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Influences of crumb rubber size and type on reclaimed asphalt pavement (RAP) mixtures

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ABSTRACT

Over the years, recycling has become one of the most attractive pavement rehabilitation alternatives, and different recycling methods are now available to address specific pavement distresses and structural needs. The objective of this study was to investigate and evaluate the engineering properties of crumb rubber size and type influences on reclaimed asphalt pavement (RAP) mixtures. The experimental design for this study included the use of three rubber sizes and two rubber types (ambient or cryogenic) in the mixture containing 25% RAP mixtures. In this study, the results of the experiments indicated that the addition of crumb rubber was helpful in increasing the voids in mineral aggregate (VMA) in Superpave mix design and improving rutting resistance of mixture regardless of rubber size and type. On the other hand, indirect tensile strength (ITS) values show no significant difference for mixtures made with three type rubber sizes. However, the increase of rubber size, regardless of rubber type, reduced the resilient modulus values but extended the fatigue life of the modified mixtures.

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1. Introduction

The use of RAP has evolved into routine practice in many areas around the world. In the United States, the Federal Highway Administration (FHWA) reported that 73 of the 91 million metric tons of asphalt pavement removed each year during resurfacing and widening projects are reused as part of new roads, roadbeds, shoulders and embankments [1–4]. The recycling of existing asphalt pavement materials produces new pavements with considerable savings in material, money, and energy. Aggregate and binder from old asphalt pavements are still valuable even though these pavements have reached the end of their service lives. They have been used, for many years, with virgin aggregates and binders to produce new asphalt pavements, proving to be both economical and effective in protecting the environment. Furthermore, mixtures containing RAP have been found, for the most part, to perform as well as the virgin mixtures [5–9].

However, although it is helpful in reducing the utilization of virgin asphalt binder and improving rut resistance, the aged binder in RAP is thought to be a potential contributing factor responsible for asphalt pavement thermal and fatigue cracking failures. This is due to volatilization and oxidation in short and long-term performance of mixtures [10]. As a result, a subgroup of the FHWA Superpave Mixtures Expert Task Group developed interim guidelines for the use of RAP based on past experience. These guidelines established a tiered approach for RAP usage where additional softer binder is added to increase the amount of the light oils and small molecular size fraction in the binder to reduce the aged binder influence.

The market for crumb rubber has been growing over the past several years both in the United States and in other countries. Most laboratory and field experiments have indicated that the rubberized asphalt concretes (RAC), in general, show an improvement in durability, crack reflection, fatigue and skid resistances, and resistance to rutting not only in an overlay, but also in stress absorbing membrane (SAM) layers [11,12]. Two types of crumb rubber (ambient and cryogenic) are being used in the HMA due to the different processing methods. Previous research indicated that the crumb rubber modified (CRM) binders, containing ambient rubber, resulted in higher interaction effect and particle effect values than the CRM binders made with cryogenic rubber [13,14]. This is due to the increased surface area and irregular shape of the ambient CRM. The physico-chemical properties of the two types completed by Xiao et al. [15] indicated that after removal of asphalt binder from crumb rubber particles, the dimensions of the crumb rubber are reduced as a result of interaction with asphalt binder. This can be attributed to the breakdown, or depolymerization of the rubber particles digesting in hot asphalt binder. The size reduction of rubber material increases with mixing, or digestion, duration and with decreasing crumb rubber size. Xiao et al. [15] also found that, due to the variability of the energy dispersive X-ray spectrum data, it was difficult to detect statistically

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significant differences between the elemental compositions of rubber in different treatments (such as zinc oxide, oxygen, calcium, silicon, and so on) [16].

On the other hand, the previous research indicated that the rubber particle size is also important factor in affecting the rheological and engineering properties of mixtures [13,14]. Nowadays, various rubber sizes are being used in the HMA mixtures around the world. Furthermore, research has shown that fatigue behavior of rubberized mixtures was found to be significantly improved compared to conventional mixtures. At the same time, the crumb rubber improved the resistance to aging [17,18].

However, the influence of two byproducts (crumb rubber and RAP) mixed with virgin mixtures together has not yet been identified clearly. Especially, the effects of rubber size or type on the physical properties of recycled mixtures have not been investigated in detail. For example, pavement engineers only know the aged binder will reduce fatigue life and increase the potential risk of thermal and fatigue cracking of HMA, while the addition of crumb rubber is helpful in improving the aging and extending the long-term performance of HMA. Because of the complicated relationships of these two materials in the modified mixtures with respect to rubber size and type influences, it is important to conduct research projects to obtain a better understanding of their interaction.

The objective of this study was to evaluate the laboratory performance of RAP containing three different sizes and two types of crumb rubber in various HMA. This was accomplished through the evaluation of engineering properties such as indirect tensile strength (ITS), toughness, resilient modulus, rutting resistance, and fatigue life.

2. Experimental design and testing procedures

The experimental design (Fig. 1) detailed in this study included the use of two rubber types (ambient and cryogenic), one rubber content (10% by weight of virgin binder), three crumb rubber sizes (−40 mesh [−0.425 mm], −30 mesh [−0.600 mm], and −14 mesh [1.350 mm]), as shown in Table 1, and one RAP content (25% by weight of the modified mixture). The properties of virgin PG 64-22 asphalt binder and aged binder extracted from RAP that were used for preparing binder testing samples in this project are shown in Table 2 [19–21].

The gradations of various aggregates, including virgin and RAP aggregate sources, are shown in Table 3. In this paper, the RAP material passing the 12.5 mm (1/2 in.) and passing the 4.75 mm (No. 4) sieve are referred to as +4 RAP and −4 RAP, respectively. The RAP was taken from the same geographical area as the new aggregates to ensure that the aggregates in the RAP have similar properties to the virgin aggregates. The analysis of the binder content and aggregate gradation was separated according to these two types (+4 RAP and −4 RAP). The asphalt binder content of the −4 RAP was significantly greater than that of the +4 RAP. The sieved RAP was used for testing sample preparation of the modified mixtures.

A reaction time of 30 min was considered suitable based on a preliminary study indicating that the mixing time did not significantly influence the binder properties [10,13]. The modified binders were allowed to cool at room temperature and sealed prior to mix design. Previous research conducted by the Asphalt Rubber Technology Services (ARTS) staff at Clemson University provides some detailed information regarding the behavior of asphalt binder modified with crumb rubber [10,13]. These modified binders were mixed with virgin aggregate and RAP to fabricate Superpave mixtures.

There were a total of 8 Superpave mix designs conducted. A nominal maximum size 9.5 mm Superpave mixture was used for all mix designs. Gradations of the 9.5 mm mixtures are illustrated in Fig. 2. The temperatures were determined in accordance with previous research projects [10]. Both mixing and compacting temperatures increase as the percentage of RAP or crumb rubber increases regardless of the type of RAP or rubber. The increase in temperature, resulting from the increase of viscosity, is caused by aged binder and the addition of crumb rubber to produce modified binders [10,14]. These particular mix designs are used as a primary route surface course mixes in many states including South Carolina. The 9.5 mm Superpave volumetric and compaction specifications are described in AASHTO PP19 and AASHTO T312 procedures which were followed for the preparation of HMA specimens.

For this study, the optimum binder content (OBC), during the Superpave mix design process, was defined as the amount required to achieve 4.0% air voids at a given number of design gyrations

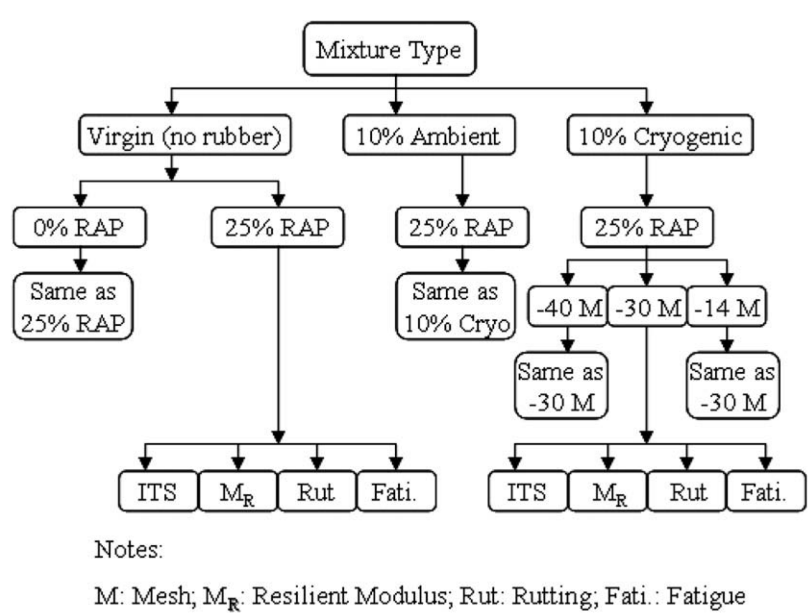

Fig. 1. Flowchart of experimental design.

Table 1
Gradations of crumb rubber

% Passing mesh size (mm)	Ambient			Cryogenic		
	−14 M	−30 M	−40 M	−14 M	−30 M	−40 M
No. 14 (1.41)	100.0	100.0	100.0	100.0	100.0	100.0
No. 16 (1.19)	97.1	100.0	100.0	100.0	100.0	100.0
No. 20 (0.84)	70.3	100.0	100.0	63.8	100.0	100.0
No. 30 (0.60)	44.1	100.0	100.0	26.9	99.5	99.3
No. 40 (0.42)	27.0	60.8	91.0	4.0	34.2	91.7
No. 50 (0.30)	16.7	19.3	59.1	3.3	3.6	45.9
No. 80 (0.18)	9.0	13.1	26.2	3.3	3.6	11.5
No. 100 (0.15)	7.6	11.1	18.6	3.3	3.6	7.4

Note. M – mesh.

Table 2
Engineering properties of asphalt binder

Aging states	Test properties	PG64-22	Extracted binder
No aging	Viscosity @135 °C (Pa s)	0.430	5.982
	$G^*/\sin(\delta)$ @64 °C (kPa)	1.279	58.542
RTFO	$G^*/\sin(\delta)$ @64 °C (kPa)	2.810	109.780
PAV	$G^*\sin(\delta)$ @25 °C (kPa)	4074	8000
	Stiffness @-12 °C (MPa)	217	294
	m-Value @-12 °C	0.307	0.241

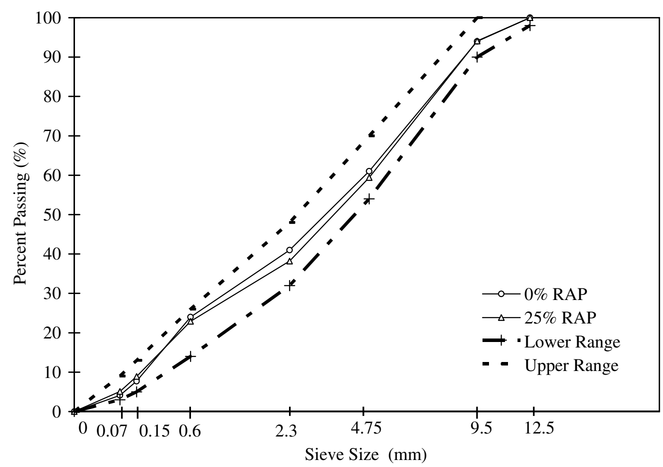

Fig. 2. Gradations of 9.5 mm mixtures.

(N_{design} = 75). Six ITS specimens, compacted to 7 ± 1% air voids, were used to evaluate the moisture susceptibility of various mixtures as modified AASHTO T283 procedures (no freeze/thaw cycle) were followed.

Four specimens, one for destructive indirect tensile test and three others for repeated loading, were also compacted to 7 ± 1% air voids and then employed to perform resilient modulus testing at three different temperatures (5 °C, 25 °C and 40 °C). All specimens had a height of 75 ± 1 mm and a diameter of 150 ± 1 mm. The resilient modulus values for all mixtures were determined based on AASHTO TP31 testing procedure. The indirect tensile testing mode produces a highly nonlinear stress field with the least variability at the center of the sample, and linear variable differential transducers (LVDT) were used to measure the response.

Six dry cylindrical Asphalt Pavement Analyzer (APA) specimens, for each mix type, were compacted using a Superpave gyratory compactor. All testing with the APA was carried out to 8000 cycles to measure the rut depth of the HMA at 64 °C [22]. The testing temperature was based on the virgin binder's "performance grade" used in this study. To be able to compare the potential rut depth under the same test conditions, it was necessary to conduct all tests at the same temperature based on the original asphalt binder PG grade.

Fatigue beams were made in the laboratory and four beams of each mixture were tested in this study. The total aggregate weight of 10,800 g was used for making one large beam. The mix was placed in the oven for 2 h as a short-term aging. The vibratory compactor equipment was used to compact the flexural bending fatigue beams used in this study. The compacted beam was sawn into two small test fatigue beams after bulk specific gravity testing. Test specimens were sawn to a 380 mm (15 in.) length by 63 mm (2.5 in.) width and 50 mm (2 in.) thick sections. The beams were stored at 25 °C (77 F) for a week before obtaining their specific gravities and air voids. All tests were performed in a temperature-controlled chamber at 20 ± 0.5 °C. To maintain the testing temperature, each beam specimen was placed in the environmental chamber for 2 h prior to beginning the test. In this study, a repeated sinusoidal loading at a frequency of 5 Hz was used. 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).

Table 3
Gradations of aggregate and RAP

Type of aggregate	12.5 mm 1/2″	9.5 mm 3/8″	4.75 mm #4	2.36 mm #8	0.60 mm #30	0.150 mm #100	0.075 mm #200
#789 stone	100	90	35	6.3	1.4	0.7	0.44
Reg. screenings	100	100	99.8	96	60.5	22.3	12
Manufactured sand	100	100	99.4	82.5	47.2	7.6	2.3
+4 RAP	100	97	59	45	30	14	8
−4 RAP	100	100	100	88	57	24	14

Note. Asphalt binder content: −4 RAP = 6.96%; +4 RAP = 4.66%.

3. Experimental result and discussions

3.1. Superpave mix design analysis

The Superpave gyratory compactor (SGC) was used to compact the specimens, having a diameter of 150 mm. A design number of equivalent single axle loads (ESALs) of 0.3 to <3 million was selected for all mixtures. The N_{ini}, N_{des}, and N_{max} values used in this study were 7, 75, and 115, respectively. The OBCs, bulk specific gravity (BSG), voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA) for mix designs with various percentages of RAP, rubber size and type are shown in Table 4. It can be seen that the OBCs of the mixtures decrease slightly, as expected, as RAP is added. The OBCs of the modified mixtures using cryogenic rubber were found to be slightly higher than those of the mixtures using ambient rubber. It also can be found that the OBC increases slightly as the rubber size increases, in general.

In most cases, the modified mixtures incorporating rubber and RAP had lower OBC values than the virgin mixture. The VMA and VFA values of the mixtures did meet the Superpave mix design requirements except for the mixture with 25% RAP and no rubber, which had a VMA value of 14.7%, which is less than the minimum requirement of 15.5% specified by SCDOT. In this study, it can be seen that the addition of crumb rubber is helpful in increasing the VMA of the mixture and this increase is generally more noticeable as the rubber size increases for both types of rubber. The BSG values do not show a clear trend due to the effect of rubber size and type (Table 4).

3.2. ITS and toughness analysis

The ITS and tensile strength ratio (TSR) test is often used to evaluate the moisture susceptibility of an asphalt mixture. Some of the ITS values (10% rubber and 25% RAP) used in study were taken from the research project completed by Xiao et al. [14]. Fig. 3 shows that the addition of RAP results in an increase in ITS values. With respect to the effect of rubber size, in general, it can be seen that the different rubber sizes do not result in significant differences in ITS values using the same percentage of RAP (25%) regardless of moisture conditioning type (dry or wet). However, the specimens containing cryogenic rubber generally have greater ITS values. At the same time, Fig. 3 also shows that, in most cases, the ITS values of dry specimens are greater than the wet conditioned specimens. Moreover, the TSR values of all of the mixtures, except the virgin mix, were higher than 85% (Table 4), which is the SCDOT minimum specification.

Toughness was defined as the area under the tensile stress–deformation curve up to a deformation of twice that incurred at maximum tensile stress [23,24]. The average toughness of dry virgin specimens was greater than that of other specimens containing rubber and RAP, while the wet specimens show similar toughness values regardless of rubber size and type (Table 4). Furthermore, statistical analysis shows that there was not a significant difference in any of the rubber types and sizes.

3.3. Resilient modulus analysis

In the indirect repeated load testing, the resilient modulus was determined using the recoverable horizontal and vertical deformations that occurred during the unloading portion of the load–unload cycle. The test is normally performed over a range of temperatures and stresses to simulate moving vehicles over a pavement structure (e.g., surface, subbase, and subgrade) during the service life of the asphalt pavement.

The resilient modulus values of all mixtures are shown in Fig. 4. It can be seen that as the temperature increases, the resilient modulus significantly decreases regardless of rubber size and type. Fig. 4 also shows that the addition of RAP results in a significant increase of resilient modulus value at the same temperature condition. However, in general, increasing the rubber size leads to a slight decrease in resilient modulus regardless of rubber type or test temperature. In addition, the resilient modulus values of the mixtures containing ambient rubber were greater than those utilizing cryogenic rubber.

3.4. Rut resistance analysis

Rutting is the consolidation of HMA pavement by traffic loading after construction. Some increased rutting resistance can be obtained by using stiffer (high viscosity and low penetration) asphalt binders, such as polymer or rubber modified binders. Certain mineral fillers can also increase the apparent viscosity of asphalt binder, thus making the mix more resistant to rutting [14,22,25].

Fig. 5 shows that the rut depths of the APA specimens which were recorded every cycle by a data acquisition system for 8000 cycles. As shown in the Fig. 5, the virgin specimens present a significantly greater rut depth than the other modified specimens. Fig. 5 also indicates that the rut depth increases sharply for the first 1000 cycles and then the increase becomes more gradual. It also can be seen that the mixture made with −14 mesh rubber shows a slightly higher rut value than other mixtures after the specimens were being tested.

Fig. 6 shows the average measured rut depths of APA specimens after 8000 cycles. It can be seen that the addition of RAP and/or crumb rubber plays a key role in reducing the rut depth of the mixture. Ambient rubber is more effective in improving rutting resistance than cryogenic. With respect to the rubber size, the specimens made with −30 mesh crumb rubber show a better rutting resistance than other sizes. Some of rutting depth values were taken from the projects completed by Xiao et al. [14].

Table 4
Superpave mix design, TSR, and toughness of modified mixtures

Testing property	Virgin	25% RAP						
		No rubber	10% 40 mesh		10% 30 mesh		10% 14 mesh	
			Ambient	Cryogenic	Ambient	Cryogenic	Ambient	Cryogenic
BSG	2.345	2.364	2.339	2.362	2.352	2.332	2.348	2.347
VMA (%)	16.6	14.7	15.6	16.0	15.7	15.8	15.6	17.1
VFA (%)	73.9	74.4	73.7	75.3	73.1	74.1	75.8	76.5
OBC (%)	5.40	4.70	5.08	5.35	5.08	5.18	5.23	5.80
TSR (%)	81	88	107	99	93	113	96	96
Toughness								
Dry (N/mm)	3.3	3.1	3.1	3.0	3.0	2.9	3.1	3.0
Wet (N/mm)	2.8	2.8	3.0	2.9	3.0	2.8	3.0	3.1

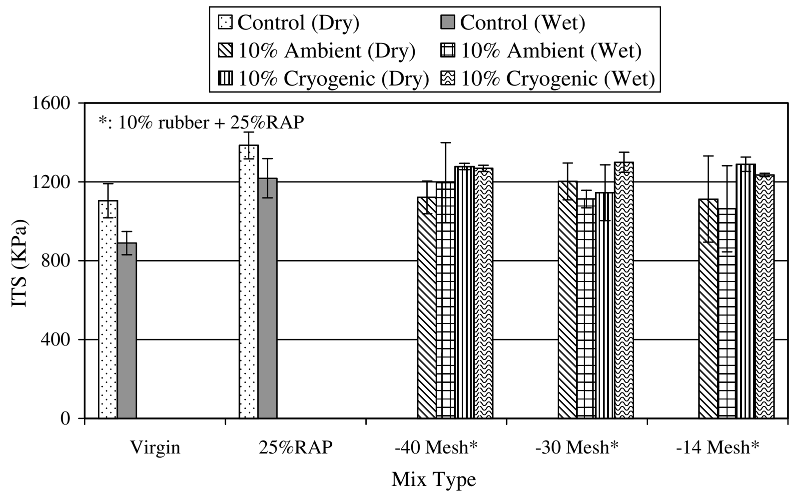

Fig. 3. ITS values of modified mixtures.

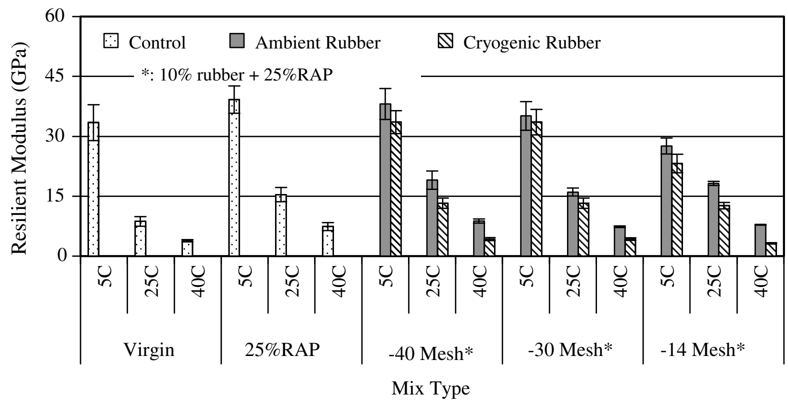

Fig. 4. Resilient modulus values of modified mixtures.

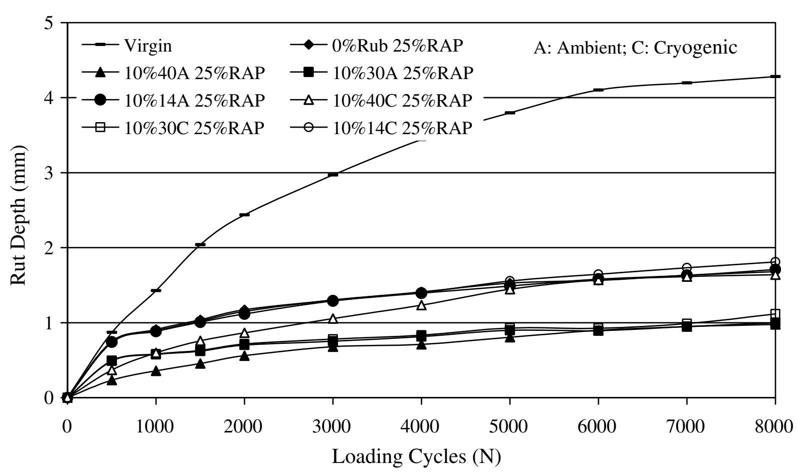

Fig. 5. Rutting behavior of modified mixtures.

3.5. Fatigue life analysis

Fatigue, associated with repetitive traffic loading, is considered to be one of the most significant distress modes in pavements and is related to various properties of HMA. Previous studies have been conducted to understand how fatigue life can be extended under repetitive traffic loading [26,27].

Fig. 7a indicates that the stiffness value of the mixture using 25% RAP is lower than that of the mixture using virgin asphalt binder, while the addition of crumb rubber increases the stiffness value of the modified mixtures. For the two types of rubber, the mixtures containing ambient rubber present a smaller stiffness than those with cryogenic rubber. For the mixtures made with binders containing ambient rubber, in general, statistical analysis

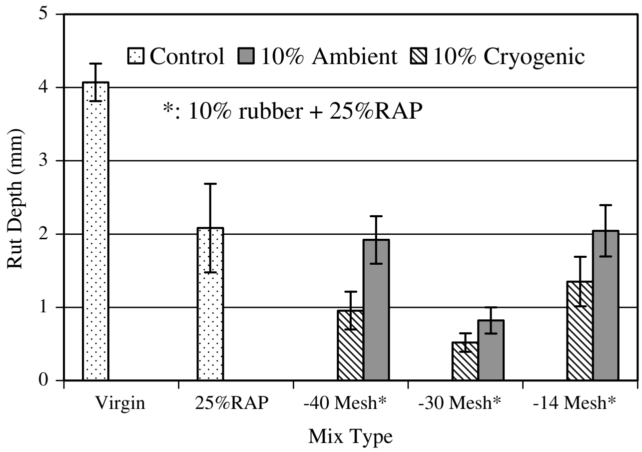

Fig. 6. Rut depth of modified mixtures.

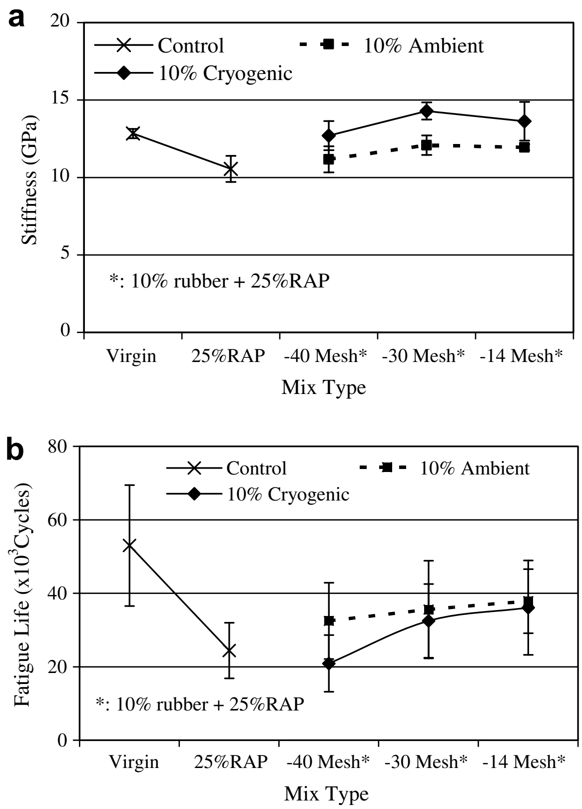

Fig. 7. Properties of modified mixtures: (a) stiffness value and (b) fatigue life.

shows there were no significant differences in stiffness values of the mixtures due to rubber size effect. For the mixtures made with cryogenic rubber, the −30 mesh rubber had a slightly higher value than the other two rubber sizes. The results illustrate that the mixtures using various rubber sizes exhibit similar potential deformation values under the same repeated loading.

As shown in Fig. 7b, the fatigue life of the virgin mixture was significantly greater than that of the other mixtures. The addition of RAP has a negative influence on the fatigue resistance of HMA mixture tested in this study. The fatigue resistance will be improved; however, as crumb rubber is added to the mixture regardless of the rubber type. In this study, the ambient rubber generally shows greater fatigue resistance than cryogenic. In Fig. 7b, it can also be seen that the mixtures using larger rubber sizes show a slightly higher fatigue life values regardless of the rubber type. It is obvious from this study that the crumb rubber can offset the negative effect of the addition of RAP on fatigue resistance and is beneficial in extending the long-term performance of the modified mixtures.

4. Conclusions

Based on the experimental data shown in this study, the following conclusions have been reached:

- In Superpave mix design, the use of RAP in modified mixtures provides such benefits as decreasing the virgin asphalt binder content, increasing the ITS and TSR values, and thus improving the moisture resistance of HMA mixtures. Although the additional crumb rubber slightly increases the OBCs, in general, it is beneficial in increasing the VMA values due to its small particle size. The rubber size and type have noticeable effects on the performance of the modified mixtures.
- The addition of RAP and rubber increases the resilient modulus values at various temperatures. Increasing rubber size results in a decrease in the resilient modulus values for modified mixtures regardless of rubber types. The mixtures containing ambient rubber had slightly greater resilient modulus values than those made with cryogenic rubber.
- Both the crumb rubber and RAP play an important role in improving the rutting resistance of HMA. These additional recycling materials significantly enhance the potential high temperature performance in HMA and are being encouraged for use in hot climates.
- Although the RAP in modified mixtures has a significant negative influence on the long-term performance of HMA and results in a reduction in fatigue life, the addition of rubber is helpful in increasing its fatigue resistance regardless of the rubber size and type. At the same time, the fatigue life of rubberized mixture slightly increases as the rubber size increases.

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