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Research Paper

3-D Move Mechanistic Analysis and Cost Effectiveness of Asphalt Rubber and Polymer Modified Asphalt Pavement Under Various Axle Loading Conditions

*Logan Proffer, Mena I. Souliman **

Department of Civil Engineering, University of Texas at Tyler, 3900 University Blvd. Tyler, Texas, 75701, USA

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ABSTRACT

A variety of axle loading conditions can lead to different tensile strains in asphalt pavements. One way to increase resistance to these tensile strains is to add materials such as crumb rubber or polymers to the pavement mixture. Using three given asphalt pavement design mixtures, a 3D-Move mechanistic analysis was performed to determine the fatigue life of three given mixtures: unmodified reference, asphalt rubber, and polymer modified. These mixtures were tested under various axle loading conditions. This mechanistic analysis was then combined with a cost analysis which showed that despite the increase in cost, the asphalt rubber design mixture was the most cost-effective, with the polymer modified mixture finishing in second ahead of the unmodified reference mixture.

1 Introduction

Improving the design life of asphalt pavement will always be a goal for pavement engineers. Using different aggregate gradations and materials, layer thicknesses, and mixture properties, such as the air and asphalt binder content of the mix, can all lead to improved performance for a given asphalt pavement. One such thing that can improve the fatigue life of an asphalt pavement is modifying the pavement with selected additives, such as crumb rubber or polymers. These additive mixtures, while more expensive than standard pavement designs, have been shown to increase the lifespan of an asphalt pavement [1-3].

One of the most important factors over the lifespan of an asphalt pavement is the tensile strain experienced by the pavement due to various axle loading conditions. Small local roads will experience very consistent loading conditions, as the

* *Corresponding author. Tel.: +1-480-304-2162.*
E-mail address: msouliman@uttyler.edu

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main traffic on these roads is standard passenger vehicles. Other roads, such as interstates and highways, may experience more varied loading conditions, including buses, semi-trucks, and trailers with multiple axle configurations. These various loading conditions can have differing impacts on these pavements, and different asphalt pavement mixture designs may be more suited to the varied loadings on these types of roads.

2 Literature Review

Feiteira Dias et al. [1] evaluated the performance of two gap-graded asphalt rubber mixtures and compared the results to a similar non-rubber mixture. They found that the asphalt rubber mixture had a better overall mechanical performance than the similar non-rubber mixture. They also found that the asphalt rubber mixture had similar performance when produced with both a dry and wet process. It was also determined that the rubber did not have as significant of a contribution to the mixture performance when mixing was performed above 175 ºC.

Huang et al. [4] constructed eight asphalt pavement sections using crumb rubber-modified (CRM) mixtures. The sections were constructed using eight different CRM processes, and they were constructed across five state highway projects in Louisiana. Each project included a pavement section built with CRM mixtures as well as a control section built with a conventional mixture that included no rubber additive. It was found that across all five projects, the CRM mixtures performed better across a variety of tests when compared to the control sections.

A study completed by Chen et al. [3] examined performance of a virgin binder compared to a CRM binder. The study determined that the addition of CRM led to an increase in binder content for a given design mixture. It was also determined that gap graded CRM mixes showed a higher resistance to cracking than dense graded CRM mixes. The study also showed that CRM binders had a higher cracking resistance than the tested virgin binders.

Multiple other studies [4-7] have investigated how crumb rubber can be used to improve the performance of asphalt pavement. These studies have various methods of adding the crumb rubber, whether through a wet process modified binder, or a dry process rubber aggregate. Some of the studies also look at the difference in performance between coarse and fine crumb rubber. Despite these differences, these studies show that a crumb rubber additive has been shown to improve the performance and design life of the tested asphalt pavement mixtures.

3 Material Discerption

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 (Gmm) 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.

4 Objectives

The objective of this study was to perform a mechanistic and cost analysis of three different pavements under six different loading conditions. The three pavements include an unmodified reference mixture, an asphalt rubber modified mixture, and a polymer modified mixture. These pavements were subjected to three different axle configurations: single axle dual tire, double axle dual tire, and triple axle dual tire. Each axle configuration was tested with axle loads of 18,000 lbs and 36,000 lbs. This paper examines the long-term performance of the three pavement mixtures, while also comparing the cost of each mixture to its performance relative to the unmodified reference pavement.

5 Data Collection

Using the mix design characteristics from "Mechanistic Analysis and Cost-Effectiveness of Rubber and Polymer Modified Asphalt Mixtures" [8], the three given mixtures were input into 3D-Move for mechanistic analysis. Each mixture was tested under the six different axle loading configurations, and the maximum tensile strain for each configuration was recorded. Using the given tensile strains, the fatigue life (N_f) of the asphalt pavement can be calculated using the following relationship:

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

where k_1 and k_2 are the regression constants at 70 ºF.

The resulting fatigue life (N_f) values were then used to determine the fatigue ratio for each mixture design. The fatigue ratio was calculated using the following relationship:

$$\text{Fatigue Ratio} = \frac{N_f(\text{Asphalt Rubber or Polymer Modified})}{N_f(\text{Unmodified Reference})} \tag{2}$$

where N_f for the unmodified reference mixture is a fixed value of 1.00. The calculated fatigue ratios for each mixture and axle loading combination can be seen in Table 1.

6 Mechanistic Analysis

For this study, a mechanistic analysis of each asphalt pavement and axle loading condition combination was performed in 3D-Move. 3D-Move Analysis Software is one of the powerful software packages that has been utilized for the analysis of asphalt pavements. The program was released by University of Nevada, Reno (UNR), under a cooperative agreement with the Federal Highway Administration (FHWA) to analyze asphalt pavements under variety of loading conditions. The software uses a continuum-based finite-layer approach to compute pavement responses. The finite layer approach treats each pavement layer as a continuum and uses the Fourier transform technique. Therefore, the program can handle complex surface loadings such as multiple loads and non-uniform tire pavement contact stress distribution [9]. One of the important aspects of the program is that the tire and loading configurations are adjustable to meet user requirements. Screenshot of the program is shown in Figure 3. Some of the advanced applications of 3D-Move Analysis include (1) Estimation of pavement performance at intersections, which account for effect of braking on pavement response and (2) Estimation of damage under off-road farm vehicles [10]. There are numerous computer programs available for analyzing and modelling hot mix asphalt pavements. The reason of utilizing 3D move software package in this study besides being an open source free software are the below mentioned elements and features [11, 12] :

- The software utilizes finite layer continuum approach.
- The ability to model moving 3D-surface stresses (dynamic, normal and shear contact stresses).
- Accounts for visco-elastic material characterization utilizing symmetrical sigmoidal function.
- The ability to analyze tire imprint of any shape (circular, rectangular or elliptical).

Table 1 – 3D-Move mechanistic analysis results for unmodified mixture

Pavement Mixture	Axle Loading Configuration	Velocity (mph)	Maximum Strain Value (µm)	k_1	k_2	N_f (cycles)	Fatigue Ratio	Average Fatigue Ratio		
Unmodified Reference	Single 18 K	10	647	5E-10	4.17	9943	1.00	1.00	1.00	1.00
		45	553			19,134	1.00			
		75	529			23,023	1.00			
	Single 36 K	10	1,284			570	1.00	1.00		
		45	1,092			1,121	1.00			
		75	1,040			1,374	1.00			
	Double 18 K	10	670			8,595	1.00	1.00	1.00	
		45	584			15,242	1.00			
		75	562			17,888	1.00			
	Double 36 K	10	1,321			507	1.00	1.00		
		45	1,150			903	1.00			
		75	1,105			1,067	1.00			
	Triple 18 K	10	663			8,980	1.00	1.00	1.00	
		45	578			15,912	1.00			
		75	553			19,134	1.00			
	Triple 36 K	10	1,336			483	1.00	1.00		
		45	1,166			853	1.00			
		75	1,116			1,024	1.00			

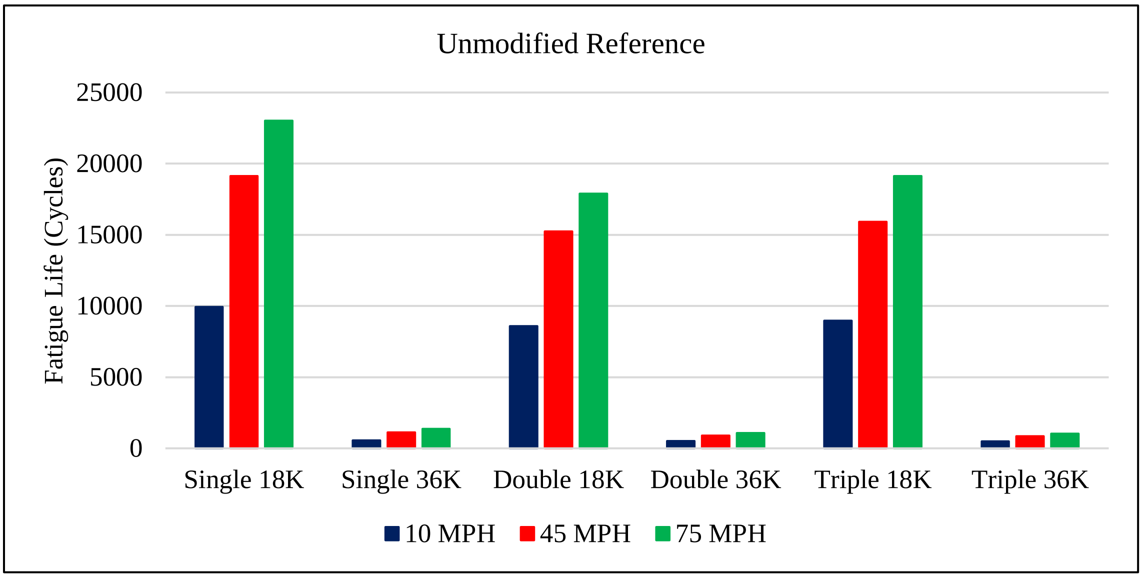

Fig. 1 – Unmodified reference design mixture results

- The ability to analyze non-generic axle and tire configurations.

- The ability to predict responses at any locations required by the user, and actually this point is very important to replicate the FWD sensor locations, so that the new defined response points will be equivalent to the actual FWD sensor locations.

- Accounts for the effect of braking on pavement response.

- The ability to analyze pavement responses due to non-standard vehicles such as off-road farm vehicles and oversize or overweight (OS/OW) vehicles.

Table 2 – 3D-Move mechanistic analysis results for asphalt rubber mixture

Pavement Mixture	Axle Loading Configuration	Velocity (mph)	Maximum Strain Value (µm)	k_1	k_2	N_f (cycles)	Fatigue Ratio	Average Fatigue Ratio		
Asphalt Rubber	Single 18 K	10	683	1.00E-09	4.37	68,168	6.86	5.99	5.58	5.92
		45	613			109,345	5.71			
		75	595			124,555	5.41			
	Single 36 K	10	1,356			3,404	5.97	5.18		
		45	1,213			5,540	4.94			
		75	1,176			6,343	4.62			
	Double 18 K	10	702			60,465	7.04	6.29	5.94	
		45	637			92,451	6.07			
		75	621			103,321	5.78			
	Double 36 K	10	1,381			3,143	6.20	5.60		
		45	1,248			4,893	5.42			
		75	1,214			5,520	5.17			
	Triple 18 K	10	689			65,612	7.31	6.60	6.23	
		45	623			101,880	6.40			
		75	604			116,646	6.10			
	Triple 36 K	10	1,384			3,113	6.44	5.86		
		45	1,250			4,859	5.70			
		75	1,212			5,560	5.43			

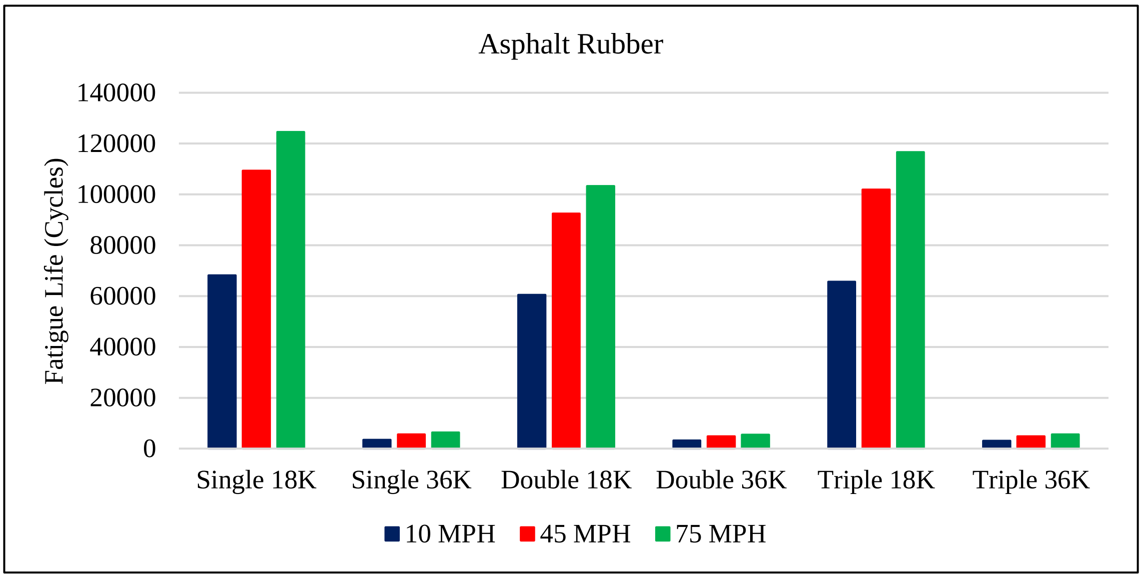

Fig. 2 – Asphalt rubber design mixture results

Table 3 – 3D-Move mechanistic analysis results for polymer modified mixture

Pavement Mixture	Axle Loading Configuration	Velocity (mph)	Maximum Strain Value (μm)	k_1	k_2	N_f (cycles)	Fatigue Ratio	Average Fatigue Ratio		
Polymer Modified	Single 18 K	10	650	2.00E-09	4.16	36,250	3.65	3.25	3.25	3.32
		45	576			59,934	3.13			
		75	558			68,396	2.97			
	Single 36 K	10	1,289			2,101	3.68	3.26		
		45	1,138			3,528	3.15			
		75	1,101			4,048	2.95			
	Double 18 K	10	673			31,368	3.65	3.32	3.34	
		45	604			49,194	3.23			
		75	588			55,007	3.08			
	Double 36 K	10	1,326			1,867	3.69	3.36		
		45	1,187			2,960	3.28			
		75	1,154			3,329	3.12			
	Triple 18 K	10	666			32,763	3.65	3.34	3.37	
		45	596			52,000	3.27			
		75	577			59,503	3.11			
	Triple 36 K	10	1,341			1,782	3.69	3.40		
		45	1,199			2,839	3.33			
		75	1,160			3,258	3.18			

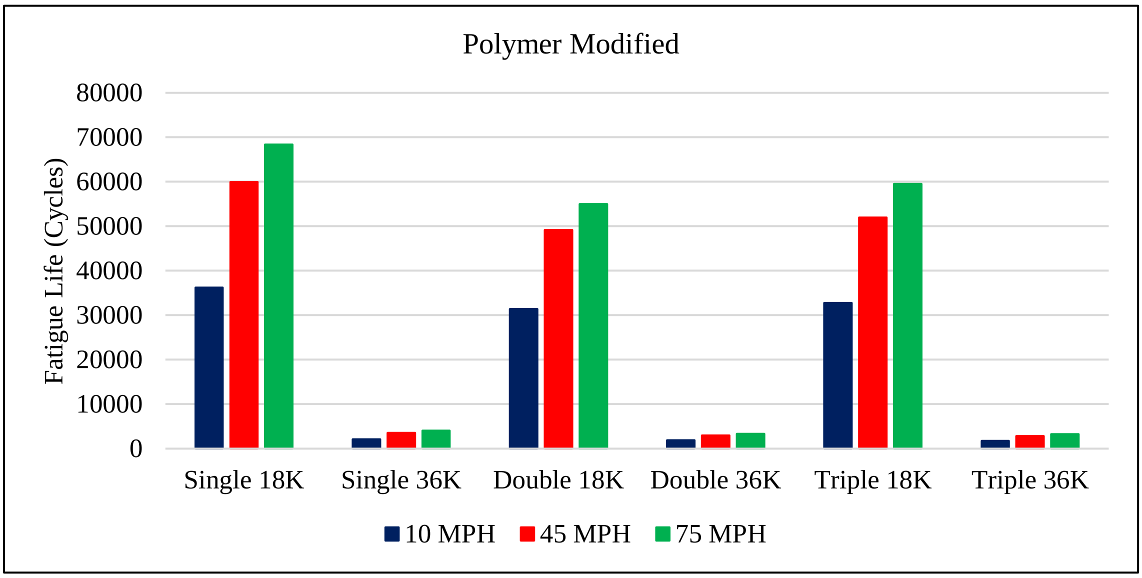

Fig. 3 – Polymer modified design mixture results

Three different asphalt mixture designs (unmodified reference, asphalt rubber, polymer modified), three different speeds (10, 45, and 75 MPH), and six different axle loading conditions (single axle dual tire, double axle dual tire, and triple axle dual tire, each at 18 Kips and 36 Kips) were examined during the analysis. The software, using the given conditions for each case, calculated the maximum tensile strain in the given asphalt pavement for each tested scenario. This calculated maximum tensile strain was then used to determine the fatigue life (using Equation 1) of the given asphalt pavement design under a specific loading condition. The results of the 3D-Move mechanistic analysis performed can be seen in Tables 1 to 3 and Figures 1-4.

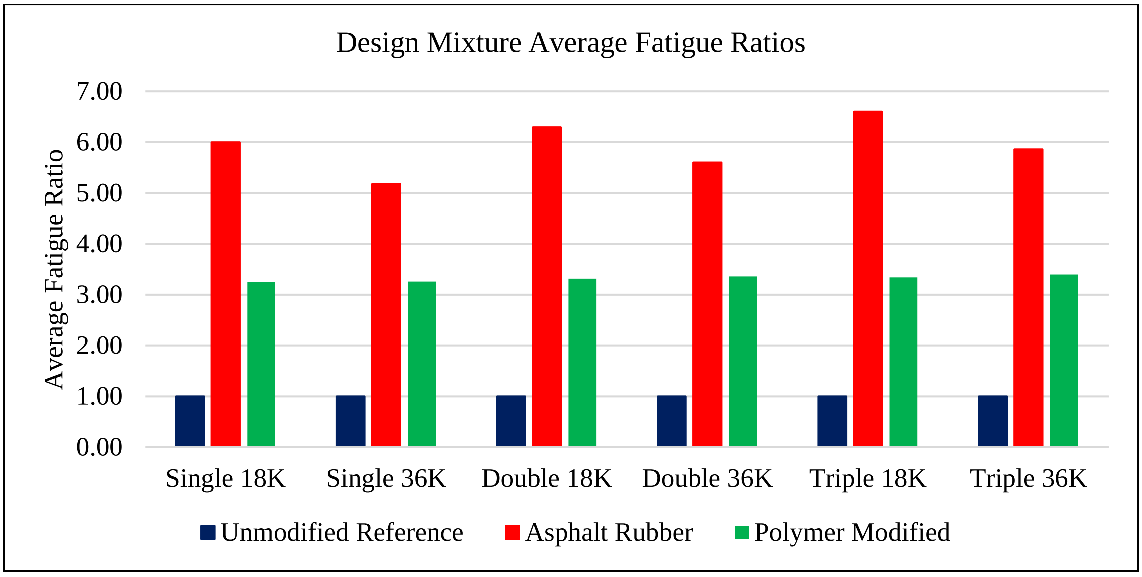

Fig. 4 – Design mixture average fatigue ratios

The results in the above table and figures show that across the various axle loading conditions, both the polymer modified and asphalt rubber mixtures outperformed the unmodified reference mixture. The asphalt rubber mixture significantly outperformed the reference mixture, with an average fatigue ratio of 5.92. Both the asphalt rubber and polymer modified mixtures showed an increase in fatigue ratio at lower speeds.

Both mixtures also showed an increased fatigue life as the number of loading axles increased, which can be seen in Figure 4. This trend can especially be seen in the asphalt rubber design mixture, which had an average single-axle fatigue ratio of 5.58, an average dual-axle fatigue ratio of 5.94, and an average triple-axle fatigue ratio of 6.23. This means that in locations that experience a higher amount of multi-axle traffic, the asphalt rubber and polymer modified design mixtures are an even better option than they would be in a location that experiences only single-axle traffic.

7 Cost Analysis

In order to better understand the difference in performance between the three asphalt pavement mixtures, a cost analysis was also performed. For this cost analysis, a 1-mile section with a width of 15-feet was used. This study used a 4-inch-thick asphalt pavement layer and an assumed density of 110 lb/sq-yd-in. These values can be used to calculate the required pavement quantities as follows:

$$(4 \text{ inches thick})\text{x}(5 \text{ yards wide})\text{x}(1760 \text{ yards long})\text{x}(110 \text{ lb/sq} - \text{yd} - \text{in}) \; = 387{,}200 \text{ lbs} \; = 1{,}936 \text{ tons}$$

Based on estimates from “Mechanistic Analysis and Cost-Effectiveness of Rubber and Polymer Modified Asphalt Mixtures”, one ton of asphalt pavement is $65.37 [8]. The cost of the asphalt rubber mixture is estimated at $84.35 per ton, and the cost of the polymer modified mixture is estimated at $65.52 per ton [8]. Using these values, the cost for a 1-mile section of each pavement can be estimated as follows:

$$(\$65.37 \text{ per ton})\text{x}(1{,}936 \text{ tons}) = \$126{,}556.32 \text{ (Unmodified Reference)}$$

$$(\$84.35 \text{ per ton})\text{x}(1{,}936 \text{ tons}) = \$163{,}301.60 \text{ (Aphalt Rubber)}$$

$$(\$65.52 \text{ per ton})\text{x}(1{,}936 \text{ tons}) = \$126{,}846.72 \text{ (Polymer Modified)}$$

Using these values, a cost ratio was determined by using the following relationship:

$$\text{Cost Ratio} = \frac{\text{Cost of Aspahlt Rubber or Polymer Modified (Per Mile)}}{\text{Cost of Unmodified Reference (Per Mile)}}$$

The resulting cost ratios can be seen in Table 4. This table also shows the ratio between the average fatigue ratio and the cost ratio for each of the three design mixtures. As shown, the asphalt rubber mixture is significantly better, even when the cost of the mixture is considered.

Table 4 – Cost analysis results

Pavement Mixture	Cost Per Mile ($)	Cost Ratio	Average Fatigue Ratio	Average Fatigue Ratio/ Cost Ratio
Unmodified Reference	126,556.32	1.00	1.00	1.00
Asphalt Rubber	163,301.60	1.29	5.92	4.59
Polymer Modified	126,846.72	1.00	3.32	3.31

8 Conclusions and Recommendations

This study looked at the fatigue life of three different pavement design mixtures under various axle loading conditions. The resulting fatigue ratios show that the asphalt rubber is the best performing design mixture, followed by the polymer modified mixture, with the unmodified reference mixture performing the worst. When the difference in material costs were accounted for, the asphalt rubber mixture still proved to be the highest ranked option, followed by the polymer modified mixture, with the unmodified reference mixture again ranking last. Based on the results of this study, it is recommended that the asphalt rubber mixture is utilized in areas where fatigue issues are common.

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