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Research Article

Aging Influence on Fatigue Characteristics of RAC Mixtures Containing Warm Asphalt Additives

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Aging is an important factor to affect the long-term performance of asphalt pavement. The fatigue life of a typical warm mix asphalt (WMA) is generally related to various factors of rheological and mechanical properties of the mixture. The study of the fatigue behavior of the specific rubberized WMA is helpful in recycling the scrap tires and saving energy in terms of the conventional laboratory aging process. This study explores the utilization of the conventional fatigue analysis approach in investigating the cumulative dissipated, stiffness, and fatigue life of rubberized asphalt concrete mixtures containing the WMA additive after a long-term aging process. The aged beams were made with one rubber type (−40 mesh ambient crumb rubber), two aggregate sources, two WMA additives (Asphamin and Sasobit), and tested at 5 and 20°C. A total of 55 aged fatigue beams were tested in this study. The test results indicated that the addition of crumb rubber extends the fatigue resistance of asphalt binder while WMA additive exhibits a negative effect. The study indicated that the WMA additive generally has an important influence on fatigue life. In addition, test temperature and aggregate source play an important role in determining the cumulative dissipated energy, stiffness, and fatigue life of an aged mixture.

1. Introduction

The long-term aging process of crumb rubber-modified (CRM) binder and warm mix asphalt (WMA) mixture is a complex process caused by the interaction of the crumb rubber, WMA additive, and the binder. However, Zeng and Huang [1] indicated that laboratory aging methods for simulation of field aging of asphalt binders and evaluation of aging characteristics of virgin or modified asphalt mixtures are effective. In addition, the use of rheological properties of asphalt binders can be used to characterize the asphalt-aggregate mixtures [2]. In terms of its chemical composition, the asphalt binder is a complex mixture of organic molecules, comprised mainly of hydrocarbons with trace amounts of functional groups such as oxygen, nitrogen, and sulfur.

Fatigue cracking is often associated with loads that are too heavy for the pavement structure or more repetitions of a given traffic loading than provided for in design. The fatigue life of an asphalt pavement is related to the various aspects of hot mix asphalt (HMA). Previous studies have been conducted to understand how fatigue life can occur and be extended under repetitive traffic loading [3–6]. The fatigue life of an asphalt pavement is directly related to various engineering properties of a typical HMA. The complicated microstructure of asphalt concrete is related to the gradation of aggregate, the properties of aggregate-binder interface, the void size distribution, and the interconnectivity of voids [7, 8]. As a result, the component of mixture plays a key role in determining its fatigue characteristics. In addition, the performance temperature seriously affects the fatigue resistance of asphalt pavement [9, 10]. For example, Xiao [9] indicated that, at a lower testing temperature, the falling fatigue life can be obtained.

The recycling of scrap tires has been of interest to the domestic and international asphalt industry for over 40 years. The utilization of crumb rubber (CR) in asphalt binders has proven to be beneficial from many standpoints. The use of CR, expanded to HMA, continues to evolve since the CRM binders enhance the performance of asphalt mixtures by increasing the resistance of the pavements to

Table 1: Aggregate property of mixture.

Aggregate Source	LA Abrasion Loss (%)	Absorption (%)	Specific Gravity			Soundness % Loss at 5 cycles			Sand Equivalent	Hardness
			Dry (BLK)	SSD (BLK)	Apparent	11/2 to 3/4	3/4 to 3/8	3/8 to #4		
A	51	0.80	2.740	2.770	2.800	0.2	0.1	0.1	—	5
B	34	0.60	2.780	2.800	2.830	0.4	0.6	0.9	35	5

permanent deformation, thermal and fatigue cracking, and aging in the field. Many researchers have found that utilizing crumb rubber in pavement construction is both effective and economical [11, 12].

As the asphalt industry is getting more aware of the warm mix technology, there is an increasing need to perform research to determine the feasibility of these technologies. WMA is widely being used in the HMA industry as a means of reducing energy requirements and lowering emissions. Reduced mixing and paving temperature decreases the energy required to produce HMA, reduces emissions and odors from plants, makes for better working conditions at both the plant and the paving site, and reduces the potential aging in asphalt binder [10, 13–21]. Although the WMA technology has developed very fast in the United States since 2006, the fatigue characteristics of crumb rubber and WMA additives mixed with virgin mixtures together have not yet been identified clearly after a long-term aging. Because the relationships of these two materials (crumb rubber and WMA additive) in the modified mixtures are complicated and very few fatigue studies of these modified asphalt mixtures have been performed in recent years, the detailed information will be beneficial to help understand their fatigue resistance after a long-term aging process.

The objective of this study was to investigate the fatigue characteristics of the rubberized asphalt concrete mixtures containing WMA additives, after a long-term aging process. This study is related to the subject of the aggregate source, the WMA additive, and the testing temperature. Experiments were carried out to evaluate fatigue life, dissipated energy, stiffness values of the modified mixture as well as their statistically significant analysis amongst various aged mixture types.

2. Experimental Program and Procedures

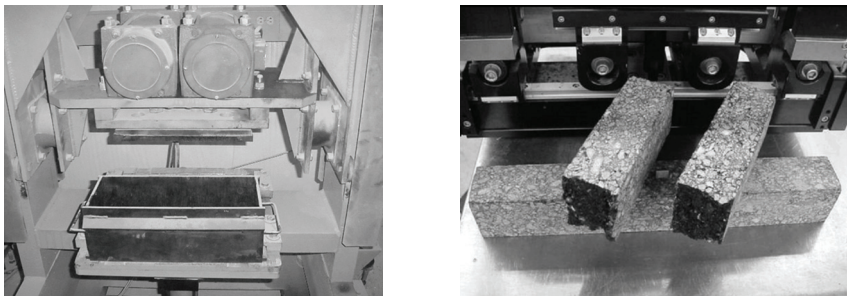
2.1. Materials. PG 64-22 asphalt binder, crumb rubber-modified (CRM) binder (PG 64-22 + 10% −40 mesh rubber), CRM binder with Asphamin or Sasobit were employed. One type of rubber, −40 mesh ambient rubber, was used in this study. Previous research and field projects conducted in South Carolina indicated that the −40 mesh ambient rubber is effective in improving the engineering properties of rubberized mixtures [12]. Two aggregate sources (A and B) were used for preparing the samples (Table 1). Aggregate A, a type of granite, is predominantly composed of quartz and potassium feldspar while aggregate B (schist) is a metamorphic rock. Hydrated lime, used as an anti-strip additive, was added at a rate of 1% by dry mass of aggregate. A total number of 55 aged fatigue beams were evaluated in this research. In this paper, the mixtures made from aggregates A and B without rubber and WMA additive are referred to as ACO and BCO; and the mixtures with rubber but no WMA additive are referred to as ARO and BRO. In addition, the mixtures with rubber and Asphamin are designated as ARA and BRA, and the mixtures with rubber and Sasobit are labeled as ARS and BRS, respectively.

Table 2: Property of WMA additive.

Properties	Asphamin	Sasobit H8
Ingredients	Sodium aluminosilicate $Na_2O \cdot Al_2O_3 \cdot 2SiO_2$	Solid saturated hydrocarbons
Physical state	Granular Powder	Pastilles, flakes
Color	White	Off-white to pale brown
Odor	Odorless	Practically odorless
Molecular weight	365	Approx. 1000
Specific Gravity	2 (20°C)	0.9 (25°C)
Bulk density	500–600 kg/m^3	—
Ph values	11∼12	Neutral
Flashpoint	—	285°C (ASTM D92)
Solubility in water	Insoluble	Insoluble

Asphamin is Sodium-Aluminum-Silicate that is hydro thermally crystallized as a very fine powder. It contains approximately 21% crystalline water by weight. By adding it to an asphalt mix, the fine water spray is created as all the crystalline water is released, which results in volume expansion in the binder, therefore increasing the workability and compactability of the mix at lower temperatures. Sasobit is a long chain of aliphatic hydrocarbons obtained from coal gasification using the Fischer-Tropsch process. After crystallization, it forms a lattice structure in the binder which is the basis of the structural stability of the binder containing Sasobit [13, 14]. The typical physical and chemical properties of two WMA additives are shown in Table 2.

2.2. Superpave Mix Design. The combined aggregate gradations for the 12.5 mm mixtures were selected in accordance with the specifications set by the South Carolina Department of Transportation (SCDOT). The gradations for each aggregate source (A and B) are shown in Table 3, which shows that the design aggregate gradations for each aggregate source are



(a) (b)

Figure 1: Fatigue testing equipment and sample beam of mixture: (a) vibratory compactor; (b) test apparatus and beam.

Table 3: Aggregate gradations.

Sieve size (mm)	Limits	Agg. A Passing (%)	Agg. B Passing (%)
19.0	98∼100	98.99	99.56
12.5	90∼100	93.86	93.72
9.5	74∼90	88.62	83.75
4.75	46∼62	48.78	49.27
2.36	25∼41	29.56	39.05
0.6	9∼21	18.33	17.84
0.15	4∼12	6.63	8.54
0.075	2∼8	3.34	5.12
Aggregate blend		Blend (%)	
Stone 67		9	11
Stone 789		61	46
Regular Screenings		10	17
Man. Screenings		19	25
Lime		1	1

the same when using different WMA additives (Asphamin and Sasobit) at the same percentages of rubber (0% or 10% rubber), while the gradations are similar when comparing mixtures from both aggregate sources.

Superpave mix design defines that the laboratory mixing and compaction temperatures can be determined by using a plot of viscosity versus temperature. There are no previous specifications available regarding the mixing and compaction temperatures for rubberized mixture containing WMA additives, some researchers have developed guidelines for mixing and compaction temperatures when using either WMA or rubber [9, 12–14]. The temperatures, shown in Table 4, were determined in accordance with previous research projects [22]. Superpave mix design of all mixtures were shown in Table 5.

2.3. Fatigue Beam Fabrication, Conditioning, and Test Procedures. Fatigue beams were made in the laboratory. The total aggregate weight of 10,800 grams was used for making one big beam. The mix was placed in the oven for two hours as a short-term aging at a specified temperature shown in Table 4. The vibratory compactor equipment, as shown in Figure 1(a), was used to compact the flexural bending fatigue beams used in this study. The compaction time was dependent on the type of the mixture. The compacted beam was sawn into two small test fatigue beams after bulk specific gravity testing. A compacted beam and a sawed small beam are shown in Figure 1(b). Test specimens were sawn to a 380 mm (15 inches) length by 63 mm (2.5 inches) width and 50 mm (2 inches) thickness.

Table 4: Mixing and compaction temperatures of mixtures.

	Mixing temperature (°C)	Compacting temperature (°C)
ACO/BCO	155 ± 3	135 ± 3
ARO/BRO	173 ± 3	155 ± 3
ARA/BRA	150 ± 5	140 ± 5
ARS/BRS	150 ± 5	140 ± 5

Fatigue beams were conditioned in a forced-draft oven for five days at 85°C and then were cooled at room temperature for 16 ± 1 h (AASHTO R30). Three to four beams of each mixture were tested for this study. All tests were performed in two controlled-temperature rooms at 20.0 ± 0.5°C and 5.0 ± 0.5°C. In order to maintain the testing temperature, each beam specimen was placed in the environmental chamber of the fatigue testing equipment for two hours prior to beginning the test. In this study, a repeated sinusoidal loading at a frequency of 10 Hz was used; in addition, the controlled strain mode was employed. The control and data acquisition software measured the deflection of the beam specimen, computed the strain in the specimen and adjusted the load applied by the loading device (AASHTO T321).

The test apparatus also recorded load cycles, applied load, and beam deflections. Failure is assumed to occur when the stiffness reaches half of its initial value, which is determined from the load at approximately 50 repetitions; the test is terminated automatically when this load has diminished by 50 percent. The flexural stiffness and dissipated energy of fatigue beam are determined as follows (AASHTO T321).

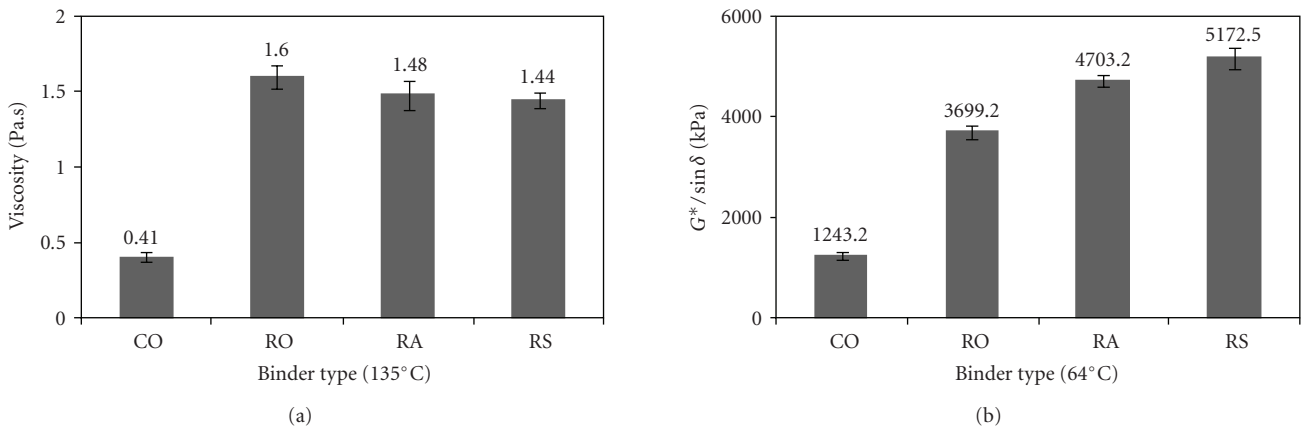


Figure 2: Viscosity and $G^*/\sin\delta$ values of virgin binders: (a) viscosity; (b) $G^*/\sin\delta$.

(1) Maximum tensile stress (Pa):

$$\sigma = \frac{3aP}{bh^2}, \tag{1}$$

where P is the applied peak-to-peak load, in Newton; b is the average beam width, in meters; h is the average beam height, in meters; and a is the space between inside clamps, in meters

(2) Maximum tensile strain (m/m):

$$\varepsilon = \frac{12h\delta}{3l^2 - 4a^2}, \tag{2}$$

where δ is the beam deflection at neutral axis, in meters; and l is the length of beam between outside clamps, in meters

(3) Flexural stiffness (Pa):

$$S = \frac{\sigma}{\varepsilon} = \frac{aP(3l^2 - 4a^2)}{4b\delta h^3}, \tag{3}$$

where σ is the tensile stress, in Pa; ε is the maximum tensile stain, in m/m; P is the applied peak-to-peak load, in Newton; a is the space between inside clamps, in meters; b is the average beam width, in meters; h is the average beam height, in meters; δ is the beam deflection at neutral axis, in meters; and l is the length of beam between outside clamps, in meters.

(4) Dissipated energy (J/m^3) per cycle:

$$D = \pi\sigma\varepsilon\sin(360f\theta), \tag{4}$$

where f is the load frequency, in Hz; and θ is the time lag between $P_{\max}$ and $\delta_{\max}$, in second

(5) Cumulative dissipated energy (J/m^3):

$$W = \sum_{i=1}^{i=n} D_i, \tag{5}$$

where $D_i = D$ for the ith load cycle.

3. Analysis of Test Results

3.1. Statistical Considerations. Results of the stiffness, cumulative dissipated energy, and fatigue life values in terms of mix type, aggregate source as well as test temperature were statistically analyzed with 5% level of significance (0.05 probability of a Type I error) in terms of analysis of variance (ANOVA). For these comparisons, it should be noted that all specimens were produced at optimum binder content.

3.2. Binder Analysis. Figure 2(a) shows that the viscosity of rubberized asphalt binder is remarkably (approximately 3.9 times) greater than that of the virgin binder while this viscosity value slightly (approximately 0.9 times) decreases as the WMA additive is added. As shown in Figure 2(b), the high-temperature performance ($G^*/\sin\delta$) of overall binders increases with the addition of WMA additive. The unaged binder test result shows that the Asphamin and Sasobit can improve the workability (viscosity) and rutting resistance ($G^*/\sin\delta$) of mixtures. While the aged rubberized binders show that the $G^*\sin\delta$ values decrease with the addition of rubber, these values increase slightly (approximately 1.2 times) as the WMA additives are added (Figure 3(a)). It also can be seen that the stiffness values of binders have similar trends with $G^*\sin\delta$ values due to the addition of these materials (Figure 3(b)). Generally, aged binder properties show that the WMA additives produce a slightly effect on the long-term performance of asphalt binder.

3.3. Analysis of Fatigue Test Results. In this study, fatigue life was defined as the number of repeated cycles corresponding to a 50-percent reduction in initial stiffness, which was measured at the 50th load cycle. Several fatigue beam specimens were tested to characterize the fatigue behavior of a mixture in order to avoid too much or too little loss in stiffness. This procedure involved testing control specimens (ACO and BCO samples) at a 500 microstrain level with the controlled strain mode of loading at a frequency of 10 Hz.

The fatigue characteristics of asphalt mixtures are usually expressed as relationships between the initial stress or strain and the number of load repetitions to failure determined

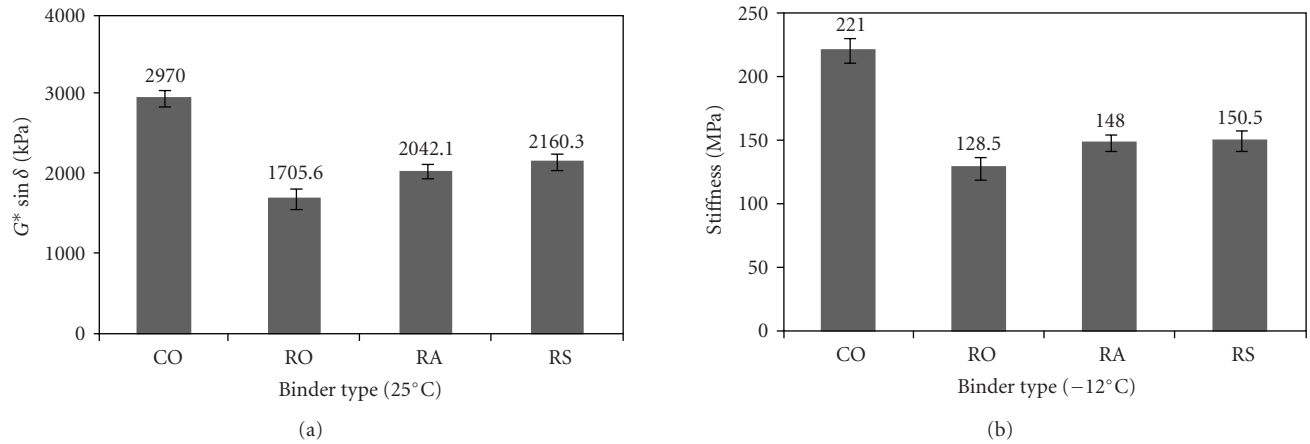


Figure 3: G^* sin δ and stiffness values of aged binders: (a) G^* sin δ; (b) stiffness.

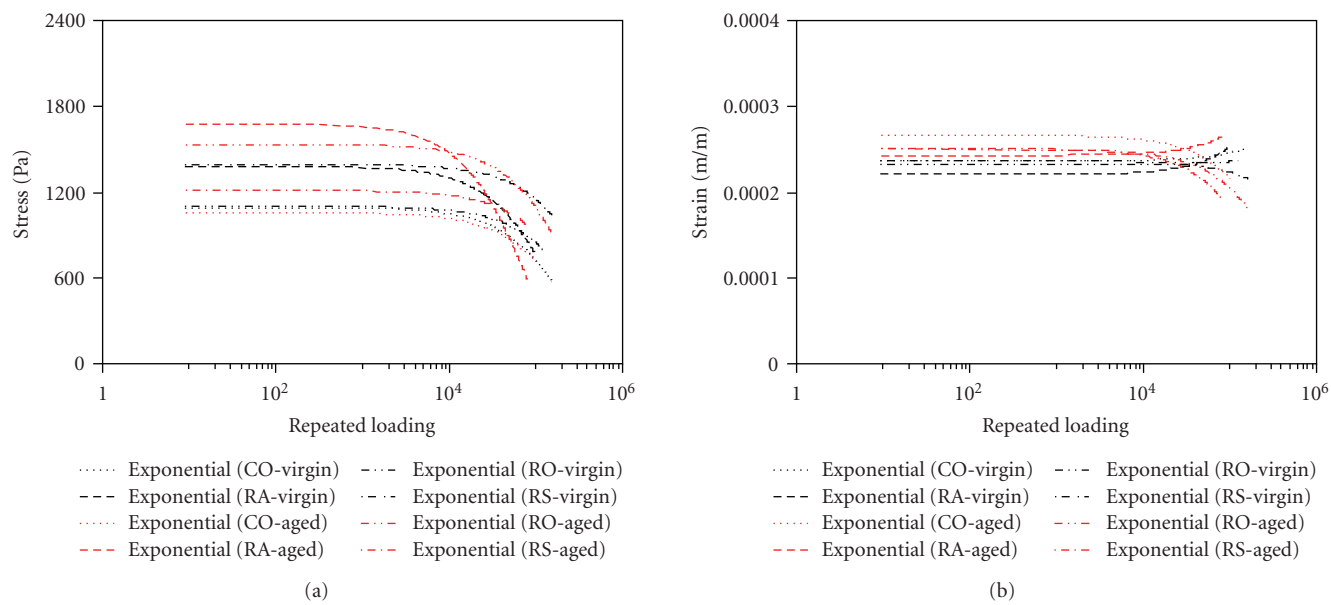


Figure 4: Stress and strain versus loading number of various mixtures: (a) stress; (b) strain.

by using repeated flexure, direct tension, or diametral tests performed at several stress or strain levels. The fatigue behavior of a specific mixture can be characterized by the slope and relative level of the stress or strain versus the number of load repetitions to failure and can be defined by a relation of the following form [23]:

$$N_f = a\left(\frac{1}{\varepsilon_0}\right)^b\left(\frac{1}{S_0}\right)^c \quad \text{or } N_f = a\left(\frac{1}{\sigma_0}\right)^b\left(\frac{1}{S_0}\right)^c, \tag{6}$$

where N_f is the number of load application or crack initiation; ε_0, σ_0 are tensile strain and stress, respectively; a, b, c are experimentally determined coefficients.

The typical analysis of stress or strain with the number of load repetitions is shown in Figure 4. It can be noted that the stress values decrease quickly as the load repetitions are more than 10,000 cycles for all mixtures (Figure 4(a)). Generally, mixtures from various types exhibit different stress values during fatigue testing. Additionally, Figure 4(b) indicates that the induced strain values of all mixtures are similar under a controlled strain test (500 microstrain levels). Figure 4 illustrates that stresses and strains from various mixtures do not exhibit an obvious trend.

Previous research indicated that the stiffness at any number of load repetitions is computed from the tensile stress and strain at that specific value [9, 23–27]. The stiffness of fatigue beam, determined by the tensile stress and strain, can be plotted using stiffness (S) against load cycles (n) and best fitting the data to exponential function of the form shown as follows:

$$S = Ae^{bn}, \tag{7}$$

where e is the natural logarithm to the base e, and A, b are experimentally determined coefficients.

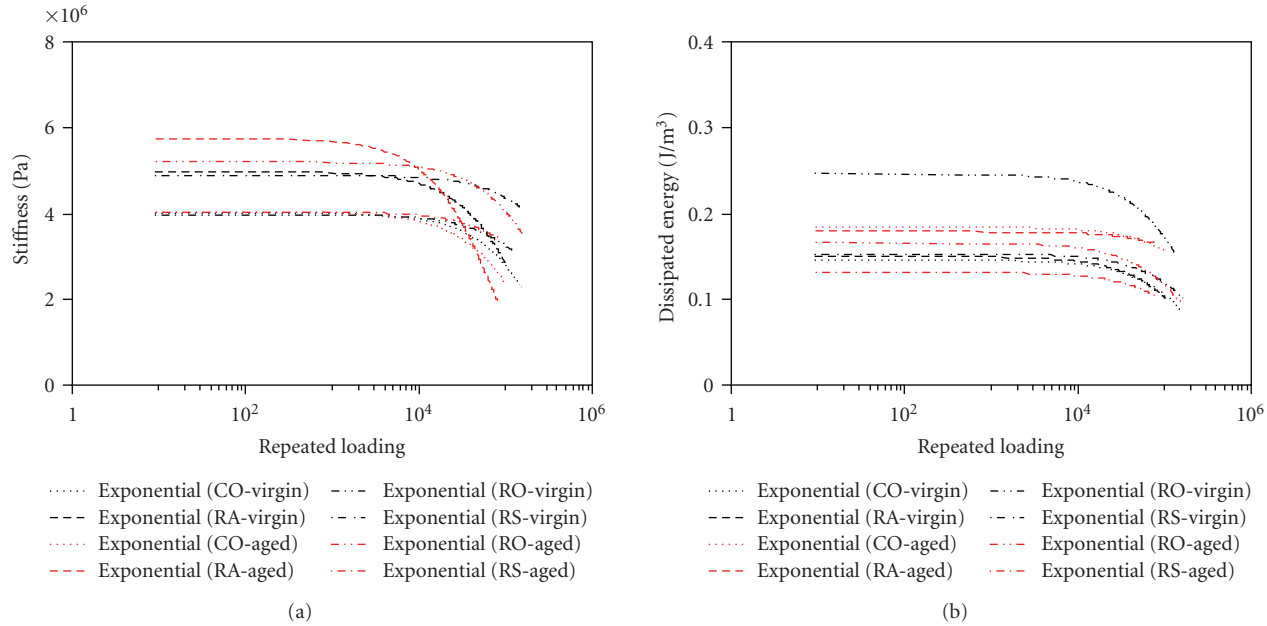


Figure 5: Stiffness and dissipated energy versus loading number of various mixtures: (a) stiffness; (b) dissipated energy.

Table 5: Volumetric properties of mixtures.

Mix type	Aggregate A					Aggregate B				
	OBC	BSG	MSG	VMA	VFA	OBC	BSG	MSG	VMA	VFA
Control	5.7	2.472	2.373	17	77	4.2	2.627	2.524	14	72
Rubberized	6.2	2.477	2.379	18	78	5.0	2.583	2.482	16	75

Note: OBC: optimum binder content; BSG: bulk specific gravity; MSG: maximum specific gravity; VMA: Voids in the mineral aggregate; VFA: Voids filled with Asphalt.

Figure 5(a) shows a typical plot of stiffness ratio (defined as quotient of stiffness at the ith load repetition to the initial stiffness) versus the number of load repetitions for flexural beam fatigue tests in controlled-strain modes of loading. It can be noted that the aged mixture generally shows a higher stiffness value during repeated loading.

The dissipated energy per cycle decreases with an increasing number of load repetition in the controlled-strain fatigue test. The cumulative dissipated energy to failure for a flexural beam fatigue test is the area under the curve between dissipated energy and number of cycles. In this study, since the flexural beam fatigue test used the controlled-strain test, the number of cycles has a greater increase than the controlled-stress test. Research has shown that the dissipated energy approach will make it possible to predict the fatigue behavior of mixtures in the laboratory over a wide range of conditions from the results of a few simple fatigue tests [23, 28–30]. Such a relationship can be characterized in the form of the following equation:

$$W_N = a\left(N_f\right)^b, \tag{8}$$

where N_f is the fatigue life; W_N is the cumulative dissipated energy to failure; and $a, b$are experimentally determined coefficients.

The variation of dissipated energy per cycle with number of load repetitions is shown in Figure 5(b). The dissipated energy per cycle decreased as the number of load repetitions increased in the controlled-strain fatigue test. Dissipated energy decreased significantly after the fatigue life reaches 10,000 cycles in general. However, no obvious trend in dissipated energy is found for aged and virgin mixtures.

The flexural stiffness (3) of an asphalt pavement is related to the various aspects of HMA, such as rutting, resilient modulus, and fatigue life. The test results shown in Figure 6 illustrate that the initial stiffness value of the aged mixture is significantly higher at a test temperature of 5°C than 20°C regardless of aggregate source and mixture type. In addition, at 5°C or 20°C, the stiffness values of all aged mixture are generally close. However, Figure 6 indicates that the aged mixture from aggregate B has greater stiffness values at two test temperatures. This greater stiffness may be the result of different aggregate sources producing different interfaces among the binder, voids, and aggregate, thus, affecting the corresponding fatigue behavior of the pavement [9]. However, the influence of WMA additive on the initial stiffness values of the aged rubberized mixtures is not significant in this study. Moreover, with respect to the influence of aggregate source, statistical analysis (AVOVA) in Table 6 indicates that aggregate source does not have a significant influence on the stiffness values of varying aged

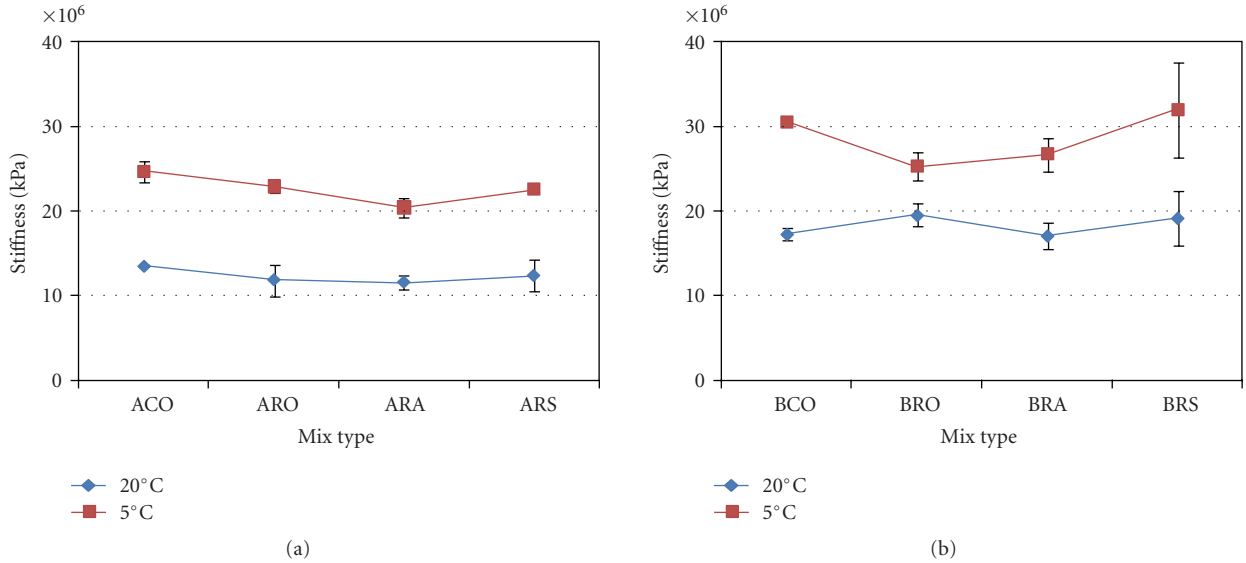


Figure 6: Stiffness value of mixture: (a) aggregate A; (b) aggregate B.

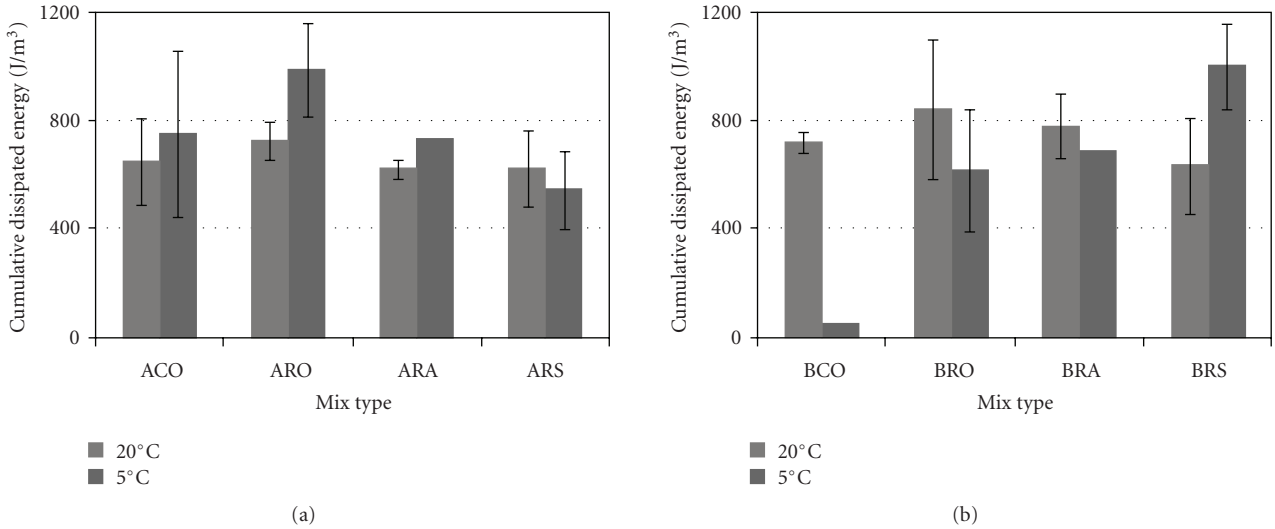


Figure 7: Cumulative dissipated energy of aged beam: (a) aggregate A; (b) aggregate B.

Table 6: Statistical analysis of mechanical properties in terms of aggregate sources.

	Aggregate A∼Aggregate B			
	Control	Rubberized	Rubberized + Asphmin	Rubberized + Sasobit
Significant (20°C)				
Cumulative energy	Y	Y	Y	N
Stiffuess	Y	Y	N	N
Fatigue life	Y	Y	Y	Y
Significant (5°C)				
Cumulative energy	N	N	N	N
Stiffness	N	N	N	Y
Fatigue lifu	Y	Y	Y	Y

Note: Y: P-value $< \alpha = .05$ (significant difference); N: P-value $> \alpha = .05$ (no significant difference).

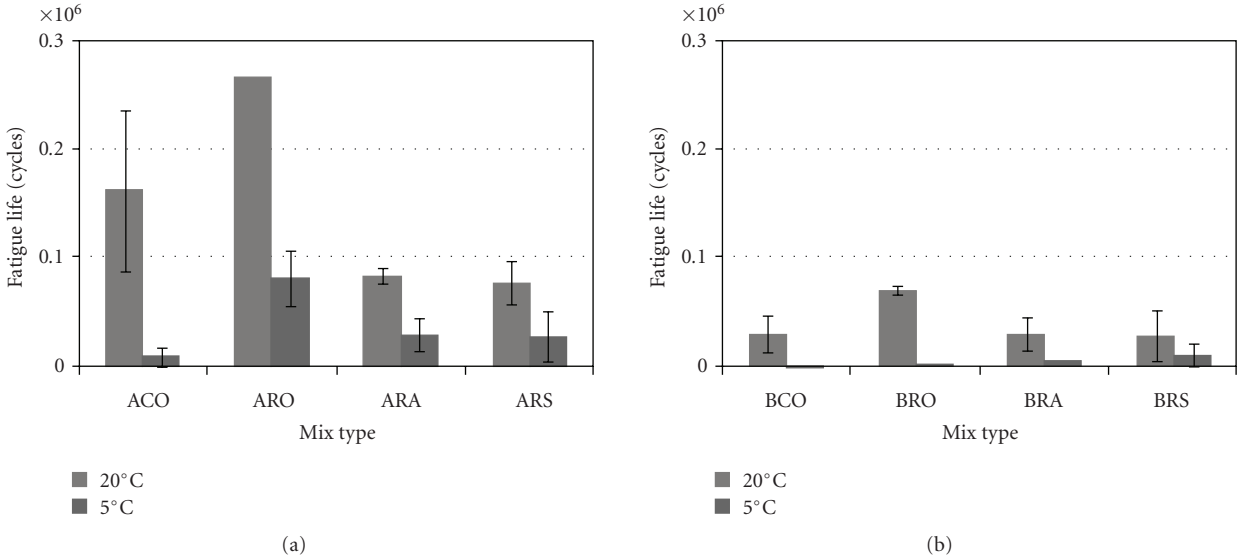


Figure 8: Fatigue life value of mixture: (a) aggregate A; (b) aggregate B.

Table 7: Statistical analysis of mechanical properties in terms of mixture types.

	Mixture type (0-control, I-rubberized, 2-rubberized + Asphmin, 3-rubberized + Sasobit)					
	0∼1	0∼2	0∼3	1∼2	1∼3	2∼3
Significant (20°C)						
Cumulative energy	N	N	N	N	N	N
Stiffness	N	N	N	N	N	N
Fatigue life	N	Y	Y	Y	Y	N
Significant (5°C)						
Cumulative energy	N	N	N	N	N	N
Stiffness	N	N	N	N	N	N
Fatigue life	Y	N	N	Y	Y	N

Note: Y: P-value < α = .05 (significant difference); N: P-value > α = .05 (no significant difference).

mixture types generally at 5°C, while there are significant difference in stiffness values for the aged hot mixtures (control and rubberized) made from two aggregates at 20°C. On the other hand, as shown in Table 7, no significant difference in initial stiffness value is found between any two mixtures at 5°C and 20°C.

The dissipated energy, computed from (4) and (5), was used as an indicator of fatigue cracking in the asphalt layer [23, 28–31]. As shown in Figure 7, the typical cumulative dissipated energy of mixture is higher at 5°C than at 20°C for mixtures from aggregate. However, due to the aging influence, the mixture from aggregate B does not have an obvious trend in the cumulative dissipated energy. In addition, in these aged mixtures, the effects of WMA additive on the cumulative dissipated energy are inconsistent for mixtures from two aggregates. Statistical results in Table 6 indicate that, except for the mixture with Sasobit additive, other mixtures from two aggregate sources do not show significantly different cumulative dissipated energy values regardless of the test conditions. With respect to the effect of rubber and WMA additive, Table 7 shows that the influence of WMA additive on the cumulative dissipated energy is not significant for any two rubberized mixtures.

The test results presented in Figure 8 show that the fatigue life of fatigue beams is remarkably higher at 20°C than 5°C for all aged mixtures. In addition, Figure 8 also illustrates that the mixture made from aggregate A has a greater fatigue life than those made from aggregate B, though aggregate B has a lower LA abrasion loss and absorption values. Moreover, the aged rubberized mixture with WMA additive shows a relative lower fatigue life than mixture without WMA additive; from this standpoint, it seems that WMA additive has a negative effect on fatigue life in the long term aging process. Similar properties ($G^* \sin \delta$) from binder tests are shown in Figure 3(a). The fatigue values shown in Figure 8(b) indicate that the aging process plays a key role in affecting the long-term performance of asphalt pavement. Additionally, the standard deviation of the fatigue test results for each mixture is large since the variability of fatigue life is generally based upon the microstructure of beams (e.g., the aggregate-binder interface, the void size distribution, the interconnectivity of voids, distribution of aggregate particles,

film thickness, and the aged status of binder). Previous research found that increasing the number of the repeated specimens reduced the variability [9]. In addition, statistical analysis in Table 6 indicates that, with respect to the effect of aggregate source, there is a significant different fatigue life value between any two aggregate sources regardless of the aged mix types and test conditions. Moreover, as shown in Table 7, the aged rubberized mixture generally has the significantly different fatigue life values with other aged mixtures at two test temperatures. There are no significant differences between the aged mixtures with Asphamin and Sasobit additives.

4. Conclusions

The following conclusions were determined based upon the limited experimental data presented regarding the fatigue life of the modified binder and aged mixtures.

(i) The addition of WMA additive slightly increases the $G^* \sin\delta$ and stiffness values of rubberized binder. However, after a long-term aging performance, these increases in fatigue factor ($G^* \sin\delta$) and stiffness of CR binder weakens its fatigue resistance.

(ii) The stiffness value of the aged mixture is noticeable greater at 5°C than 20°C. Generally, the mixture from aggregate B has a slightly higher (approximate 1.5 times) stiffness value than that from aggregate A. Statistical significance can be found for these aged mixtures from two aggregate sources at different test temperatures. In addition, with respect to the effect of mixture type, statistical analysis results illustrated that there are no significant differences in the stiffness values for overall mixtures (control, rubberized, or WMA mixtures).

(iii) The experimental results indicated that the trend in cumulative dissipated energy values of the aged mixture are not obvious regardless of the aggregate types and test temperatures. However, statistical analysis indicates that there are not significant difference in cumulative dissipated energy for mixtures made from various WMA additives.

(iv) Fatigue life values from the aged rubberized mixtures are generally greater than other mixtures with or without WMA additive and the aged mixture has a greater fatigue life at 20°C than 5°C. In addition, statistical results presented that the fatigue life is significant different for the mixture from various aggregate sources while the mixture type (i.e., addition of crumb rubber and WMA additive), in most cases, does not play a key role in determining its fatigue life.

Acknowledgments

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