HMA Mixtures Containing Recycled Asphalt Shingles (RAS): Low Temperature and Fatigue Performance of Plant-Produced Mixtures

Dr. Walaa S. Mogawer, P.E. - PI
Milad Zokaei Ashtiani
Alexander Austerman, P.E.

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Professor Walaa S. Mogawer, P.E. – Principal Investigator (PI)
Milad Zokaei Ashtiani
Alexander Austerman, P.E.

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University of Massachusetts Dartmouth
285 Old Westport Road
North Dartmouth, MA 02747

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16. Abstract

In the paving industry, there is increased interest in using recycled materials like Recycled Asphalt Shingles (RAS) and Reclaimed Asphalt Pavements (RAP) due to the valuable asphalt binder contained within them. The major concern with using these materials is that the binder contained within is highly aged which could lead to reduced mixture durability. Therefore, a method is needed to quantify the extent that the aged binders from these materials blend with virgin binder when producing mixtures in order to better understand their effects on mixture performance.

In this study, a new approach to quantify the amount of blending that occurs between aged RAS and RAP binders and a virgin binder was developed. Asphalt binders were extracted and recovered from RAS and RAP stockpiles and blended with a PG64-28 virgin binder in varying proportions and their master curves were constructed at 20ºC. Asphalt mixtures containing different proportions of the same RAS and RAP stockpiles were then designed and the mixture dynamic moduli were measured to construct mixture master curves at 20ºC.

The binder master curves for each blending proportion were then substituted into a locally calibrated Hirsch model to predict the mixture master curves. Comparing measured and predicted mixture master curves suggested that the aged binder from RAS and RAP blends with the virgin binder less than 40% and 60%, respectively. Cracking tests were also conducted to validate the proposed degrees of blending from a mixture mechanical performance point of view.

17. Key Words
Moisture, Warm Mix Asphalt, Reclaimed Asphalt Pavement, Moisture Susceptibility, Low Temperature Cracking

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

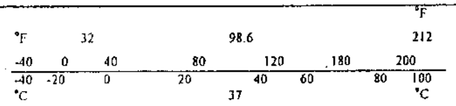
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C+32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

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1.0 INTRODUCTION

Many state transportation agencies are interested in using recycled materials like Recycled Asphalt Shingles (RAS) and Reclaimed Asphalt Pavements (RAP) in new paving mixtures because they contain valuable asphalt binder. One of the main obstacles in utilizing RAS and/or higher amounts of RAP is that is unknown how much of the aged asphalt binder contained with them will blend, or be activated, in a new mixture. Depending on this quantity of blending, the resulting mixture performance could be impacted in terms of resistance to distresses. More blending of the aged material may result in a stiffer mixture which could be more prone to cracking but also more rut resistant. Since the asphalt binder used to produce RAS is a stiff air blown asphalt, the impact could be more severe when compared to the addition of RAP (*1*). Several studies have evaluated the blending in terms of whether it occurs or not. No studies have endeavored to quantify in a numerical sense how much blending is occurring. As an alternative, several studies have taken advantage of mechanical tests to evaluate the effect of using more recycled materials in mixtures with respect to distress (*2, 3, 4, 5*).

Two terms have been used interchangeably in regards to blending. Binder contribution is a term used to describe a quantity of asphalt binder from RAS or RAP that participates as effective binder in a mixture design. Degree of blending, on the other hand, refers to the binder formed as a result of diffusion between two binders that have different rheological properties when combined (*6,7*). Researchers have utilized different approaches to study the degree of blending, mainly focusing on whether blending does occur or not.

Previous research into blending has been conducted (*8-14*). An approach to study the degree of blending was recommended by Bonaquist to utilize models which correlate the mixture dynamic modulus and binder shear modulus (*15*). Beside its simplicity, the Hirsch model was found to be more beneficial to link mechanical to rheological performance of asphalt mixtures when blending is concerned (*16, 17*). Extending the calculation from Hirsch model to binder master curves, researchers were able to assess the degree of blending when RAS or RAP were used (*5, 18*). However, none of the methods mentioned above were aimed to numerically quantify the degree of blending between aged and virgin binder throughout the whole mixture. This study attempted to present a new approach to numerically quantifying the degree of blending.

2.0 OBJECTIVES

The objectives of this study were as follows: (1) propose a procedure which can be used to quantify the amount of binder from RAS or RAP that blends with a virgin binder, (2) validate the procedure using mixture tests that measure the cracking susceptibilities of mixtures and (3) investigate the effects of RAS and RAP on cracking susceptibility.

3.0 MATERIALS AND MIXTURE DESIGN

For this study, three aggregate stockpiles were used: 12.5mm coarse aggregate, 9.5mm coarse aggregate, and stone sand. RAP was also obtained from the same contractor as the aggregates. RAS was obtained from two sources: Tear-Off Scrap Shingles (TOSS) and Manufacturer Waste Scrap Shingles (MWSS).

A Superpave 12.5 mm mixture was designed and used in the study. Using the ignition oven test according to AASHTO T308, the binder content of TOSS, MWSS, and RAP was 31.5%, 17.4%, and 5.5%, respectively. Table 1 shows aggregate gradations and specific gravity of each stockpile. Optimum binder content for this mixture, using all virgin materials, was measured to be 5.2% by weight of the mixture. A Performance Grade PG64-28 binder was used as it is the standard specified binder grade in Massachusetts

TABLE 1 Aggregate Gradation and Aggregate Specific Gravities

Sieve Openings (mm)	**Percent Passing**						
	Job Mix Formula (JMF)	**12.5mm Coarse**	**9.5mm Coarse**	**Stone Sand**	**RAP**	**MWSS**	**TOSS**
19	100	100	100	100	100	100	100
12.5	95	87.1	99.9	100	99.4	100	100
9.5	80	27.8	91.2	100	93.3	100	100
4.75	49	5.4	19.7	97	63.1	99.8	99.8
2.36	32	2.1	3.3	71	45.4	98.6	99.3
1.18	22	1.8	2.6	46	34.7	80.7	81.7
0.6	15	1.7	2.4	30	27.1	55.7	67.7
0.3	11	1.6	2.2	17	20.2	46.1	52.0
0.15	7	1.5	2	8	13.6	36.0	42.5
0.075	4	1.0	1.5	4.4	8.1	26.2	30.3
G_{sb}[a]	2.750	2.773	2.754	2.715	2.770	2.839	3.070
Binder Content (%)	5.2	na[b]	na	na	5.5	17.4	31.5

[a] G_{sb} = Aggregate specific gravity
[b] na = not applicable

To achieve the objectives of this research, four different mixtures were developed: (1) mixture without recycled materials as control mix (Control), (2) mixture containing 5% MWSS, (3) mixture containing 5% TOSS, and (4) mixture containing 15% RAP. Following the recommendation from some researchers, RAS was limited to 5% as it is the highest amount that is allowed to be used in the production of hot mix asphalt without changing to a softer virgin binder grade (*19*).

Binder contributions were measured by first assuming 100% of the binder from RAS or RAP is effective. In cases that the Superpave criteria were not met, changes to the binder contribution assumption were made so that the volumetric requirements for the 12.5-mm dense graded mixture were satisfied (AASHTO M323-13). All mixtures met Superpave criteria for 75 gyrations mixtures at a traffic level of Equivalent Single Axle Load (ESAL) of 0.3 to <3 million.

To better replicate identical aggregate skeletons, individual sieving was implemented to match the Job Mix Formula (JMF) gradation for all four blends. The Superpave Gyratory Compactor (SGC) was used to fabricate all mixture samples unless otherwise specified. Volumetric properties for the mixtures are presented in Table 2. Following a procedure utilized in previous studies, dried RAS and RAP were added to heated aggregates five minutes and two hours prior to mixing, respectively, at 155°C and then conditioned at compaction temperature of 145°C. These mixing and compaction temperatures were specified by the asphalt binder supplier for the PG64-28 virgin binder used in this study.

TABLE 2 Mixture ID and Volumetric Properties

Mix ID	Volumetric Properties				
	Maximum Theoretical Specific Gravity (G_{mm})	**Air Voids (%)**	**Voids in Mineral Aggregates (VMA) (%)**	**Voids Filled with Asphalt (VFA) (%)**	**RAP/RAS Binder Contribution (%)**
Control	2.576	3.7	14.2	74.1	na[a]
5% MWSS	2.577	3.7	14.4	74.4	100
5% TOSS	2.555	3.7	15.5	76.0	70
15% RAP	2.554	3.6	14.3	76.6	100

[a] na = not applicable

4.0 BINDER TESTING

By means of a centrifuge and the rotary evaporator, asphalt binder from RAS and RAP were extracted and recovered using toluene as a solvent (ASTM D6847-02, ASTM D7906-14). Various proportions of virgin binder combined with recovered binder were considered that were equivalent to certain degrees of blending that were assumed might be present in the mixtures (see Table 3). Calculations of the equivalent degree of blending were completed by knowing the amount of virgin binder added to fabricate each mixture and the binder contents of RAS and RAP.

Multiplying binder contents of RAS or RAP by total weights they have been introduced into mixtures results in the total binder attributed from recycled materials. Multiplying this total aged binder coming from RAS or RAP by the binder contributions, therefore, results in their effective binder contents. Subtraction of the optimum binder content of the Control mix from the effective binder from RAS or RAP would result in the amount of virgin binder needed to add into mixtures. Assumptions on the degree of blending can then be made on how much the effective binder from RAS or RAP blends into virgin binder. To exemplify, 100% blending is a case in which all the binder from recycled materials is melted into the virgin binder, and 0% blending is equivalent to the virgin binder.

Recovered binders were heated to 170°C and then added to the virgin binder at 135°C as suggested by Bonaquist (*19*). In order to ensure thorough blending, the blend of recovered and virgin binders were kept at 163°C for 90 minutes and stirred every 30 minutes. The blended binders were tested to measure their high, intermediate, and low continuous PG temperatures, and to construct master curves after aging in the Pressure Aging Vessel (PAV). Table 3 also illustrates the continuous true PG of the blended binders. Because the RAP binder was not as stiff as the RAS binder, no blending proportion lower than 60% were assumed for 15% RAP mixture. Moreover, previous research studies indicated the degree of blending for RAP is believed to fall between 70 and 100% depending on the percentage of RAP used (*20*). Recovered RAS and RAP binders were also graded.

5.0 METHODOLOGY

To accomplish the first objective, extracted and recovered binders from each RAS and RAP were blended with a virgin binder in several assumed percentages which translate to different degrees of blending ranging from 0 to 100% for the mixtures. Each blended binder was tested in the Dynamic Shear Rheometer (DSR) to obtain a shear modulus (G*) data for subsequent construction of a binder master curve at a reference temperature of 20°C. This provided a set of G* master curves for each RAS and RAP blend showing the effects of assumed blending.

TABLE 3 Performance Grading of Various Binder Contributions

Binder Type	Binder Blending Proportions (%)		Equivalent Degree of Blending in Mixtures (%)	True High PG	True Intermediate PG	True Low PG	PG
	Virgin	Recovered					
Virgin	100	0	0	69.8	16.97	-29.5	64-28
MWSS	96.8	3.2	20	71.5	17.03	-28.4	70-28
	93.6	6.4	40	73.7	17.95	-28.2	70-28
	90.4	9.6	60	75.2	18.26	-27.0	70-22
	87.2	12.8	80	80.6	19.10	-25.7	76-22
	84	16	100	81.6	20.10	-25.3	76-22
	0	100	na[a]	164.9[b]	40.8	NA[c]	NA
TOSS	93.2	6.8	20	72.8	18.55	-27.8	70-22
	87.2	12.8	40	80.6	20.27	-26.4	76-22
	81.9	18.1	60	83.7	21.30	-24.3	82-22
	77.3	22.7	80	90.2	22.89	-23.4	88-22
	73.1	26.9	100	92.1	23.50	-18.5	88-16
	0	100	na	NA	48.8	NA	NA
RAP	90	10	60	72.0	18.32	-28.9	70-28
	85	15	100	72.6	18.67	-28.2	70-28
	0	100	na	92.3[b]	31.62	-13.9	88-10

[a] na = not applicable

[b] High PG was determined assuming recovered binder was RTFO aged

[c] NA = not available

Next, for each mixture, a dynamic modulus (E*) master curve at a reference temperature of 20°C was obtained using the Asphalt Mixture Performance Tester (AMPT). The E* master curve of the control mixture was also measured and used to calibrate the Hirsch model. This calibrated Hirsch model was then used to estimate a set of E* master curves for each mixture from its corresponding set of (G*) master curves and various mixture properties. Each measured E* master curve was then compared to its corresponding set of estimated E* master curves to quantify degree of blending.

To validate the results of the degree of blending analysis and to assess the cracking susceptibilities of mixtures, the following tests were carried out: four-point flexural beam fatigue, Semi-Circular Bending Beam (SCB) and Disc-Shaped Compact Tension (DCT).

5.1 Asphalt Binder Master Curve (G*)

A master curve is a plot that summarizes the values of complex modulus (G*) at varying frequencies. Limited capabilities of experimental equipment to run cyclic loading tests at frequency ranges other than 0.01 to 100 rad/sec (or Hertz) have compelled researchers to make use of time-temperature superposition principal. In that, if measurements of a material's response are made at varying temperatures, shifting the measured values to a reference temperature would cover a wider range of frequency. A functional form can then be fitted into the shifted data to form a single smooth plot of G* versus frequency (or equivalently temperature) known as a master curve. For this study, frequency sweep tests from 0.01 to 100 rad/sec at temperatures of 10, 22, 34, 46, 58, and 70°C were used to construct master curves at reference temperature of 20°C. Arrhenius and modified Williams-Landel-Ferry (WLF) by Kealble are two shift factor equations at colder and warmer temperatures, respectively, commonly used to construct master curves (Equations 1 and 2). Standard sigmoid function (Equation 3) with a higher asymptote has been shown to best describe the behavior of a binder master curve. A simultaneous solution of the shift factor equations and a functional form will result in the general shape of master curves (*21*). Figure 1 shows the master curves for all assumed blending proportions fabricated from mixing aged and virgin binder as described earlier. From Figure 1, the effect of adding more recovered binder to virgin binder is evident as they have higher values of G* at same frequencies.

$$\boldsymbol{Arrhenius}: \boldsymbol{loga_T = a + b\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)} \tag{1}$$

$$\boldsymbol{Kealble\ Modification\ of\ WLF}: \boldsymbol{loga_T = -\frac{C_1(T-T_{ref})}{C_2+|T-T_{ref}|}} \tag{2}$$

$$Standard\ Sigmoid: logG^* = \delta + \frac{\alpha}{[1+\lambda e^{\beta+\gamma(log\omega)}]^{1/\lambda}} \tag{3}$$

<u>Where:</u>
a_T = shift factor,
T = temperature (Kelvin),
T_{ref} = reference temperature (Kelvin),
ω = frequency (Hz), and
Other variables are constants.

5.2 Asphalt Mixture Master Curve (E*)

Specimens 150mm in height and 100mm in diameter were cored and cut from original samples fabricated in the SGC. Using AMPT and following AASHTO PP61-13, a haversine wave of loading is applied to measure the dynamic modulus which is the ratio of peak stress to peak strain. Each sample was tested at 4°, 20°, and 40°C at frequencies of 10, 1, 0.1, and 0.01 Hz. Dynamic modulus data were then shifted at 20°C to create master curves for mixtures. The Arrhenius equation is thought to provide a good estimation of shift factors for asphalt mixtures (Equation 2). Equation 4 is also a general logistic sigmoid form to fit the shifted points into one smooth graph (Figure 2) (*21*). Variables in this equation are as described earlier. Figure 2 indicates the stiffer binder from RAS made the master curve of 5% RAS to be higher than 15% RAP, which itself is slightly higher than Control. This observation indicates that the effect of blending could be significant even for mixtures containing RAS.

$$logE^* = \delta + \frac{\alpha}{1+e^{\beta+\gamma(log\omega)}} \tag{4}$$

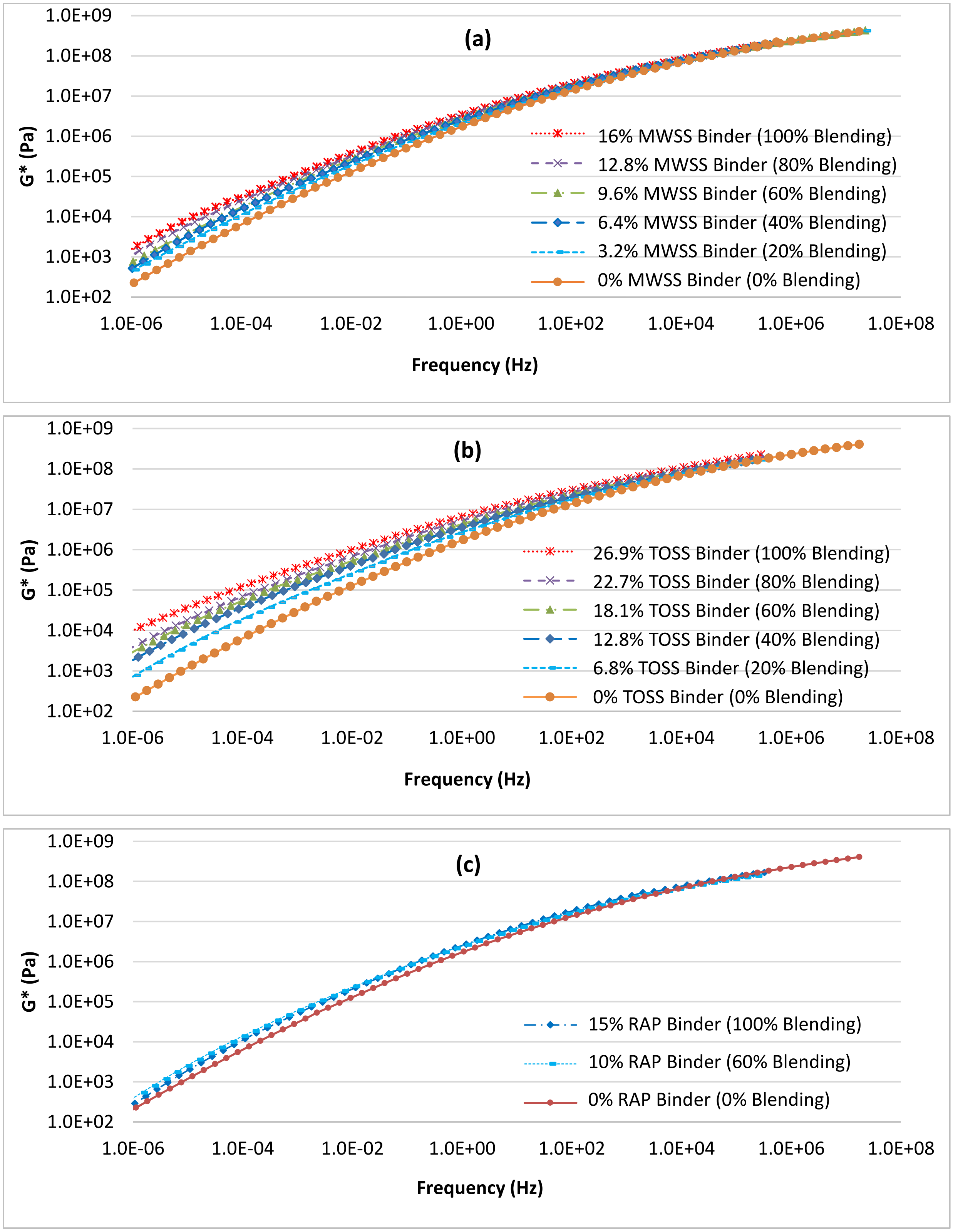

FIGURE 1 Asphalt binder master curves at 20°C for various degrees of blending of virgin binder and recovered binder from (a) MWSS, (b) TOSS, and (c) RAP.

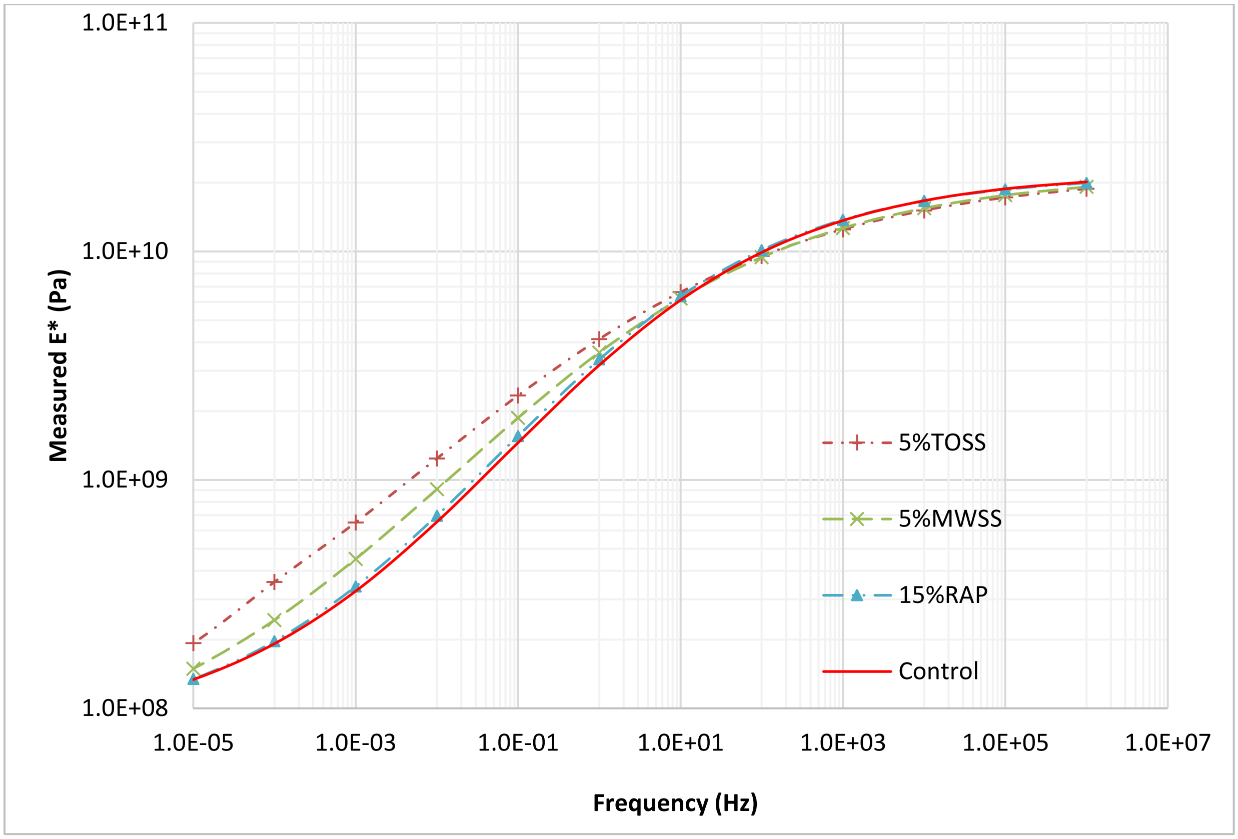

FIGURE 2 Asphalt mixture master curves at reference temperature of 20°C.

5.3 Estimation of E* from Hirsch Model

Modulus is the link between load and deformation, which all mechanical properties of a structure depend on. For temperature-dependent viscoelastic materials like asphalt mixtures, the complex modulus is defined to account for the effect of loading time and temperature. Both aggregate skeleton and asphalt binder influence mixtures' modulus. The Hirsch model represents a relationship between mixture dynamic modulus (|E*|) and asphalt binder shear modulus (|G*|) (Equations 5 and 6). This model is valid only if same temperature and same frequency be used for binder and mixture, and the model is most accurate at intermediate frequencies and temperatures (*16*, *17*).

$$|E^*|_m = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G*|_b\left(\frac{VMA\times VFA}{10{,}000}\right)\right]+\frac{(1-P_c)}{\frac{1-VMA/100}{4{,}200{,}000}+\frac{VMA}{3|G*|_b(VFA)}} \tag{5}$$

$$P_c = \frac{\left(20+3|G*|_b{}^{(VFA)}/_{(VMA)}\right)^{0.58}}{650+\left(3|G*|_b{}^{(VFA)}/_{(VMA)}\right)^{0.58}} \tag{6}$$

<u>Where:</u>

$|E^*|_m$ = asphalt mixture dynamic modulus, psi,

$|G^*|_b$ = asphalt binder complex shear modulus, psi,

VMA = voids in mineral aggregate,

VFA = voids filled with asphalt, and

P_c = aggregate contact volume.

Back calculation of |G*| from Hirsch equation is a method to determine whether blending takes place. Degree of blending has been qualitatively assessed for mixtures containing RAP in some studies. However, in most cases extraction and recovery has been made on the mixtures that undergone the dynamic modulus test (*5, 11, 18*). The main disadvantage of this approach is that the virgin and aged binder will dissolve together and form a homogenous binder that represents only 100% blending scenario. Thus, some attentions have been drawn to artificially make different ratios of recycled asphalt binder and virgin binder to investigate the effect of several degrees of blending on the performance grade of asphalt binders (*12, 19*).

The original Hirsch model proposed by Christensen et al. made use of a database containing limited measured values of E* and G*. Moreover, no detailed information is provided by the developers of this model that can be used to evaluate its applicability to any specific mixture design. Level of binder aging, type of aggregates and gradation, mixing and conditioning temperatures of mixtures used to fabricate dynamic modulus samples, and volumetric properties of the mixtures are some of the factors that may affect the validity of the Hirsch model. In this essence, the original Hirsch model could be incapable of accurately estimate E* from G* for all mixtures. To overcome probable shortcoming of the original model, local calibration of the model was completed based on the Control mixture and virgin binder used in this study. Equations 7 and 8 reformulate the Hirsch model to replace constant values with parametric variables.

$$|E*|_m = P_c\left[a_1\left(1-\frac{VMA}{100}\right)+3|G*|_b\left(\frac{VMA\times VFA}{10{,}000}\right)\right]+\frac{(1-P_c)}{\frac{1-{}^{VMA}/_{100}}{a_1}+\frac{VMA}{3|G*|_b(VFA)}} \tag{7}$$

$$P_c = \frac{\left(a_2+3|G*|_b{}^{(VFA)}/_{(VMA)}\right)^{a_4}}{a_3+\left(3|G*|_b{}^{(VFA)}/_{(VMA)}\right)^{a_4}} \tag{8}$$

Since the Control mixture dynamic modulus samples in this study were fabricated using only a virgin binder, substitution of binder master curve data into the Hirsch model should produce an accurate estimation of its associated mixture master curve. Calibration of the Hirsch model was completed based on the hypothesis that measured master curve for the Control mixture must match the predictions from the model. Using the Solver tool in Microsoft Excel, the sum of squared errors between prediction and observation were minimized to optimize new coefficients of the Hirsch model (see Equations 9 and 10). This model was used for calculations of the E* values in the next section. Since a unique JMF was followed to design mixtures in this study, this local calibration is more accurate as it contains the properties of the aggregate structure (gradation and modulus) used to produce mixtures. Constants in the calibrated Hirsch model were not significantly different than the original model proposed by its developers which shows the strength of this formulation and its reliance on only one volumetric property of the mixture, VMA.

$$|E*|_m = P_c\left[3{,}954{,}491\left(1-\frac{VMA}{100}\right)+3|G*|_b\left(\frac{VMA\times VFA}{10{,}000}\right)\right]+\frac{(1-P_c)}{\frac{1-{}^{VMA}/_{100}}{3{,}954{,}491}+\frac{VMA}{3|G*|_b(VFA)}} \tag{9}$$

$$P_c = \frac{\left(307+3|G*|_b{}^{(VFA)}/_{(VMA)}\right)^{0.834}}{10{,}159+\left(3|G*|_b{}^{(VFA)}/_{(VMA)}\right)^{0.834}} \tag{10}$$

6.0 DEGREE OF BLENDING ANALYSIS AND RESULTS

Mixture dynamic modulus measurements along with the mixture volumetric properties satisfies the requirement for two of the Hirsch model inputs. To calculate the values of E* from the Hirsch model, for each mixture of 5%MWSS, 5%TOSS, and 15%RAP, all binder master curves were substituted into the model from Figures 1-a, 1-b, and 1-c, respectively. As a result, mixture master curves were estimated based on different blending proportions. As explained previously, each blending proportion of virgin and aged binder was equivalent to an assumed degree of blending from a mixture perspective. Refer to Table 3 for details on equivalent degrees of blending for each blending proportion.

Figure 3 shows the results derived from substituting binder dynamic modulus (G*) into the Hirsch model to estimate E*. This figure also indicates the E* values measured from the AMPT device. This figure is limited to frequencies of 1 to 10Hz to avoid using extrapolated values in the analysis. Mid-range frequency acts as an average value for the measurements carried out on the complex moduli. Therefore, to establish an average degree of blending through the mixture, only the frequencies that fall in a range that all measurements are taken may result in the most precise region of a master curve. In addition, the Hirsch model seems to produce the most reliable results at the intermediate temperature regimes.

From Figure 3-a, experimentally measured master curve of the 5%MWSS is plotted along with the predicted master curves for various degrees of blending. Figures 3-b and 3-c are also demonstrating the same concept but for 5%TOSS and 15%RAP mixtures, respectively. It was estimated that between 20% to 40% of binder from 5%MWSS was activated in the mixture, whereas less than 20% was activated for 5%TOSS. Activation of RAP binder was estimated at less than 60% for the 15%RAP mixture.

Several interpretations could be concluded from these results. First, the degree of blending is more for RAP than RAS, which was expected beforehand. Asphalt binder from RAP is less oxidized than RAS which in turn causes the stiffness of RAS binder to be much higher. Moreover, a higher binder content from RAS appears to result in a thicker binder film around its particles. Both of which may explain reasons for higher degree of binder blending from RAP. Similarly, degree of blending for TOSS is observed to be lower than MWSS which could be addressed to higher stiffness of the binder from the former compared to the latter. Higher binder content of TOSS could also result in a thicker film of binder around stone particles that may share a part in its lower degree of blending.

Second, although having lower degree of blending, RAS could be more detrimental than RAP in a mixture. Degree of blending by itself will not show the priority of one mixture to another, but the characteristics of the aged binder from RAS or RAP plays a prominent role. Assume the degree of blending for 5%MWSS, 5%TOSS, and 15%RAP are rounded up to 40, 20, and 60%, respectively. In the same order, from Table 3 and assuming a linear blending chart their true performance grades would bePG73.7(17.95)-28.2, PG72.8(18.55)-27.8, and PG72(18.32)-28.9. Therefore, it appears that the effect of adding RAS to mixtures is more noticeable at low temperatures than at intermediate when compared to RAP. No significant difference is observable at intermediate temperature; however, the effect of TOSS on fatigue properties of the mixture seems to be the most severe as the intermediate PG is higher. At high temperature, addition of recycled materials improves the rutting resistance as previously discussed by many researchers. Subsequent sections present mechanical cracking tests on the mixtures designed in this study is investigated to further examine the results of the methodology proposed.

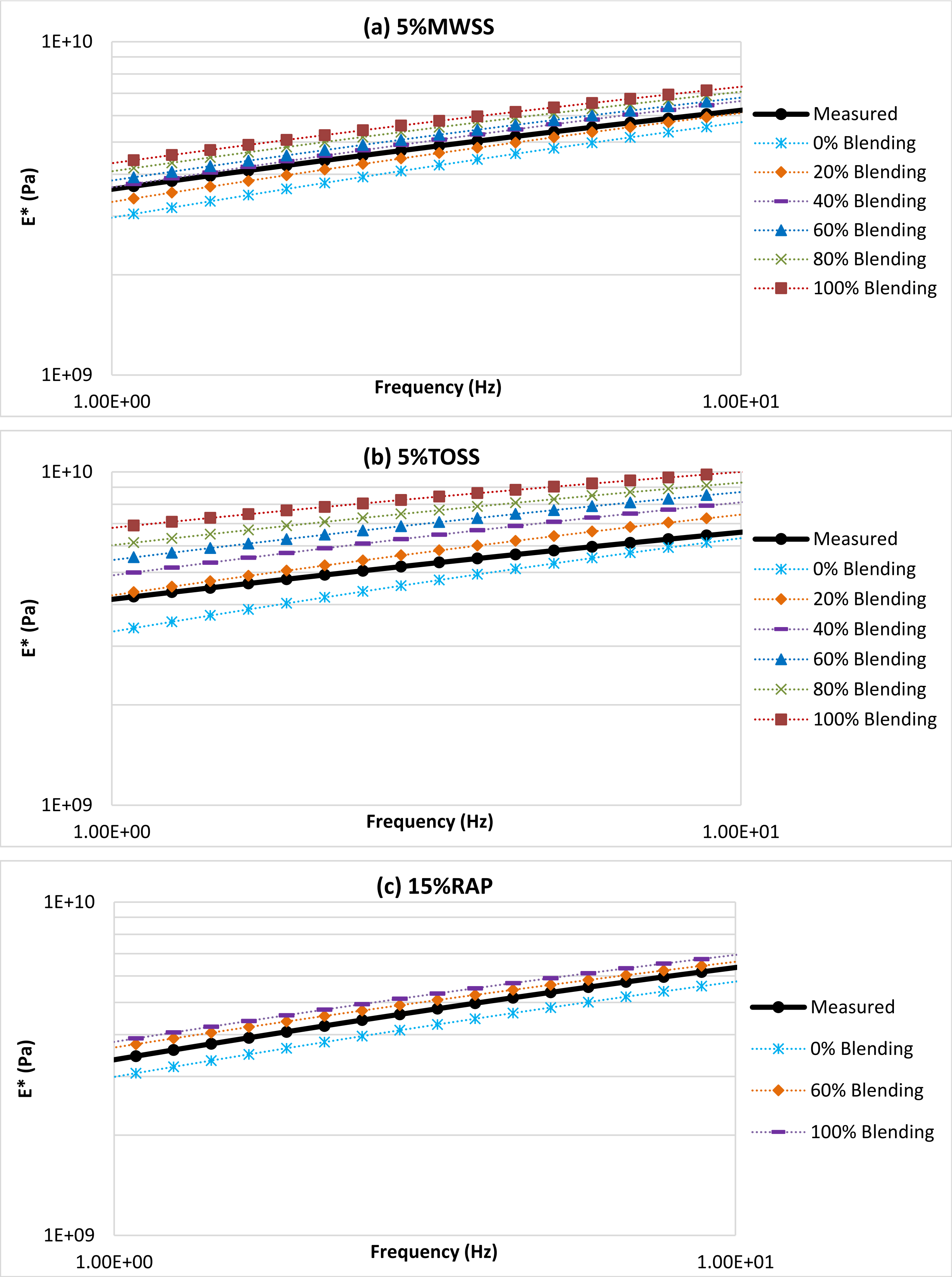

FIGURE 3 Degree of blending analysis for (a) 5%MWSS, (b) 5%TOSS, and (c) 15%RAP.

7.0 MIXTURE CRACKING TESTS

Cracking of asphalt pavements due to cyclic traffic load and environmental circumstances has been under investigation of researchers in recent decades. With the use of additives and recycled materials, the mechanical behavior of pavement has become even more complicated. Cracks seem to initiate from tearing apart binder bonds at the weakest point in terms of tension, and then propagates mainly from the mastic phase of the mixture. Asphalt binder, in this essence, plays a major role in studying cracking phenomenon. In addition, when including RAS or RAP into mixtures and due to partial blending, the PG of the resultant binder would be neither the same as the virgin binder nor the aged binder. To shed more lights on the effect of partial blending on the mechanical behavior of mixtures at intermediate and low temperatures, cracking performance tests were carried out in this study.

7.1 Crack Initiation: Four-Point Flexural Beam Fatigue Test

To investigate the fatigue cracking potential of the asphalt mixtures, a four-point beam fatigue test was carried out following ASTM D7460-10. The IPC Pressbox was used to compact slabs that were 450mm×150mm×150mm. The testing beams, 380mm×63mm×50mm, were cut from the slabs. The target air voids of final beams were set to 7%. A strain-controlled mode used to run the test at two strain levels of 500 and 750 micro strains and at temperature of 15°C. Flexural stiffness is the ratio of maximum tensile stress to maximum tensile strain and was computed for every 10 successive cycles.

The number of cycles to failure for the two strain levels are defined as the number in which flexural stiffness at the mid-span of beams exceeds half of its initial value. Excessive brittleness coming from aged binder of RAS or RAP influences the mixture performance under fatigue loading. Figure 4 indicates lower reduced number of cycles to failure for mixtures with RAS and RAP which was as expected. A same trend was also observed for the proposed degrees of blending in previous section. Intermediate true PG of the binders yielded same conclusions as observed in the beam fatigue results. In that, equivalent true PG's for the 5%MWSS, 5%TOSS, and 15%RAP were determined as 17.95, 18.55, and 18.32°C, respectively. The higher the intermediate true PG, thus, implies that less resistance is expected due to cyclic fatigue loads. However, closeness of true intermediate PG for the proposed degrees of blending of RAS and RAP binder suggests that the behavior of their mixtures should not be significantly different. This in fact explains why the differences in number of cycles to failure for mixtures are insignificant.

7.2 Crack Propagation: Semi-Circular Bending Beam Test (SCB) and Disc-Shaped Compact Tension Test (DCT)

Capability of a mixture to withstand crack propagation is another parameter influenced mostly by binder properties. In SCB test setup, a semi-circular sample with a thickness of 50mm and target air void of 7% is notched at its center to artificially create the crack (AASHTO TP 105-13). It is alleged that an intermediate temperature of 25°C and a loading rate of 50mm/min can depict differences with higher reliability (*3, 22*). The DCT test also evaluates the cracking potential of an asphalt mixture at low temperatures when a crack is already started. According to ASTM D7313-13, a disk-shaped specimen 50mm in thickness and 7% target air void is notched at one end and load is applied from two holes cored on each side of the notched crack to simulate a tension mode around the crack tip. A crack opening displacement rate of 0.017mm/s at -18°C was used for this research.

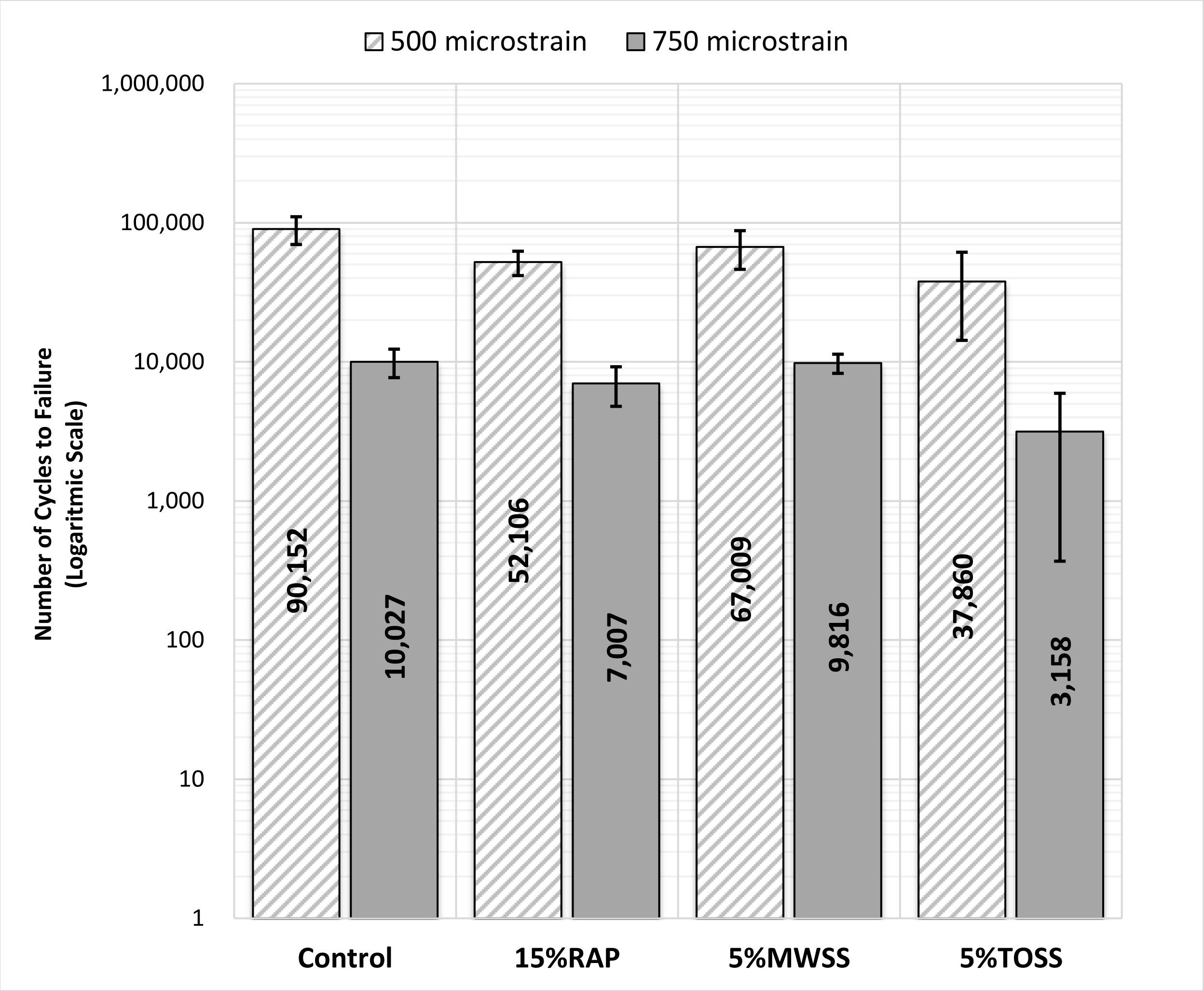

FIGURE 4 Flexural beam fatigue test results.

Loading is then applied against the notch and causes the crack to propagate through the whole section of specimens. The data collected are the load amplitude and resulted deformation. Fracture energy, which is the area under the load-displacement curve, has been measured as the only output of both the SCB and DCT test. Nevertheless, researchers at Illinois Center for Transportation have recently developed a parameter called Flexibility Index (FI), believing that this index would better distinguishes between mixtures. This index takes into account the post peak behavior of mixtures by considering the slope of load-deformation curve after its peak has reached.

Figure 5 illustrates the FI and fracture energy results for SCB and DCT, respectively. A significant difference between FI for Control and 5% RAS mixtures may explain the adverse effects of adding RAS into mixtures. Despite higher degree of blending between RAP and virgin binder, lower stiffness of RAP binder compared to RAS could have caused the RAP to be more resistant to crack propagation at intermediate temperatures. Lower fracture energies from DCT results for mixtures containing RAS or RAP further indicate a disadvantage of adding recycled materials at low temperatures. However, standard deviations of DCT test results show no statistically significant difference.

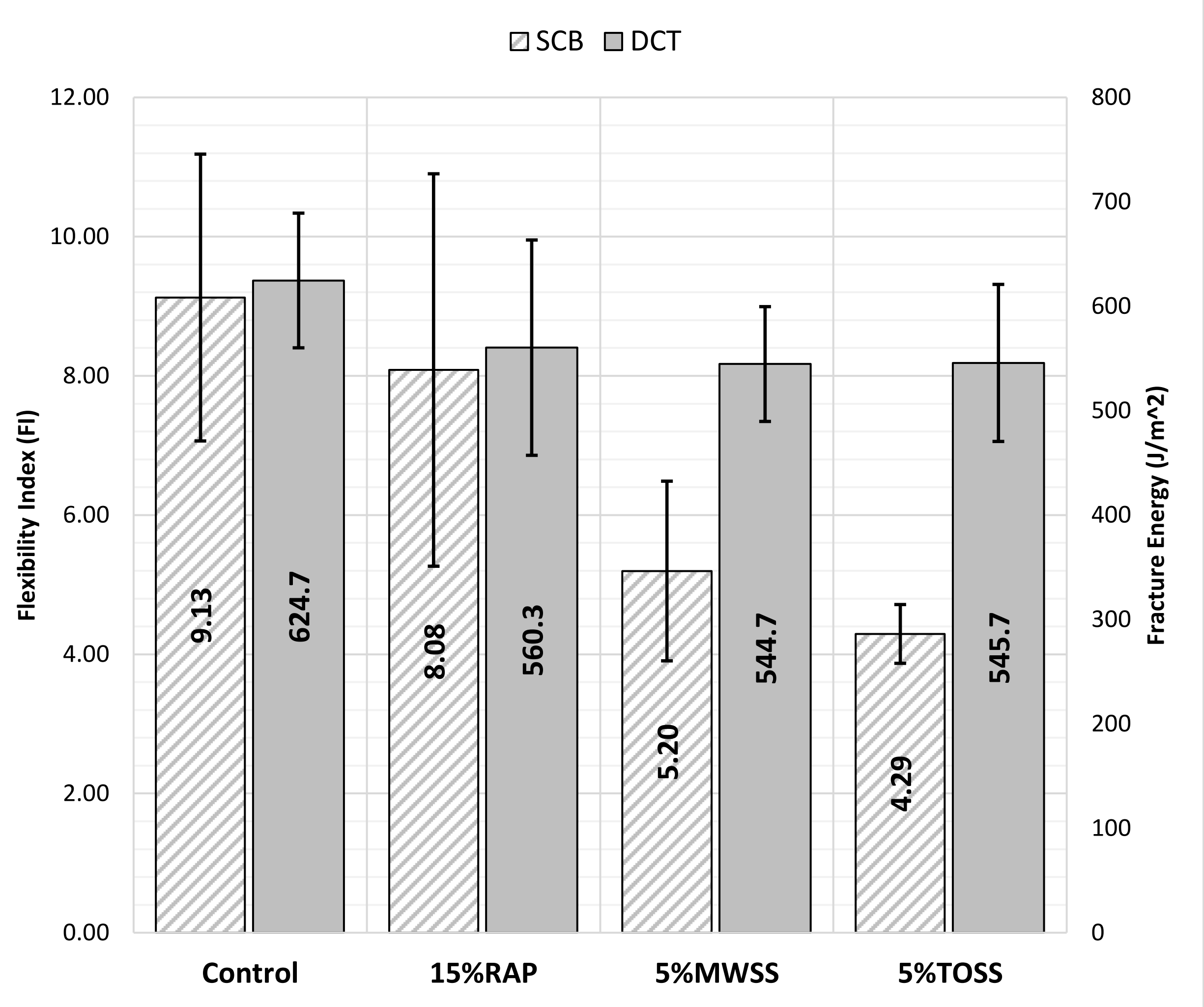

FIGURE 5 SCB and DCT results.

Nevertheless, one cannot neglect the fact that under-asphalting would also affect the results when RAS is added to a mixture. A combination of under-asphalting and partial blending can then justify the lower cracking resistance of mixtures produced with RAS and RAP. It is worthy of notice that as binder PG system used in this study does not account for crack propagation, it is not yet understood that how different binder degrees of blending can affect this type of distress in a binder rheology point of view. In other words, even knowing the exact degree of blending may not suffice to predict mixtures behavior in crack propagation.

Referring to the proposed degrees of blending and their true intermediate and low PG, similar conclusions to the beam-fatigue test results could be made. Running SCB at 25°C and DCT at -18°C should correlate with the true intermediate and low PG of the proposed degrees of blending. Continuous true PG of PG73.7(17.95)-28.2, PG72.8(18.55)-27.8, and PG72(18.32)-28.9 for 5%MWSS, 5%TOSS, and 15%RAP respectively can be compared to the one for virgin binder which was determined as PG69.8(16.97)-29.5. Since no more than three measurements made to calculate binder true PG, no statistical comparison is reasonable to be made on the temperatures. However, negative effects coming from the TOSS binder is still evident and more severe than the other two recycled materials. Crack propagation test results at both intermediate and low temperatures also support the hypothesis that PG of the proposed degrees of blending could be used as an indication of the mixture performance. Using higher percentages of recycled materials, on the other hand, may depict differences more clearly and is recommended for future research.

8.0 SUMMARY AND CONCLUSIONS

Based on the work conducted in this study, the following conclusions are made:

- In this study, a new method to quantify the amount of blending that occurs between aged RAS and RAP binders was developed. Local calibration of the Hirsch model was carried out by considering a control mixture containing only virgin materials. Asphalt binder master curves for assumed blending proportions were substituted into the calibrated model which results in an estimation of their corresponding asphalt mixture master curve.

- Using this method, it was estimated that around 20% to 40% of RAS binder from manufacturer's shingle waste was activated in the mixture, whereas less than 20% was activated for RAS binder from tear off shingles. Activation of RAP binder was estimated at 40 to 60%.

- Four-point beam fatigue, SCB, and DCT test configurations were implemented to further investigate the degree of blending results from a cracking perspective. In all cases a consistent trend was observed between the results of mixture cracking tests and the PG of the proposed degree of binder blending.

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