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Research Article

Engineering Behavior of Warm Mix Asphalt Mixtures

Peter E Sebaaly*, Elie Y Hajj and Murugaiyah Piratheepan

Department of Civil and Environmental Engineering, University of Nevada, USA

***Corresponding author:** Peter E Sebaaly, Professor, Department of Civil and Environmental Engineering, University of Nevada, Reno, USA

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Abstract

This paper presents the results of an extensive research that evaluated the laboratory characteristics of hot and warm mix asphalt mixtures manufactured with 100% virgin materials and with 15 and 35% recycled asphalt pavement. The overall objective of the study was to evaluate the engineering properties and performance characteristics of the mixtures while the specific objective was to assess the ability of the warm mix additives in allowing the use of higher content of recycled asphalt pavement without changing the performance grade of the virgin binder.

All mixtures were designed with the Marshall mix design method. The engineering properties consisted of the dynamic modulus master curve while the performance characteristics covered the mixtures resistances to moisture damage, rutting, thermal and fatigue cracking. The analysis of the data led to the following conclusions: warm mix additives were effective in moderating the increase in the engineering property of the mixtures containing 15 and 35% recycled asphalt pavement as compared to the hot mixtures without significantly reducing their resistance to rutting and thermal cracking, however, the warm mix additives were not capable of maintaining good resistance to fatigue cracking, therefore, the idea of using warm mix additives to allow higher recycled pavement in the asphalt mix is not supported by the measured resistance of the mixture to fatigue cracking.

Keywords: Warm mix; Recycled asphalt pavement; Marshall mix design; Dynamic modulus; Moisture damage; Rutting; Thermal and fatigue cracking

Introduction

Production of asphalt mixtures have always been challenging in terms of environmental friendliness and workers' health. Various efforts are taken to address these concerns in paving industry. One of the approaches taken is to maximize the use of Recycled Asphalt Pavement (RAP) in asphalt mixtures, which helps in minimizing the use of natural asphalt binder and aggregates. Another approach is replacing Hot Mix Asphalt (HMA) with Warm Mix Asphalt (WMA) technologies, that lowers the production and laying temperatures of asphalt mixtures.

The majority of the states in US started using WMA and over 20WMA technologies are available in the US market. Boriak et al. conducted a laboratory study to examine the effect of 20 and 40% RAP contents on asphalt mixtures when the optimum asphalt binder is increased by 0.5% [1]. Evaluation of the mixtures were based on dynamic modulus, rutting resistance, and fatigue resistance of the asphalt concrete (AC) mixtures. An increase of 0.5% in the optimum asphalt binder content in mixtures with 0% and 20% RAP improved rutting and fatigue resistance of the mixtures while maintaining similar dynamic modulus. However, a significant drop in rutting resistance with no change in fatigue resistance was observed in the case of mixtures with 40% RAP.

Hajj et al. conducted a laboratory evaluation for the use of RAP in HMA mixtures [2]. Rutting, fatigue and thermal cracking, and moisture resistance characteristics of the HMA mixtures with 15 and 30% of RAP contents from three different sources were included in the evaluation. For polymer-modified mixtures, the study concluded that mixtures with 15 or 30% RAP will have an acceptable moisture resistance, equivalent rutting resistance, but reduced fatigue cracking resistance regardless of the sources of RAP.

Loria et al. evaluated asphalt mixtures with high RAP content in terms of resistance to moisture damage and thermal cracking

[3]. Laboratory and field mixtures were compared based on their properties and performance. The research concluded that HMA mixtures with 50% RAP have acceptable resistance to thermal cracking and moisture damage. Measured Performance Grade (PG) temperatures from the recovered asphalt binder and the estimated critical temperatures from blending charts showed acceptable correlations. Overall, the study concluded that the resistance to moisture damage and thermal cracking of field produced asphalt mixtures can be evaluated from laboratory produced mixtures.

Objective and Scope

The objective of this study was to conduct comparative evaluations of mixtures that include various WMA technologies and different percentages of RAP. The research evaluated HMA and WMA mixtures from the "Spanish Springs" aggregate source, with three WMA technologies: Advera, Evotherm 3G, and Sonnewarmix and the HMA and WMA mixtures from the "Lockwood" aggregate source with the same three WMA technologies in addition to the Water Foam technology. Both aggregate sources are located in the northern part of the state of Nevada, USA and commonly used in the production of asphalt mixtures. All mixtures used the PG64-28NV polymer modified asphalt binder. Table 1 presents the summary of the experimental plan.

Table 1: Experimental Plan.

Aggregate Source	RAP Aggregate (%)	HMA	WMA-Advera	WMA-Evotherm	WMA-Sonne Warmix	WMA-Water Foam
Spanish Springs	0	X	X	X	X	--
	15	X	X	X	X	--
	35	X	X	X	X	--
Lockwood	0	X	X	X	X	X
	15	X	X	X	X	X
	35	X	X	X	X	X

Materials Characterization

Aggregates

Table 2: Gradations of Spanish Springs Aggregates.

Sieve Size	Percent Passing (%)				
	0% RAP	15% RAP	35% RAP	Control Points	
				Min	Max
25.0mm	100	100	100	100	100
19.0mm	99.9	99.9	99.9	90	100
9.5mm	78.4	79	78.5	63	85
4.75mm	58.4	58.8	55.5	45	65
2.00mm	36.6	39.3	37.3	30	44
0.425mm	16.2	17.6	18.2	12	22
0.075mm	6.6	6.7	7.3	3	8
Aggregate	**Description**		**Bin Percent**		
			0% RAP	**15% RAP**	**35% RAP**
Stockpile 1	19mm: Coarse Aggregate		20	20	20
Stockpile 2	12.5mm: Coarse Aggregate		25	22	23
Stockpile 3	Concrete Sand		5	12	5
Stockpile 4	Impact Sand		30	17	5
Stockpile 5	Wade Sand		20	14	12
Stockpile 6	RAP		0	15	35

Table 3: Gradations of Lockwood Aggregates.

Sieve Size	Percent Passing (%)				
	0% RAP	15% RAP	35% RAP	Control Points	
				Min	Max
25.0mm	100	100	100	100	100
19.0mm	100	100	100	90	100
9.5mm	80.3	79.7	83.6	63	85
4.75mm	59.2	57.9	59.8	45	65
2.00mm	39.3	41.5	41.6	30	44
0.425mm	16	19.4	19.9	12	22
0.075mm	5.6	5.6	7	3	8
Aggregate	**Description**		**Bin Percent**		
			0% RAP	**15% RAP**	**35% RAP**
Stockpile 1	19mm: Coarse Aggregate		15	15	10
Stockpile 2	12.5mm: Coarse Aggregate		10	10	10
Stockpile 3	9.5mm: Coarse Aggregate		20	16	12
Stockpile 4	Crusher Fines		45	27	23
Stockpile 5	Wade Sand		10	17	10
Stockpile 6	RAP		0	15	35

Aggregates used in this study were obtained from Spanish Springs and Lockwood sources. Five stockpiles of virgin aggregates and a RAP stockpile were used from each of the two aggregate sources. Aggregates blends were prepared from the aggregate stockpiles of each source that meet the Regional Transportation Commission (RTC) aggregate gradation specifications. Tables 2 & 3 present the bin percentages from the stockpiles and final gradation of the prepared blends. Specific gravity and relevant aggregate properties of various blends prepared are presented in the mix design summary. Difference in specific gravities among the stockpiles were less than 0.2, therefore, corrections of blend gradations were not required. Specific gravities of Spanish Springs aggregates were slightly higher than Lockwood aggregates. In addition, Lockwood aggregates had higher absorption compared to Spanish Springs aggregates. It should be noted that the aggregates were conditioned with hydrated lime for 48 hours prior to mixing process following the procedure specified in RTC specifications.

Asphalt Binder

The asphalt binder used for the study graded as PG64-28NV, which is a polymer modified asphalt binder. Performance grade (PG) of the asphalt binder was verified in the University laboratory following AASTHO M320 standard procedure. The actual grades for the asphalt binder were determined as 68.6 and -32.5 for the high and low temperatures, respectively. Range for mixing and compaction temperatures were provided by the supplier; 160 °C to 165 °C for mixing and 150 °C to 155 °C for compaction.

RAP Materials

RAP materials were collected from the Spanish Springs and Lockwood aggregate sources. Average asphalt binder contents for the Spanish Springs and Lockwood RAP were determined as 4.4% and 5.5% by dry weight of aggregate, respectively. Actual PGs for the Spanish Springs RAP binder were determined as PG87.9-27.8 whereas for the Lockwood RAP binder as PG85.3-26.3. Therefore, the standard PG of the RAP asphalt binders for both sources were identified as PG82-16. RAP aggregates were recovered and evaluated for gradation and specific gravity. The Nominal maximum size of both RAP aggregates was identified as 9.5mm. Absorption of the Lockwood RAP aggregates is higher than the absorption of the Spanish Springs RAP aggregates which was also the case for virgin aggregates**.**

Mix Designs

Nomenclature for the various mixtures were established according to the modification type and RAP aggregate percentage. For instance, HMAO, ADV15 and EVO35 represent HMA control mixture with no RAP, mixture with advera modification and 15 percent RAP, and mixture with evotherm modification and 35 percent RAP. Summary of the mixtures nomenclatures is presented in Table 4. Marshall Mix designs were conducted following the standard procedures established in the Asphalt Institute Manual "MS-2", and criteria meeting the RTC specifications which are presented in Table 5. Mixing and compaction temperatures for the control mixtures were considered as provided by the supplier. However, for the WMA mixtures, mixing and compaction temperatures were selected at 135 °C and 120 °C, respectively, which are also the recommendation provided by the WMA technology suppliers. Table 5 summarizes the mix design results for both aggregate sources, three level of RAP contents, and various WMA technologies. It can be observed that the optimum binder content (OBC) at a specified air voids are higher for the Lockwood aggregate which is explained by its high absorption capacity compared to Spanish Springs Aggregate. All mixtures satisfy the requirement criteria for VMA, VFA, Marshall Stability, and Marshall Flow.

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Table 4: Mixtures Nomenclatures.

Label	Warm Mix Technology	RAP Content, %	Remarks
HMA0	None	0	HMA Mix
HMA15		15	HMA Mix
HMA35		35	HMA Mix
ADV0	Advera	0	WMA Mix
ADV15		15	WMA Mix
ADV35		35	WMA Mix
EVO0	Evotherm 3G	0	WMA Mix
EVO15		15	WMA Mix
EVO35		35	WMA Mix
SON0	SonneWarmix	0	WMA Mix
SON15		15	WMA Mix
SON35		35	WMA Mix
FOM0	Water Foaming	0	WMA Mix
FOM15		15	WMA Mix
FOM35		35	WMA Mix

Table 5: d Summary of Marshall Mix Designs.

Source	Mix Type	Optimum Binder Content (%)	Air-Voids (%)	VMA (%)	VFA (%)	Marshall at 60 °C		Tensile Strength at 25 °C		
						Stability (N)	Flow (mm)	Dry (kPa)	Wet (kPa)	Ratio (%)
Specs		**NA**	**5-Mar**	**≥13**	**65-75**	**≥8000**	**2 – 5**	**≥450**	**NA**	**≥70**
Spanish Springs	HMA0	4.8	4	15	74	20000	2.8	1100	1065	97
	HMA15	4.9	4	15	73	21400	2.5	990	905	92
	HMA35	4.9	4.2	14	71	23100	3.3	1285	1055	82
	ADV0	4.7	4.9	16	70	15200	3.3	780	670	85
	ADV15	4.9	4.8	16	70	15600	3.1	855	745	87
	ADV35	5	4.3	15	71	17500	3.6	980	815	83
	EVO0	4.8	5	16	68	17200	3.3	910	855	94
	EVO15	5.4	5	17	70	12900	4.1	945	805	85
	EVO35	5	4.5	15	70	16400	3.3	905	780	87
	SON0	4.7	4.9	16	69	15000	2.5	805	655	81
	SON15	4.9	4.8	16	69	15500	3.1	775	745	97
	SON35	4.9	4.6	15	69	15900	3.3	665	760	100
Lockwood	HMA0	5.2	3.9	15	74	18100	3.8	770	760	94
	HMA15	5	3.8	14	72	23450	3.3	1075	940	87
	HMA35	5.2	3.9	13	70	23300	3.8	1350	1210	89
	ADV0	5.4	4.7	16	70	15100	4.6	690	600	87
	ADV15	5.2	4.2	15	70	16800	3.3	830	740	89
	ADV35	5.4	4.5	14	67	15700	4.6	1030	990	96
	EVO0	5.4	4.8	16	69	13100	4.1	720	685	95
	EVO15	5.2	4.2	14	70	15600	3.8	740	695	94
	EVO35	5.4	4.7	14	67	16600	4.3	1075	980	91
	SON0	5.4	4.8	16	69	13900	4.3	690	620	90
	SON15	5.2	4.3	15	70	14300	4.3	760	705	93
	SON35	5.4	4.8	14	66	14900	4.1	1065	920	86
	FOM0	5.4	4.4	15	70	14100	3.6	890	785	88
	FOM15	5.2	4.6	14	68	15700	3.1	830	800	97
	FOM35	5.4	4.9	15	65	13000	4.3	1152	1035	90

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For the Spanish Springs mixtures, the OBC for WMA mixtures with RAP were greater or similar to the HMA control mixtures. WMA mixtures were observed to have higher percentage of air voids at OBC than HMA control mixtures. It was also observed that, except for HMA control mixtures, air voids at OBC decreased with the increase in RAP content. Marshall Stability was observed to be increasing with the increment in RAP content. Also, WMA mixtures exhibited lower Marshall Stabilities compared to HMA mixtures. HMA mixtures have shown higher Marshall Flow than the WMA mixtures. However, a clear trend was not observed for the Marshall Flow with the percentage of RAP.

In the case of Lockwood mixtures, air voids at OBC for the HMA mixtures were observed lower than WMA mixtures. WMA mixtures had OBC higher than HMA mixtures by 0.2%, at all levels of RAP content. It was interesting to observe that the OBC for the 0 and 35% of RAP were similar, but the mixtures with 15% RAP had lower OBC. Trend for the Marshall Stability was similar to Spanish Spring mixtures. However, it was interesting to observe that the flow for mixtures with 15% RAP was lower than for the 0 and 35% RAP mixtures.

Coating of WMA Mixtures

Coating of aggregates in the WMA mixtures were determined following the AASTHO T195 standard procedure (AASHTO 2018). Unaged samples were checked for coating criteria of minimum 95% of the coarse aggregate that must be fully coated. All of the mixtures satisfied the aggregate coating criteria.

Moisture Sensitivity

Moisture sensitivity of all HMA and WMA mixtures were evaluated following the AASHTO T283; "Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage" as briefly summarized below:

I. Separate the compacted samples into two groups with similar air voids: unconditioned and moisture-conditioned.

II. Measure the TS of the unconditioned group at 25 °C.

III. Subject the moisture-conditioned samples to the following:

IV. 75% saturation

V. Subject the saturated samples to a freeze-thaw cycle consisting of freezing at -16 °C for 16 hours followed by 24 hours thawing at 40 °C and 2 hours at 25 °C.

VI. Measure the TS after the freeze-thaw cycle at 25 °C.

VII. The TSR is calculated as the ratio of the average moisture-conditioned TS over the average unconditioned TS times 100.

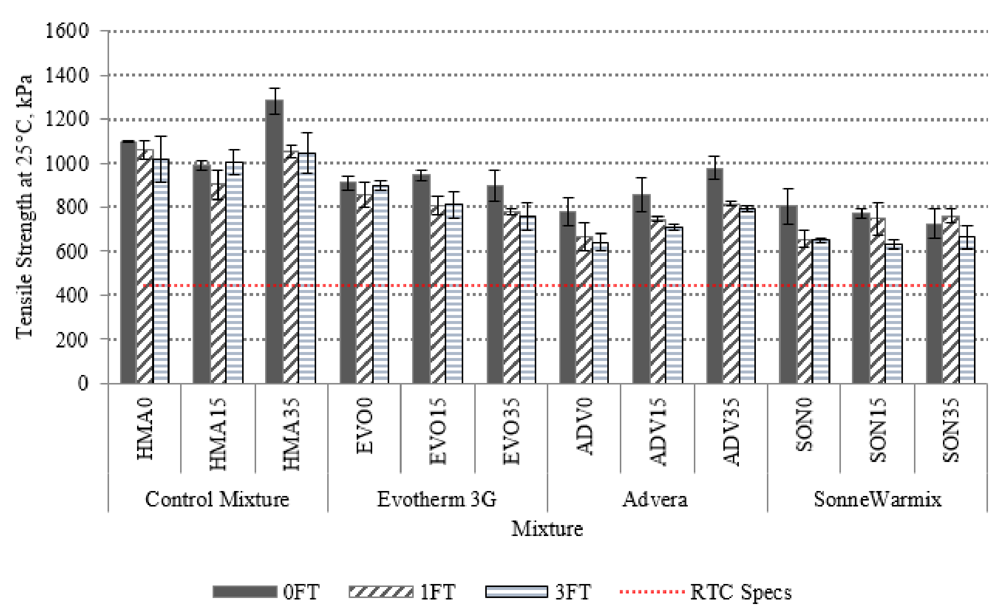

Figure 1: Tensile Strength at 0, 1, and 3 F-T Cycles for the Spanish Springs Mixtures.

Figures 1 & 2 present the tensile strength properties and the tensile strength ratio of the Spanish Springs mixtures, respectively. The Spanish Springs mixtures were evaluated after 1 and 3 FT cycles to assess the impact of multiple FT cycling on the moisture sensitivity of the mixtures. The average values are also summarized in Table 5. The bars in the Figures represent the averages while the whiskers represent the 95% confidence interval. Overlapping confidence intervals among mixtures indicate that the measured TS are statistically similar. The difference in tensile strength values between the 1 and 3 FT cycles was not statistically significant. This is can be attribute to the lime treatment of all mixtures. Therefore, the Lockwood mixtures were only subjected to 1 FT cycle. Figures 3 & 4 present the tensile strength properties and the tensile strength ratio of the Lockwood mixtures, respectively.

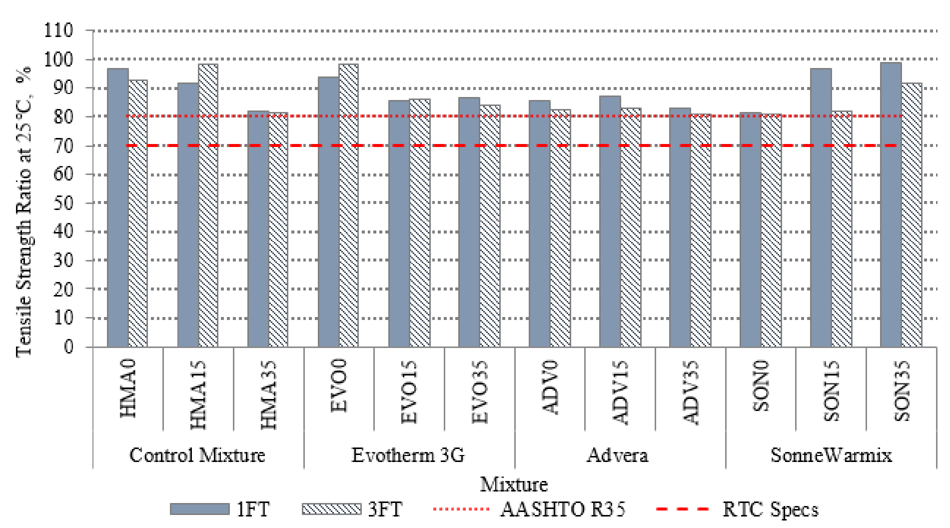

Figure 2: Tensile Strength Ratio after 1 and 3 F-T cycles for the Spanish Spring Mixtures.

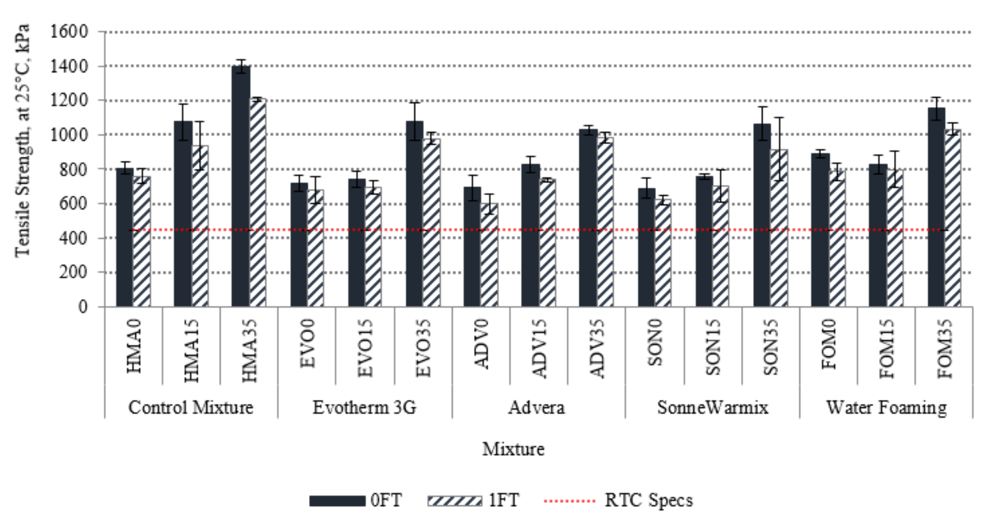

Figure 3: Tensile Strength at 0 and 1 Freeze/Thaw Cycles for the Lockwood Mixtures.

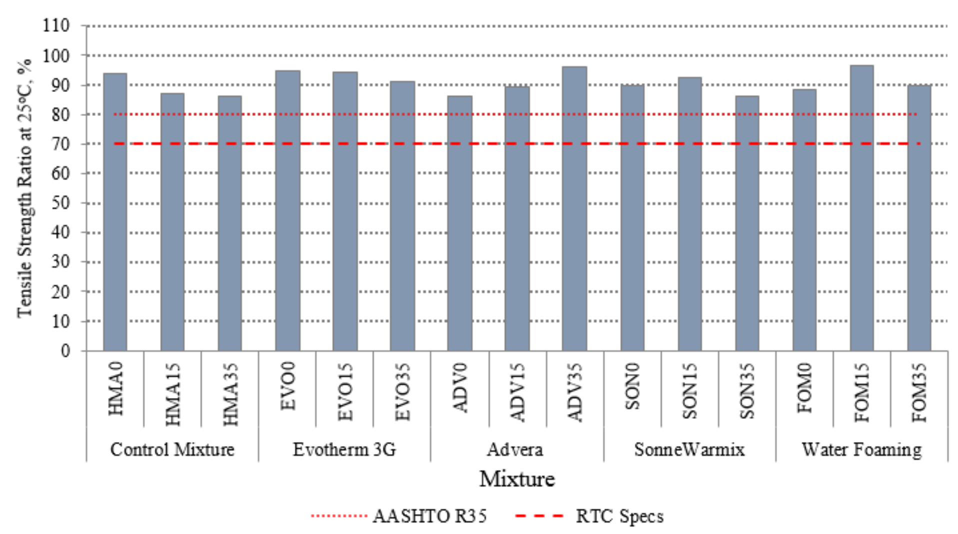

Figure 4: Tensile Strength Ratio after 1 F-T Cycle for the Lockwood Mixtures.

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In the case of the Spanish Springs source, all mixtures exhibited tensile strength higher than the RTC specification requirement of a minimum of 450kPa at 25 °C. Two main observations were made from the results. First, HMA mixtures had higher tensile strength values than WMA mixtures. Second, tensile strength increased with the increase in percentage of RAP. Tensile strength ratios for the mixtures were greater than the RTC specification requirement (70%) and AASHTO R35 (Superpave) requirement (80%). No clear trends were observed in the tensile strengths with the variation in WMA technology and RAP contents. Few minor variations in the above mentioned results can be observed which might have been introduced by differences in asphalt binder content and volumetric properties, and the variability in the test itself.

In the case of Lockwood source, tensile strength results of various mixtures were similar to the trends shown in Spanish Springs mixtures. However, water foaming mixtures had slightly higher tensile strength than other WMA mixtures. All of the mixtures satisfied the RTC standard specifications of minimum dry tensile strength of 450kPa and minimum tensile strength ratio of 70% at 25 °C. Hence, no significant difference in the tensile strength properties were observed between the two sources of aggregates.

Engineering Property: Dynamic Modulus

The AASHTO Mechanistic-Empirical Design (M-E Design) uses the dynamic modulus (E*) master curve to evaluate the structural response of the asphalt pavement under various combinations of traffic loads, speed, and environmental conditions. The dynamic modulus of various mixtures were measured according to “AASHTO TP 79: Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).” The E* tests were conducted on 100mm diameter by 150mm cylindrical specimens cored from the centre of sample compacted in the Superpave gyratory compactor (SGC). The test is conducted at frequencies of: 25, 10, 5, 0.5, 0.1Hz and at temperatures of: 4, 21, 40, and 54 °C. Using the visco-elastic behaviour of the asphalt mix (i.e. interchangeability of the effect of loading rate and temperature) the master curve is constructed and can be used to identify the appropriate E* for any combination of pavement temperature and traffic speed.

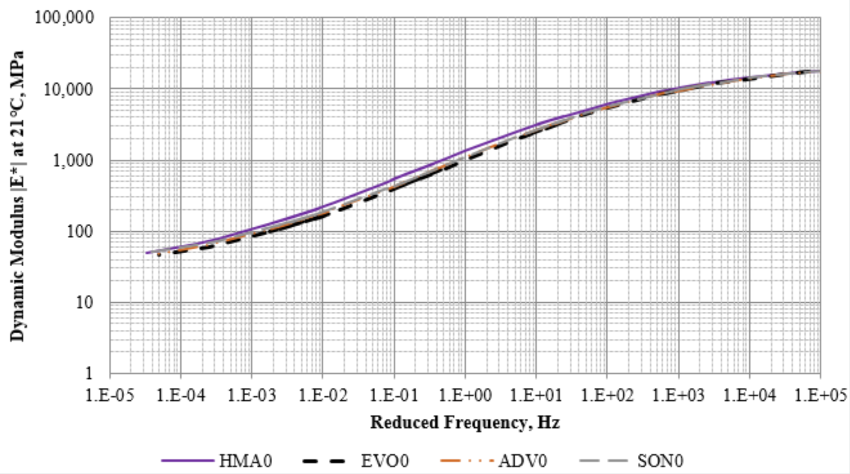

Figure 5: Master Curves for Spanish Springs Mixtures with 0% RAP Content.

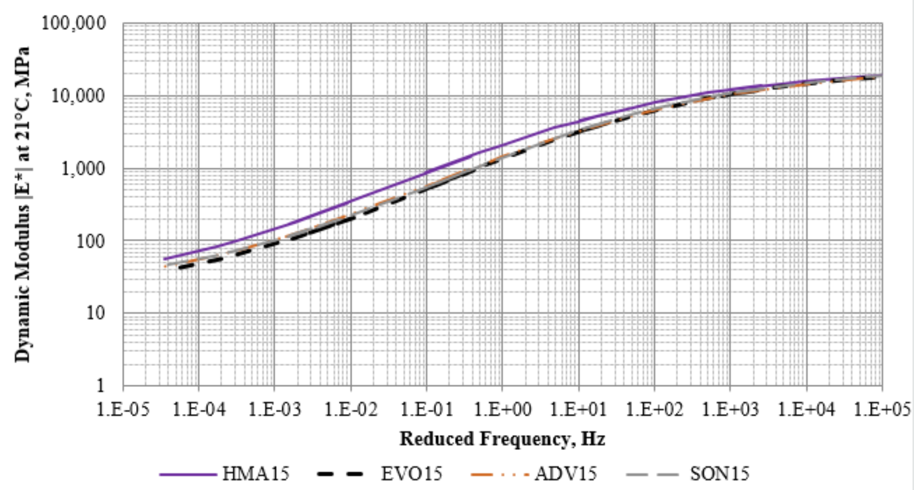

Figure 6: Master Curves for Spanish Springs Mixtures with 15% RAP Content.

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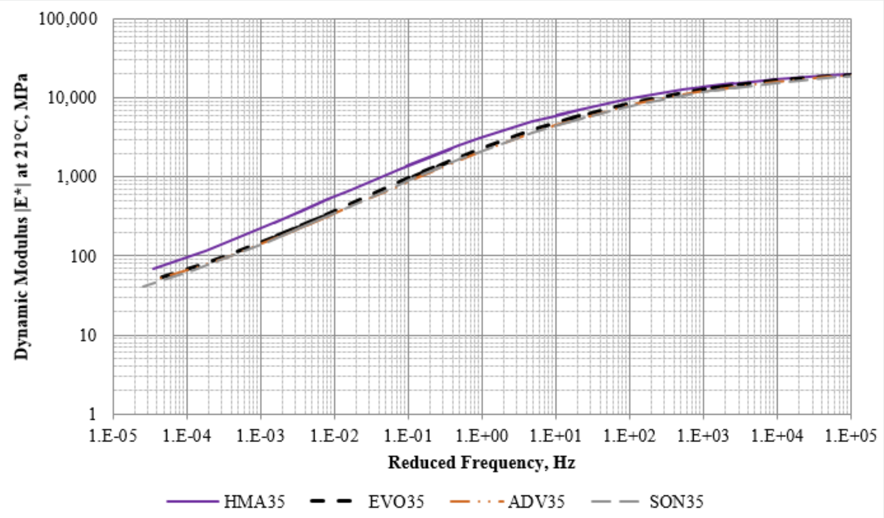

Figure 7: Master Curves for Spanish Springs Mixtures with 35% RAP Content.

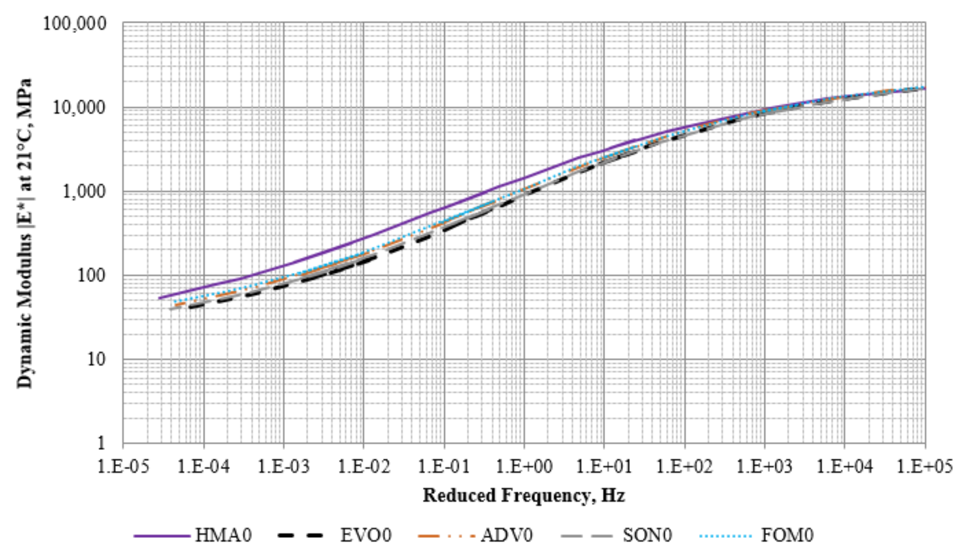

Figure 8: Master Curves for Lockwood Mixtures with 0% RAP Content.

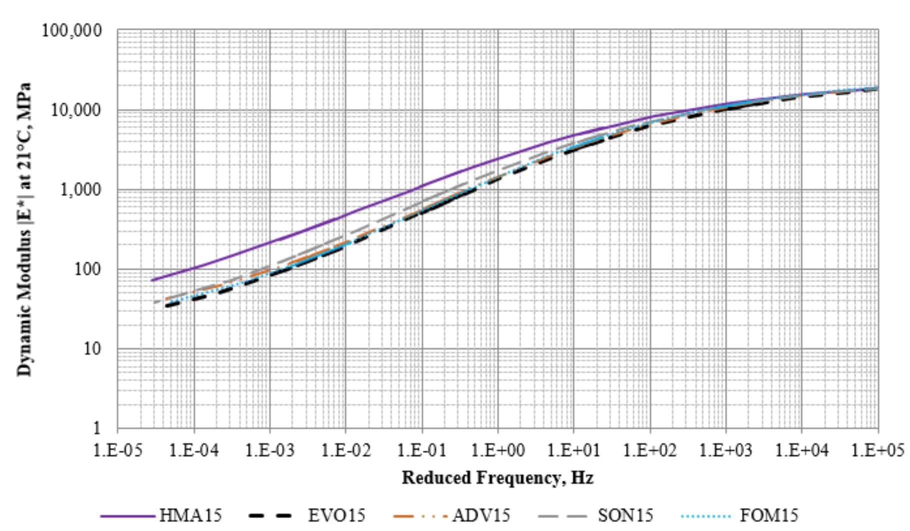

Figure 9: Master Curves for Lockwood Mixtures with 15% RAP Content.

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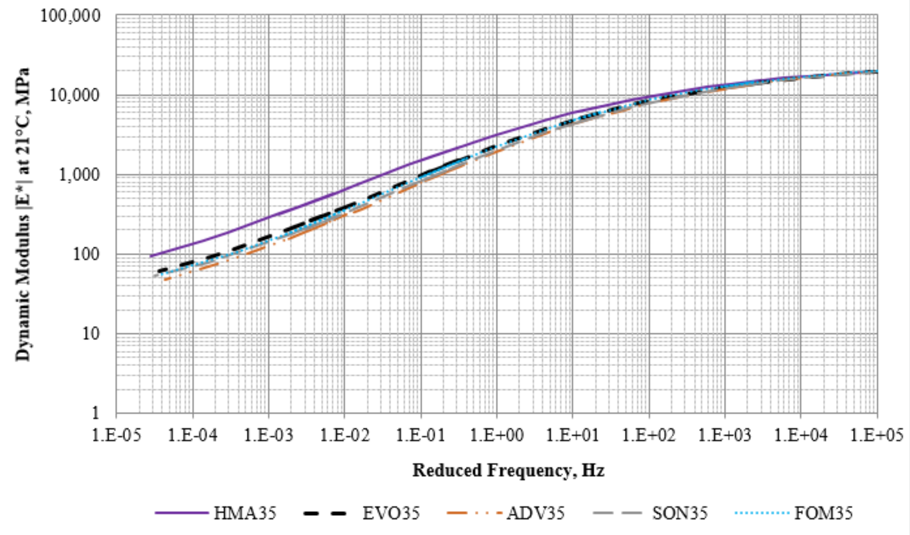

Figure 10: Master Curves for Lockwood Mixtures with 35% RAP Content.

Figures 5-10 present the dynamic modulus master curves for 0, 15 and 35 percent RAP contents for Spanish Springs and Lockwood mixtures. In the case of Spanish Springs mixtures, it can be observed that the dynamic modulus curve for HMA control mixtures are above WMA mixtures. This means, that the modulus of HMA control mixtures at a selected temperature and frequency will be higher than WMA mixtures. Another interesting point to observe is that the master curves of HMA control mixtures are shifted upwards for RAP mixtures. This means, with RAP in a mixture, dynamic modulus is significantly dropped with WMA additives. It should be noticed that the master curves are plotted in log scale, meaning that even a small change of value in curve is significant.

Similar to the trend of Spanish Springs mixtures, the use of WMA additive in Lockwood RAP mixtures, will drop the dynamic modulus value at a given temperature and frequency. However, master curves of WMA mixtures can be visualized more distinctly, i.e. they do not overlap as much as in the case of Spanish Springs mixtures. At a certain temperature and frequency, dynamic modulus values of Water foaming, Sonnewarmix and Evotherm mixtures are higher than the Adera WMA mixture for all 0, 15 and 35 percent RAP contents.

Figures 11 & 12 present the dynamic modulus values of various mixtures at 10Hz and at temperature of 20°C representing typical truck speed and critical temperature for fatigue cracking of asphalt pavements, respectively. The whiskers on top of the bars represent the 95% confidence interval of the measured values. Mixtures from both sources exhibited similar trends;

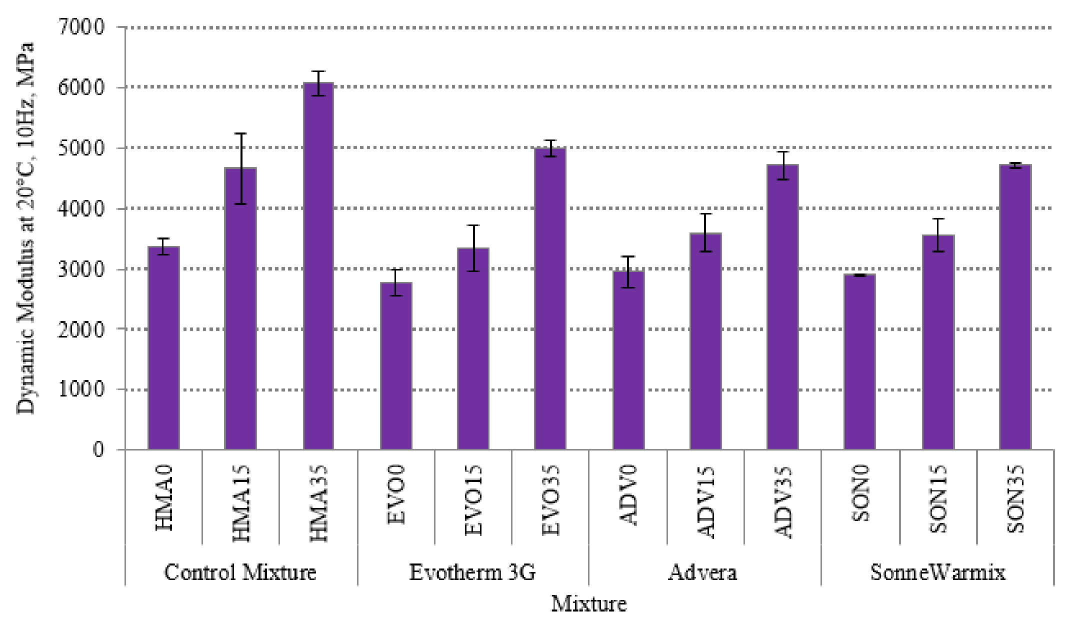

Figure 11: Dynamic Modulus at 20 °C and 10Hz for the Spanish Springs Mixtures.

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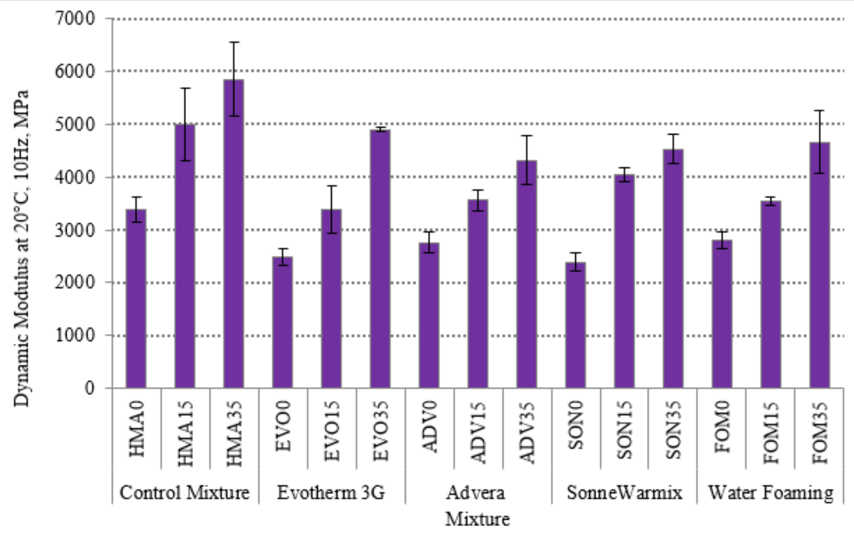

Figure 12: Dynamic Modulus at 20 °C and 10Hz for the Lockwood Mixtures.

a) Dynamic modulus increased with the increase in RAP percentage and

b) WMA mixtures had lower dynamic modulus than HMA mixtures at similar RAP content.

A significant increase in the dynamic modulus at 20 °C may cause a reduction in the mixture's resistance to fatigue cracking due to brittleness. The data in Figures 11 & 12 show that the WMA additives may be able to counter-balance the negative impact of RAP on the fatigue resistance of the mixtures. This observation will be verified through fatigue testing of the mixtures presented in the later part of the paper.

Resistance to Rutting: Flow Number

Asphalt mixtures are expected to resist rutting during the first 5 years of their service life while the asphalt binder is still un-aged. Rutting is typically formed by the permanent strains in the asphalt mix caused by heavy loads during hot weather. The resistance of the mixtures to rutting were evaluated using the Flow Number (FN) test according to "AASHTO TP 79: Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)." The FN tests were conducted on 100mm diameter by 150mm cylindrical specimens cored from the centre of samples compacted in the SGC. The mixtures for the FN test were only short-term aged (loose mix aged for 2 hours at compaction temperature) since rutting is an early pavement life failure. The samples are subjected to a dynamic deviator stress of 70psi and a static confining stress of 10psi. The number of load repetitions at the start of the Tertiary Zone represents the FN of the mix. A higher FN value indicates higher resistance to rutting. The measured FN values for various mixtures are presented in Figures 13 & 14. Test temperature was selected at 58 °C for Reno based on the LTTP Bind 3.1 software.

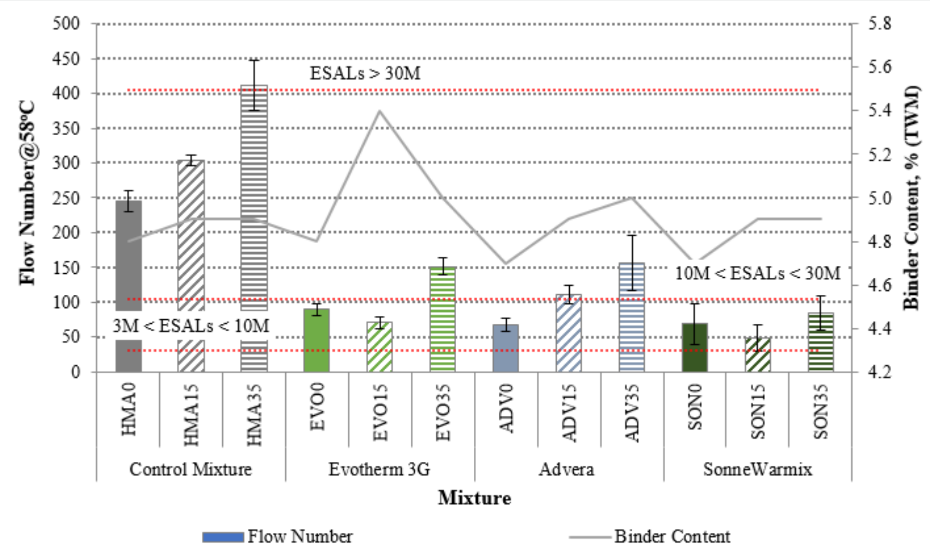

Figure 13: Flow Number for the Spanish Springs Mixtures.

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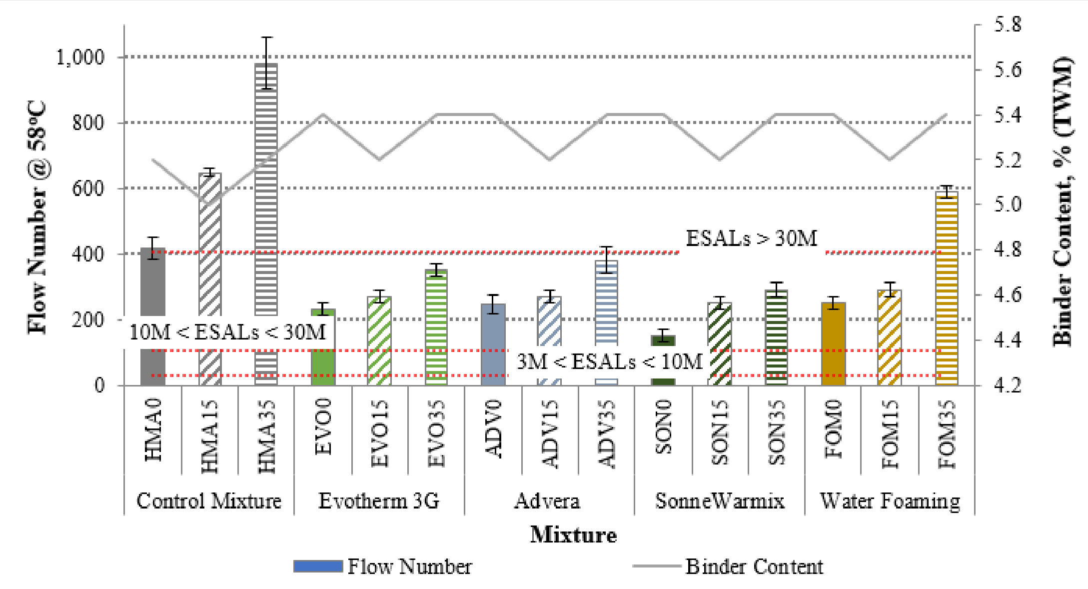

Figure 14: Flow Number for the Lockwood Mixtures.

In the case of Spanish Springs mixtures, two general trends were observed;

a. HMA mixtures had flow number higher than WMA mixtures and

b. The flow number of the mixture increased with the increase in RAP content.

Such trend is observed because RAP adds additional stiffness to the mixtures. The measured flow numbers of the mixtures were checked for the requirement specified by AASTHO R35 as shown on the figures. HMA mixtures qualified for higher traffic level requirement that is between 10 and 30 million ESALs while WMA mixtures qualified only for the traffic levels between 3 and 10 million ESALs, except in the case of EVO35 and ADV35 which qualify for higher levels of traffic. In the case of Lockwood mixtures, HMA mixtures qualified for higher traffic levels that is more than 30 million ESALs while WMA mixtures qualified for traffic levels between 10 and 30 million ESALs. Sonnewarmix exhibited the lowest flow number. Advera, Evotherm and Foaming mixtures exhibited similar flow number at similar RAP contents.

Resistance to Thermal Cracking

The Uniaxial Thermal Stress and Strain Test (UTSST) was used to determine the thermal cracking resistance of the various mixtures. The test cools down the specimen at a rate of 10 °C/hour while restraining it from contracting. While the sample is being cooled down, tensile stresses are generated due to the ends being restrained. The asphalt mixture would fracture as the internally generated stress exceeds its tensile strength. The temperature when fracture occurs is referred to as "fracture temperature" and represents the field temperature under which the pavement will experience thermal cracking. Two 57mm diameter by 140mm height cylindrical specimens were cored sideways from a 150mm diameter by 178mm height SGC compacted specimen. All the UTSST samples were compacted in a Superpave gyratory compactor and long-term aged for 5 days at 85 °C in accordance with AASHTO R30 to simulate the long-term aging properties of the mixtures in the field when thermal cracking becomes critical. The air void levels for the cored and trimmed samples were kept within a range of 7.0 ± 0.5%.

The lower the fracture temperature, the higher the resistance of the mix to thermal cracking. Figures 15 & 16 present the fracture temperature of the various Spanish Springs and Lockwood mixtures, respectively. The whiskers on top of the bars represent the 95% confidence interval of the measured values. The fracture temperatures of the HMA mixtures became warmer with the increase in RAP content. It can be observed that the fracture temperatures for HMA-RAP control mixtures are warmer than for WMA-RAP mixtures. All mixtures without RAP exhibited similar fracture temperatures indicating the strong influence of the binder grade on the resistance to thermal cracking. In addition, the fracture temperatures of HMA and WMA mixtures, except the HMA and Lockwood WMA Evotherm with 35% RAP, are lower than the -28 °C which is the required low temperature grade for asphalt pavements in northern Nevada (i.e. PG64-28NV).

Resistance to Fatigue Cracking

The resistance of the various mixtures to fatigue cracking was evaluated using the flexural beam fatigue test according to "AASHTO T321: Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending." The 50x50x380mm beam specimen is subjected to a 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending

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moment over the centre portion of the specimen. The mixtures for the fatigue test were short-term and long-term aged since fatigue is a latter pavement life failure. The short-term aging consisted of aging the loose mix for 4 hours at the compaction temperature. The long-term aging consisted of aging the compacted samples for 5 days at 85 °C. In this research, constant strain tests were conducted at 500 microstrain using a repeated haversine load at a frequency of 10Hz, and a test temperature of 20 °C. Initial flexural stiffness is measured at the 50th load cycle. Fatigue life or failure is defined as the number of load cycles corresponding to a 50% reduction in the initial stiffness.

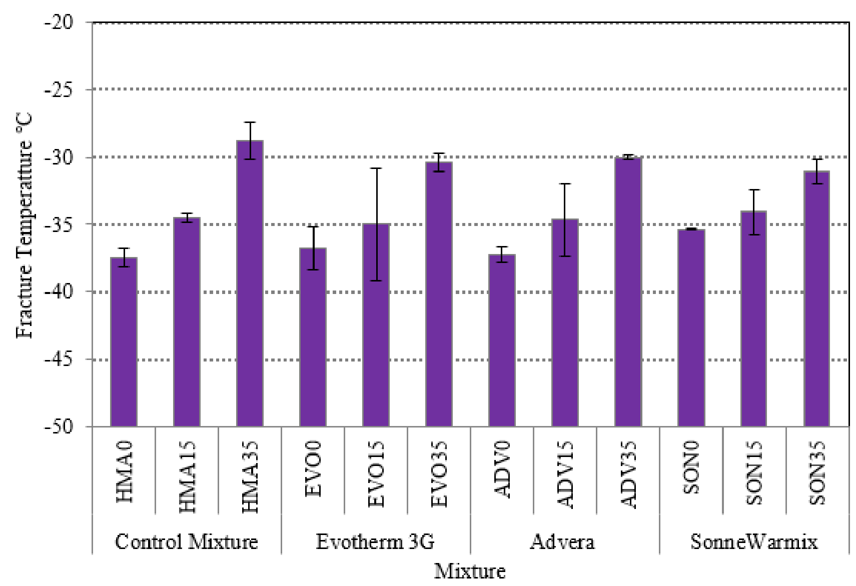

Figure 15: UTSST Fracture Temperatures of the Spanish Springs Mixtures.

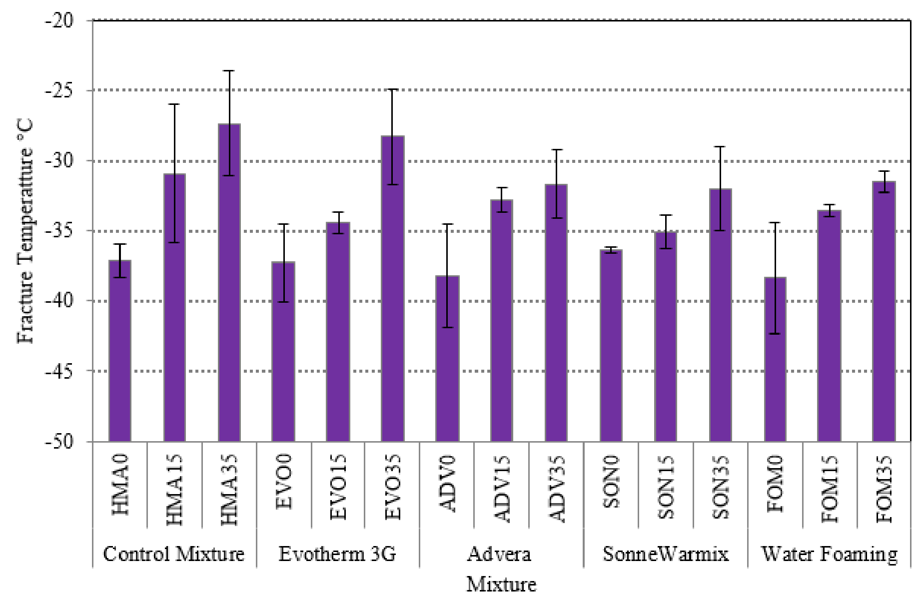

Figure 16: UTSST Fracture Temperatures of the Lockwood Mixtures.

Figures 17 & 18 present the number of cycles to fatigue failure at a strain level of 500 microstrain and 20 °C temperature for the Spanish Springs and Lockwood mixtures, respectively. It should be noted that the Spanish Springs WMA with 15% RAP were not evaluated due to lack of aggregate materials, however, the HMA with 15% was tested in order to check the general trends. It can be observed that WMA additives increase the fatigue resistance of both sources of mixtures at the 0% RAP content. However, once the RAP is added at 15 or 35%, the resistance of the mixtures to fatigue cracking is significantly reduced and the impacts of WMA additives are diminished. This indicates that the influence of the brittle RAP binder is significantly over-shadowing the benefits of the WMA additives for both aggregate sources.

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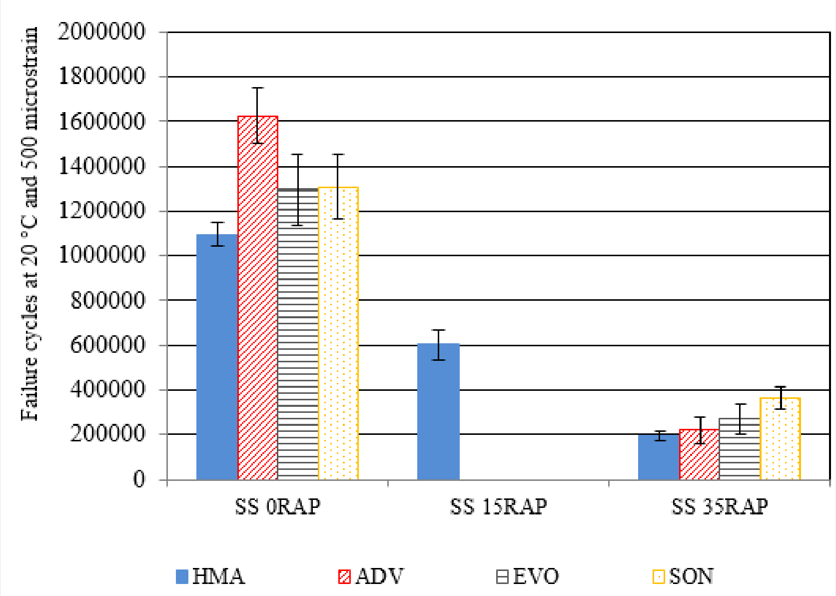

Figure 17: Fatigue Resistance of Spanish Springs Mixtures.

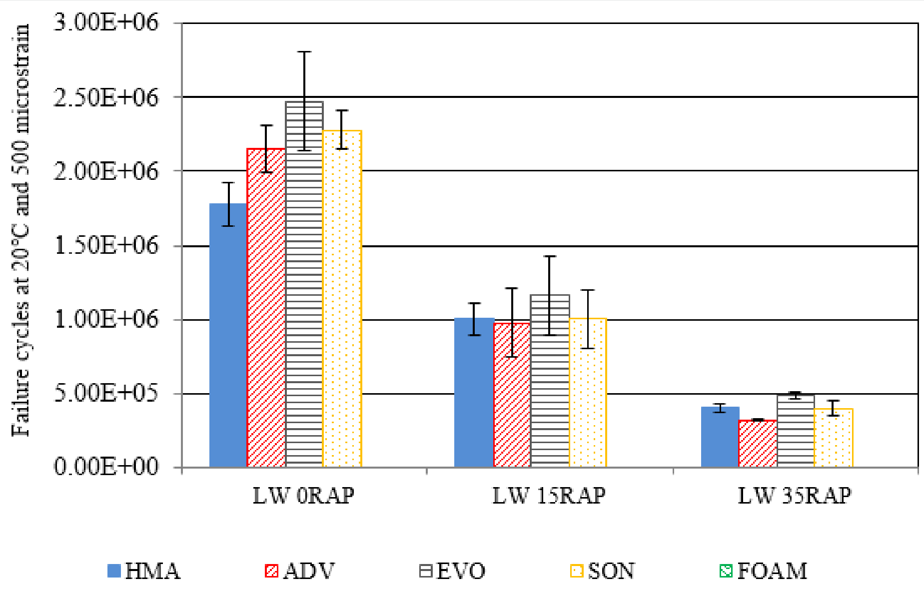

Figure 18: Fatigue Resistance of Lockwood Mixtures.

Conclusion and Recommendations

The overall objective of this study was to evaluate the combined impact of WMA additives and RAP materials on the performance of asphalt mixtures. A specific objective of the study was to assess the feasibility of incorporating 15 and 35% RAP into the asphalt mixtures without changing the PG of the virgin binder and how the different WMA additives influence the performance of such mixtures. To achieve these objectives, asphalt mixtures manufactured with a single virgin polymer-modified binder (PG64-28NV) and two aggregate sources (Spanish Springs and Lockwood) were modified with four WMA additives (Advera, Evotherm, Sonnewarmix, and Water foaming) and two RAP contents (15 and 35%) were evaluated. The analyses of the extensive laboratory data generated in this research led to the following conclusions:

A. Virgin asphalt binder provided for the study was graded as PG64-28NV, which was verified in the lab with actual grade of PG68.8-32.5. Asphalt binders recovered from both RAP sources were graded as PG82-16 which is expected for RAP materials from 20+ year old pavements.

B. Tensile strength values increased with the increase in RAP content. WMA mixtures exhibited lower tensile strength than HMA mixtures with similar RAP content. Interestingly, HMA mixtures with 35% RAP exhibited lower tensile strength ratios than WMA mixtures with 35% RAP.

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C. Dynamic modulus of the mixtures increased with the increase in RAP content. At a same level of RAP content, WMA mixtures exhibited lower dynamic modulus than HMA mixtures. It was interesting to observe that the difference in dynamic modulus values of HMA and WMA mixtures was wider in RAP mixtures.

D. At similar RAP content, Sonnewarmix mixtures exhibited highest rutting susceptibility among WMA mixtures regardless of the aggregate sources. Overall, flow numbers of WMA mixtures were lower than HMA mixtures with similar RAP content. Rate of increase of flow number with increase in RAP content was higher in HMA mixtures compared to WMA mixtures. Lockwood WMA mixtures qualify for higher traffic levels than Spanish Springs WMA mixtures in terms of rutting resistance.

E. Thermal fracture temperature became warmer with the increase in RAP content. In addition, the fracture temperature for HMA mixtures with 35% RAP was warmer than the fracture temperature of WMA mixtures with 35% RAP.

F. WMA additives increased the fatigue resistance of both sources of mixtures at the 0% RAP content. However, once the RAP is added at 15 or 35%, the resistance of the mixtures to fatigue cracking is significantly reduced and the impacts of WMA additives were diminished. This indicates that the influence of the brittle RAP binder is significantly over-shadowing the benefits of the WMA additives.

G. In reference to the specific objective of the study; to assess the feasibility of incorporating 15 and 35% RAP into the asphalt mixtures without changing the PG of the virgin binder and how the different WMA additives influence the performance of such mixtures, the following conclusions can be made:

H. The inclusion of 15% RAP in the HMA mixture without changing the PG of the virgin binder offers a noticeable advantage towards the engineering property (i.e. E*) and rutting resistance of the mixtures without significantly reducing the resistance of the mixtures to thermal and fatigue cracking.

I. The inclusion of 35% RAP in the HMA mixture without changing the PG of the virgin binder offers a significant advantage towards the engineering property (i.e. E*) and rutting resistance of the mixtures, however, it significantly reduced the resistance of the mixtures to thermal and fatigue cracking.

J. WMA additives were effective in moderating the increase in the engineering property of the 15 and 35% RAP mixtures as compared to the HMA mixtures without significantly reducing their resistance to rutting and thermal cracking. However, the WMA additives were not capable of maintaining good resistance to fatigue cracking when 15 and 35% RAP materials were added to the mix. Therefore, the idea of using WMA additives to allow higher RAP contents in the asphalt mix is not supported by the actual fatigue measurements.

K. In summary, the Regional Transportation Commission in northern Nevada is encouraged to use WMA additives combined with 15% RAP materials without changing the PG of the virgin binder to produce asphalt mixtures that are friendlier to the environment and healthier towards the production and paving work force. However, increasing of the RAP content to 35% without changing the PG of the virgin binder is not recommended with or without WMA additives.

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