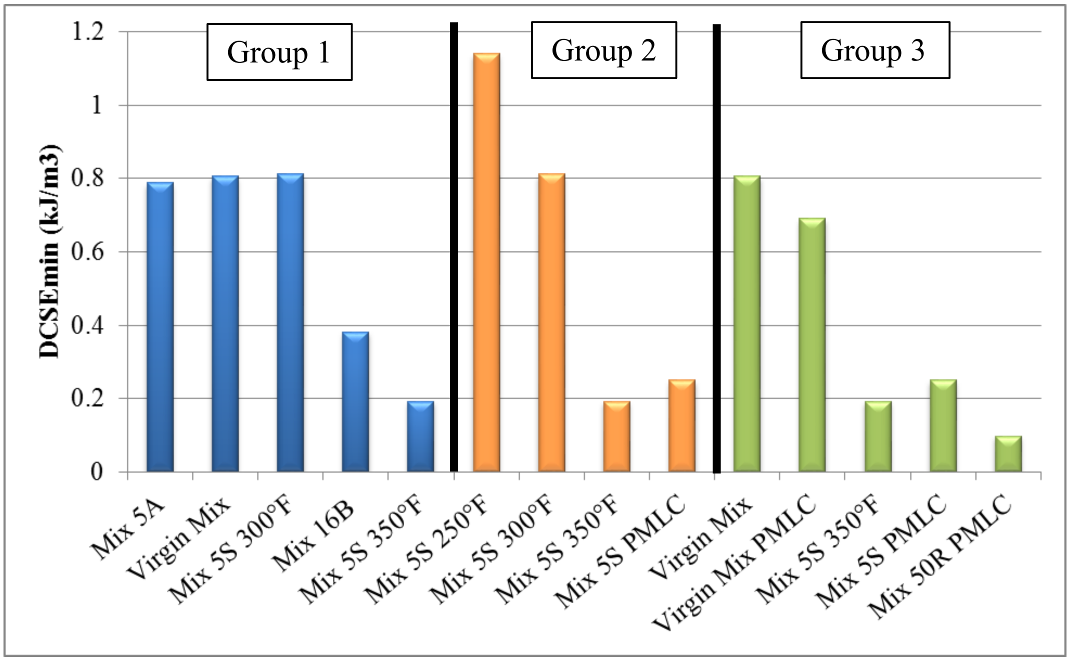


Figure 23: DCSEmin (kJ/m^3)

V. Conclusions

This thesis evaluated the activation of shingle asphalt in RAS containing asphalt mixtures. The activation of shingle asphalt was evaluated directly using clear asphalt and dry mixing experiments, and an attempt to quantify the percent activation was performed using AASHTO PP 53. The effects of the components of RAS on asphalt mixtures were evaluated by extracting the shingle asphalt and the shingle aggregate and fibers and using the components in separate mixtures. Four mixtures were developed for this evaluation:

(1) A mixture containing 5% whole RAS – Mixture 5S (-/5|-/16)

(2) A control mixture containing all virgin materials – Virgin Mixture (-/-|-/-)

(3) the control mixture with all virgin aggregates and a portion of the total binder provided by shingle asphalt – Mixture 16B (-/-|-/16)

(4) the control mixture with all virgin binder and a portion of the aggregate blend containing shingle aggregate and fibers. – Mixture 5A (-/5|-/-)

Volumetric and mixture performance properties of the above four mixes were compared as Group #1 to assess the effects of the shingle components. The effect of mixing temperature on the activation of shingle asphalt was evaluated by mixing Mixture 5S (-/5|-/16) at 250°F, 300°F, and 350°F as Group #2. Lastly, the mixture performance properties of three plant mixed lab compacted (PMLC) mixtures placed on Lee County Road 159 (LR 159) in 2012 as part of a pavement preservation study were tested and compared as Group #3. The mixture performance tests in this study included dynamic modulus, a modified version of the Texas Overlay Test, Indirect Tension Creep Compliance Test, and the Energy Ratio method.

The conclusions from these tests were:

1. **Increasing the mixing time and/or storage time of RAS containing mixture may increase the percentage of activated shingle asphalt.**

The results from the clear asphalt and dry mixing experiments demonstrated the activation of shingle asphalt occurring in RAS containing mixtures. The clear asphalt experiment demonstrated activation during mixing, and the dry mixing experiment demonstrated activation during conditioning of the mixture. Also, it is possible the virgin asphalt binder assists in the activation and blending of shingle asphalt during mixing, because little to no activation was seen during the dry mixing process.

2. **The shingle aggregates and fibers do not appear to significantly affect the cracking resistance of the mixture.**

The results from Group #1 were used to assess the contribution of the RAS components individually. The results from the mixture performance properties testing did not show any significant differences between Mixture 5A (-/5|-/-) and the Virgin Mixture (-/-|-/-). Mixture 5A (-/5|-/-) did have the highest cycles to failure on the OT, and the ER results were slightly higher than the Virgin Mixture. Yet, the cracking resistance of Mixture 5A (-/5|-/-) was not improved enough to create a statistically significant differences; therefore, the shingle aggregates and fibers did not seem to significantly benefit Mixture 5A (-/5|-/-) in cracking resistance.

3. **The shingle asphalt may increase the stiffness and lower the cracking resistance of RAS containing mixtures.**

Mixture 16B (-/-|-/16)’s testing results were generally stiffer than Mixture 5A (-/5|-/-) and Virgin Mixture (-/-|-/-), but rarely did the increased stiffness result in a statistically significant difference between the mixtures. This could indicate the shingle asphalt in Mixture 16B (-/-|-/16) was not completely activated and blended with the virgin binder. That could have been caused by the mixing temperature (325°F), the size of the shingle asphalt particles, or possibly the process of extracting the shingle asphalt. The mixture properties of Mixture 5S 350°F (-/5|-/16) were significantly stiffer than Virgin Mixture (-/-|-/-) and Mixture 16B (-/-|-/16), and Mixture 5S 350°F (-/5|-/16) mixture properties were very similar to Mixture 5S PMLC (-/5|-/16). This may have been caused by increased activation and blending of the shingle asphalt caused by the increased mixing and compaction temperature, or it may have been caused by increased aging of the virgin asphalt.

4. **Increasing mixing and compaction temperature may increase the activation and blending of shingle asphalt in RAS containing mixtures.**

Although the analysis of compaction density for Mixture 5S (-/5|-/16) mixed at several temperatures was inconclusive, the mixture performance properties testing demonstrated Mixture 5S 350°F (-/5|-/16) to be significantly stiffer than Mixture 5S 250°F (-/5|-/16) and Mixture 5S 300°F (-/5|-/16). Mixture 5S 350°F (-/5|-/16) had significantly higher E* values, significantly lower OT cycles to failure, a lower critical temperature from the IDT thermal stress curves, and a lower creep compliance from both IDT and ER testing than Mixture 5S 250°F (-/5|-/16) and Mixture 5S 300°F (-/5|-/16). The increased stiffness and reduced tolerance to strains of Mixture 5S 350°F (-/5|-/16) may have been caused by an increased percentage of stiffer shingle asphalt being activated and blended with the virgin asphalt.

The shingle asphalt in Mixture 5S 250°F (-/5|-/16) and Mixture 5S 300°F (-/5|-/16) must have contributed to the mixture in a small way because there were no changes in the mixture properties when compared to the Virgin Mixture (-/-|-/-). If no activation was occurring, the effective binder content of the mixture would be lower than the design, and this would typically cause the mixture to become less crack resistant. Therefore, the shingle asphalt might be contributing to the effective binder content in a small way even at the lower mixing and compaction temperatures. It is possible activation occurring during the short term aging of the mixture was contributing to the effective binder content, but was not adequately diffused with the virgin binder to cause significant increases in the stiffness of the mixture. Also, other factors may be affecting the design and performance of the mixture.

5. **Further aging or increased mixing temperatures may be needed to better match laboratory produced RAS containing mixtures to plant produced RAS containing mixtures.**

Comparison of the laboratory produced mixtures to their respective PMLC mixtures demonstrated the PMLC mixture to be slightly stiffer than the laboratory produced mixtures conditioned according to the short-term aging protocol in AASHTO R30. Mixture 5S 350°F (-/5|-/16) and Mixture 5S PMLC (-/5|-/16) were not significantly different for any of the mixture performance test results, but 350°F is a higher mixing temperature than would normally be used for a PG 67-22. Also, Mixture 5S 300°F (-/5|-/16) was significantly different than Mixture 5S PMLC (-/5|-/16) for all mixture performance property tests. Mixture properties of Virgin Mixture (-/-|-/-) and Virgin Mixture PMLC (-/-|-/-) were generally not significantly different.

A. Recommendations

Recycled asphalt shingles can be effectively used in asphalt mixtures to off-set a portion of the virgin binder. However, the effect RAS on the performance of the asphalt mixture must be considered. In this thesis, Mixture 5S 350°F was believed to have increased activation of the RAS asphalt, but the laboratory test results showed the mixture had increased stiffness and poor cracking resistance. In this case, a softer grade binder of virgin binder may be able to off-set the increase in the stiffness and provide better cracking resistance and a better performing mixture.

However, in cases where the RAS asphalt is not activated, such as with Mixture 5S 250°F and Mixture 5S 300°F, using a softer virgin binder may decrease the rutting resistance of the mixture and the effective binder content of the mixture could be too low to provide adequate cracking and raveling resistance.

Therefore, to ensure the activation of the shingle asphalt occurs, it is recommended that increased mixing temperatures be used for asphalt mixtures with RAS. Further evaluation of the effect of mixing temperature on similar RAS and virgin mixtures should be performed. Also, longer storage times may allow for more activation and blending/diffusion of the shingle asphalt with the virgin asphalt binder. It is also recommended that an evaluation of laboratory design practices be performed and laboratory designed mixtures be compared to plant produced mixtures.

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Appendix A: Mixture Performance Property Tests Results

Table A - 1: Dynamic Modulus Test Results

Temp (°C)	Freq. (Hz)	**Mixture 5S 250°F**			**Mixture 5S 300°F**			**Mixture 5S 350°F**		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
4	10	13274	13872	13915	12837	13130	12965	15503	15508	14811
4	1	9769	10344	10399	9763	9994	10160	12323	12485	11833
4	0.1	6595	7066	7074	6963	7159	7443	9323	9590	9000
20	10	5982	6436	6723	6834	6831	7043	8260	8480	8159
20	1	3404	3705	3895	4267	4265	4495	5477	5774	5495
20	0.1	1723	1884	1985	2407	2395	2559	3344	3604	3363
40	10	1424	1383	1449	1883	1798	1814	2603	2822	2469
40	1	596.5	577.4	612.1	874.3	828	850.2	1348	1477	1265
40	0.1	273.6	268.1	289.5	411.7	393	412.7	666.4	739.7	628.4
40	0.01	169	162.4	180.6	239.4	224	240.1	355.6	383.7	345.4

Temp (°C)	Freq. (Hz)	**Mixture 5A**			**Mixture 16B**			**Virgin Mixture**		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
4	10	15578	14488	14148	16088	16205	14588	15358	13710	13768
4	1	12254	11274	10789	12578	12776	11445	11828	10712	10663
4	0.1	8873	8103	7574	9252	9507	8480	8452	7791	7667
20	10	7942	7259	6869	8453	8427	7207	7863	6924	6887
20	1	4936	4455	4150	5467	5482	4604	4848	4330	4276
20	0.1	2746	2429	2246	3315	3300	2695	2677	2431	2371
40	10	2021	1808	1714	2354	2357	2106	2127	2044	1911
40	1	914.5	804.9	746.6	1156	1171	1013	964.7	892.4	840.6
40	0.1	409	363.9	334.5	553.2	572.9	490.2	436.7	366.8	381.8
40	0.01	218.5	204.8	191.5	306.4	319.5	283.5	234.4	166.2	215.1

Temp (°C)	Freq. (Hz)	**Mixture 5S PMLC**			**Virgin PMLC**			**Mixture 50R PMLC**		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
4	10	16547	17401	14375	14624	13048	14329	22229	23694	20792
4	1	13429	14089	11775	11140	9877	10727	19026	20379	17985
4	0.1	10342	10818	9171	7831	6855	7425	15805	16895	15065
20	10	9246	9472	7929	7982	6674	7877	15821	16724	14808
20	1	6256	6354	5398	4889	3928	4760	12361	12939	11660
20	0.1	3859	3890	3317	2620	2003	2477	8984	9252	8517
40	10	3201	2917	2953	1381	1066	1167	5178	5612	5314
40	1	1647	1456	1539	553.8	400.2	447.4	2966	3190	3063
40	0.1	809.2	689.4	765.2	261.8	191.1	210.5	1591	1706	1632
40	0.01	416.7	360.6	405.3	170.4	133.4	140.6	937.7	965.2	890.3

Table A - 2: Overlay Test Results

Mix ID	Air Voids (%)	Width (mm)	Height (mm)	Maximum Displacement (mm)	Peak Load (lb)	Normalized Load x Cycles	93% Load Reduction
Mixture 5S 250°F	7.4%	79.57	39.29	0.381	606	8452	10492
Mixture 5S 250°F	7.1%	78.23	39.14	0.381	618	5496	6808
Mixture 5S 250°F	6.6%	78.25	38.63	0.381	636	9180	11820
Mixture 5S 250°F	6.5%	78.84	39.03	0.381	651	6084	8380
Mixture 5S 300°F	7.0%	78.65	38.05	0.381	697	6772	9564
Mixture 5S 300°F	6.8%	77.98	39.20	0.381	735	9740	14524
Mixture 5S 300°F	6.7%	77.37	39.10	0.381	697	6652	8980
Mixture 5S 350°F	6.4%	78.64	38.97	0.381	752	2202	3310
Mixture 5S 350°F	6.5%	78.49	38.40	0.381	747	1194	2258
Mixture 5S 350°F	6.9%	78.92	38.61	0.381	767	2604	3988
Mixture 5S 350°F	6.9%	79.53	38.04	0.381	726	1546	2498
Mixture 5S PMLC	7.1%	80.46	41.49	0.381	774	3820	5828
Mixture 5S PMLC	7.0%	79.59	38.41	0.381	781	169	465
Mixture 5S PMLC	7.0%	79.80	40.87	0.381	785	504	821
Mixture 16B	6.9%	77.46	38.79	0.381	747	4632	6708
Mixture 16B	6.9%	77.13	39.09	0.381	730	5192	6640
Mixture 16B	6.8%	74.96	39.85	0.381	716	6380	10060
Mixture 16B	6.7%	74.84	38.40	0.381	723	4208	5180
Mixture 5A	6.8%	78.05	39.82	0.381	692	8524	10140
Mixture 5A	6.5%	77.72	39.47	0.381	672	8412	10588
Mixture 5A	7.0%	77.49	38.77	0.381	688	10356	15524
Mixture 5A	7.1%	77.20	39.07	0.381	661	6740	8532
Virgin Mixture	7.0%	76.75	39.15	0.381	702	5676	6636
Virgin Mixture	7.1%	75.78	38.24	0.381	702	6076	7296
Virgin Mixture	6.8%	76.81	38.96	0.381	703	5676	7956
Virgin Mixture	6.8%	76.51	39.17	0.381	705	7932	9796
Virgin PMLC	7.2%	76.40	37.61	0.381	679	8012	9860
Virgin PMLC	6.9%	76.93	39.32	0.381	715	9188	11700
Virgin PMLC	7.0%	76.75	40.19	0.381	723	9188	11020
Virgin PMLC	7.0%	77.53	38.23	0.381	712	11988	14572
Mixture 50R PMLC	6.8%	76.81	38.90	0.381	802	99	165
Mixture 50R PMLC	6.8%	77.53	39.41	0.381	801	221	634
Mixture 50R PMLC	6.6%	78.12	38.27	0.381	789	96	153

Table A - 3: IDT Test Results

Mix 5S 250°F			Mix 5S 300°F			Mix 5S 350°F		
Tr	D(t)	m-value	Tr	D(t)	m-value	Tr	D(t)	m-value
1.0E+1	5.0E-7	0.168	1.0E+1	5.5E-7	0.134	1.0E+1	4.7E-7	0.133
1.3E+1	5.2E-7	0.165	1.3E+1	5.6E-7	0.137	1.3E+1	4.9E-7	0.141
1.6E+1	5.3E-7	0.163	1.6E+1	5.9E-7	0.140	1.6E+1	5.0E-7	0.146
2.0E+1	5.5E-7	0.161	2.0E+1	6.0E-7	0.142	2.0E+1	5.2E-7	0.153
2.5E+1	5.7E-7	0.159	2.5E+1	6.2E-7	0.145	2.5E+1	5.3E-7	0.159
3.2E+1	6.0E-7	0.157	3.2E+1	6.5E-7	0.148	3.2E+1	5.6E-7	0.166
4.0E+1	6.1E-7	0.154	4.0E+1	6.7E-7	0.151	4.0E+1	5.8E-7	0.172
5.0E+1	6.4E-7	0.152	5.0E+1	7.0E-7	0.154	5.0E+1	6.1E-7	0.178
6.3E+1	6.6E-7	0.150	6.3E+1	7.2E-7	0.157	6.3E+1	6.3E-7	0.185
7.9E+1	6.9E-7	0.148	7.9E+1	7.4E-7	0.159	7.9E+1	6.6E-7	0.191
1.0E+2	6.9E-7	0.145	1.0E+2	7.4E-7	0.162	1.0E+2	6.7E-7	0.197
2.6E+2	9.6E-7	0.243	2.6E+2	7.8E-7	0.275	2.1E+2	6.8E-7	0.178
3.4E+2	1.0E-6	0.252	3.4E+2	8.5E-7	0.271	2.8E+2	7.1E-7	0.183
4.2E+2	1.1E-6	0.258	4.1E+2	8.8E-7	0.268	3.4E+2	7.5E-7	0.187
5.2E+2	1.1E-6	0.266	5.2E+2	9.4E-7	0.265	4.3E+2	7.8E-7	0.192
6.6E+2	1.2E-6	0.273	6.5E+2	1.0E-6	0.262	5.4E+2	8.1E-7	0.196
8.4E+2	1.3E-6	0.281	8.3E+2	1.1E-6	0.259	6.9E+2	8.5E-7	0.201
1.0E+3	1.4E-6	0.288	1.0E+3	1.1E-6	0.256	8.6E+2	8.8E-7	0.206
1.3E+3	1.5E-6	0.295	1.3E+3	1.2E-6	0.253	1.1E+3	9.3E-7	0.210
1.7E+3	1.6E-6	0.303	1.6E+3	1.3E-6	0.250	1.4E+3	9.8E-7	0.215
2.1E+3	1.7E-6	0.310	2.0E+3	1.3E-6	0.247	1.7E+3	1.0E-6	0.219
2.6E+3	1.8E-6	0.317	2.6E+3	1.4E-6	0.244	2.1E+3	1.1E-6	0.224
6.9E+3	2.5E-6	0.378	6.7E+3	2.0E-6	0.342	4.6E+3	1.4E-6	0.261
8.9E+3	2.8E-6	0.387	8.7E+3	2.2E-6	0.347	6.0E+3	1.5E-6	0.269
1.1E+4	3.0E-6	0.394	1.1E+4	2.3E-6	0.352	7.4E+3	1.6E-6	0.276
1.4E+4	3.3E-6	0.402	1.3E+4	2.5E-6	0.356	9.2E+3	1.7E-6	0.283
1.7E+4	3.6E-6	0.410	1.7E+4	2.7E-6	0.361	1.1E+4	1.8E-6	0.290
2.2E+4	4.0E-6	0.418	2.2E+4	3.0E-6	0.367	1.5E+4	1.9E-6	0.298
2.8E+4	4.4E-6	0.426	2.7E+4	3.2E-6	0.371	1.8E+4	2.1E-6	0.305
3.4E+4	4.8E-6	0.434	3.4E+4	3.5E-6	0.376	2.3E+4	2.2E-6	0.312
4.3E+4	5.3E-6	0.442	4.2E+4	3.8E-6	0.381	2.9E+4	2.4E-6	0.320
5.4E+4	5.9E-6	0.450	5.3E+4	4.2E-6	0.386	3.6E+4	2.6E-6	0.327
6.9E+4	6.4E-6	0.458	6.7E+4	4.4E-6	0.391	4.6E+4	2.7E-6	0.334

Table A - 4: IDT Test Results

Mix 5A			Mix 16B			Virgin Mix		
Tr	D(t)	m-value	Tr	D(t)	m-value	Tr	D(t)	m-value
1.0E+1	3.9E-7	0.181	1.0E+1	4.6E-7	0.105	1.0E+1	5.1E-7	0.119
1.3E+1	4.1E-7	0.187	1.3E+1	4.7E-7	0.111	1.3E+1	5.3E-7	0.122
1.6E+1	4.3E-7	0.192	1.6E+1	4.9E-7	0.115	1.6E+1	5.4E-7	0.124
2.0E+1	4.5E-7	0.198	2.0E+1	5.0E-7	0.120	2.0E+1	5.5E-7	0.126
2.5E+1	4.7E-7	0.203	2.5E+1	5.2E-7	0.125	2.5E+1	5.7E-7	0.128
3.2E+1	4.9E-7	0.209	3.2E+1	5.3E-7	0.130	3.2E+1	5.9E-7	0.130
4.0E+1	5.1E-7	0.214	4.0E+1	5.5E-7	0.135	4.0E+1	6.1E-7	0.133
5.0E+1	5.4E-7	0.220	5.0E+1	5.7E-7	0.140	5.0E+1	6.3E-7	0.135
6.3E+1	5.7E-7	0.226	6.3E+1	5.8E-7	0.145	6.3E+1	6.4E-7	0.137
7.9E+1	6.0E-7	0.231	7.9E+1	6.0E-7	0.149	7.9E+1	6.7E-7	0.139
1.0E+2	6.2E-7	0.237	1.0E+2	6.0E-7	0.154	1.0E+2	6.8E-7	0.141
3.1E+2	8.6E-7	0.205	2.9E+2	8.5E-7	0.175	2.6E+2	9.1E-7	0.235
4.0E+2	9.1E-7	0.214	3.7E+2	8.8E-7	0.181	3.4E+2	9.7E-7	0.239
4.9E+2	9.6E-7	0.221	4.6E+2	9.2E-7	0.186	4.1E+2	1.0E-6	0.241
6.1E+2	1.0E-6	0.228	5.7E+2	9.6E-7	0.191	5.2E+2	1.1E-6	0.244
7.7E+2	1.1E-6	0.236	7.1E+2	1.0E-6	0.197	6.5E+2	1.1E-6	0.247
9.8E+2	1.1E-6	0.244	9.1E+2	1.1E-6	0.203	8.3E+2	1.2E-6	0.250
1.2E+3	1.2E-6	0.252	1.1E+3	1.1E-6	0.208	1.0E+3	1.3E-6	0.253
1.5E+3	1.3E-6	0.259	1.4E+3	1.2E-6	0.213	1.3E+3	1.3E-6	0.256
1.9E+3	1.3E-6	0.267	1.8E+3	1.2E-6	0.219	1.6E+3	1.4E-6	0.259
2.4E+3	1.4E-6	0.275	2.3E+3	1.3E-6	0.224	2.0E+3	1.5E-6	0.262
3.1E+3	1.5E-6	0.283	2.9E+3	1.3E-6	0.230	2.6E+3	1.6E-6	0.265
9.4E+3	2.2E-6	0.336	8.1E+3	1.7E-6	0.301	6.7E+3	2.2E-6	0.321
1.2E+4	2.4E-6	0.348	1.1E+4	1.8E-6	0.309	8.7E+3	2.4E-6	0.339
1.5E+4	2.6E-6	0.357	1.3E+4	2.0E-6	0.314	1.1E+4	2.5E-6	0.352
1.9E+4	2.8E-6	0.368	1.6E+4	2.1E-6	0.321	1.3E+4	2.8E-6	0.367
2.3E+4	3.1E-6	0.378	2.0E+4	2.3E-6	0.327	1.7E+4	3.0E-6	0.382
3.0E+4	3.3E-6	0.389	2.6E+4	2.5E-6	0.334	2.1E+4	3.3E-6	0.398
3.7E+4	3.7E-6	0.399	3.2E+4	2.7E-6	0.340	2.7E+4	3.6E-6	0.413
4.7E+4	4.0E-6	0.410	4.1E+4	2.9E-6	0.346	3.3E+4	4.0E-6	0.428
5.9E+4	4.4E-6	0.420	5.1E+4	3.1E-6	0.353	4.2E+4	4.4E-6	0.443
7.4E+4	4.8E-6	0.430	6.4E+4	3.4E-6	0.359	5.3E+4	4.8E-6	0.458
9.4E+4	5.2E-6	0.441	8.1E+4	3.6E-6	0.366	6.7E+4	5.2E-6	0.474

Table A - 5: IDT Test Results

Mix 5S PMLC			Mix 50R PMLC			Virgin PMLC		
Tr	D(t)	m-value	Tr	D(t)	m-value	Tr	D(t)	m-value
1.0E+1	4.3E-7	0.068	3.2E-1	2.8E-7	0.034	2.0E-1	3.1E-7	0.080
1.3E+1	4.4E-7	0.069	4.1E-1	2.8E-7	0.035	2.6E-1	3.1E-7	0.074
1.6E+1	4.4E-7	0.071	5.1E-1	2.8E-7	0.035	3.2E-1	3.2E-7	0.070
2.0E+1	4.5E-7	0.072	6.4E-1	2.8E-7	0.036	3.9E-1	3.2E-7	0.065
2.5E+1	4.6E-7	0.073	8.0E-1	2.9E-7	0.037	4.9E-1	3.2E-7	0.061
3.2E+1	4.6E-7	0.075	1.0E+0	2.9E-7	0.037	6.3E-1	3.3E-7	0.056
4.0E+1	4.7E-7	0.076	1.3E+0	2.9E-7	0.038	7.9E-1	3.4E-7	0.051
5.0E+1	4.8E-7	0.077	1.6E+0	3.0E-7	0.038	9.9E-1	3.4E-7	0.047
6.3E+1	4.9E-7	0.079	2.0E+0	3.0E-7	0.039	1.2E+0	3.5E-7	0.042
7.9E+1	5.0E-7	0.080	2.5E+0	3.0E-7	0.040	1.6E+0	3.5E-7	0.037
1.0E+2	4.9E-7	0.081	3.2E+0	3.0E-7	0.040	2.0E+0	3.5E-7	0.032
2.6E+2	5.9E-7	0.153	1.0E+1	3.2E-7	0.079	1.0E+1	4.4E-7	0.119
3.4E+2	6.1E-7	0.164	1.3E+1	3.2E-7	0.079	1.3E+1	4.5E-7	0.125
4.1E+2	6.4E-7	0.172	1.6E+1	3.3E-7	0.078	1.6E+1	4.6E-7	0.130
5.2E+2	6.7E-7	0.181	2.0E+1	3.3E-7	0.078	2.0E+1	4.8E-7	0.135
6.5E+2	7.0E-7	0.191	2.5E+1	3.3E-7	0.078	2.5E+1	4.9E-7	0.139
8.3E+2	7.2E-7	0.201	3.2E+1	3.5E-7	0.077	3.2E+1	5.1E-7	0.145
1.0E+3	7.6E-7	0.210	4.0E+1	3.5E-7	0.077	4.0E+1	5.3E-7	0.150
1.3E+3	8.0E-7	0.219	5.0E+1	3.5E-7	0.077	5.0E+1	5.5E-7	0.155
1.6E+3	8.4E-7	0.229	6.3E+1	3.6E-7	0.076	6.3E+1	5.7E-7	0.160
2.0E+3	8.8E-7	0.238	7.9E+1	3.7E-7	0.076	7.9E+1	5.9E-7	0.165
2.6E+3	9.2E-7	0.248	1.0E+2	3.7E-7	0.076	1.0E+2	6.1E-7	0.170
6.7E+3	1.2E-6	0.231	3.1E+2	4.3E-7	0.096	5.1E+2	8.0E-7	0.243
8.7E+3	1.2E-6	0.246	4.1E+2	4.4E-7	0.103	6.6E+2	8.8E-7	0.243
1.1E+4	1.3E-6	0.257	5.0E+2	4.4E-7	0.109	8.1E+2	8.9E-7	0.243
1.3E+4	1.4E-6	0.269	6.3E+2	4.5E-7	0.115	1.0E+3	9.5E-7	0.243
1.7E+4	1.5E-6	0.281	7.8E+2	4.7E-7	0.121	1.3E+3	1.0E-6	0.244
2.1E+4	1.6E-6	0.295	1.0E+3	4.9E-7	0.128	1.6E+3	1.1E-6	0.244
2.7E+4	1.7E-6	0.307	1.3E+3	5.0E-7	0.134	2.0E+3	1.1E-6	0.244
3.4E+4	1.8E-6	0.319	1.6E+3	5.1E-7	0.140	2.5E+3	1.2E-6	0.244
4.2E+4	1.9E-6	0.332	2.0E+3	5.3E-7	0.147	3.2E+3	1.3E-6	0.245
5.3E+4	2.1E-6	0.344	2.5E+3	5.5E-7	0.153	4.0E+3	1.3E-6	0.245
6.7E+4	2.2E-6	0.357	3.1E+3	5.7E-7	0.159	5.1E+3	1.3E-6	0.245

Table A - 6: Energy Ratio Results

Mix ID	Mix 5S 250°F	Mix 5S 300°F	Mix 5S 350°F	Mix 5S PMLC
m-value	0.45	0.42	0.27	0.33
D1	5.8E-7	5.2E-7	4.2E-7	2.9E-7
St (MPa)	2.42	2.47	2.89	3.01
MR (GPa)	10.77	11.57	13.00	14.45
FE (kJ/m3)	5.30	3.00	2.60	2.20
DCSEf (kJ/m3)	5.03	2.74	2.28	1.89
Stress (psi)	150	150	150	150
a	4.7E-8	4.6E-8	4.4E-8	4.3E-8
DCSEMIN (kJ/m3)	1.140	0.812	0.193	0.249
ER	4.41	3.37	11.80	7.56
Compliance Rate	5.7E-9	3.8E-9	7.3E-10	9.5E-10

Table A - 7: Energy Ratio Results

Mix ID	Mix 16B	Mix 5A	Virgin Mix	Virgin Mix PMLC	Mix 50R PMLC
m-value	0.34	0.44	0.43	0.42	0.29
D1	4.2E-7	4.1E-7	4.5E-7	4.1E-7	1.7E-7
St (MPa)	2.63	2.54	2.39	2.81	2.46
MR (GPa)	12.21	12.55	11.98	12.80	18.28
FE (kJ/m3)	3.00	3.80	2.90	4.50	0.00
DCSEf (kJ/m3)	2.72	3.54	2.66	4.19	-0.17
Stress (psi)	150	150	150	150	150
a	4.5E-8	4.6E-8	4.7E-8	4.4E-8	4.6E-8
DCSEMIN (kJ/m3)	0.382	0.788	0.806	0.690	0.097
ER	7.11	4.49	3.30	6.07	-1.71
Compliance Rate	1.5E-9	3.9E-9	4.0E-9	3.1E-9	3.9E-10