Rutting and Fatigue Behaviors of Shingle-Modified AsphaltBinders

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ABSTRACT

The recycling of asphalt shingles in flexible pavements has received considerable interests in recent years due to economic, environmental, and social reasons. The objective of this study was to evaluate the effects of adding ground shingle using the wet process on the binder rutting and fatigue behaviors. The effects of Recycled Asphalt Shingle (RAS) on the binder rutting and fatigue characteristics were investigated using the Multiple Stress Creep Recovery (MSCR) and the Linear Amplitude Sweep (LAS), respectively. Further, the influence of adding ground shingle on the binder chemical composition was investigated in the laboratory using the Fourier Transform Infrared Analysis (FTIR) and SARA fraction analysis performed using a thin film chromatography. Based on the results of the experimental program, it was found that the use of RAS in the binder blends was associated with an increase in the percentage recovery and a decrease in the non-recoverable creep compliance, which indicates an improved resistance to rutting damage. In the other hand, results of the LAS test showed that an increase in RAS content is associated with an improved resistance to fatigue cracking. This is the opposite of what would be expected as the asphalt binder in RAS is air-blown, which is extremely stiff and brittle as compared to the binder used in roadway applications. Further evaluation of the LAS test with RAS-modified binders is recommended. In addition, analysis of the FTIR spectra showed a slight increase in asphaltenes when RAS was incorporated into the asphalt binder. The increase in asphaltenes was correlated to a slight decrease in maltenes (saturates, aromatics, and resins).

Keywords: Recycled Asphalt Shingle, Fatigue, Rutting, Multiple Stress Creep Recovery,Linear Amplitude Sweep

Word Count	
Text	5,100
Figures	6x 250
Table	3x 250
Total	7,350

INTRODUCTION

The EPA estimates that each year around 11 million tons of asphalt shingles are disposed in landfills in the United States*(1)*. Of this waste, ten million tons of asphalt shingles are the results of construction and demolition (C&D) debris while one million tons originate from asphalt shingles manufacturers *(2)*. Recycling of asphalt shingles in flexible pavementshas received considerable interests in recent years due to economic, environmental, and social reasons. From an economic perspective, the use of recycled asphalt shingle (RAS) reduces the consumption of asphalt binder, a petroleum-based product, eases the disposal cost of shingles waste in landfills, and reduces energy consumption during processing and manufacturing of virgin materials. The disposal fee of waste shingles in landfills may reach as high as $90 to $100 per ton in the neighborhood of large cities *(3)*. From an environmental perspective, the use of RAS reduces emissions of harmful by-products during processing and manufacturing of virgin materials, reduces consumption of virgin materials, and diminishes consternation of public over emissions.

Current practices implemented in the recycling of asphalt shingles consist of dry blending RAS with the aggregates before the asphalt binder is added to the batch similar to Reclaimed Asphalt Pavement (RAP). Prior to use in hot-mix asphalt (HMA) production, mixed roofing materials are loaded to the recycling facility, at which non-shingle debris are removed from the recycled material. RAS is then ground to a uniform particle size ranging from 12.5 to 19.0 mm. Currently, nine states allow the use of RAS originating from manufacturer waste and in total, 28 states are in some stage of allowing RAS in hot-mix asphalt production at a content ranging from 5 to 7.5%*(4)*. However, current practices of dry blending tear-off asphalt shingles with the aggregates before asphalt binder is added to the batch are often criticized due to the large variability observed in the asphalt content of RAS and that the final Performance Grade (PG) grade of the binder is not known.

In 2010, Elseifi and co-workers introduceda new approach to recycle asphalt shingles in asphalt construction in which RAS is ground to ultra-fine particle sizes (more than 80% passing sieve No. 200 – 0.075 mm) and blended with asphalt binder through a wet process*(2)*. In the proposed wet process, the ground recycled material is blended with the binder at high temperature prior to mixing with the aggregates. The proposed wet process offers the potential for a better control of the Superpave Performance Grade (PG) of the blend and stimulateschemical and physical reactions taking place in the blend. The idea behind the proposed method was motivated by the successful recycling of scrap tires in HMA using a wet process to create what is commonly known as Asphalt Rubber (AR) or Crumb Rubber Modifier (CRM). The use of RAS through the proposed wet process is expected to act as a partial binder replacement but also as a binder extender due to the presence of fillers, rubber, and fibers in the processed RAS material. Initial test results showed that the use of RAS modification would generally improve or not influence the high temperature grade of the binder but it may reduce elongation characteristics of the binder at low temperatureespecially at high RAS contents *(2)*. An optimum shingle content may be identified that will improve the high temperature PG of the blendwithout influencing the low temperature PG of the binder.

The objective of this study is to build on PG test results by conductingthe necessary rheological experiments to investigate the effects of adding ground shingle using the wet process on the binder rutting and fatigue behaviors. The effects of RAS on the binder rutting and fatigue characteristicswere investigated using the Multiple Stress Creep Recovery (MSCR) and the Linear Amplitude Sweep (LAS), respectively. Further, the influence of adding ground shingle on the binder chemical composition was investigated in the laboratory using the Fourier Transform Infrared Analysis (FTIR) and SARA fraction analysis performed using a thin film chromatography.

BACKGROUND

The EPA estimates that 170 million tons of C&D debris are generated every year with asphalt shingles making up to 15% of this waste. While C&D debris have increased by 25% from 1996 to 2003, the recovery rate has increased from 25 to 48% during that period *(7)*. However, the recycling of asphalt shingles has trailed other construction components such as wood, concrete, and asphalt mainly due to the low economic viability of the recycling process. In recent years, considerable attention was given in using RAS in asphalt paving construction. This interest was mainly driven by the continuous increase in the cost of asphalt binder, which has experienced a 280% surge in the past eight years *(8)*.

Asphalt shingles are the most popular roofing materials in the US making up to two thirds of the residential roofing market *(1)*. They are manufactured as two main types *(9)*: organic and fiberglass. Organic shingles are composed of 30 to 35% asphalt, 5 to 15% mineral fiber, and 30 to 50% mineral and ceramic-coated granules. Fiberglass shingles are the most popular types and consists of 15 to 20% asphalt, 5 to 15% felt, 15 to 20% mineral filler, and 30 to 50% mineral and ceramic-coated granules. While glass fiber shingles have a fiberglass reinforcing backing that is coated with asphalt and mineral fillers, organic shingles have a cellulose-felt base made with paper.Air blown asphalt is typically used in the manufacturing of asphalt shingles; this type of asphalt binders has a greater viscosity and is more brittle than regular asphalt binder used in HMA *(10)*.

Use of RAS in Road Applications

While the interest in using RAS has increased in recent years, a number of research studies evaluated the use of this recycled material and its influence on the mix mechanical behavior since the late 1980s. Newcomb et al. (1993) evaluated the effects of RAS on the mixture volumetrics and mechanical properties*(11)*. Results showed that the use of RAS at a content of 5% had negligible effects on the mix laboratory performance. At a content of 7.5%, the use of RAS caused a softening of the mixture and therefore, was not recommended. The mix resistance to low temperature cracking was also reported to decrease with the increase in RAS content. The authors also noted that the amount of moisture in the recycled material should be controlled to avoid undesirable effects on the mix performance. Button et al. (1995) evaluated the influence of adding 5 to 10% of asphalt shingles on the mechanical properties of asphalt mixtures as compared to untreated mixes *(12)*. The use of RAS resulted in a decreased tensile strength and creep stiffness of the mixture but it improved the mix resistance to moisture damage.

Maupin (2010) evaluated the use of RAS in the production of HMA and a warm-mix asphalt (WMA) in Virginia *(13)*. In total, five mixes (three surface mixes and two base mixes) were produced and installed by three asphalt contractors. Both mixes were sampled during production and their performance was evaluated in the laboratory. RAS content ranged from 4 to 5%; however, one surface mix was produced with 18% RAP and 2% RAS. Laboratory testing included volumetrics, rutting test using the Asphalt Pavement Analyzer (APA),fatigue test using four-point flexural beam test, and grading of the binder recovered through extraction. Results of rut testing showed that the mixes would perform satisfactorily on high traffic conditions. Similarly, the mixes were expected to perform satisfactorily against fatigue failure. Testing of the recovered binders showed that the high temperature grade of the binder was increased due to RAS by one to three grades and that the low temperature grade deteriorated one grade on five of the six mixtures. Maupin also reported that the use of the ignition oven to estimate the binder content in RAS yielded an over estimation of the asphalt content by about 5% *(13)*.

Use of Wet Process for Recycling of Shingles

Conventional practices of dry blending tear-off asphalt shingles with the aggregates before asphalt binder is added to the batch are often criticized due to the variability observed in the asphalt content of RAS and the unknown final PG grade of the binder. Elseifi et al. (2012) introduced a new approach to recycle asphalt shingles in asphalt paving construction in which RAS is ground to ultra-fine particle sizes and blended with asphalt binder through a wet process*(2)*. Table 1 compares the wet process to the dry process in RAS recycling. Two unmodified binders classified as PG 64-22 and PG 52-28 were blended with two contrasting sources of RAS at a modification content ranging from 10 to 40% by weight of the binder. Based on the results of the experimental program, the use of RAS modification through the proposed wet process was successful. It would generally improve or not influence the high temperature grade of the binder but it may reduce the low temperature grade of the binder at high RAS contents. As demonstrated in this study, an optimum shingle content may be identified that will improve the high temperature grade without influencing the low temperature grade of the binder.

Results of the cigar-tube test showed that the use of a RAS content of 20% or less was acceptable with levels of separation less than 20%. At high RAS content of 40%, stability and workability of the blends will not be favorable given the high level of separation. Using Confocal Laser-Scanning Microscopy (CLSM), wax crystals ranging from four to eight microns in size were successfully detected. However, wax crystals were not detected in the RAS-modified binder, which may indicate that the wax molecules are absorbed by the RAS material. Results of the High-Pressure Gel Permeation Chromatography (HP-GPC) showed that the proposed wet method of modification produced a slight increase of the High Molecular Weight (HMW) (> 3000 Daltons) content in the prepared blends at high RAS contents suggesting that a fraction of the RAS binder contributes to the blend properties.

TABLE 1 Comparison between the Dry and Wet Processes for Shingle Recycling

Dry Process	Wet Process
RAS is added as an aggregate source similar to RAP	RAS is blended with the binder prior to production
Requires an additional bin at the plant	Requires an agitation tank
RAS + Virgin Binder PG grade is unknown	PG grade can be measured prior to production
Commingling between virgin and aged binder is incomplete	Commingling at high temperature and under agitation is improved
Overestimating level of blending can result in a dry mix	Level of blending at high temperature and under agitation is improved

EXPERIMENTAL PROGRAM

Test Materials

The experimental program was designed to evaluate unmodified and RAS-modified asphalt binder blends prepared using the wet process. Two asphalt binders, classified as PG 64-22 and a polymer-modified PG 70-22 according to the Superpave specifications, were selected as the base binders(Table 2). Two sources of RAS consisting of tear-off shingles from Texas and South Dakota were obtained from C&D processing plants. RAS materials were ground to anultra-fine particle size distribution at room temperature using a Pulva-Sizer® hammer mill with high rotational speed of 9,600 rpm. The particle size distribution of the processed RAS was characterized using laser diffraction. The processed RAS samples were analyzed using a Beckman Coulter Particle Size Analyzer (LS13 320) operated on a wet mode. Results of the particle size analysis using laser diffraction showedthat the mean particle sizes were 85.5 µm for the tear off shinglesfrom Texas and 201.0 µm for the tear off shingles from South Dakota.Extraction results showed that the tear off shinglesfrom both sources contained24% asphalt.

Asphalt binder blends of the virgin binders and theultra-fine RASwere prepared at modification rates of 10, 20, and 30% by weight of the binder, Table 2. These modification levels were selected based on the results of the original test program, which showed that these contents kept separation levelsbelow 20%, which is essential to ensure workability and stability of the blends *(2)*. The blendswere prepared by mixing 500 g of asphalt binder with the corresponding content of RAS at a mixing temperature of 180°C using a mechanical shear mixer rotating at a speed of 1500 rpm for 30 minutes.

TABLE 2 Descriptions of the Test Materials

Binder Abbreviation	RAS Content (%)	RAS Source	Description
64CO	0	N/A	Conventional PG 64-22 binder with no shingle
70CO	0	N/A	Conventional PG 70-22 binder with no shingle
SD610	10	South Dakota	PG 64-22 binder with 10% RAS
SD620	20	South Dakota	PG 64-22 binder with 20% RAS
SD630	30	South Dakota	PG 64-22 binder with 30% RAS
TX610	10	Texas	PG 64-22 binder with 10% RAS
TX620	20	Texas	PG 64-22 binder with 20% RAS
TX630	30	Texas	PG 64-22 binder with 30% RAS
SD710	10	South Dakota	PG 70-22 binder with 10% RAS
SD720	20	South Dakota	PG 70-22 binder with 20% RAS
SD730	30	South Dakota	PG 70-22 binder with 30% RAS
TX710	10	Texas	70-22 binder with 10% RAS
TX720	20	Texas	70-22 binder with 20% RAS
TX730	30	Texas	70-22 binder with 30% RAS

Laboratory Testing

Multiple Stress Creep Recovery Test

The multiple stress creep recovery (MSCR) test was conducted in accordance with AASHTO TP 70-13 to evaluate the effects of RAS on the binder rutting resistance. In this test, the dynamic shear rheometer is used to apply a constant shear stress for 1sec. followed by a 9-sec. rest period. This test was introduced to characterize the binder rutting resistance at high temperatures. It was reported to correlate well with the mixture rutting performance as measured by accelerated pavement testing*(14)*. It can also be used to determine the stress dependency of polymer modified binders.Two performance parameters have been suggested to evaluate the binder performance at high temperature. The non-recoverable creep compliance (J_{nr}) normalizes the strain response of the binder to stress as follows:

$$J_{nr} = \frac{\varepsilon_{nr}}{\sigma} \qquad (1)$$

where,
J_{nr} = non-recoverable creep compliance (1/kPa);
ε_{nr} = non-recoverable strain at the end of the rest period; and
σ = constant stress applied in the creep phase of the test (kPa).

The percentage recovery at the end of the recovery period is also calculated as follows:

$$\varepsilon_r = \frac{\varepsilon_1 - \varepsilon_{10}}{\varepsilon_1} x100 \qquad (2)$$

where,
ε_r= percentage recovery,
ε_1 = strain at the end of the creep phase (after 1 sec.), and
ε_{10} = strain at the end of the recovery period (after 10 sec.).

For acceptable performance, it is desirable to use a binder with a low, non-recoverable creep compliance and high percentage recovery. AASHTO TP 70-13 introduced the graphical presentation presented in Figure 1 to evaluate the delayed elastic response of the binder at high temperature. AASHTO TP 70-13 also suggested using the boundary line, defined by the equation $y = 29.371(x)^{-0.2633}$ as an indicator of the presence of elastomeric modification *(15)*. Figure 1 was used in this study to evaluate the effects of RAS on the binder rutting performance and on its elastomeric modification in case of PG 70-22.Two replicate specimens were tested at the high temperature grade of the base binder (70°C and 64°C),for each binder blend. All of the binder samples were first short-term aged using the Rolling Thin Film Oven (RTFO). Sample geometry consisted of an 8-mm diameter and a 2-mm thickness.

Linear Amplitude Sweep Test

The current binder characterization for fatigue performance, as required by the Superpave PG system, relies on the measurement of $|G^*|\sin\delta$ which, at intermediate temperature, is required to be less than 5000 kPa in order for the binder to show reasonable resistance against fatigue cracking. Deacon et al. (1997) found that $|G^*|\sin\delta$ had a satisfactory correlation with the fatigue resistance of thin (2 in. or less) asphalt-bound layers*(16)*. Since then, researchers have questioned the validity of this parameter as it is stiffness-based and is measured under conditions of low shearing strain*(17)*. The Linear Amplitude Sweep (LAS) test predicts the binder's resistance to fatigue cracking by applying a cyclic load using a linearly ramping amplitude sweep test*(18)*.

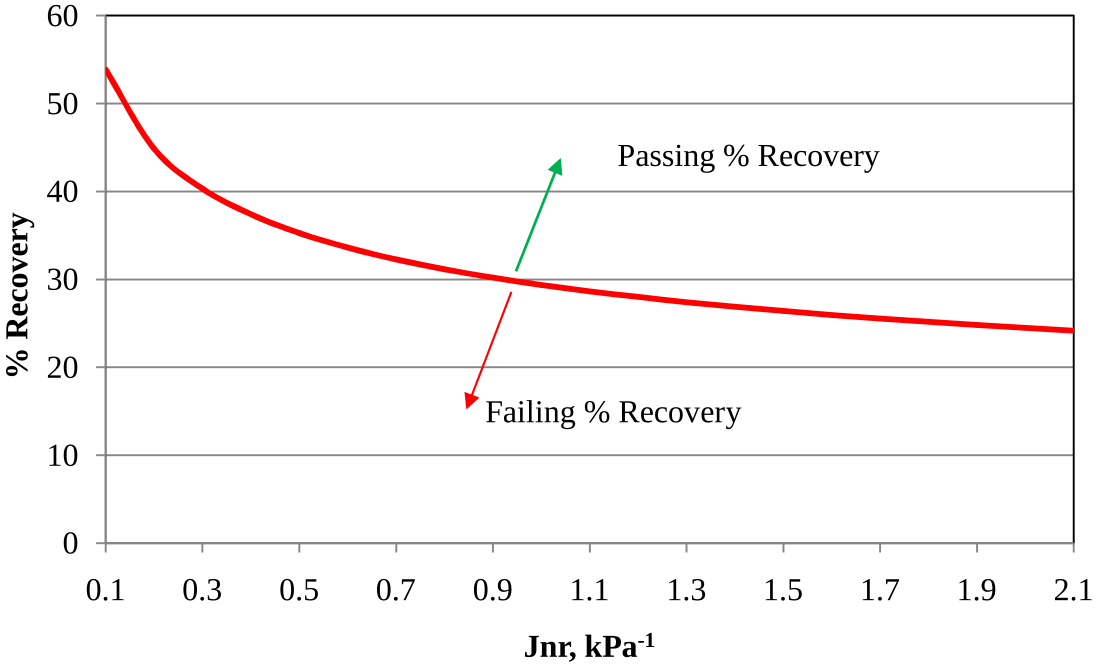


FIGURE 1 Evaluation of the Binder's Delayed Elastic Response from the MSCR Results

An Anton Paar MCR 302 rheometer with parallel plate configuration was employed by first conducting a frequency sweep test to measure the undamaged properties of the binder. A test temperature of 25°C was maintained to represent the intermediate service temperature.RTFO-aged binder was used with a sample geometry of 8-mm in diameter and 2-mm thickness. A series of increasing oscillatory cyclic loads were then applied on the sample to simulate the damaged state. Results are used to fit a phenomenal fatigue performance model to the results as described in Equation (3):

$$\mathrm{N_f} = \mathrm{A}(\gamma_{max})^{B} \quad (3)$$

where,

A, B = regression parameters; and

γ_{max} = the maximum expected binder strain for a given pavement structure.

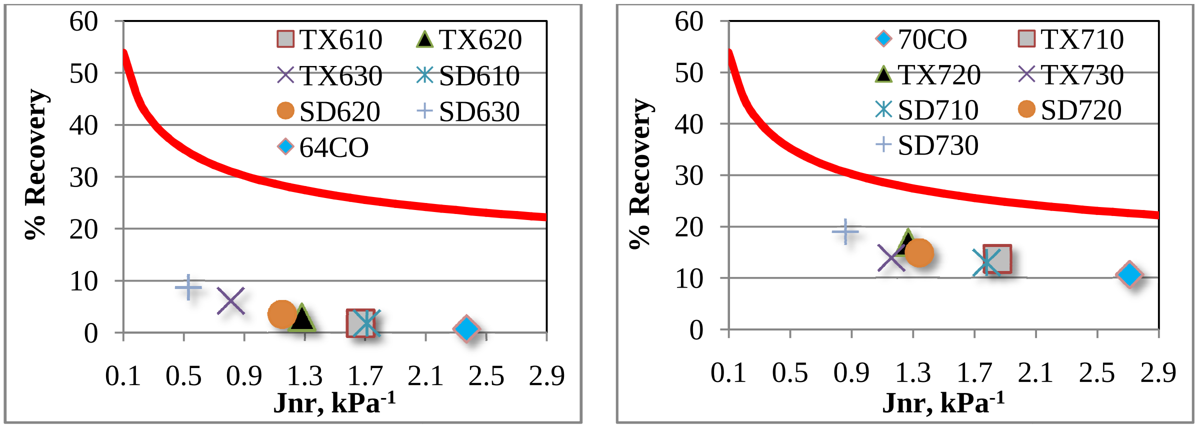
Fourier Transform Infrared Analysis

A Fourier Transform Infrared Analysis was performed on two asphalt binders shown in Table 2, the polymer-modified binder (70CO) and the binder blend prepared with 20% RAS from Texas (TX720). The analysis was performed using a Thermo Scientific Nicolet i50 FTIR + ATR module. The purpose of the FTIR analysis was to identify changes in the chemical composition of the binder when the RAS is incorporated. Specifically, changes to the asphaltene content were expected. To complement these results and in order to assess the effect of incorporating RAS on the different SARA components of the asphalt binder, a thin film chromatography was performed using an Iatroscan MK6.

RESULTS AND ANALYSIS

Multiple Stress Creep Recovery Test Results

Figure 2 (a and b) presents the variation of the average percent recovery and non-recoverable creep compliance with the increase in RAS content for the asphalt blends with PG 64-22 and PG 70-22, respectively. As shown in this figure, the increase in RAS content was associated in an increase in the percentage recovery and a decrease in the non-recoverable creep compliance. These are desirable characteristics as it would decrease the rutting susceptibility of the binders. It is also noted that the binder characteristics were similar for both RAS sources (i.e., Texas and South Dakota). However, all binder blends did not passthe binder's delayed elastic response set by AASHTO TP 70-13, even though PG 70-22 was polymer-modified.

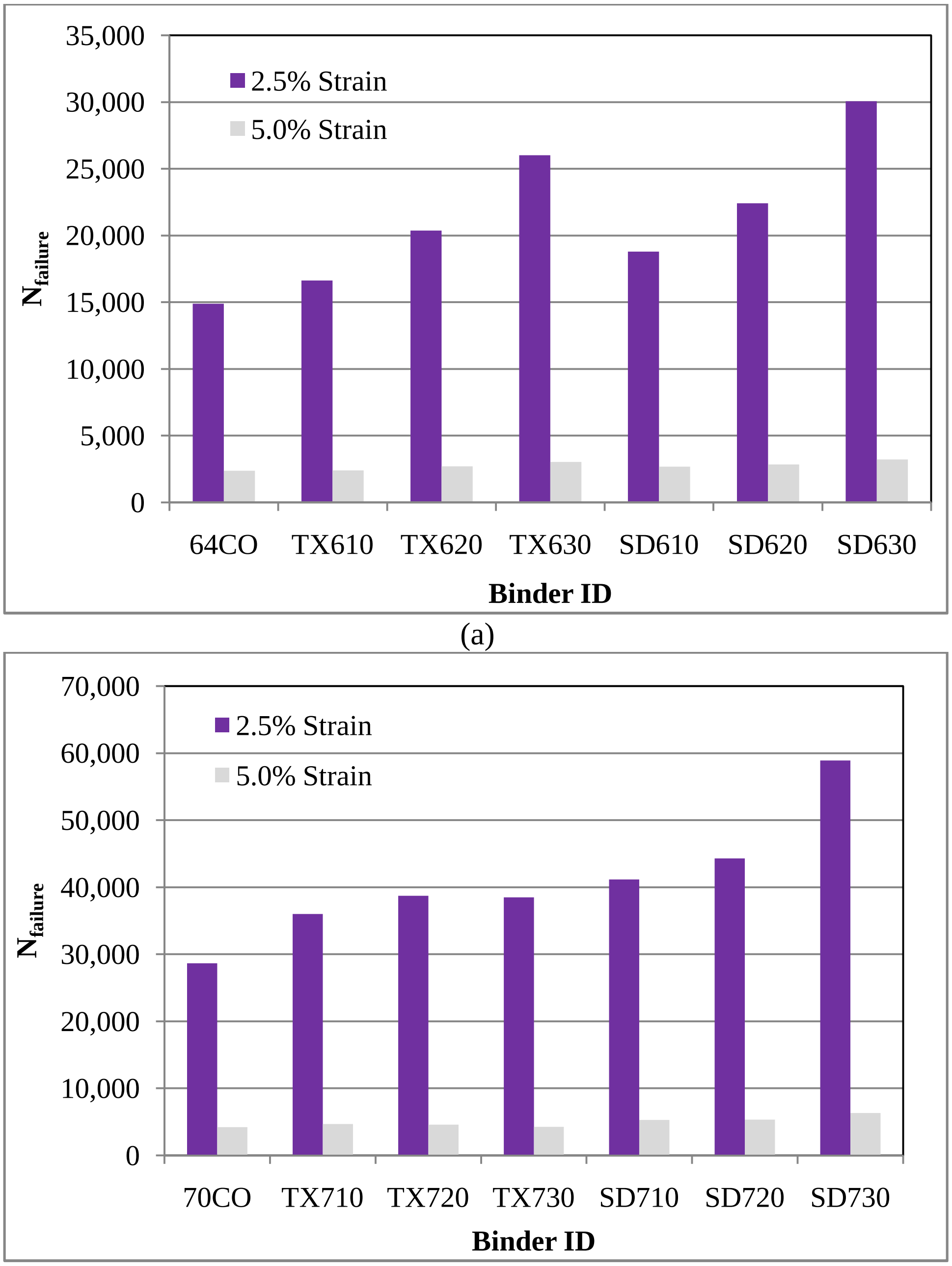


(a) (b)

FIGURE 2 Effects of RAS Modifications on the MSCR Test Results for (a) PG 64-22 Binder Blends and (b) PG 70-22 Binder Blends

Linear Amplitude Sweep Test Results

Figure 3 (a and b) presents the effects of RAS modifications on the binder fatigue resistance as predicted from the LAS testfor the asphalt blends prepared with PG 64-22 and PG 70-22, respectively. Larger number of cycles to failure (N_f) indicate greater resistance to fatigue cracking. These results imply that an increase in RAS corresponds to anincrease in the number of cycles to failure of the sample, for both PG 64-22 and PG 70-22 base binders. This is the opposite of what would be expected as the asphalt binder in RAS is air-blown, which is extremely stiff and brittle as compared to the binder used in roadway applications. In a recent study, the authors found that the RAS binders extracted from different recycling sources around the country were graded as PG 118 + - xx using the Superpave binder specification system *(19)*. These results indicate that the LAS test may not be suitable for characterizing RAS-modified asphalt binders. Other researchers have reported that the results of the LAS test may require further investigation before implementation in order to consider both viscoelastic and viscoplastic deformation in the data analysis *(20)*.

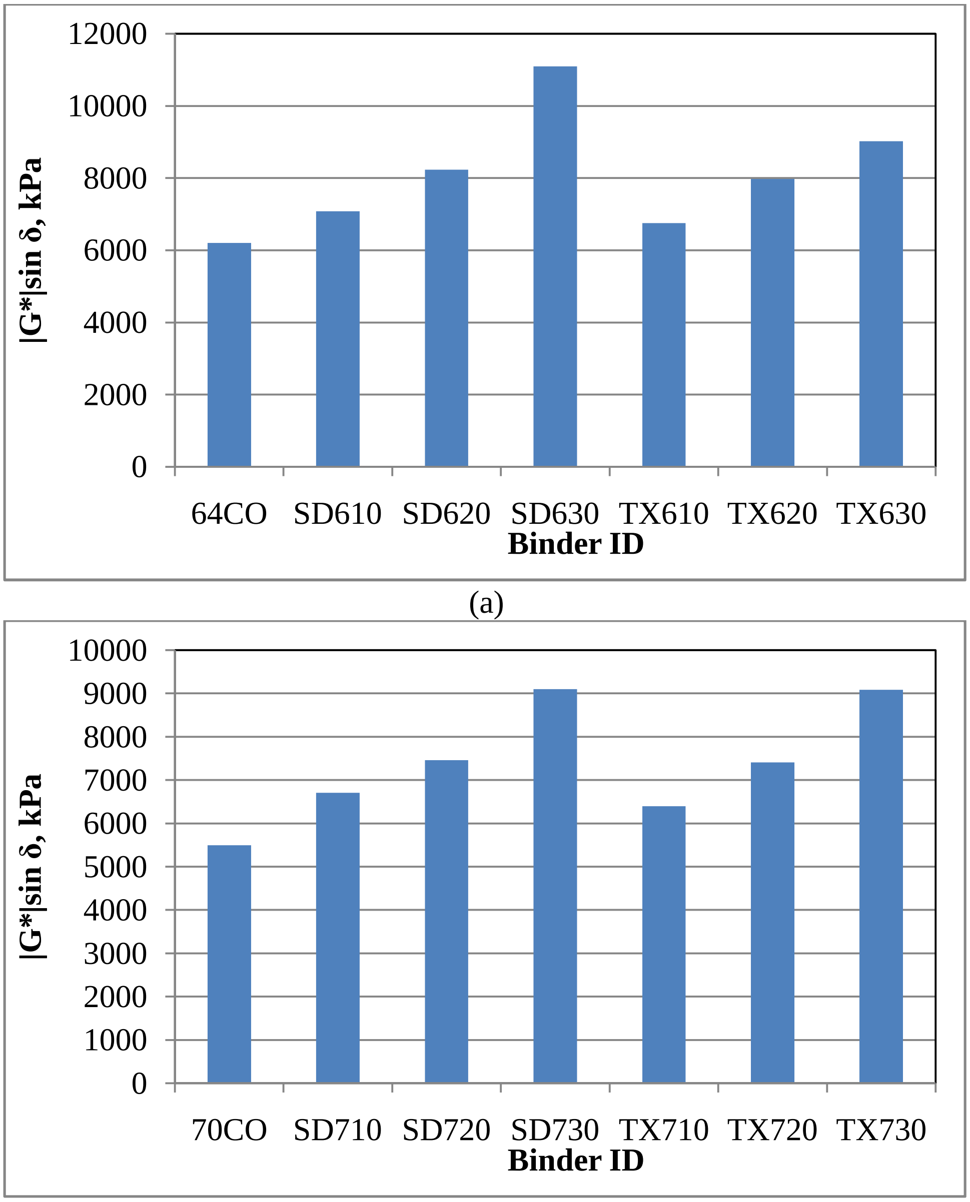


(a)

(b)

FIGURE 3 Effects of RAS Modification on the LAS Test Results

Figure 4 (a and b) presents the variation of the current Superpave parameter, |G*|sin δ, with the increase in RAS contentfor the PG 64-22 and PG 70-22 binder blends, respectively. It is noted that these results were conducted at 25^{o}C on the RTFO-aged binder residue. As shown in this figure, the increase in RAS content was associated with an increase in |G*|sin δ, which is indicative of an increased susceptibility to fatigue cracking for the binder blends with RAS.



(a)

(b)

FIGURE 4 Effects of RAS Modification on the |G*|sin δ Superpave Criterion

Fracture Resistance of Asphalt Mixture

LAS test results were compared to the fracture resistance of asphalt mixtures containing RAS using the wet process. A 12.5 mm Superpave mixture was designed according to AASHTO R 35 while incorporating 20% RAS from Texas using the wet process*(21)*. The performance of the mixture containing RAS and prepared using the wet process was compared to two control mixes with 0% RAS (70CO prepared with polymer-modified PG 70-22 and 64CO prepared with straight PG 64-22). Fracture resistance potential was assessed using the semi-circular bending (SCB) approach asdetailed elsewhere*(21)*. This test characterizes the fracture resistance of HMA mixtures based on fracture mechanics principals, the critical strain energy release rate, also called the critical value of J-integral, or J_c.

Figure 5 presents a comparison of the critical strain energy (J_c) data for the mixtures evaluated in this study. High J_c values are desirable for fracture-resistant mixtures. As shown in this figure, the use of RAS caused a slight decrease in the critical strain energy for the mix incorporating 20% RAS from Texas (70WT) as compared to the control mixture (70CO). This was expected given that the RAS-binder modified HMA mixture possessed stiffer properties than that of the conventional mixture. Given that the cracking resistance is mainly controlled by the binder in the mixture, it is likely that the use of RAS increased the brittleness of the binder at intermediate temperature.

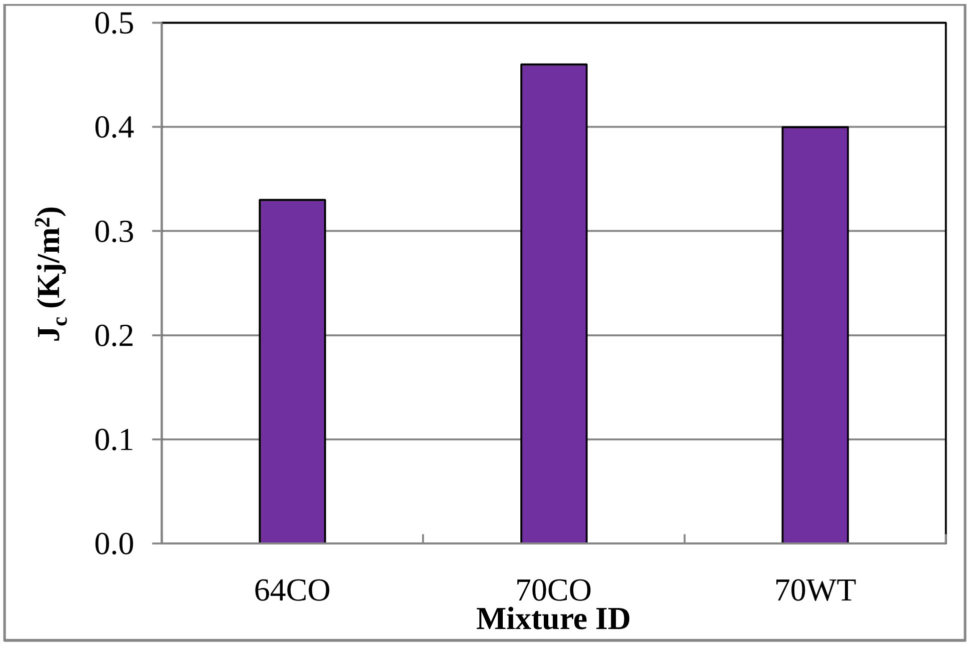


FIGURE 5 Effects of RAS Modification on the SCB Test Results

FTIR Test Results

The Fourier Transform Infrared Analysis was performed on the neat asphalt binder (PG70-22) and the asphalt blend with 20% RAS from Texas (TX720). The purpose of the FTIR analysis was to identify changes in the chemical composition of the binder when the RAS is incorporated. Specifically, changes in the transmittance intensity bands associated to the asphaltene content were expected. The FTIR results are shown on Figure 6. As shown in these results, there were no significant differences in the spectrums of the neat and RAS modified binders. However, small increment can be observed on the 1400 cm^{-1} and 900 cm^{-1} spectrum bands when the change to the reference line is considered.

To further evaluate the effects of incorporating RAS on the different SARA components of the asphalt binder, a thin film chromatography, by means of Iatroscan, was performed. Results, which are shown in Table 3, show a slight increase in asphaltenes when RAS was incorporated into the asphalt binder. However, the more significant change can be attributed to the aromatics and the resins. It appears that with the aging process, the aromatics have decreased and changed to resins, which are very similar in composition to asphaltenes.The previous changes were verified by analyzing the FTIR spectra associated with the asphaltenes for each of the binder samples. A slightly lower intensity in the spectrum bands associated with the asphaltenes in the neat binder suggests an increase in asphaltene content when incorporating RAS. The increase in asphaltenes is also correlated to a slight decrease in maltenes (saturates, aromatics, and resins).

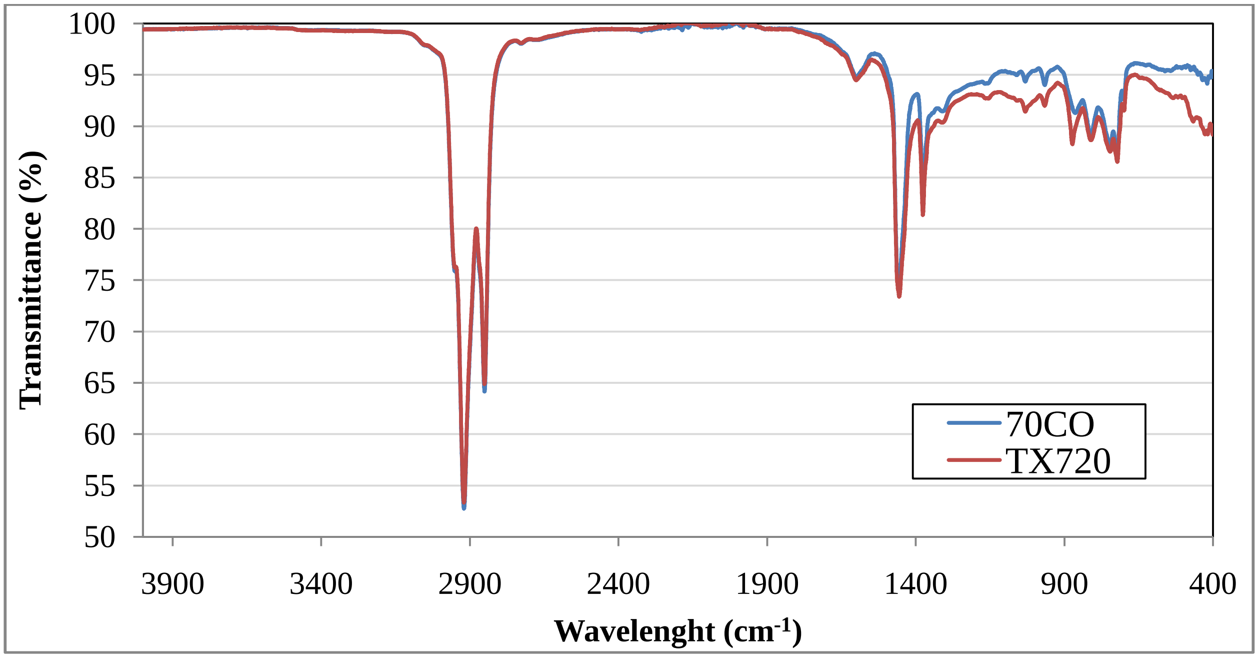


FIGURE 6 FTIR Spectra for Analyzed Binders

TABLE3 Iatroscan SARA Fraction Analysis

SARA Fraction(%)	**70CO**	**TX720**	
		Value	**Difference**
Saturates	5.58 (0.5*)	5.23 (0.59)	-0.35
Aromatics	55.75 (0.64)	52.27 (0.9)	-3.48
Resins	24.18 (0.42)	26.77 (1.23)	2.59
Asphaltenes	14.69 (0.69)	15.73 (0.69)	1.04

(*) The values in parenthesis correspond to the standard deviation associated to the individual measurements for each fraction.

SUMMARY AND CONCLUSIONS

The objective of this study was to evaluate the effects of adding ground shingle using the wet process on the binder rutting and fatigue behaviors. The effects of RAS on the binder rutting and fatigue characteristics were investigated using the Multiple Stress Creep Recovery (MSCR) and the Linear Amplitude Sweep (LAS), respectively. Further, the influence of adding ground shingle on the binder chemical composition was investigated in the laboratory using the Fourier Transform Infrared Analysis (FTIR) and SARA fraction analysis performed using a thin film chromatography. Based on the results of the experimental program, the following conclusions may be drawn:

- The use of RAS in the binder blends was associated with an increase in the percentage recovery and a decrease in the non-recoverable creep compliance, which indicates an improved resistance to rutting damage.
- Results of the LAS test showed that an increase in RAS content is associated with an improved resistance to fatigue cracking. This is the opposite of what would be expected as the asphalt binder in RAS is air-blown, which is extremely stiff and brittle as compared to the binder used in roadway applications. Further evaluation of the LAS test with RAS-modified binders is recommended.
- Analysis of the FTIR spectra showed a slight increase in asphaltenes when RAS was incorporated into the asphalt binder. The increase in asphaltenes was also correlated to a slight decrease in maltenes (saturates, aromatics, and resins).

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