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Cost-effectiveness of rubber and polymer modified asphalt mixtures as related to sustainable fatigue performance

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Abstract

Load associated fatigue cracking is one of the major distress types occurring in flexible pavements. Flexural bending beam fatigue laboratory test has been used for several decades and is considered an integral part of the Superpave advanced characterization procedure. One of the most significant solutions to sustain the fatigue life for an asphaltic mixture is to add sustainable materials such as rubber or polymers to the asphalt mixture. A laboratory testing program was performed on three gap-graded mixtures: unmodified, Asphalt Rubber (AR) and polymer-modified. Strain controlled fatigue tests were conducted according to the AASHTO T321 procedure. The results from the beam fatigue tests indicated that the AR and polymer-modified gap graded mixtures would have much longer fatigue lives compared to the reference (unmodified) mixture. In addition, a mechanistic analysis using 3D-Move software coupled with a cost-effectiveness analysis study based on the fatigue performance on the three mixtures were performed. Overall, the analysis showed that the AR and polymer-modified asphalt mixtures exhibited significantly higher cost-effectiveness compared to unmodified HMA mixture. Although AR and polymer-modification increases the cost of the material, the analysis showed that they are more cost effective than the unmodified mixture.

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Keywords: Rubber; polymer, fatigue, cost-effectivness

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1. Introduction

In 2008, a first cooperative effort between Arizona State University (ASU) and the Swedish Road Administration (SRA) took place in testing unmodified, Asphalt rubber and polymer- modified 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: unmodified, Asphalt Rubber-modified mixtures, as well as polymer-modified asphalt mixtures placed on highway E18 between the interchanges Järva Krog and Bergshamra in the Stockholm area of Sweden.

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 until testing.

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 polymer- modified mixture (designation: ABS 16 Nypol50/100-75), and a rubber-modified mixture (designation: GAP 16) that contained approximately 20 percent ground tire rubber (crumb rubber).

The Swedish Road Administration provided information stating that the field compaction produced air voids for the three mixtures around 3.0% for all mixtures. 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 also reported in Table 1, which include percent binder content by mass of the mix, Marshall percent void content by volume of the mixture, and maximum theoretical specific gravity of the mixes (G_{mm}) estimated at the ASU laboratory. The base bitumen used was Pen 70/100 and the rubber was called GAP 16. No field fatigue performance data are currently available.

Table 1. Average aggregate gradations and mixture characteristics

	Sieve Size (mm)	Reference Unmodified Mixture	AR Mixture	Polymer-Modified Mixture
Percent Passing	22.4	100	100	100
	16	98	98	98
	11.2	65	68	65
	8	38	44	38
	4	23	24	23
	2	21	22	21
	0.063	10.5	7.5	10.5
Binder Content (%)		5.9	8.7	5.9
Air Voids (%)		2.6	2.4	2.6
G_{mm}		2.464	2.359	2.456

Previous publications showed that asphalt rubber mixtures as well as polymer-modified mixtures had superior fatigue resistance performance over the unmodified HMA mixture (1). The remaining unanswered question is: do AR and polymer-modified mixtures represent cost-effective solutions to resist fatigue cracking compared to unmodified HMA mixtures?

2. Objective

The objective of this study was to assess the cost-effectiveness of rubber and polymer modified asphalt mixtures as related to fatigue performance. The paper combines the results of the mechanical fatigue laboratory evaluations with the long-term mechanistic performance as well as the cost of AR and polymer-modified mixtures to assess the full benefits of such additives relative to their added costs.

3. Literature search

Roberts et al. (2) 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 only 10 percent, while increasing its structural coefficient 12.5 percent.

Von Quintus et al. (3) evaluated the benefits of using polymer-modified mixtures based on accelerated field pavement testing data from 36 pavement sections in the United States. It was evident that the use of polymer-modification certainly extends the service life of flexible pavements and HMA overlays. The study concluded that pavements incorporating polymer-modified mixtures showed lower amounts of fatigue cracking, transverse cracking and rutting, which extended the pavement service lives by 5 to 10 years.

Another study was conducted at the Asphalt Institute (4) to compare polymer-modified mixtures with unmodified HMA mixtures in terms of the potential to reduce occurrence of distresses and the increase in pavement life as well as conducting a life cycle cost analysis (LCCA) between the two mixtures. Eighty-four Long Term Pavement Performance (LTPP) sections were utilized in the study. Damage index (observed number of cycles to failure in the field over the predicted number of cycles to failure) was computed for the two mixtures to obtain the difference in expected service lives. It was found that polymer-modified mixtures had an extended life that ranged from one to ten years depending on the site factor (e.g., foundation, water table, drainage, etc.). In addition, the LCCA showed a potential saving ranging from 4.5% to 14% when polymer-modified mixtures are used compared to unmodified HMA mixtures.

The improved performance of AR and polymer-modified pavements compared with unmodified bitumen pavements has relatively resulted from improved rheological properties of the modified asphalt binder. 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 and polymer modifications with unmodified asphalt binder seems to enhance the fatigue resistance, as illustrated in a number of other studies (6-10). 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 the three mixtures (unmodified, AR, and polymer-modified) is needed to quantify the true cost effectiveness of rubber and polymer-modified asphalt mixtures as related to fatigue performance.

4. Mechanistic-empirical analysis of unmodified, AR and polymer-modified pavements

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 the 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. In this part of the study, the mechanistic-empirical approach has been used to estimate the performance life of the unmodified HMA, AR, and polymer-modified pavements based on the fatigue characteristics of the mixtures.

Two pavement structures; thin and thick, and two vehicle speeds; 16 and 113 km/h (10 and 70 mph), were selected for the analyses. The thin pavement structure consisted of 100 mm (4 inches) of a surface layer over 150 mm (6 inches) of crushed aggregate base and an infinite granular subgrade, whereas the thick pavement structure consisted of 200 mm (8 inches) of surface layer over same base and subgrade as the thin pavement. The surface layer can either be a reference unmodified HMA, asphalt rubber, or polymer modified.

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:

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

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 unmodified HMA, AR, and the polymer-modified pavements, laboratory beam fatigue tests were conducted according to AASHTO T321 along with an analytical model were used. The analytical 3D-Move model (11), which is based on a continuum-based finite-layer approach, was used in this study. The 3D-Move Analysis model can account for important pavement factors such 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 HMA, AR, and polymer-modified mixtures. Input parameters for the analyses include pavement layer thicknesses, materials properties, and traffic loads and speeds. Dynamic moduli measured at 5 temperatures (-10, 4.4, 21.1, 37.8, and 54.4°C) and six frequencies (0.1, 0.5, 1, 5, 10, 25Hz) for each HMA, AR and polymer-modified mixtures were used in the analysis (12). The resilient moduli of the base and the subgrade were assumed to be 193 MPa (28 ksi) and 55 MPa (8 ksi), respectively. 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. A summary of the results of the maximum tensile strains is presented in Table 2. Utilizing the laboratory fatigue performance equations developed from the beam fatigue tests (Table 2), the fatigue lives for reference unmodified HMA, AR, and polymer-modified mixtures were calculated based on the maximum tensile strains determined from the 3D-Move analyses. The number of cycles calculated at the maximum tensile strain represents the fatigue life of the pavement constructed with reference unmodified HMA, AR, and polymer-modified mixtures. The ratio of fatigue life of the AR and polymer-modified mixtures over the fatigue life of the reference unmodified HMA mixture are presented in Table 2.

Table 2. Mechanistic fatigue analysis results

Pavement	Velocity (km/h)	Strain at the bottom of the pavement layer (microns)	k_1	k_2	N_f (Cycles)	Fatigue Ratio	Average Fatigue Ratio
Reference Unmodified Hot Mix Asphalt							
Thin	16	264	5.00E-10	4.17	416,926	1	1
	113	194			1,521,577	1	
Thick	16	135			6,852,999	1	
	113	94			30,372,021	1	
Asphalt Rubber Mixture							
Thin	16	301	1.00E-09	4.37	2,407,806	5.8	5.5
	113	236			6,968,196	4.6	
Thick	16	154			44,968,613	6.6	
	113	116			155,041,336	5	
Polymer-modified Mixture							
Thin	16	273	2.00E-09	4.16	1,338,423	3.2	2.8
	113	216			3,545,703	2.3	
Thick	16	138			22,862,988	3.3	
	113	104			74,160,270	2.4	

The number of repetitions to fatigue cracking was calculated using the highest strain and the appropriate K values. Summary of results that the maximum tensile strains for different combinations of pavement structures, materials, and speeds are presented in Table 2. The table shows that, at the same thickness and vehicle speed levels, similar tensile stains at the bottom of the asphalt layer was observed among the three asphalt mixtures. The table also illustrate that, within each mixture, thicker pavement structures experience less tensile strains at the bottom of the asphalt layer compared to thinner pavements. Lastly, it was noticed that the tensile strain at the bottom of the asphalt concrete layer increases by decreasing vehicle speed from 113 km/h (70 mph) to 16 km/hr (10 mph).

Table 2 also shows the tensile strains, fatigue constants (k_1 and k_2) and number of load cycles to failure (N_f) for all combinations of pavement structures, materials, and speeds. The ratio of fatigue life of each mixture over the fatigue life of the control of HMA mixture is also shown in Table 2.

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

- The AR mixture showed slightly larger tensile strains at the bottom of the surface layer as compared to unmodified and polymer-modified mixtures.
- The AR mixture has a much higher fatigue performance as compared to the HMA and polymer-modified mixtures. A fatigue ratio of 5.5 of the AR mixture is obtained as compared to the unmodified mixture, which implies that the pavement with AR layer is expected to have 5.5 times the fatigue life of the corresponding pavement with an HMA layer.
- The polymer-modified mixture has an intermediate fatigue performance as compared to the HMA and polymer-modified mixtures. A fatigue ratio of 2.8 of the polymer-modified mixture is obtained as compared to the unmodified mixture, which implies that the pavement with AR layer is expected to have 2.8 times the fatigue life of the corresponding pavement with an HMA layer.
- Within each mixture, the thicker surface 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.
- Within each mixture, the tensile strain at the bottom of the asphalt concrete layer increases by decreasing vehicle speed from 113 km/h (70 mph) to 16 km/h (10 mph). This resulted in higher fatigue lives for pavements loaded with high vehicle speed compared to low vehicle speed.

5. Cost comparison based on fatigue performance

In order to evaluate the economic values of all mixtures based on fatigue performance, a pavement section of 1.6 km (1 mile) with 4.57 m (15 feet) wide single lane was considered. Based on the assumed density of 110 lb./sq.-yd.-in, the required quantities for paving 100 and 200 mm (4 and 8 inch) thick asphalt concrete layers are as follows:

- For the 100 mm thick asphalt concrete layer: 1600 m (length) x 4.57 m (width) x 100 mm (thickness) x 59.67 kg/m2 (110 lb./square yard) = 1,936 tons.
- For the 200 mm thick asphalt concrete layer: 1600 m (length) x 4.57 m (width) x 100 mm (thickness) x 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:

- Optimum binder content in the mixture = 4.5% by total weight of mixture.
- Quantity of binder required = 4.5 tons
- Quantity of aggregates = 95.5 tons
- Total cost of binder @ $600/ton = 4.5 x 600 = $2,700
- Total cost of aggregates @ $14/ton = 95.5 x 14 = $ 1,337
- Cost of plant and equipment lump sum for 100 tons of HMA mixture = $2,500
- Total cost for the production of 100 tons of the HMA mixture =

- $2,700+$1,337+$2500 = $6,537
- Therefore, the cost of HMA per ton = $65.37

The additional cost for AR mixtures per ton was estimated to be around $18.98 based on the AASHTO Crumb Rubber Modified (CRM) 1993 cost survey conducted by Steiner (13). Therefore, the estimated cost of one ton of asphalt rubber is $65.37 (Cost of HMA per ton) + $18.98 = $84.35 per ton. Similarly, the additional cost for polymer-modified mixtures per ton was estimated to be around $0.15 per ton of asphalt mixture (14). Therefore, the estimated cost of one ton of polymer-modified mixture is $65.37 (Cost of HMA per ton) + $0.15 = $65.52 per ton. Knowing the cost of the HMA, AR, and polymer-modified mixtures per ton, the required cost to pave 1.6 km (1 mile) of the pavement section with various mixtures were calculated as follows:

- Cost to pave one mile of 100 mm thick HMA = 1,936 tons x $65.37ton = $ 126,556
- Cost to pave one mile of 200 mm thick HMA = 3,872 tons x $65.37/ton = $ 253,113
- Cost to pave one mile of 100 mm thick AR mixture= 1,936 tons x $84.35/ton = $ 163,302
- Cost to pave one mile of 200 mm thick AR mixture= 3,872 tons x $84.35/ton = $ 326,603
- Cost to pave one mile of 100 mm thick polymer-modified mixture = 1,936 tons x $65.52/ton = $ 126,847
- Cost to pave one mile of 200 mm thick polymer-modified mixture = 3,872 tons x $65.52/ton = $ 253,693

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 and polymer-modified mixtures and their corresponding reference unmodified 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 were determined and are summarized in Table 3. The lower the cost per mile per 1000 cycles of fatigue life indicates more cost-effectiveness.

Table 3. Cost calculation per mile per 1000 cycles fatigue performance

Pavement	Velocity (km/h)	Cost ($/ton)	Cost of Pavement per 1000 Cycles of Fatigue Life per 1.6 km (1-mile) ($)	Average Cost of Pavement per 1000 Cycles of Fatigue Life per 1.6 km (1-mile) ($)
Reference Unmodified Hot Mix Asphalt				
Thin	16	65.37	303	108
	113		84	
Thick	16		37	
	113		8	
Asphalt Rubber Mixture				
Thin	16	84.35	68	25
	113		23	
Thick	16		7	
	113		2	
Polymer-modified Mixture				
Thin	16	65.52	95	36
	113		36	
Thick	16		11	
	113		3	

6. Cost-effectiveness analysis

Cost-effectiveness analysis is an economic evaluation technique for comparing the cost paid to the gained benefit for the purpose of evaluating alternatives. Several methods are available to evaluate the cost-effectiveness of alternatives (15, 16). For the purpose of comparing the cost-effectiveness of the unmodified, AR and polymer-modified mixture, a simple approach is used in this study by dividing the expected performance of each mixture by its cost as shown in Equation 2.

$$Cost\ Effectiveness = \frac{Expected\ Performance}{Mixture\ Unit\ Cost} \quad (2)$$

Equation 2 can be viewed as estimating the “bang for the buck” for each case. The alternative that provides the greatest ratio of the benefit to the cost is the “best.” In this analysis, only the initial material’s cost is used. Other costs, such as maintenance and salvage value, are ignored.

Table 4. Cost-effectiveness of all mixture combinations

Pavement	Velocity (km/h)	Cost of one mile ($)	N_f (Cycles)	Cost-Effectiveness (Cycles/ cost of one mile)	Average Cost-Effectiveness (Cycles/ cost of one mile)	Average Cost-Effectiveness Ratio
Reference Unmodified Hot Mix Asphalt						
Thin	16	126,556	416,926	3.3	41.2	1
	113	126,556	1,521,577	11.9		
Thick	16	253,113	6,852,999	27.0		
	113	253,113	30,372,021	122.4		
Asphalt Rubber Mixture						
Thin	16	163,302	2,407,806	15.0	170.5	4.1
	113	163,302	6,968,196	43.4		
Thick	16	326,603	44,968,613	140.1		
	113	326,603	155,041,336	483.4		
Polymer-modified Mixture						
Thin	16	126,847	1,338,423	10.6	105.2	2.6
	113	126,847	3,545,703	28.0		
Thick	16	253,693	22,862,988	90.1		
	113	253,693	74,160,270	292.3		

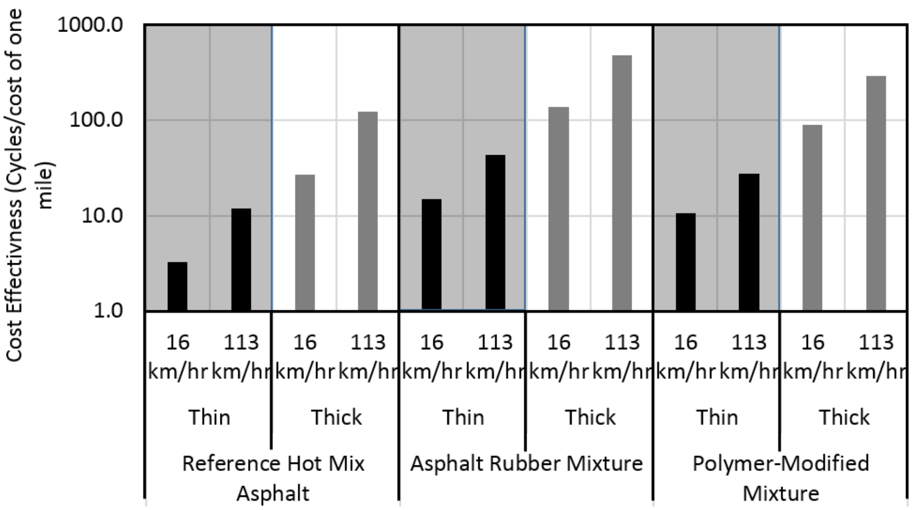

Fig. 1. Cost-effectiveness for all mixture combinations

In this case, the expected performance is the predicted number of fatigue cycles to failure (Table 2), while the mixture unit cost was determined as the cost of one mile. For example, the cost-effectiveness for a thin (4”) unmodified mixture at a vehicle velocity of 16 km/h will be the expected performance life (416,926 cycles) divided by the unit cost ($126,556 per cost of one mile), which will result in 3.3 3 cycles/cost of one mile.

Based on the results presented in Table 4 and Figure 1, the following observations can be made:

- The AR mixture resulted in the highest cost-effectiveness among all mixtures, followed by the polymer-modified mixture. Cost-effectiveness values of 170.5, 105.2 and 41.2 cycles per cost of one mile are obtained for the AR, polymer-modified and the unmodified mixtures, respectively. Moreover, the average cost-effectiveness ratio for AR and polymer-modified mixtures (calculated as the average cost-effectiveness of AR or polymer-modified mixtures divided by average cost-effectiveness of the reference mixtures) was 4.1 and 2.6, respectively.
- Within each mixture, the thick surface layer (200 mm) has significantly higher cost-effectiveness compared to the corresponding thin surface layer (100 mm).
- Within each mixture, it was noticed that the cost-effectiveness increases by increasing vehicle speed from 16 km/h (10 mph) to 113 km/h (70 mph).

7. Conclusions and recommendations

Based on the results presented, the following observations are drawn:

- Asphalt rubber mixtures exhibited significantly higher cost-effectiveness (larger cycles per cost of one mile) compared to reference HMA mixtures. On average, the cost-effectiveness of AR was 4.1 times higher than the unmodified mixture, while the polymer-modified mixture was 2.6 times higher than the unmodified mixture.
- The thicker pavement (200 mm asphalt concrete) is more cost-effective than the thinner pavements (100 mm asphalt concrete) for the same material and vehicle speed.
- The cost-effectiveness increase by increasing vehicle speed from 16 km/h to 113 km/h for the same material and pavement thickness.

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