Asphalt mixture performance and testing

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

Fabricio Leiva[1], Randy West[1], David Farris[2]
[1]NCAT - Auburn University, [2]Bituminous Roadways, Inc.

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. This could result in under-asphalted mixtures; also, 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. In this study, the activation of shingle asphalt was investigated and estimated using several different methods. The first investigation involved mixing aggregate and RAS without any additional asphalt. The second approach evaluated laboratory prepared mixtures containing 5% RAS at mixing and compaction temperatures ranging from 250°F to 350°F. A third method involved laboratory performance tests to evaluate the effect of mixing and compaction temperatures on mixture properties and provide an indication of the degree of RAS binder activation. The results of this study indicated that shingle asphalt might increase the stiffness and lower the cracking resistance of mixtures containing RAS. In addition, increasing the mixing temperature increases the stiffness of the mixtures. This increased stiffness may be caused by increased activation of shingle asphalt, 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 mixtures containing RAS may be needed to better match plant-produced properties.

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1. 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 fine aggregate material. In 2003, 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 [1]. 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 ton of manufacturer's waste shingles [2]. 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 [2]. 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 [3-6].

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, and 8 of these 11 states allowed only the use of manufacturer's waste RAS (MWRAS) [7]. By 2013, 23 state highway agencies had adopted specifications for routine use, 10 of which allowed either post-consumer RAS (PCRAS) or MWRAS [8]. 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 [9].

Asphalt used in the manufacture of shingles is commonly air-blown to significantly increase the asphalt's viscosity. PCRAS shingles, which are removed from roofs, are further oxidized from years of direct ultra-violet radiation. If the shingle asphalt is not completely activated and blended when RAS is used in an asphalt mixture, the mixture will have a low total asphalt content. This can potentially lead to difficulties in placement and compaction, and ultimately, an increase in susceptibility to cracking and raveling. Also, under-estimating the amount of activation and blending of the shingle asphalt or not compensating for the higher stiffness of the shingle asphalt can increase the paving mixture's stiffness beyond its ability to relax strains. If not used properly, potential savings gained by using recycled shingles can be quickly negated by a decrease in pavement life.

2. OBJECTIVE AND SCOPE

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. To meet the above objective, several laboratory experiments were conducted using asphalt mixtures containing 5% RAS by weight of total aggregate blend. The first method involved mixing aggregate and RAS without any additional asphalt. The second approach evaluated the activation of shingle asphalt by mixing and compacting a 5% RAS mixture at temperatures ranging from 250°F to 350°F. Mixture performance testing was conducted to assess the effect of the shingle components on the performance properties of the mixtures prepared at the different temperatures. Dynamic modulus, Texas Overlay, IDT Creep Compliance and Strength, and energy ratio testing were used to gain a better understanding of the effect of mixing temperature on the activation of shingle asphalt and the effect each shingle component had on laboratory performance (the experiment included separating the RAS binder from the granules and fiber).

3. MIXTURE DESIGNS

Four laboratory produced mixtures were design in this study as shown in Table 1. The first two replicated a 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 on Lee Road 159 as closely as possible. The remaining two mixtures were designed to include 5% and 16% RAS.

All mixtures were designed according to AASHTO M323-13 and AASHTO R35 for 3-10 million ESALs and an Ndesign 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 2 shows the volumetric properties of each mixture determined during the design phase. Mixture 5A has 5% shingle aggregates and fiber but no shingle asphalt in the mixture. Mixture 16B has only 16% recycled shingle asphalt.

The Gsb of the RAS was determined according to AASHTO PP53-09, which recommends determining the Gse of RAS using AASHTO T209. AASHTO PP53-09 notes that shingle granules are not very absorptive, and therefore, Gsb and

Gse 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. 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.

Table 1. Aggregate Gradations of Mixtures

Sieve Size (mm)	Virgin	Mixture 5S	Mixture 5A	Mixture 16B
9.5	100.0	100.0	100.0	100.0
4.75	97.4	97.7	97.7	97.7
2.36	74.7	77.6	77.6	76.6
1.18	50.6	54.7	54.7	53.2
0.6	32.5	35.5	35.5	34.2
0.3	18.8	20.9	20.9	19.4
0.15	12.1	13.8	13.8	12.4
0.075	8.7	10.0	10.0	9.0
Limestone	74%	63%	63%	66%
Sand	25%	30%	30%	32%
Hydrated Lime	1%	1%	1%	1.1%
Bag House Fines	0%	1%	1%	1,1%
RAS	0%	5%	5%	16%

Table 2. Design Volumetric Properties of 4.75 mm Mixtures

Property	Superpave Criteria	Mixture 5S	Mixture 5A	Virgin	Mixture 16B
Pb	-	6.3	6.2	6.4	6.4
Va	4.0 - 6.0	4.1	4.0	4.7	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

4. QUANTIFYING 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 during mixing 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 examined by mixing aggregate and RAS without any additional asphalt. The hypothesis was that the RAS particles would break due to mixing and the RAS asphalt would soften as heat transferred to the particles. As the RAS binder heated up, it 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 were transfer of asphalt from the shingles to aggregate particles (evident by discolored aggregates) and agglomeration of non-shingle particles and shingle particles.

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 examine the effect of mixing temperature on the activation of shingle asphalt and the effect each shingle component had on the mixture's laboratory performance. Table 3 shows the grouping of mixtures used in this study to conduct analysis of mixture properties.

Table 3. Grouping of Mixtures for Analysis of Mixture Properties

Mixtures	Group #1: Shingle Components	Group #2: Mixing Temperature
Mixture 5S mixed at 250°F		X
Mixture 5S mixed at 300°F	X	X
Mixture 5S mixed at 350°F	X	X
Virgin	X	
Mixture 5A	X	
Mixture 16B	X	
Mixture 5S Plant Produced		X

The laboratory-produced mixtures were short-term aged for mechanical property testing for four hours according AASHTO R30-02: 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 two years old at the time of testing and a preliminary comparison of laboratory results and field evaluation was desired.

The two 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 a change in the stiffness and cracking resistance 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 and compare those results to the plant-produced lab compacted (PMLC) Mixture 5S. The hypothesis for Group #2 was that increasing the mixing temperature would change the stiffness and cracking resistance of the mixture. The change in stiffness and cracking resistance could be caused by increased activation and blending of the shingle asphalt at the higher temperatures, or it could also be caused by increased aging from the higher temperatures.

4.1. Mixing aggregate and RAS without any additional asphalt

The first activation experiment consisted of mixing a 5% RAS mixture at 300 °F without any virgin binder. 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 1 (a), there was little to no asphalt coating any of the aggregate and intact shingle pieces were evident and coated with fine aggregate. Figure 1 (b) shows the larger particles of the mixture after being washed according to AASHTO T11: 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 sample was mixed in the same manner and then placed in an oven for two hours at 275°F to simulate aging according to AASHTO R30. 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 single asphalt was activated enough to absorb the fine aggregates, as shown in Figure 1 (c). The change in color was more notable in the fine aggregates, as shown in Figure 2 (a) and (b). This change in color during the conditioning process indicates the occurrence of activation after mixing and during storage time of mixtures.

(a) (b) (c)

Figure 1. 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 2. Dry Mixing of Aggregates and RAS (a) Passing ASTM #16 Aggregates after Dry Mixing (b) Passing ASTM #16 Aggregates after Dry Mixing and Aging

4.2. Analysis of the Effect of Temperature on the Activation of Shingle Asphalt

The Gmb results from mixing Mixture 5S at six different temperatures are shown in Figure 3. The plot shows a trend of increasing Gmb with higher mixing temperatures, which could have been caused by either increasing activation and blending of the shingle asphalt or from better compactability due to a lower viscosity of the asphalt at higher temperatures. An analysis of variance (ANOVA) showed that temperature had a high influence on the compaction of these specimens ($p=0.0001$).

The data was further analysed using the Tukey method of grouping with a 95% confidence interval. The results shown in Figure 3 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 could indicate different levels of activation of the RAS asphalt with little to no activation at the lowest temperature, minor activation at the mid-range temperatures, and more complete activation at the highest temperature.

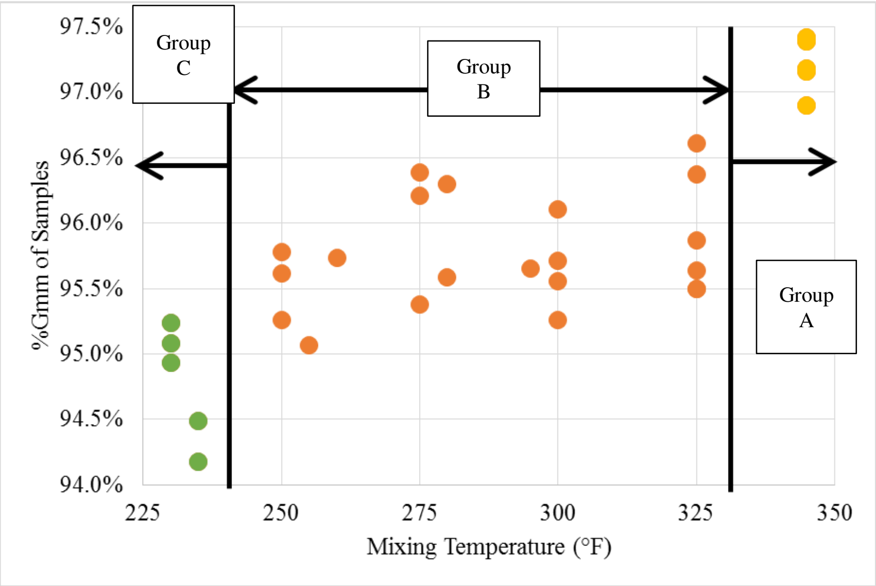


Figure 3. Compaction Results from Increasing Mixing Temperatures for Mixture 5S

5. Analysis of Mixture Performance Testing

5.1. Dynamic Modulus (E*)

Figure 4 shows the E* master curves for the mixtures in Group #1. The analysis of these results showed that the E* values for the Virgin Mixture, Mixture 5A, and Mixture 5S 300°F were not statistically different at any temperature or loading frequency. Therefore, this indicates that the RAS binder in Mixture 5S 300°F was not sufficiently activated to affect the mixture stiffness. However, Mixture 5S 350°F and Mixture 16B had significantly higher E* values compared to Virgin Mixture and Mixture 5A at the higher temperatures/lower frequencies. Therefore, the increased stiffness in Mixture 5S 350°F and Mixture 16B indicate activation and blending of the shingle asphalt with the virgin binder. This is consistent with conclusions from other studies, which found that increasing the blend percentage of shingle asphalt increasingly stiffens the composite binder [10-12].

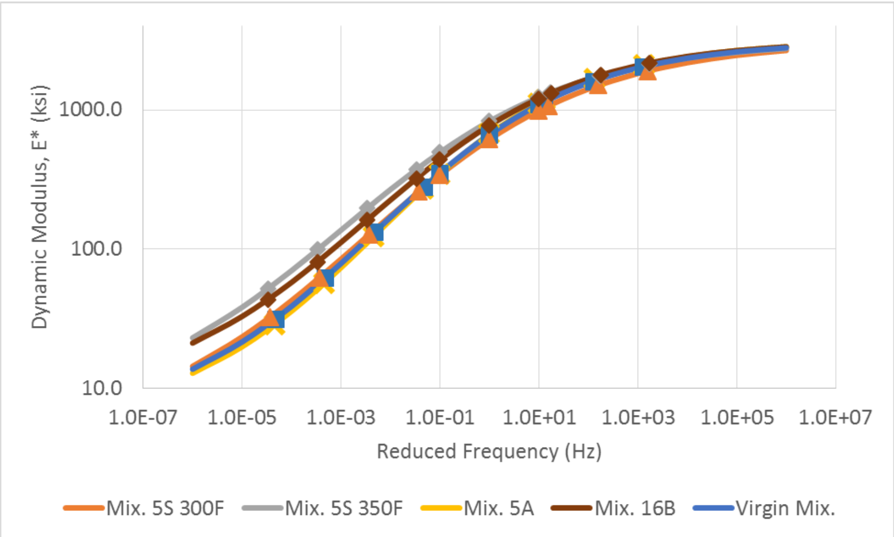


Figure 4. RAS Component Effects on Dynamic Modulus

Figure 5 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 stiffening/aging of the asphalt caused by the increased mixing and compaction temperatures. It should also be noted that in Group #1, Mixture 5S 300°F was not significantly different from the Virgin Mixture. Mixture 5S PMLC (produced at 325°F) and Mixture 5S 350°F were not significantly different except at the highest temperature and 10 Hz frequency. This may indicate that a higher mixing temperature is needed for laboratory-produced mixtures to simulate the conditions of plant-produced mixtures.

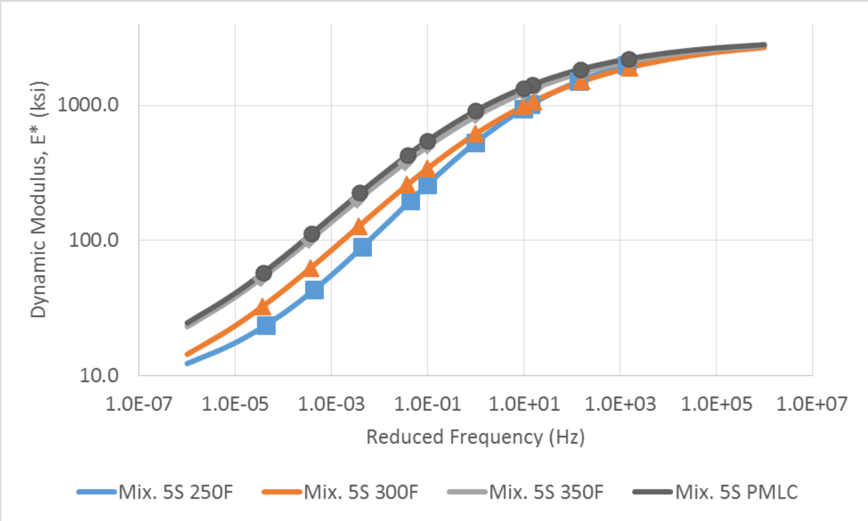


Figure 5. Temperature Effects on the Dynamic Modulus of Mixtures Containing RAS

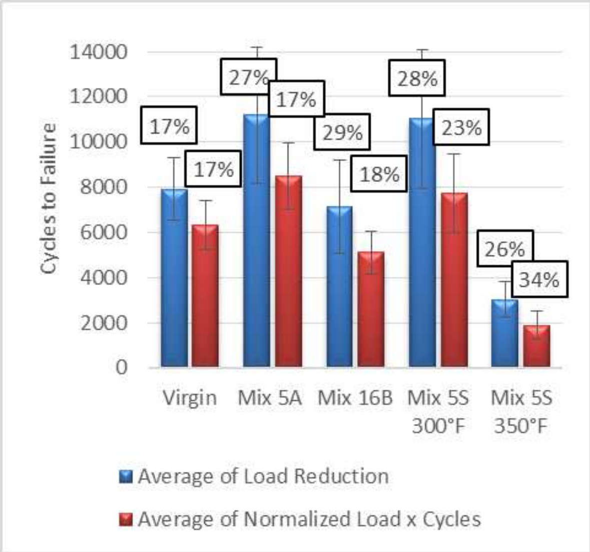
The dynamic modulus test results indicated an increased stiffness in Mixture 5S 350°F and Mixture 16B, which may indicate an increased activation and blending of the shingle asphalt in those mixtures. Conversely, Mixture 5A, Virgin Mixture, and Mixture 5S 300°F were not significantly different, indicating no significant activation of the RAS at 300°F. Mixture 5S 250°F had a decreased stiffness at the high temperatures/low frequencies.

5.2. Texas Overlay Tester

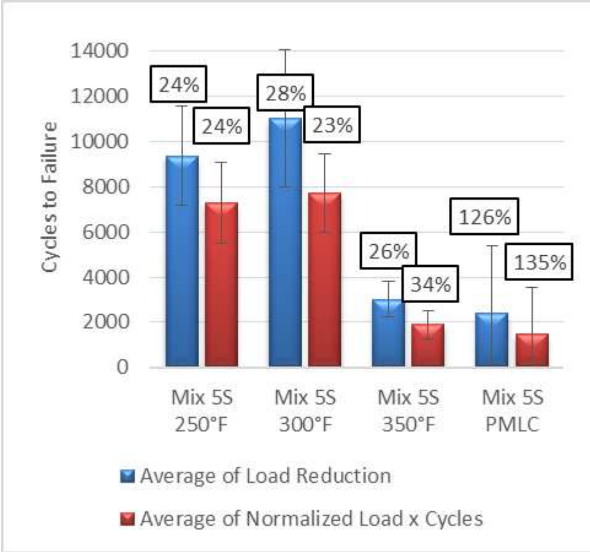
The number of cycles to failure using the AMPT Overlay Test was determined in two ways: first by the traditional 93% load reduction (93%LR) method, and second by the normalized load x cycle (NLC) method. Each of these two methods were analyzed separately and the results were compared for further evaluation of the normalized load x cycles as a viable method of analysis. Figure 6 compares the cycles to failure for each group using bar charts.

Figure 6 (a) compares the mixtures in the Group #1. Mixture 5A had the highest number of cycles to failure in this group, but its OT results were not statistically different from the Virgin mixture nor Mixture 5S 300°F for both the 93% LR and NLC evaluation methods. In addition, this statistical grouping indicates that the shingle asphalt in Mixture 5S 300°F 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 and Mixture 16B were significantly lower than Mixture 5A. 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 was not significantly lower than for the Virgin Mixture.

An analysis of the mixtures in Group #2 as shown in Figure 6 (b) gives similar results as the E* testing. A statistically significant difference was seen between Mixture 5S 300°F and Mixture 5S 350°F. This supports the hypothesis that increased mixing temperatures increases mixture stiffness and decreases tolerance to high strains. Alternatively, the difference in OT results could have been due to the increased aging of the mixture at 350°F. OT cycles to failure for Mixture 5S 350°F and Mixture 16B were significantly lower than Mixture 5A, suggesting that when the RAS asphalt is activated, the resistance to high strains decreases.



(a)



(b)

Figure 6. Overlay Testing Results (a) Group #1 – Shingle Components (b) Group #2 – Mixing Temperature

5.3. 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 T322-07, the creep compliance analysis should be performed at -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 contained aged asphalt, which has been shown to affect mixture results for low temperature properties [13-15].

After analyzing both data sets, the [-10°C, 0°C, and 10°C] set was found 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 Mixture 50R PMLC 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.

The estimated critical pavement temperature for low temperature cracking is shown in Table 4. The critical temperature was determined using the LTSTRESS workbook [16], but when the critical temperatures were plotted, the temperatures did not line up with the thermal stress curves.

Table 4. IDT Critical Temperature Results

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

As shown in Table 4, there is no relationship between IDT strength and critical temperature. The shift of the thermal stress curve has a greater impact on the critical temperature than changes in the strength. The laboratory-produced Virgin Mixture, and Mixture 5S 250°F had critical temperatures of about -17°C. This may indicate that at the mixing temperature of 250°F, the RAS binder is not activated. Mixture 5S 300°F, Mixture 5A, and Mixture 16B had critical temperatures of about -15°C. Although the slightly higher critical temperature for Mixture 5S 300°F could be due to minor activation of the RAS binder, it would not be the case for Mixture 5A since it did not contain any RAS binder. Mixtures 5S PMLC and 5S 350°F had critical temperatures of about -13°C, perhaps indicating that the recycled binders were more fully activated and had a negative effect on thermal cracking resistance. 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 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. The creep compliance master curves are shown for each group 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 as the approximate mid-point of the data at each temperature tested: 10°C, 0°C, and -10°C, respectively.

Figure 7 shows little differences 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 and Mixture 16B are somewhat lower than the other mixes in the group, possibly indicating activation and blending of the shingle asphalt, and consequently, a less compliant (stiffer) composite binder.

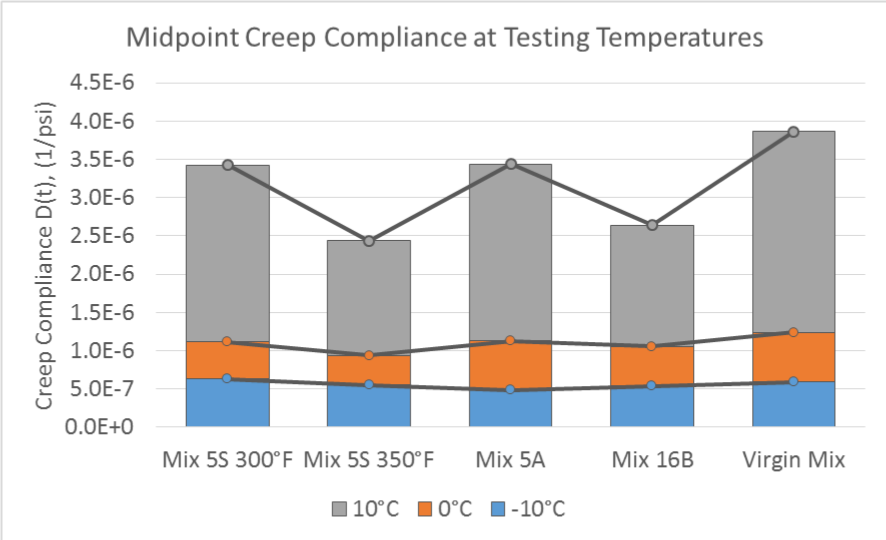


Figure 7. Group #1 Creep Compliance Midpoint Values

Figure 8 shows the data for Group #2. There is a clear decrease in creep compliance with increased mixing temperature, and Mixture 5S PMLC 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. 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 [17].

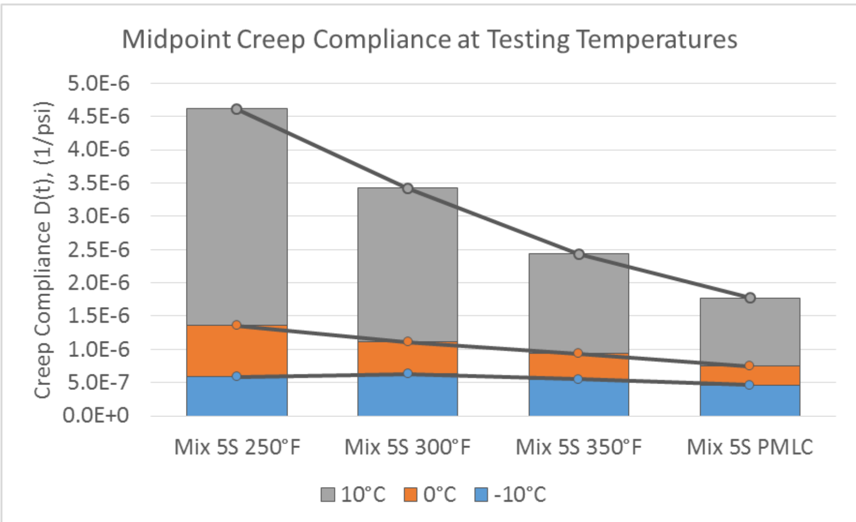


Figure 8. Group #2 Creep Compliance Midpoint Values

Three apparent groupings of the mixtures were observed for the critical temperatures. The virgin mixtures and RAS mixtures at low mixing temperature had the lowest critical temperatures. The stiffer mixtures, as shown by E* and OT results, had higher critical temperatures. The shift 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 because Mixture 5A had a higher critical temperature than the virgin mixtures. The RAS fibers may have contributed to a lower compliance of the mixture.

The creep compliance values for Mixture 5S 350°F and Mixture 16B 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.

6. CONCLUSIONS

The results from the dry aggregate mix experiments seem to indicate that RAS did not tend to be activated during the short period of dry mixing at normal mixing temperatures, but after conditioning for two hours at elevated temperatures, a minor amount of activation occurred to allow some of the RAS binder to adhere to fine aggregate.

Increasing mixing and compaction temperatures may increase the activation and blending of shingle asphalt in mixtures containing RAS. Although activation of the RAS binder increases the density of laboratory compacted samples and may indicate more effective binder in volumetric property analyses, the activation of the RAS binder also increases the stiffness and brittleness of mixtures containing RAS, making them more susceptible to cracking. The hypothesis that higher mixing temperatures increases the activation of RAS binder was partially supported by statistically significant differences in the results of the performance tests for the mixes prepared at different temperatures. The confounding effect is that higher mixing and compaction temperatures would also tend to age the virgin binder and could cause differences in performance test results.

Based on the available data, it is not possible to determine if the differences in mix performance test results (E*, OT, creep compliance, DCSE) were caused by more activation of the RAS binder or due to more short-term aging at the higher mixing and compaction temperatures. However, the fact that results of the mix with 5% RAS (Mix 5S) mixed at 300°F were not statistically different from the mix with RAS granules, fibers, and fillers (Mix 16B), certainly indicates that the RAS binder was not active at 300°F.

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.

Recycled asphalt shingles can be effectively used in asphalt mixtures to offset a portion of the virgin binder. However, the effect of RAS on the performance of the asphalt mixture must be considered. To ensure that 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 that laboratory-designed mixtures be compared to plant-produced mixtures.

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