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Research Article

Mechanistic and Economical Characteristics of Asphalt Rubber Mixtures

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Load associated fatigue cracking is one of the major distress types occurring in flexible pavement systems. Flexural bending beam fatigue laboratory test has been used for several decades and is considered to be an integral part of the new superpave advanced characterization procedure. One of the most significant solutions to prolong the fatigue life for an asphaltic mixture is to utilize flexible materials as rubber. A laboratory testing program was performed on a conventional and Asphalt Rubber- (AR-) gap-graded mixtures to investigate the impact of added rubber on the mechanical, mechanistic, and economical attributes of asphaltic mixtures. Strain controlled fatigue tests were conducted according to American Association of State Highway and Transportation Officials (AASHTO) procedures. The results from the beam fatigue tests indicated that the AR-gap-graded mixtures would have much longer fatigue life compared with the reference (conventional) mixtures. In addition, a mechanistic analysis using 3D-Move software coupled with a cost analysis study based on the fatigue performance on the two mixtures was performed. Overall, analysis showed that AR modified asphalt mixtures exhibited significantly lower cost of pavement per 1000 cycles of fatigue life per mile compared to conventional HMA mixture.

1. Introduction

The improved performance of AR pavements compared with unmodified bitumen pavements has relatively resulted from improved rheological properties of the modified asphalt binder [1–3]. Modified bituminous materials can introduce measurable benefits to highway maintenance and construction divisions, in terms of better-performance and longer lasting roads, as well as cost savings in the road service life. The use of crumb rubber modifications with unmodified asphalt binder seems to enhance the fatigue resistance, as illustrated in a number of studies [4–8]. What has to be ascertained in practice is the degree of modification of the asphalt mixtures that takes place and its cost effectiveness. A detailed comparison between AR mixtures and unmodified mixtures is needed to quantify the true cost effectiveness of rubber-modified asphalt mixtures as related to fatigue performance.

Roberts et al. also [9] performed a research study to evaluate the overall pavement performance under accelerated

loading of hot mix asphalt mixtures containing powdered rubber modifier (PRM) as compared to similar mixtures with unmodified HMA and to optimize the use of these materials in the pavement structure. Additionally, the study determined an appropriate structural coefficient (a -value) for use of these materials in the structural design of flexible pavements using the AASHTO design procedure. The resulting structural coefficient (a -value) for the powdered rubber base was 0.45 compared to 0.40 for an unmodified base course using AC-30. The addition of the powdered rubber increased the cost of the binder by only 10 percent, while increasing its structural coefficient by 12.5 percent.

Another study by Jones et al. [10] included a comprehensive laboratory as well as field accelerated pavement testing experiment focused on a comparison of gap-graded, terminal-blend modified binder mixes with gap-graded AR and unmodified HMA mixtures. The analysis indicated that gap-graded mixes with modified binder and a combination of modified binder and 15% recycled rubber will provide superior performance in terms of reflection cracking compared

with the half thickness of AR mixture and full thickness of unmodified HMA mixture used in thin overlays on cracked HMA pavements.

2. Objective

The objective of this study was to assess the impact of added rubber on the mechanical, mechanistic, and economical attributes of asphaltic mixtures. This paper combines the results of the mechanical fatigue laboratory evaluations with the long-term mechanistic performance as well as the cost of AR mixtures to assess the full benefits of AR mixtures relative to their added costs.

3. Background

In 2008, a first cooperative effort between Arizona State University (ASU) and the Swedish Road Administration (SRA) took place in testing conventional and Asphalt Rubber-gap-graded mixtures placed on Malmo E6 External Ring Road in Sweden. In 2009, SRA and ASU undertook another joint effort to test three types of gap-graded mixtures: conventional mixture, Asphalt Rubber-modified mixtures, and polymer modified asphalt mixtures placed on highway E18 between the interchanges Järva Krog and Bergshamra in the Stockholm area of Sweden. In this paper, only the reference conventional mixture and the Asphalt Rubber (AR) mixtures are compared.

Rice specific gravities for the mixtures were determined. Beam specimens were prepared according to the Strategic Highway Research Program (SHRP) and the American Association of State Highway and Transportation Officials (AASHTO): SHRP M-009 and AASHTO T321-03 (equivalent European test standards are EN12697-24 A to D). Air voids, thickness, and bulk specific gravities were measured for each test specimen and the samples were stored in plastic bags in preparation for the testing program. The designated road section within the construction project had three asphalt mixtures: a reference gap-graded mixture (designation: ABS 16 70/100) used as a control, a rubber-modified mixture (designation: GAP 16) that contained approximately 20 percent ground tire rubber (crumb rubber), and another polymer modified asphalt mixture which is out of the scope of this paper. Test sections were located at fast lanes on highway E18 between the Järva Krog and Bergshamra interchanges. The Swedish Road Administration provided information stating that the field compaction/air voids for the three mixtures were around 3.0%. The original mix designs were done using the Marshall Mix design method. Table 1 shows the reported average aggregate gradations for each mixture. The in situ mixture properties of the Stockholm pavement test sections are reported in Table 2, which includes % binder content by mass of the mix, Marshall Percent void content by volume of the mix, and maximum theoretical specific gravity of the mixes estimated at ASU laboratories. The base bitumen used was Pen 70/100 and rubber was called GAP 16. Higher asphalt content for AR mixture was implemented to insure a full coating for both aggregate and the added crumb rubber particles.

4. The Cost of Variations in Long-Term Performance

The concept of mechanistic-empirical pavement design is a comprehensive approach for the design of pavement layers thickness. A mechanistic approach explains the phenomena caused by physical action. In the pavement thickness design, the phenomena are the stresses, strains, and deflections within a pavement structure and the physical causes are the loads, climatic conditions, and material properties of the pavement structure. These effects and their physical causes are generally described using a mathematical model. Various mathematical models are used; the most common is the multilayer elastic model. Along with this mechanistic approach, empirical parameters are used when defining the life of the pavement structure based on the calculated stresses, strains, and deflections. The relationship between physical effect and pavement failure is correlated by empirically derived equations that estimate the numbers of loading cycles needed to cause failure. This mechanistic-empirical approach allows the selection of the thicknesses of pavement layers with appropriate materials under specific traffic conditions at the project location. The design criterion is based on the long-term performance of the pavement over the entire design period meeting specific levels of distresses. In this part of the study, the mechanistic-empirical approach has been used to estimate the performance life of the AR and HMA pavements based on the fatigue characteristics of the mixtures.

4.1. Mechanistic-Empirical Analysis of AR and HMA Pavements. Two pavement structures, thin and thick, and two vehicle speeds, 16 and 113 km/hr (10 and 70 mph), were selected for the analyses. The thin pavement structure consisted of 100 mm (4 inches) of asphalt concrete over 150 mm (6 inches) of crushed aggregate base (CAB), and the thick pavement structure consisted of 200 mm (8 inches) of asphalt concrete over same thickness of CAB layer. The asphalt concrete layer can be constructed with either AR or the reference conventional HMA mixtures. The resilient moduli of the CAB and the subgrade were assumed to be 193 MPa (28 ksi) and 55 MPa (8 ksi), respectively.

The fatigue life (N_f) of the asphalt concrete layer is a function of the tensile strain (ϵ_t). The number of load cycles to fatigue failure increases exponentially with a decrease in strain level. The fatigue relationship can be modeled as follows:

$$N_f = k_1 \left(\frac{1}{\epsilon_t} \right)^{k_2}, \quad (1)$$

where k_1 and k_2 are the regression constants at 21.1°C (70°F) which is the critical temperature for fatigue cracking.

In order to evaluate the long-term fatigue performance of the reference conventional HMA and AR pavements, the laboratory beam fatigue data along with analytical model were used. The analytical model (3D-Move) adopted here to undertake the pavement response computations uses a continuum-based finite-layer approach. The 3D-Move analysis model can account for important pavement factors such

TABLE 1: Average aggregate gradations and mixture characteristics, Stockholm highway.

	Sieve size (mm)	Reference conventional	AR
Gradation (% passing by mass of each sieve)	22.4	100	100
	16	98	98
	11.2	65	68
	8	38	44
	4	23	24
	2	21	22
	0.063	10.5	7.5
Binder content (%)		5.9	8.7
Air voids (%)		2.6	2.4
G_{mm}		2.464	2.359

TABLE 2: Mechanistic fatigue analysis results.

Depth (mm)	Velocity (mph)	Strain (microns)	K_1	K_2	N_f (cycles)	Fatigue ratio	Average fatigue ratio
Reference conventional hot mix asphalt							
100	16	264	$5.0E - 10$	4.17	416,926	1.0	1
	113	194			1,521,577	1.0	
200	16	135			6,852,999	1.0	
	113	94			30,372,021	1.0	
Asphalt Rubber mixture							
100	16	301	$1.0E - 09$	4.37	2,407,806	5.8	5.5
	113	236			6,968,196	4.6	
200	16	154			44,968,613	6.6	
	113	116			155,041,336	5.0	

as the moving traffic-induced complex 3D contact stress distributions (normal and shear) of any shape, vehicle speed, and viscoelastic material characterization for the asphalt concrete layer. The 3D-Move software developed by the Western Regional Superpave Center at the University of Nevada, Reno, was used to calculate the tensile strains at the bottom of the asphalt concrete layer constructed with either HMA or AR mixtures. Input parameters for the analyses include pavement layer thicknesses, materials properties, and traffic loads. As discussed earlier, two different asphalt concrete layer thicknesses were analyzed. Dynamic modulus measured at 5 different temperatures (-10 , 4.4 , 21.1 , 37.8 , and 54.4°C) and six different frequencies (0.1 , 0.5 , 1 , 5 , 10 , and 25 Hz) for each of HMA and AR mixtures were used in the analysis (Figure 2). The pavements were loaded with a standard single axle load of 80 KN (18 kips) over dual tires spaced at 304.8 mm (12 inches) with an inflation pressure of 827.4 kPa (120 psi).

Tensile strains at the bottom of the asphalt concrete layer were analyzed at two locations: under the center of one tire and midway between the centers of the two tires in order to identify the maximum tensile strain. Summary of the results of the maximum tensile strains is presented in Figure 3 and Table 2. Utilizing the laboratory fatigue performance equations developed from the beam fatigue tests (Figure 1), the fatigue lives for both reference conventional HMA and AR mixtures were calculated based on the maximum tensile strains determined from the 3D-Move analyses. The number

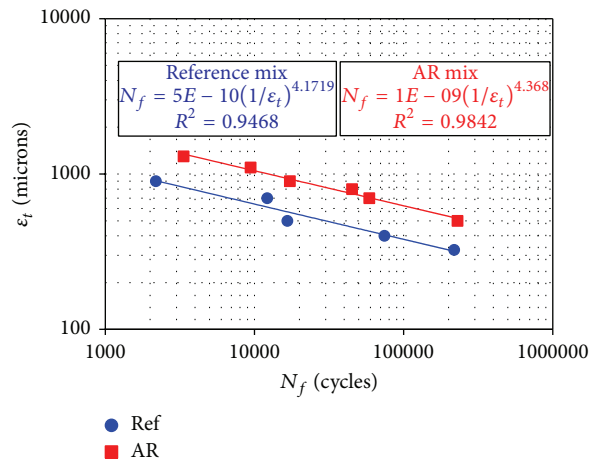


FIGURE 1: Fatigue life comparison between conventional reference conventional mixture and AR mixture at 21°C using N_f at 50% of the initial stiffness [12].

of cycles calculated at the maximum tensile strain represents the fatigue life of the pavement constructed with both reference conventional HMA and AR mixtures. The ratio of fatigue life of the AR mixture over the fatigue life of the reference conventional HMA mixture is presented in Table 2.

The number of repetitions to fatigue cracking was calculated using the highest strain and the appropriate K

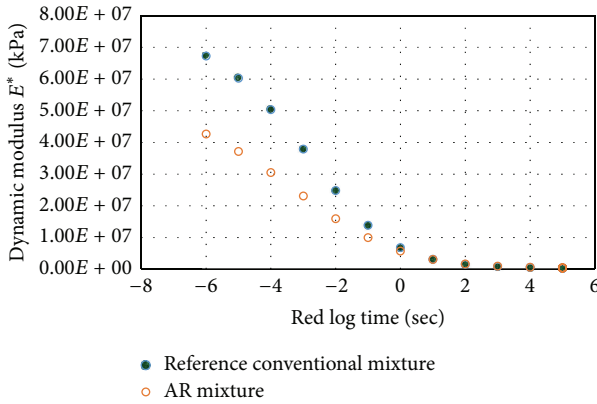


FIGURE 2: Average E^* Master Curves for HMA and AR mixtures [13].

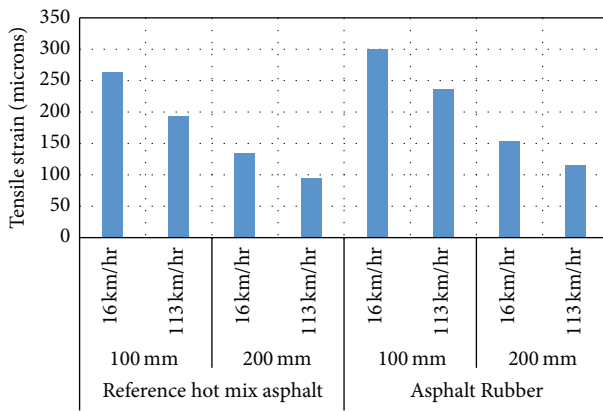


FIGURE 3: Tensile strains at the bottom of the HMA and AR layers for both pavement structures and two vehicle speeds.

values. Summary of results of the maximum tensile strains is presented in Table 2 and Figure 3. The number of cycles calculated at the maximum tensile strain represents the fatigue life of pavement constructed with HMA and Asphalt Rubber mixtures. The ratio of fatigue life of each mixture over the fatigue life of the control of HMA mixture is presented in Table 2.

Based on the results presented in Table 2 and Figure 3, the following observations can be made:

- (i) All HMA mixtures and AR mixtures exhibited similar tensile strain values at the bottom of the asphalt concrete layer.
- (ii) With the superior fatigue performance of AR mixtures compared to the corresponding HMA mixtures, this resulted in an average fatigue ratio of 5.5 for AR mixtures. A fatigue ratio of 5.5 implies that the pavement with an AR layer is expected to have 5.5 times the fatigue life of the corresponding pavement with an HMA layer.
- (iii) Within each mixture, the thicker asphalt concrete layer (200 mm) has significantly lower tensile strain compared to the corresponding thin asphalt concrete

layer (100 mm). This resulted in higher fatigue lives for thick pavements compared to thin pavements.

- (iv) Within each mixture, it was noticed that the tensile strain at the bottom of the asphalt concrete layer increases by decreasing vehicle speed from 113 km/hr to 16 km/hr. This resulted in higher fatigue lives for pavements loaded with high vehicle speed compared to low vehicle speed.

4.2. Cost Comparison Based on Fatigue Performance. In order to evaluate the economic value of AR and HMA mixtures based on fatigue performances, a pavement section of 1.6 km (1 mile which is equal to 1760 yards) with 4.57 m (15 feet which are equal to 5 yards) wide single lane was considered. Based on the assumed density of 110 lb/sq-yd-in, the required quantities for paving 4- and 8-inch-thick asphalt concrete layers are as follows:

- (i) for 100 mm thick asphalt concrete layer, 1600 m (length) \times 4.57 m (width) \times 100 mm (thickness) \times 59.67 kg/m² (110 lb/square yard) = 1,936 tons,
- (ii) for 200 mm thick asphalt concrete layer, 1600 m (length) \times 4.57 m (width) \times 100 mm (thickness) \times 59.67 kg/m² (110 lb/square yard) = 3,872 tons.

The cost of production of 100 tons of HMA mixture can be calculated as follows:

- (i) optimum binder content in the mixture = 4.5% by total weight of mixture,
- (ii) quantity of binder required = 4.5 tons,
- (iii) quantity of aggregates = 95.5 tons,
- (iv) total cost of binder @ \$600/ton = 4.5 \times 600 = \$2,700,
- (v) total cost of aggregates @ \$14/ton = 95.5 \times 14 = \$1,337,
- (vi) cost of plant and equipment lump sum for 100 tons of HMA mixture = \$2,500,
- (vii) total cost for the production of 100 tons of the HMA mixture = \$2,700 + \$1,337 + \$2500 = \$6,537,
- (viii) therefore, the cost of HMA per ton = \$65.37.

The additional cost for AR mixtures per ton can then be estimated to be around \$18.98 based on the AASHTO Crumb Rubber-Modified (CRM) 1993 cost survey conducted by Steiner [11]. Therefore, the estimated cost of one ton of Asphalt Rubber is \$65.37 (cost of HMA per ton) + \$18.98 = \$84.35 per ton. Knowing the cost of the HMA and AR mixtures per ton, the required cost to pave 1.6 km (1 mile) of the pavement section with various mixtures was calculated as follows:

- (i) cost to pave on mile of 100 mm thick HMA = 1,936 tons \times \$65.37/ton = \$126,556,
- (ii) cost to pave on mile of 200 mm thick HMA = 3,872 tons \times \$65.37/ton = \$253,113,
- (iii) cost to pave on mile of 100 mm thick AR = 1,936 tons \times \$84.35/ton = \$163,302,

TABLE 3: Cost calculation per mile per 1000 cycles fatigue performance.

Depth (mm)	Velocity (km/hr)	Cost (\$/ton)	Cost of pavement per 1000 cycles of fatigue life per 1.6 km (mile) (\$)	Average cost of pavement per 1000 cycles of fatigue life per 1.6 km (1 mile) (\$)
Reference conventional hot mix asphalt				
100	16	65.37	304	108
	113		83	
200	16		37	
	113		8	
Asphalt Rubber				
100	16	84.35	68	25
	113		23	
200	16		7	
	113		2	

(iv) cost to pave on mile of 200 mm thick AR = 3,872 tons \times \$84.35/ton = \$326,603.

Combining the cost of the pavement per mile with the fatigue lives from the mechanistic-empirical analyses, the costs of 1000 cycles of fatigue life per pavement mile were calculated for the AR mixtures and their corresponding reference conventional HMA mixtures. This cost figure was derived by dividing the total cost of the 1-mile pavement section by the number of 1000 cycles to fatigue failure (i.e., $N/1000$ as summarized in Table 3). In other words, the cost of a 1.6 km (1 mile) pavement section for every 1000 cycles of fatigue life was determined and is summarized in Table 3.

5. Conclusions and Recommendations

Based on the results presented in Table 3, the following observations are drawn:

- (i) AR mixtures exhibited significantly lower cost of pavement per 1000 cycles of fatigue life per mile compared to HMA mixtures. On average, the cost of AR pavement per 1000 cycles of fatigue life per mile was \$25 compared to \$108 for HMA conventional mixture.
- (ii) Within each mixture, thicker pavements (200 mm asphalt concrete) have significantly lower cost of pavement per 1000 cycles of fatigue life per mile compared to thinner pavements (100 mm asphalt concrete).
- (iii) Within each mixture, it was noticed that the cost of pavement per 1000 cycles of fatigue life per mile increases by decreasing vehicle speed from 113 km/hr to 16 km/hr.

Given the results of the cost analysis it is recommended that Asphalt Rubber be implemented as a fatigue-resistance layer. The average fatigue ratio of AR mixture was two times that of the reference conventional HMA.

Competing Interests

The authors declare that they have no competing interests.

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