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RESEARCH ARTICLE

Evaluating the Effects of Using Recycled Asphalt Pavements on Fatigue Properties of Warm Mix Asphalt

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Abstract

This paper presented an experimental study to characterize the stiffness modulus and fatigue life of warm mix asphalt mixture containing recycled asphalt pavements (RAP) with and without a rejuvenating agent. For this purpose, warm mix asphalts were produced using Sasobit and Asphamin as two of the most common additive materials. The following five mixes were prepared and tested: a mix with 30% RAP, two mixes with 30% RAP plus warm mix asphalt additives, and two mixes with 30% RAP plus warm mix asphalt additives and a rejuvenating agent. The results indicated no significant difference in the stiffness modulus of warm mix asphalt mixtures containing RAP and conventional mixtures including recycled asphalt pavement. However, the indirect tensile fatigue test results showed that the addition of the warm mix asphalt additives and rejuvenating agent improved the fatigue life of the mixtures at different temperatures.

Keywords

Warm mix asphalt, recycled asphalt pavement, rejuvenating agent, fatigue life, stiffness modulus

1 Introduction

Use of reclaimed asphalt pavement (RAP) provides a very economic method for building asphalt (cold recycled, hot mix asphalt) pavements. RAP contains both aggregates and binder; hence, its use saves our natural resources and money and is environmentally friendly.

Usage of RAP in HMA has been limited by many highway agencies due to the concern that these materials might get aged at high temperatures and would potentially lead to early cracking of roads [1]. Warm mixed asphalt (WMA) has been studied in recent years and is quickly becoming one of the major areas of interest in bituminous materials. Combining WMA and high RAP contents presents appealing qualities (reduced energy consumption, reduced emissions, and use of all available RAP), while posing many technical challenges (livening extent of aged RAP bituminous material, effect of warm mix additives, compaction promotion extent by aged asphalt, and performance of the mixture) [2].

National Asphalt Pavement Association (NAPA) has concluded in their research that high RAP mixtures containing 30–40% RAP could be produced although major restrictions of producing quality RAP mixtures result from the extreme stiffness of the RAP asphalt binders. A disadvantage of using RAP materials is that RAP asphalt binders may force the producer to use a very soft asphalt binder within the mixture. It was suggested that up to 15% RAP could be used in Superpave mixtures without changing the grade of the added virgin asphalt binder. For mixtures containing 25% RAP, blending charts of RAP asphalt binders containing a rejuvenating agent should be used for selecting the type and determining the content of softer asphalt binders/rejuvenators [3].

The report No. 253 of National Cooperative Highway Research Program (NCHRP) has illustrated that an increase in mixture stiffness leads to a decrease in fatigue life [4]. To address the properties of the hardened recycled binder, it must be mixed with a recycling agent or soft asphalt binder in order to restore its rheological properties [5]. In addition to a soft binder, softening and rejuvenating agents are commonly used. Softening agents reduce the viscosity of the aged binder, while

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rejuvenating agents restore the physical and chemical properties of the old binder [6].

Fatigue life of asphalt concrete pavements depends on the stiffness of the mix, content of bitumen, softening point of bitumen, viscosity of bitumen, grading of aggregates, construction practice, traffic, and climate [7]. Fatigue cracking is one of the three major distresses (fatigue cracking, low temperature cracking, and rutting) of flexible pavements [8].

1.1 Literature review

To date, studies have been conducted on the use of RAP in asphalt mixtures. In a study by Moghadas Nejad et al. [1], rutting performance prediction of warm mix asphalt containing reclaimed asphalt pavements was investigated. The WMA mixtures containing 0, 15, 30, 50, and 60% RAP were plant prepared. To assess the impact of RAP on the rutting properties of warm mix asphalt, the mixtures were tested using Marshall and dynamic creep tests. It was found that replacing up to 60% of the virgin aggregate with RAP improved rutting properties of the asphalt mixtures, because RAP increased asphalt binder's viscosity as a main factor of rutting, especially at high temperatures.

Luo et al. [9] evaluated the fatigue life of rubberised asphalt concrete mixtures containing RAP, which was investigated through probabilistic analysis. The results indicated that probabilistic analysis using the point estimate approach and Monte Carlo simulation methodologies could be effectively used for exploring the probability of fatigue life, require very limited computational effort, and thus have the potential and ease as a practical tool for being employed in pavement engineering. Also, Xiao and Amirkhanian [10] focused on investigating the moisture susceptibility of rubberized asphalt concrete containing RAP. The conducted testing included the determination of binder viscosity, toughness, and indirect tensile strength (ITS) analysis. The results indicated that, in general, the additional RAP was beneficial in improving the ITS values and reducing the moisture susceptibility of the mixture although adding crumb rubber had a slightly negative effect.

It has been shown in National Cooperative Highway Research Program, report No. 752, that asphalt pavements containing up to 50% RAP in the projects with diverse climate and traffic have very positive in-service performance. Several researchers have examined data from experimental sections in the Long-Term Pavement Performance Program to compare overlays with RAP and virgin mixes. Those studies have shown that the overlays containing 30% RAP have been performing equal to, or better than, virgin mixes for most measures of pavement performance [11].

In another study, the behavior of base layer mixture containing RAP was investigated at different quantities using resilient modulus (M_R) from laboratory testing. Resilient modulus tests showed that, as RAP content increased, M_R increased. Results also demonstrated a strong positive correlation between M_R and density. Conclusions indicated that RAP has a potential to be used at high percentages in pavement base layer applications. Doing so may help alleviate a growing environmental problem while providing a strong pavement foundation [12].

1.2 Statement and scope of the present study

This research aimed to investigate the effects of WMA additives on fatigue properties of RAP mixtures with and without rejuvenating agent based on the results of indirect tensile stiffness modulus and fatigue tests. In this study, the asphalt mixtures were manufactured in the laboratory incorporating two WMA additives (Sasobit and Asphamin), rejuvenator agent, 30% RAP, and one asphalt binder (AC 60-70).

2 Materials

2.1 Aggregate and asphalt binder

Locally available limestone aggregates were used in this study to prepare the mixtures. The physical properties of the limestone are given in Table 1. Conventional test methods such as penetration test, softening point test, and ductility were performed to characterize the properties of the base asphalt binder. The engineering properties of the asphalt binder are presented in Table 2.

Table 1 Physical properties of the aggregate

Test	Standard	Limestone	Specification limit
Specific gravity (coarse agg.)	ASTM C 127		
Bulk		2.612	–
SSD		2.643	–
Apparent		2.659	–
Specific gravity (fine agg.)	ASTM C 128		
Bulk		2.618	–
SSD		2.633	–
Apparent		2.651	–
Specific gravity (filler)	ASTM D854	2.640	–
Los Angeles abrasion (%)	ASTM C 131	25.6	Max 45
Flat and elongated particles (%)	ASTM D 4791	9.2	Max 10
Sodium sulfate soundness (%)	ASTM C 88	2.56	Max 10-20
Fine aggregate angularity	ASTM C 1252	46.65	Max 40

Table 2 Test results for 60–70-penetration asphalt binder

Test	Standard	Result
Penetration (100 g, 5 s, 25 ºC), 0.1 mm	ASTM D5-73	64
Penetration (200 g, 60 s, 4 ºC), 0.1 mm	ASTM D5-73	23
Penetration ratio	ASTM D5-73	0.36
Ductility (25 ºC, 5 cm/min), cm	ASTM D113-79	112
Solubility in trichloroethylene, %	ASTM D2042-76	98.9
Softening point, ºC	ASTM D36-76	51
Flash point, ºC	ASTM D92-78	262
Loss of heating, %	ASTM D1754-78	0.75
Properties of the TFOT Residue		
Penetration (100 g, 5 s, 25 ºC), 0.1 mm	ASTM D5-73	60
Specific gravity at 25 ºC, g/cm3	ASTM D70-76	1.020
Viscosity at 135 ºC, cSt	ASTM D2170-85	158.5

Table 3 Gradation of virgin aggregates and RAP aggregates

Sieve size	Sieve size (mm)	Percent Passing (%)	
		Virgin Aggregates	Extracted aggregates From RAP
¾ in	19	100	100
½ in	12.5	91	93
# 4	4.75	68	72
# 8	2.36	51	54
# 30	0.6	27	23
# 50	0.3	15	13
# 100	0.15	6	4
# 200	0.075	5	3

2.2 Additives

2.2.1 RAP

The milled RAP materials were collected from a highway with medium to high volumes in Tehran, Iran. The RAP materials used in this project had 4.5% asphalt binder content. Penetration of the asphalt recovered from RAP was 8.7 mm at 25◦C.

The gradation of virgin aggregates and extracted aggregates used in the study (mid limits of ASTM specifications for dense aggregate gradation) is given in Table 3, with 19.0 mm as the nominal gradation size.

2.2.2 WMA additives

Sasobit (Sa) and Asphamin (As) were the WMA additives used in this study. Sasobit is a long-chain aliphatic hydrocarbon obtained from coal gasification by the Fischer–Tropsch process. The Fischer-Tropsch process is a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into various forms of liquid hydrocarbons in the presence of iron and cobalt as catalysts. Sasobit forms a homogeneous solution with the base binder upon stirring (1.5% by weight of the binder) and yields a marked reduction in the binder's viscosity. After crystallization, Sasobit forms a lattice structure in the binder and provides structural stability of the binder [13]. Asphamin is a sodium aluminum silicate that has been hydrothermally crystallized as a very fine powder. It contains about 21% crystalline water by weight and is added to the mixture with the amount of 0.3% by weight of the mixture. Its addition to the binder ensures that a very fine water spray is created as all the crystalline water is released. This issue causes volume expansion in the binder, thereby increasing the workability and compatibility of the mixture at lower temperatures [14]. In the present study, asphamin was added to the mixture with the amount of 0.3% by weight of the mixture.

2.2.3 Rejuvenator agent

Suitable rejuvenators have a high percentage of polar compounds and the primary amin acid until with solving, resolve the asphaltenes well in their. In other words, an active compound in the mixture reduces the viscosity and increase the degree of influence in old asphalt. Also this material should have a high flash point, so the high temperatures used in hot mix.

The rejuvenator agent that was used for this study was an oil type of rejuvenator agent, which is commonly used in Iran. Considering the quantity of RAP materials and extracted binder from RAP, it has been suggested by the rejuvenator agent's producing company that the dosage of rejuvenator agent should be 5% by weight of the RAP binder. The properties of the rejuvenator agent are given in Table 4.

3 Experimental setup and procedure

3.1 Mix design

The asphalt mixtures were designed using the standard Marshall mix design procedure with 75 blows on each side of the cylindrical samples. The samples were compacted and tested by deploying the following standard procedures: the bulk specific gravity (ASTM D2726), the stability and flow test (ASTM D1559), and the maximum theoretical specific gravity (ASTM D2041). Five different mixes were used. The first mix was HMA and contained 30% RAP. The second and third mixes were two kinds of WMA mixtures including 30% RAP. The last two types of mixes were WMA mixtures with 30% RAP in addition to the rejuvenating agent. The optimum asphalt binder quantity in an asphalt mixture without RAP materials and without any additive was found to be 5.7%. The amount of new asphalt binder to be added to the trial mixes of the recycled mixture, expressed as percent by weight of total mix, could be calculated by Eq. (1) [15]:

$$P_{nb} = \frac{\left(100^2 - rP_{sb}\right)P_b}{100\left(100 - P_{sb}\right)} - \frac{\left(100 - r\right)P_{sb}}{100 - P_{sb}} \tag{1}$$

where: P_{nb} is the percentage of new asphalt binder in the recycled mix, r the new aggregate expressed as percentage of the total aggregate in the recycled mix, P_b the percentage of optimum asphalt binder content and P_{sb} the percentage of asphalt binder content of RAP. In this study, it was calculated that 4.4% of the virgin binder should be added to RAP mixtures.

Table 4 Properties of the rejuvenator agent was used in this study

Property				Ingredient			
Viscosity (60 ◦C, Pa s)	Flash point (◦ C)	Ratio of viscosity	Density (g/cm3)	Asphaltene	Saturate	Aromatic	Resin
202	232	1.37	1.011	2.0%	51.9%	33.2%	12.7%

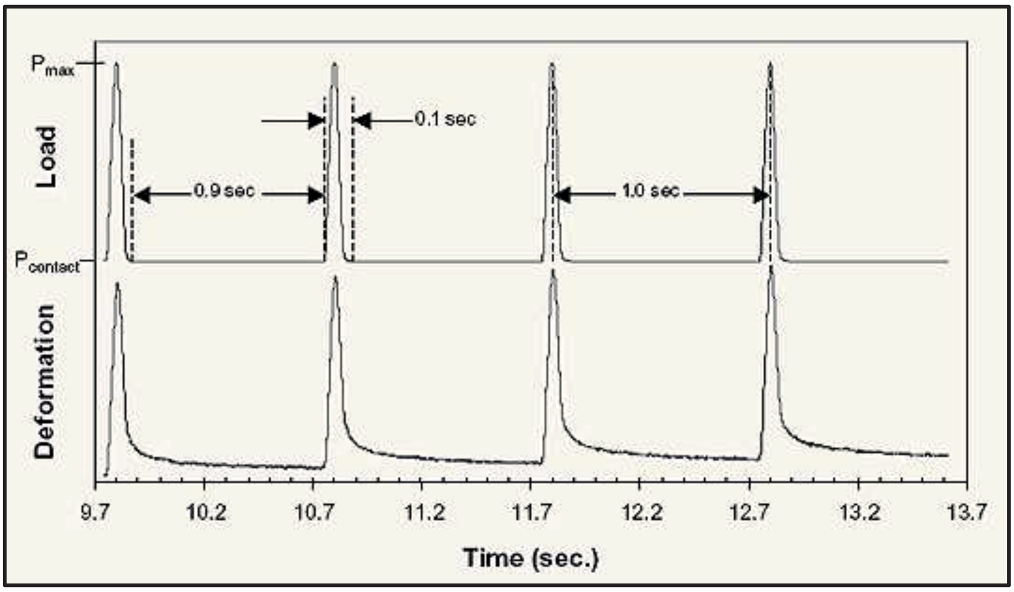

Fig. 1 Load and deformation variation with time in the dynamic loading ITSM test (Arabani et al. 2013)

The mixtures containing 30% RAP were mixed at 155°C and compacted at 145°C. However, all the mixtures containing warm additives were mixed at 135°C and compacted with the target temperature of 125°C. The rejuvenated aged binder was prepared by mixing a rejuvenator agent with the aged binders when they were heated at 135°C. For each mixture, at least three samples were produced to determine the reproducibility of the results [16].

3.2 Indirect tensile stiffness modulus (ITSM) test

Stiffness of the bituminous material can be measured quickly and easily using the ITSM test, which is a non-destructive method and has been widely used for determining stiffness modulus values [17]. In this research, it was undertaken in accordance with recognized guidelines [18]. The indirect tensile stiffness modulus test was performed by applying a linear force along the diameter axis of the specimen. Each loading cycle was 0.1 s long. Thus, given the total duration of loading and unloading of 1 s, the resting time period of each cycle was 0.9 s. The diagrams of the applied load and deformation versus time are shown in Figure 1. In the indirect tensile stiffness modulus test, the value of the stiffness modulus can be determined by applying Eq. (2) [15]:

$$M_R = \frac{p(\vartheta + 0.27)}{t \times \Delta H} \tag{2}$$

where M_R is stiffness modulus, Mpa; p is repeated load, N; ϑ is the Poisson ratio, which is assumed to be 0.35 in HMA; t is thickness of sample in mm; and ΔH is the recoverable horizontal deformation in mm.

Cylindrical specimens with the diameter and height contents of 101.6 mm and 62.5 mm were tested, respectively. Three samples for each mix were tested under the diametrical stiffness modulus test at three testing temperatures (5, 25, and 40ºC).

3.3 Indirect tensile fatigue (ITF) test

To determine the fatigue performance of asphalt, the ITF test was operated. This test was simple, effective, and also widely used [19]. The indirect tensile fatigue test is able to characterize the fatigue behavior of the mixture [20].

This test was carried out according to the procedure described by British Standard In-situation [21]. Fatigue tests were performed in both controlled strain mode and controlled stress mode. In the controlled strain mode, the strain was maintained by reducing the stress on the sample. In the controlled stress mode, the stress was held constant to increase the strain within the sample [20]. The relationship between tensile strain and number of cycles to failure for each material was established. A linear relationship was also recorded when strain was plotted against the numbered cycles to failure on a logarithmic scale and the fatigue life prediction equations were developed [22].

In this study, using regression analysis, the fatigue equations were developed in the form of Monismith's fatigue prediction model (Eq. (3)).

$$N_f = K_1 \left(\frac{1}{\varepsilon_t} \right)^{-K_2} \tag{3}$$

where N_f is the number of cycles to failure of specimen, ε_t is the applied strain, and K_1 and K_2 are the coefficients related to mixture properties.

In this study, the fatigue life of the specimens (101.6 mm in diameter and 40 mm thick) was measured in constant strain mode by applying repeated loads with fixed amplitude along the diametrical axis of the specimen.

The following conditions were considered in the fatigue test:

- Sinusoidal loading with frequency of 10 Hz (0.1 s of loading and 0.9 s of resting),
- Strain levels of approximately 700, 900, 1100, 1300, and 1500 micro strains,
- Test temperatures of 10 and 20°C, and
- Fatigue criterion defined as the number of cycles corresponding to a 50% reduction in initial stiffness.

4 Results and discussion

4.1 Indirect tensile stiffness modulus test

The stiffness modulus results were determined as shown in Figure 2. In general, because of the high sensitivity of bitumen to the variations of temperature, the stiffness modulus of the control and modified mixtures decreases at higher temperatures. This phenomenon can be explained by the viscosity and stiffness modulus of the bitumen, which decrease at higher temperatures. Therefore, the stiffness modulus of the mixture decreases as a result of the greater ease with which the aggregates slide and softening of the HMA specimens. When the temperature increases, viscosity of the binder decreases, thus allowing it to flow within the mix and relieve the stresses. However, bitumen may lose its ability to bind the aggregates together at high temperatures. Therefore, as the temperature increases, the recoverable needed strain increases as well, resulting in a lower stiffness modulus.

On the other hand, the results showed that the reduction of stiffness modulus of 30% RAP mixture is lower than modified samples with increasing in temperature from 5 to 25°C. At 40°C, the stiffness modulus for 30% RAP mixture significantly decreased from the previous temperatures, which could be due to the adequate blending of the RAP binder with the virgin binder for the 30% RAP mixture contributing stiffer asphalt. However, this characteristic did not exist in the mixture containing WMA additives or rejuvenating agent.

Also, the results showed that the specimens of the mixture with 30% RAP (without WMA additives or rejuvenating agent) had the highest stiffness modulus. However, using WMA additives (Sasobit and Asphamin) and rejuvenator agent, the stiffness modulus of the mixture was decreased. Their addition to the base binder resulted in the reduction of viscosity compared with the viscosity of the base binder.

4.2 Indirect tensile fatigue test

The results of the indirect tensile fatigue test are given in Figures 3 and 4. In these figures, regression lines were drawn through the mean results of each sample at each strain level. The results showed the usual linear relationship between the logarithm of the applied initial tensile strain and the logarithm of fatigue life (number of applied load repetitions until failure).

As a result, using Sasobit and Asphamin improved the fatigue life of the asphalt mixtures compared with 30% RAP

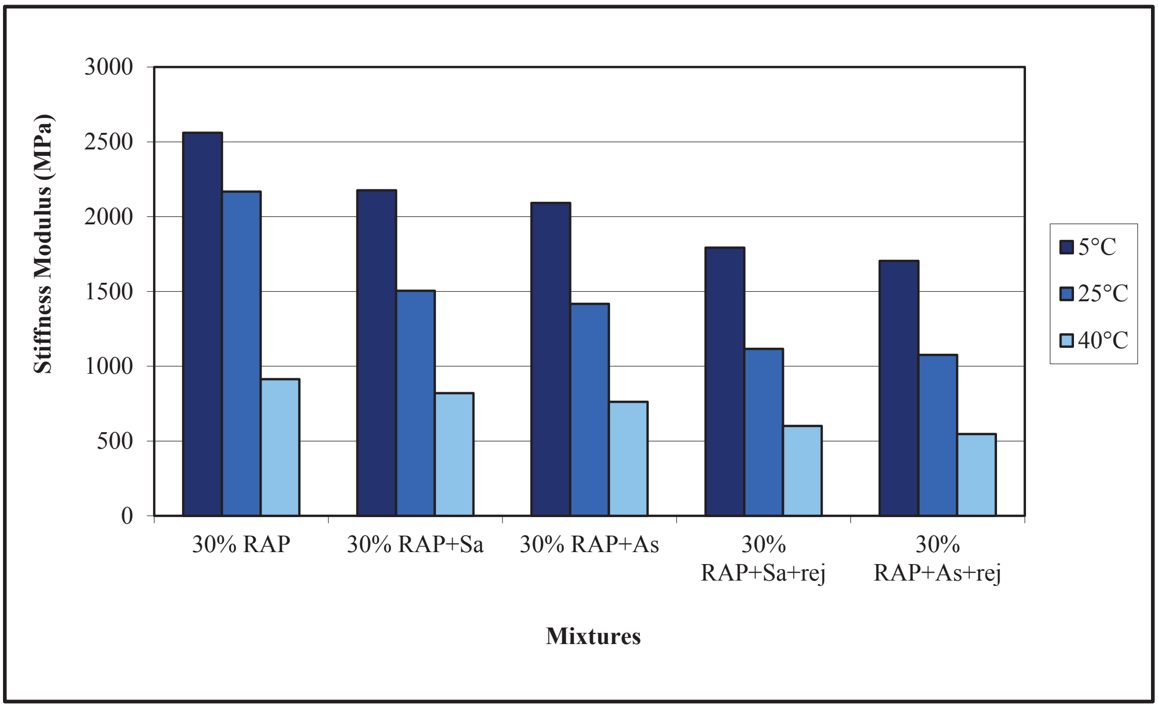

Fig. 2 Results of indirect tensile stiffness modulus test

Table 5 Fatigue prediction equations of mixtures

Temperatures	Mixtures	N_f	K_1	K_2	R^2
10°C	30%RAP	$N_f = 5210\varepsilon^{-0.168}$	5210	0.168	0.9892
	30%RAP+Sa	$N_f = 6806\varepsilon^{-0.185}$	6806	0.185	0.9841
	30%RAP+As	$N_f = 8149\varepsilon^{-0.199}$	8149	0.199	0.9862
	30%RAP+Sa+rej	$N_f = 10864\varepsilon^{-0.218}$	10864	0.218	0.9971
	30%RAP+As+rej	$N_f = 11980\varepsilon^{-0.225}$	11980	0.225	0.9994
20°C	30%RAP	$N_f = 5643\varepsilon^{-0.171}$	5643	0.171	0.9848
	30%RAP+Sa	$N_f = 8078\varepsilon^{-0.196}$	8078	0.196	0.9948
	30%RAP+As	$N_f = 9214\varepsilon^{-0.205}$	9214	0.205	0.9941
	30%RAP+Sa+rej	$N_f = 11621\varepsilon^{-0.22}$	11621	0.22	0.9986
	30%RAP+As+rej	$N_f = 13629\varepsilon^{-0.232}$	13629	0.232	0.9959

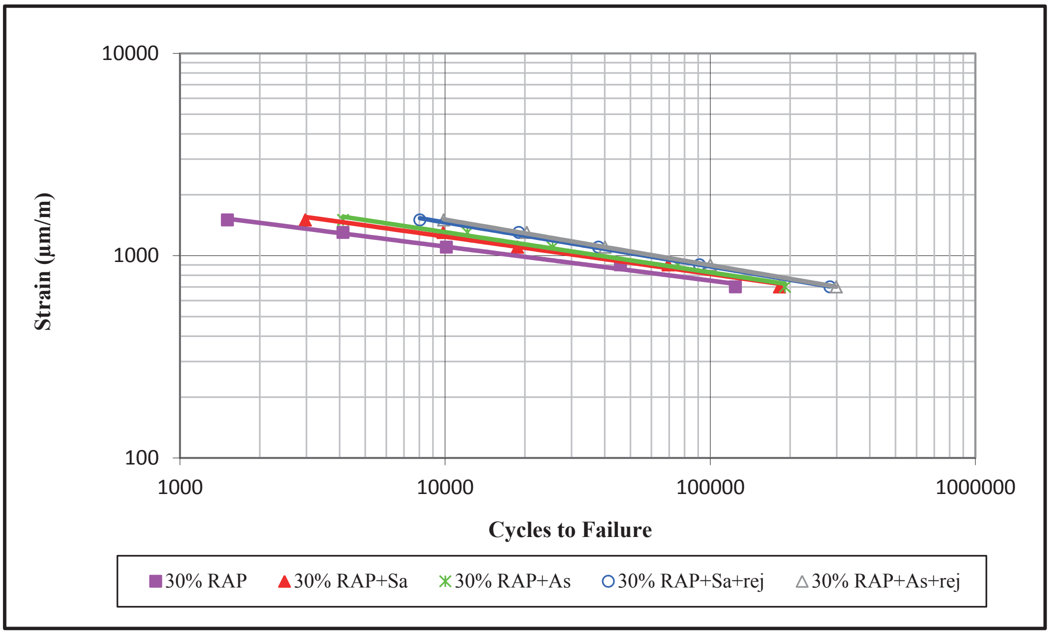

Fig. 3 Comparing fatigue behavior of different mixes at 10°C

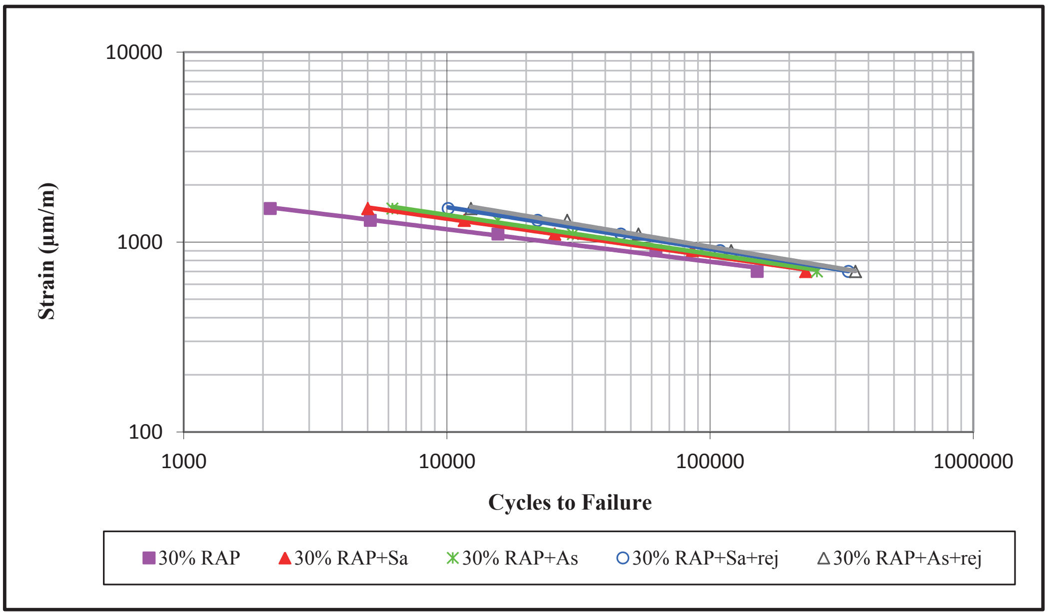

Fig. 4 Comparing fatigue behavior of different mixes at 20°C

mixture. Thus, their addition was effective in lowering the RAP stiffness. Since in this research, fatigue test is performed by strain control method, decreased stiffness of the modified asphalt mixtures can be one of the reasons for their increased fatigue life. As mentioned in various references [15], if fatigue test is done using stress control method, decreased stiffness of asphalt mixtures would reduce their fatigue life.

On the other hand, the mixes with Sasobit and Asphamin additives achieved higher bulk specific gravities and lower air voids, which were expected due to the probable increase in the workability and fatigue life of the mixes with the WMA additives; but, Asphamin showed better improvement in fatigue properties.

Also, the addition of the rejuvenating agent was effective in increasing fatigue life of the mixture with 30% RAP, which has been a major concern for all RAP mixes. This point implies that the rejuvenating agent is effective in reducing the embrittlement of the aged RAP and thus improving its fatigue life performance. In addition, by increasing temperature to 20°C, the fatigue life of all the specimens increased; this behavior has high sensitivity of bitumen to temperature.

Overall, using the regression analysis, the fatigue equations were developed in the form of Monismith's fatigue prediction model (Eq. (2)). For every type of mixture at every two temperature levels, the fatigue equations are shown in Table 5. It can be observed that all the values K1 and K2 increased when WMA additives or rejuvenating agent were added, which resulted in an increase in the cycle numbers to failure for the asphalt mixtures.

5 Conclusions

This investigation was undertaken to evaluate the performance of asphalt concrete mixes using RAP, WMA additives, and rejuvenating agent. To fulfill this objective, laboratory evaluation of the asphalt concrete mixes with different combinations of additives were conducted.

Based on the experimental results, the following conclusions can be drawn:

1. 30% RAP mixture had the highest stiffness modulus of all the mixtures.
2. No significant differences were found between the fatigue live of the mixes with two WMA additives; but, Asphamin showed better improvement in fatigue properties.
3. Addition of the rejuvenating agent helped increase the fatigue life of the mixture, which was the result of the embrittlement of the aged RAP.
4. By increasing temperature to 20°C, fatigue life of all the specimens increased, which showed the sensitivity of bitumen to temperature.

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