Journal of Materials and Engineering Structures

Research Paper

Mechanistic Analysis and Economic Benefits of Fiber-Reinforced Asphalt Overlay Mixtures

Nitish Raj Bastola, Mena I. Souliman, Ashish Tripathi, Alexander Pearson*

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

ARTICLE INFO

Article history:

Received : 30 October 2019

Revised : 3 February 2020

Accepted : 7 February 2020

Keywords:

Mechanistic analysis

Overlay

Fatigue cracking

Rutting

Fatigue and rutting life

Cost-effectiveness

ABSTRACT

Among the various distresses in flexible pavement structures, rutting and fatigue cracking can be accounted as two of the major distresses that need to be addressed by pavement engineers. Laboratory tests, such as four-point bending beam and flow number are utilized to characterize the rutting and cracking resistance of flexible pavements. Various construction practices are introduced to reduce the effect of fatigue and rutting in pavement structures. One of such methods is applying fibers to the asphalt mixture to prolong the serviceability and the performance of the pavement structures. The use of fibers is applicable to freshly constructed pavements as well as in the pavement rehabilitation and maintenance work, such as overlay. This paper primarily analyses the application of fibers in the overlay of pavements. The two major cases of the pavement with original asphalt overlay and the one with fibers mixed asphalt overlay is considered utilizing a developed testing program where the mechanistic analysis as well as the economic effectiveness is evaluated. 3D move analysis software package is utilized extensively as a means of mechanistic analysis tool. It is found that the fiber mixture pavement overlay had a higher pavement life than the ordinary asphalt overlay. In addition, the cost effectiveness in terms of fatigue and rutting of fiber-reinforced overlay structures were 4.4 and 4.1 times the unmodified mixtures, respectively. The use of fibers in the overlay of pavement resulted in higher pavement life with a high cost effectiveness.

1 Introduction

There are many diverse types of cracks in asphalt pavement, but it is crucial to understand that once the pavement develops interconnected cracks generated from the bottom of HMA and transferred to the hot mixed asphalt layer, it is then referred to as fatigue cracking [1]. These multiple cracks when acted upon by traffic loading will form a pattern similar to the pattern on alligator’s back, which is where alligator cracking gets its name from. Patching is one type of solution that often can repair and remove fatigue cracking. However, if the crack surfaces were large, it would need an overlay. Overlay is the best way for the rehabilitation of large amounts of fatigue cracking. Similarly, rutting is another common type of structural failure which can be fixed by overlay to treat longitudinal depression on pavement structures.

* *Corresponding author.*
E-mail address: msouliman@uttyler.edu

e-ISSN: 2170-127X,

RESEARCH REVIEW of Sciences and Technologies

Distress in the pavement likely occurs overtime after the construction of the pavement structure has finished. Cracking and rutting are a great concern when there is a need of economical design of the pavement. Among the various options on enhancing and rehabilitating the pavement, fibers are often thought of, but they are quite new, causing a concern related to their long-term performance. The use of fibers as a material to reinforce the pavement has been practiced for many decades. Moreover, the use of fibers in preventing the drain-down of binder in aggregate particles are common but they are rarely used in the rehabilitation of diverse cracks in the asphalt pavement structures such as rutting and fatigue cracking. Numerous varieties of fibers are used nowadays. This study also utilizes fibers in overlays to determine the improved performance of pavement overlays to improve the permanent deformation and fatigue cracking resistance of flexible pavements [2].

The use of fiber is a cost-effective method of strengthening the pavement structures for a prolonged service life. The background for this study initiated in 2008 when FORTA Corporation and the City of Tempe in Arizona used a Type C-3/4 base, and surface course layers were selected for the pavement of Evergreen Drive (East of the Loop 101 and North of University Drive). Two main asphalt mixtures were used for the most deteriorated section of the Evergreen Drive, where the 2 mm overlay was used after milling the edge of the pavement. The overlay was done on 64.31m of the pavement for the purpose of the study. In this study, laboratory samples of 150 mm diameter gyratory specimens were prepared, which includes the compaction for repeated load deformation testing or flow number testing [2]. AASHTO TP8 test protocols [3] were used for the preparation of beam specimens and compaction. Air void level was 7 %. Various properties such as dynamic modulus, triaxial shear strength, and repeated load for flexural beam tests for fatigue and evaluation of rutting resistance were tested. These tests were useful in providing ASTM Ai-VTSi consistency-temperature relationships.

2 Literature Review

Flexible pavements refer to the kind of pavement that bends when acted by the force of the tire. There will be a specific design objective of preventing excessive failure in any kind of layer in flexible pavements. The load distribution patterns also change from layer to layer in a flexible pavement. With this loading and variable environment conditions, flexible pavements are very prone to distress, such as alligator cracking and rutting. Among various methods to rehabilitate the pavement, one of the most known processes is the use of fibers. The use of fibers in pavement did not start until the late 1950s. The Johns-Manville Company, US Army Corps of Engineers, and the Asphalt Institute initiated the first evaluation of asbestos fibers in HMA [4]. This study concluded an increase in tensile strength, compressive strength, stability, ability to sustain load after reaching maximum stability, and resistance to weathering. This study was performed on pavement construction but the use of fibers in overlay has a muchshorter history.

Von Quintus et al. [5] performed a research study to determine the difference between polymer modified asphalt (PMA) and conventional unmodified HMA mixture for reducing occurrence of distress and increasing pavement life. Various conditions were identified to have the effect of PMA, maximizing the overlay life. The use of fibers led to the minimization of fatigue cracking, transverse cracks, and rutting with an adequate increase in service life.

Similarly, Severo and Ruwer performed research to determine the performance of hot mixed asphalt rubber overlay. The mix was of 88% asphalt and 12 % ground tire rubber. A bad section of the road was taken for the study and analysed for 2 years. The effect of using the rubber mixed overlay was analysed for 2 years and found that the overlay was crack free with no rutting and maintenance required [6].

Lee et. al. [7] conducted research on long-term pavement performance of fiber-grid reinforced asphalt overlay pavements. In this research, roughness, crack, rutting, and other various distress conditions related to fibers reinforced and common sections were compared. The application of the fiber was along the grid system and the fiber material that used was glass and carbon. The reduction of the cracking, higher IRI, and low rutting was the outcome of this study.

Jaskula et. al. [8] research was as well focused on the overlay construction with the various mixtures of asphalt and polymer fibers. The use of Aramid-Polyalphaolefin fibers was notable. Low temperature cracking and resistance to permanent deformation were illustrated. Various performances related to high temperatures were analysed by using the curve of dynamic modulus. The results throughout the research indicated that the evaluated fibers can improve low temperature pavement performance.

Similarly, Echols [9] also found that fiber-reinforced asphalt overlay is better than ordinary overlay in the case of maintenance of the road and application over multi-course. The research concluded that the advantages of freeze-thaw resistance and effective control of reflective cracking could be obtained when fiber-reinforced asphalt is used. In the same way, McDonald and Shah [10] also conducted research to find the performance of a variety of materials added to asphalt binders and mixtures to change properties relating to rutting and cracking. Seven polymers and particulate modifiers were included in this approach, which was supplemented by laboratory characterization. Different performances were concluded in the field trials when various modifiers were used, such as polyesters fibers, neoprene, SBR, asphalt rubber, PAC, Novonhalt, and Multi-grade asphalt cement. Modifiers did not guarantee in the case of rutting, but in the cracking, dramatic differences were noticed. This indicates that not all the modifiers were effective at changing asphalt properties though some provided cost-effective options.

Noorvand et al. [11] investigated the effect of synthetic fibers on mechanical performance of fiber-reinforced asphalt concrete, where the use of Aramid fiber in their study demonstrated an improved performance in permanent deformation or flow number. While performing the flow number test, the fibers were oriented parallel to the loading direction to strengthen the crack.

This extensive literature review facilitated learning the uses of fibers in the construction of flexible pavement and overlays. It provides guidance to knowing the mechanistic analysis of the HMA pavement as the analysis explains the phenomena caused due to the numerous physical actions such as stresses, strains, and deflection within a structure. Various mechanistic analysis are performed in the course of time, for example, Coleri et al. [12] used recycled materials on mechanical-empirical simulations and life cycle cost analysis, and Souliman et al. [13] conducted a mechanistic analysis using 3D-Move which was based on the fatigue performance on unmodified asphalt rubber and polymer modified mixture with a cost-effectiveness analysis. The initial cost was increased but higher cost effectiveness was achieved when asphalt rubber and polymer modified mixture was used.

3 Objectives

The objective of this study is to determine the cost effectiveness of fiber-reinforced asphalt overlay when it accounts for the distress conditions of fatigue and rutting. Various results from mechanical laboratory evaluations and long-term mechanistic performance were utilized in evaluating the benefits of reinforcing an overlay with the fibers in terms of cost analysis in this study.

4 Mechanistic Analysis Utilizing 3-D Move Software Package

A comprehensive concept for the design of a pavement layer thickness is referred as mechanistic empirical pavement design. The phenomenon caused by physical action such as stress, strain and deflection within the structure are explained by mechanistic empirical pavement design. Climatic conditions, properties of the materials of the pavement structure and loads are the cause of these phenomenons. Empirical parameters are used along with the mechanistic approach for defining the life of a pavement structure based on above described phenomenon.

Analysis of asphalt pavement requires various technological software packages, in which 3-D Move analysis was deemed most powerful. University of Nevada, Reno, under the cooperative agreement with Federal Highway Administration Agency, released the software [14]. Continuum finite layer approach is applied for computing pavement responses, which leads the program to handle complex surface loading such as multiple loads and non-uniform tire pavement contact stresses. Loading configuration and tire is adjustable according to path requirements. Estimation of damage under off-road farm vehicles and estimation of pavement performance at the intersection are some of the advanced application of the 3-D Move software. Similarly, some of the salient features regarding the software are the modelling of 3D surface stresses, analyzing the imprints of any shape, analyzing non-generic axle and tire configuration, as well as accounting for viscoelastic material characterization utilizing symmetrical conditions. Figure 1 represents the 3-D Move software and its various applications.

In this study, the approach of empirical equation based upon the physical effects and the failure of the pavements was implemented to estimate the performance of original mixture and fiber-reinforced mixture based on fatigue and rutting characteristics. Two pavement overlay structures of 25mm and 50mm characterized as thin and thick, respectively, were included for the analysis. Three vehicular speed of 16, 72 and 120 kph along with the parameters such as material properties, pavement layer thickness and single axle traffic load of 80 KN over dual tires spaced at 304.8 mm were utilized for the analysis of the pavement overlay in terms of fatigue and rutting lives.

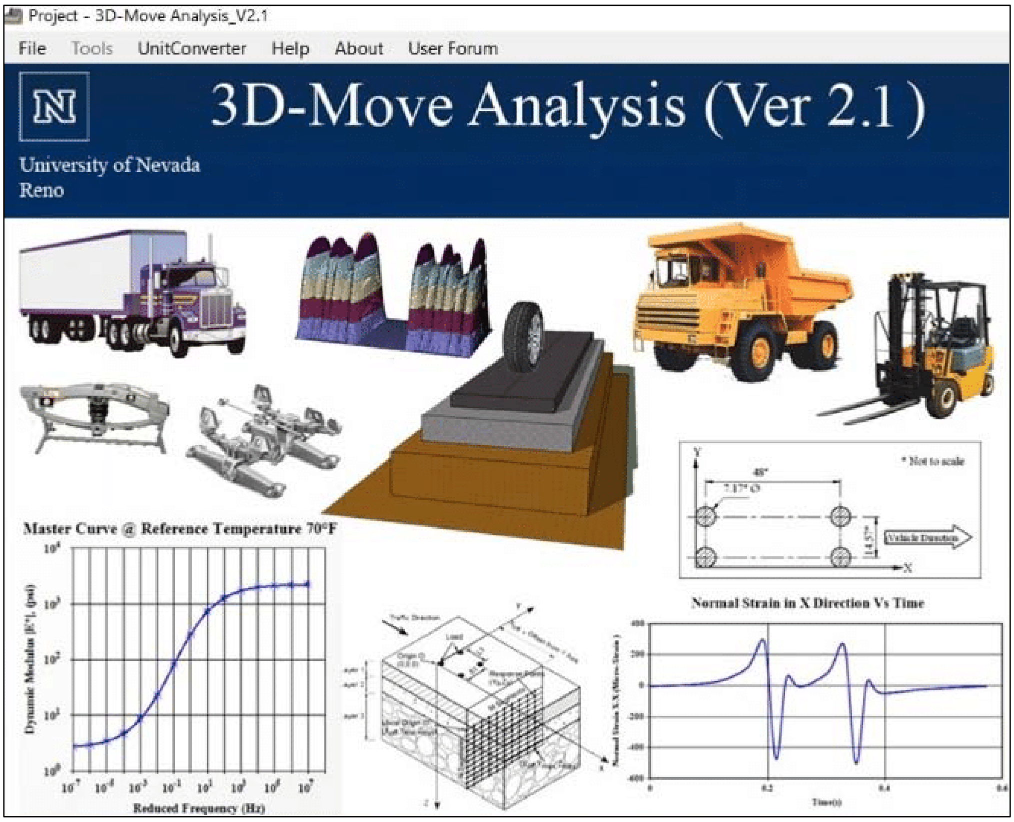

Fig. 1- Move software and its application

5 Fatigue Mechanistic Analysis

When an HMA pavement is exposed to repeated traffic loading under various conditions of the environment, it results in the creation of tensile stress. This tensile stress initiates cracking in the bottom of the HMA surface which eventually leads to fatigue cracking when acted on by continuous traffic loads. Fatigue cracking is often rehabilitated using an overlay. The use of fibers in overlay results in the strengthening of HMA pavements. It is very important to reinforce the overlay of the pavement structure against fatigue cracking.

For analysing the pavement for fatigue cracking, 36 individual 3-D move analysis were performed. The analysis cases were 2 mixtures types, 2 pavement structures types, 3 speed types, and 3 pavement temperatures, summing up to the 36 cases. Maximum tensile strains were identified by analysing tensile strains at the bottom of the asphalt concrete layer under the center point between the dual tires. The strains obtained from 3-D move analysis were used in calculating the fatigue life NF using the following relationship [2, 17].

$$\mathrm{NF} = \mathrm{K}_1(1/\varepsilon\,\mathrm{t})\mathrm{K}_2 \tag{1}$$

Where K_1 and K_2 are the regression constants and the values of these constant are presented in table 1.

Table 1-Regression coefficient for two different types of mixtures for fatigue [15]

Mixture Type	K_1	K_2
Unmodified Original Mixture	4E-14	4.95
Fiber-reinforced Mixture	4E-18	5.98

The fatigue ratio was then calculated as follows:

$$\text{Fatigue Ratio} = \frac{N_F \text{of Fiber–reinforced mixture}}{N_F \text{of original mixture}} \tag{2}$$

Table 2 given below summarizes the N_F cycles, derived from strains for both original and fiber-reinforced mixture.

Table 2-Mechanistic Fatigue Analysis Results for Original Mixture and Fiber-Reinforced Mixtures for Overlay Pavement Structures

Pavement Layer Thickness	Speed (kph)	Temp. (˚C)	Original Mixture N_F (Cycles)	Fiber-Reinforced Mixture N_F (Cycles)	Fatigue Ratio
Thin	16	-12	35,637,609	148,214,363	4.16
		22	634,094	2,955,500	4.66
		38	74,490	134,506	1.81
	72	-12	42,390,662	186,547,889	4.4
		22	1,260,856	7,145,845	5.67
		38	124,740	360,645	2.89
	120	-12	55,656,490	210,000,034	3.77
		22	1,985,318	11,730,583	5.91
		38	202,582	661,878	3.27
Thick	16	-12	112,130,179	688,038,164	6.14
		22	1,156,952	8,198,969	7.09
		38	86,468	200,181	2.32
	72	-12	139,696,815	797,519,376	5.71
		22	2,663,465	21,846,873	8.2
		38	179,953	692,913	3.85
	120	-12	175,829,706	927,883,904	5.28
		22	4,058,175	33,393,097	8.23
		38	303,979	1,175,680	3.87
Average Fatigue Ratio					4.8

As stated earlier, fatigue mechanics analysis was conducted with 3D move software. For both the mixture of two HMA overlay layers, N_F cycle were determined at various speed of 16, 72, and 120 kph, respectively and at temperature -12, 22, and 38°Cwith equation 1, tensile strain and regression constant.

Fatigue ratios were also calculated, and it is noticed that the fiber-reinforced mixture had higher N_F cycle compared to the ordinary mixture and it is explicitly noticed that the fatigue performance of fiber- reinforced mixture was 4.8 times more than controlled unmodified mixtures. Similarly, the tensile strain in the bottom of HMA layer is given below in figure 2.

Figure 2 shows that with the increase in the pavement thickness in the same mixture, tensile strain decreased at the bottom of HMA. Similarly, with respect to the vehicular speed from lower the higher, the tensile strain decreased and for the temperature increment, the strain value also increased.

Figure 3 below represents the NF cycle of modified and fiber-reinforced mixture and it shows that a thick pavement when acted with higher vehicle speed has higher pavement life within the mixture. The control mixture and fiber-reinforced mixture has the average NF of 31,892,919 cycles and 169,261,133 cycles, respectively, as shown in figure 2. This indicates that the fiber-reinforced mixture has higher fatigue life than the controlled mixture.

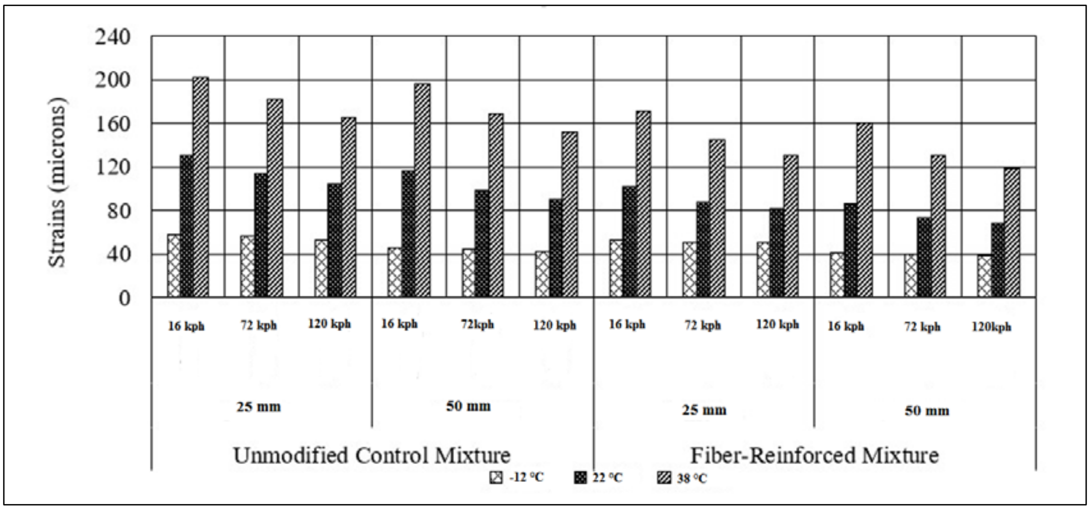

Fig.2 - Tensile Strains at the Bottom of the Asphaltic Layers for Different Pavement Structures and Vehicle Speeds for Overlay Pavement Structures

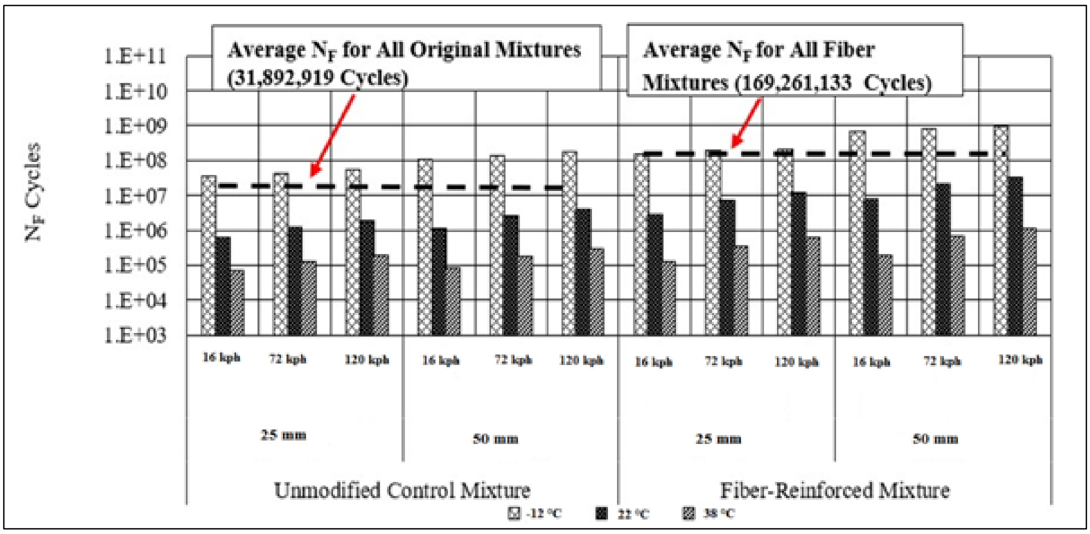

Fig. 3- N_F Cycles for Unmodified Original Mixture and Fiber-Reinforced Mixture for Different Temperatures for Overlay Pavement Structures

6 Rutting Mechanistic Analysis

Longitudinal depression failures on the pavement surface are known as rutting [11]. Rutting is a distress mode in the pavement, which leads to the premature failure of the pavement and results in early and expensive rehabilitation. Deeps ruts can affect the pavement with longitudinal cracking which leads to the penetration of water and debris, which deteriorate hot mix asphalt pavement.

For HMA overlay, rutting is taken as a major form of distress. In an overlay rutting of HMA, there are two different mechanisms of rutting: densification and repetitive shear deformation. These mechanisms are influenced by pavement material properties, traffic loading, and pavement structures. When subgrades are exposed to seasonal variation with bituminous materials subjected to high temperature; it can have a significant effect on rutting development. Similar to fatigue mechanistic analysis, rutting mechanistic analysis also involves 36 individuals' cases (2 mixture x 3 pavement structure x 3 vehicle speed x 3 pavement temperature) on 3-D Move. 100 mm of HMA and 150 mm of crush aggregate base was followed by overlay structure of 25mm and 50mm.

The following εp-NR relationship [2] is utilized in calculating the no. of cycle of rutting failure based on flow number NR and rutting ratio test:

$$\varepsilon p(N_R) = A(N)^B + C(e^{D(N)} - 1) \tag{3}$$

Where NR is the number of loading cycles to reach rutting failure, εp is permanent strain and A, B, C & D are regression constant, which is represented in table 3 for two different mixture.

Table 3- Regression coefficient for two different types of mixtures for rutting [15]

Type of Mixture	A	B	C	D
Original Mixture	0.04871	0.635511	0.01325648	0.01002681
Fiber-Reinforced Mixture	0.02142	0.582121	0.001629	0.00103547

The rutting ratio was then calculated as follows:

$$\text{Rutting Ratio} = \frac{N_R \text{ of Fiber - reinforced mixture}}{N_R \text{ of original mixture}} \tag{4}$$

The following tables and figures represent the maximum displacement, M_R Cycle and rutting ratio.

Table 4-Displacement and Percent Strains for Controlled and Fiber-Reinforced Mixtures for Overlay Pavement Structures

Pavement Layer Thickness	**Speed (kph)**	**Temp. (˚C)**	**Unmodified Original Mixture**		**Fiber-Reinforced Mixture**	
			Displacement (mm)	Percent Strain	Displacement (mm)	Percent Strain
Thin	16	-12	0.5842	0.21	0.57658	0.21
		22	0.889	0.32	0.7874	0.28
		38	1.1176	0.40	1.016	0.36
	72	-12	0.5588	0.20	0.5588	0.20
		22	0.8382	0.30	0.7366	0.26
		38	1.0668	0.38	0.9398	0.34
	120	-12	0.5334	0.19	0.5334	0.19
		22	0.8128	0.29	0.7366	0.26
		38	1.0414	0.37	0.9398	0.34
Thick	16	-12	0.4826	0.16	0.4572	0.15
		22	0.762	0.25	0.6604	0.22
		38	0.9906	0.32	0.889	0.29
	72	-12	0.4572	0.15	0.44196	0.14
		22	0.7112	0.23	0.635	0.21
		38	0.9144	0.30	0.8128	0.27
	120	-12	0.4318	0.14	0.4318	0.14
		22	0.6858	0.22	0.6096	0.20
		38	0.889	0.29	0.7874	0.26

The value of the displacement for both test mixture of two HMA pavement layers of 25 and 50mm thick at three different speeds and at three different temperatures was determined using the 3-D Move Software. Observations from the table 4 indicate that the displacement decreases when speed of vehicles and thickness of the pavements were increased whereas the temperature increment results in the decrement of the displacement of the same mixture. Also, it is notable that the percentage strains also followed the same pattern as followed by the displacements for the mixtures.

Table 5-Mechanistic Rutting Analyses for Controlled and Fiber-Reinforced Mixtures for Overlay Pavement Structures

Pavement Layer Thickness	Speed (kph)	Temp. (˚C)	Unmodified Original Mixture	Fiber-Reinforced Mixture	Rutting Ratio
			N_R based on Flow Number	N_R based on Flow Number	
Thin	16	-12	10	51	5.1
		22	19	83	4.4
		38	27	128	4.7
	72	-12	9	47	5.2
		22	17	75	4.4
		38	25	118	4.7
	120	-12	8	44	5.5
		22	16	70	4.4
		38	24	109	4.5
Thick	16	-12	6.5	29	4.5
		22	13	55	4.2
		38	19	88	4.6
	72	-12	6	26	4.3
		22	11	53	4.8
		38	17	79	4.6
	120	-12	5.4	26	4.8
		22	10.5	48	4.6
		38	16	75	4.7
Average Rutting Ratio					4.7

N_R based on flow number of the both mixtures were calculated with percentage strain and respective regression coefficient in equation 3, which is used in equation 4 to know the rutting ratios. The above table also shows that the unmodified original mixture has lower N_R based on the flow rate and the rutting performance of the fiber-reinforced mixture is 4.7 times higher than unmodified controlled mixture. The following figure 4 illustrates the displacement at top of subgrade layer for modified and unmodified mixture.

Figure 4 shows that the thick surface layer of pavement had lower displacement compared to the corresponding thin layer. Displacement also decreases when speed rises and increases when temperature rises. Figure 5 shows that NR cycle for two different mixtures.

Higher vehicle speed with a thicker overlay had a higher pavement life in the mixture as shown in figure 5. The original mixture and fiber-reinforced mixture have average NR of 14 and 67 respectively, which indicated that fiber-reinforced mixture has a higher rutting life.

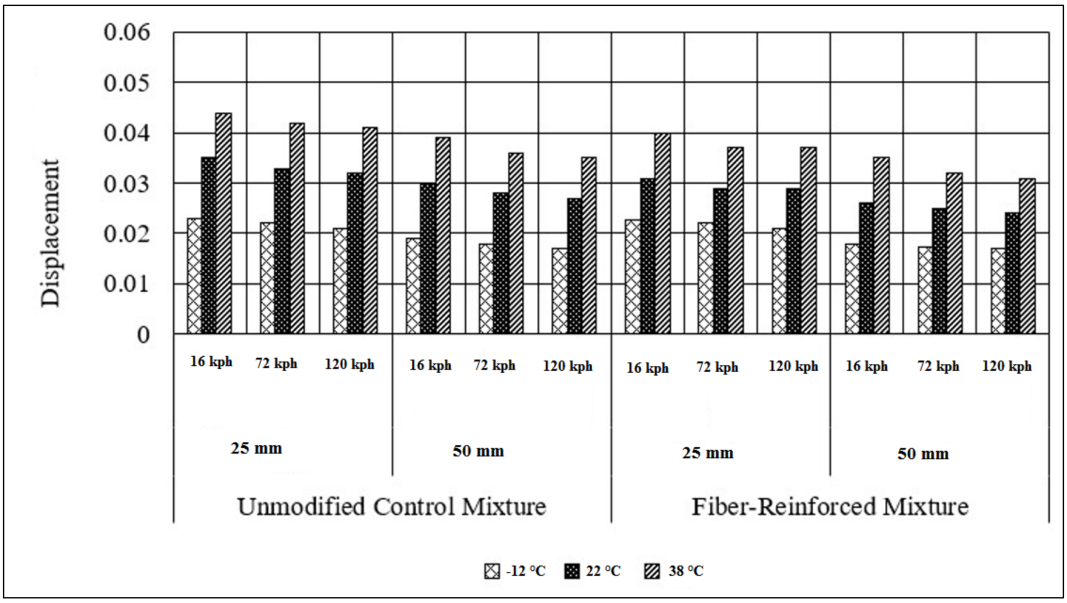

Fig. 4-Displacement at Top of the Subgrade Layers for Different Pavement Structures and Vehicle Speeds for Overlay Pavement Structures

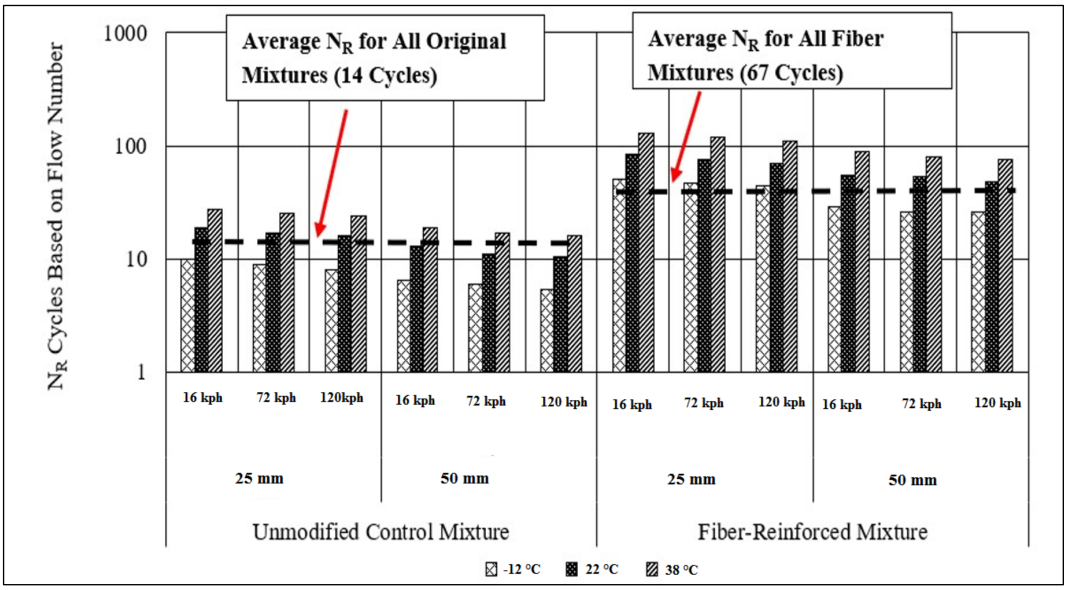

Fig. 5- Cycles Based on Flow Number for Unmodified Original Mixture and Fiber-Reinforced Mixture for Different Temperatures for Overlay Pavement Structures

7 Cost Comparison Based on Fatigue and Rutting Performance

A comparative cost analysis was conducted and is presented below for unmodified HMA and fiber-reinforced overlays. For this, a pavement section of 1600m (1 mile) with 3.66m (12ft) single lane was considered. The density of asphalt concrete is assumed to be 2694 kg/m^3. The cost is given by equation 5 and 6.

$$\text{Cost of Pavement per 1000 Cycles of Fatigue Life} = \frac{Cost\ of\ 1.6\ km\ Pavement}{\left(\frac{NF\ Cycles}{1000}\right)} \tag{5}$$

$$\text{Cost of Pavement per Cycles of Rutting Life} = \frac{Cost\ of\ 1.6\ km\ pavement}{NR\ Cycles} \tag{6}$$

If 100 tons of HMA mixture is to be prepared with 5% of optimum binder content, the quantity of aggregate will be 95 tons and binder will be 5 tons. With these values and unit price given in the table 6, following cost can be calculated :

Table 6-Cost of the Materials [16]

Materials	Unit Price	Total Price
Binder	$740/ton	$3700
Aggregate	$22/ton	$2090

Equipment and plants cost for the 100 tons of HMA mixture is taken as $2500. It led to the total cost of $8290. The price of a ton of unmodified mixture is $82.9, but the addition of fiber has the estimated cost of $12 per ton. Consequently, the unit ton price of unmodified and modified mixture is $82.9 and $94.9, respectively.

In the case of 25 and 50-mm-thick HMA overlay layers, the required quantities are :

For 25 mm thick asphalt concrete layer, 1600m*3.66m*0.025m*2694kg/m3 = 394.5 tons

For 50 mm thick asphalt concrete layer, 1600m*3.66m*0.050m*2694kg/m3 = 793.6 tons

The cost required for paving the pavement for the given section with the given mixture can be calculated as,

Cost to pave 1.6 km (1 mile) of 25 mm thick original mix without fibers = 394.5 tons* $82.9/ton = $32704.05

Cost to pave 1.6 km (1 mile)of 50 mm thick original mix without fibers = 793.6 tons * $82.9/ton = $65789.44

Cost to pave 1.6 km (1 mile)of 25 mm thick mixture that contained fibers = 394.5 tons*$94.9 /ton = $37438.05

Cost to pave 1.6 km (1 mile)of 50 mm thick mixture that contained fibers = 793.6 tons*$94.9 /ton = $75312.64

Table 7- Cost Calculation per 1.6 km per 1000 Cycles Fatigue Performance for Original and Fiber-Reinforced Mixtures for Overlay Pavement Structures

			Unmodified Original Mixture		Fiber-Reinforced Mixture	
Pavement Layer Thickness	**Speed (kph)**	**Temp. (˚C)**	Cost of pavement per 1000 cycles of fatigue life per 1.6 km ($)	Average cost of pavement per 1000 cycles of fatigue life per 1.6km ($)	Cost of pavement per 1000 cycles of fatigue life per 1.6 km ($)	Average cost of pavement per 1000 cycles of fatigue life per 1.6km ($)
Thin	16	-12	0.87	133.39	0.25	56.92
		22	51.58		12.67	
		38	439.04		278.34	
	72	-12	0.77		0.20	
		22	25.94		5.24	
		38	262.18		103.81	
	120	-12	0.59		0.18	
		22	16.47		3.19	
		38	161.44		56.56	
Thick	16	-12	0.59		0.11	
		22	56.86		9.19	
		38	760.85		376.22	
	72	-12	0.47		0.09	
		22	24.70		3.45	
		38	365.59		108.69	
	120	-12	0.37		0.08	
		22	16.21		2.26	
		38	216.43		64.06	

On table 7, equation 5 is used for finding the costs of 1000 cycles per pavement mile(1.60 km) for two types of mixture by utilizing mechanistic empirical analysis. It is observed that fiber-reinforced mixture has lower cost of pavement per 1000 cycles of fatigue life if compared to the unmodified mixture. This indicates that more cost-effectiveness in the case of fiber-reinforced mixture and in the most figurative way, the fiber-reinforced mixture over 1000 fatigue life cycles had 2.34 times lower cost than the unmodified mixture.

Table 8 - Cost Calculations per 1.6 km per Cycles Rutting Performance for Original and Fiber-Reinforced Mixtures for Overlay Pavement Structures

			Unmodified Original Mixture		Fiber-Reinforced Mixture	
Pavement Layer Thickness	**Speed (kph)**	**Temp.(˚C)**	Cost of pavement per cycles of rutting life per 1.6 km ($)	Average cost of pavement per cycles of rutting life per 1.6 km ($)	Cost of pavement per cycles of rutting life per 1.6 km ($)	Average cost of pavement per cycles of rutting life per 1.6km ($)
Thin	16	-12	3,270	4,588	734	1,132
		22	1,721		451	
		38	1,211		292	
	72	-12	3,634		797	
		22	1,924		499	
		38	1,308		317	
	120	-12	4,088		851	
		22	2,044		535	
		38	1,363		343	
Thick	16	-12	10,121		2,597	
		22	5,061		1,369	
		38	3,463		856	
	72	-12	10,965		2,897	
		22	5,981		1,421	
		38	3,870		953	
	120	-12	12,183		2,897	
		22	6,266		1,569	
		38	4,112		1,004	

Similarly, utilizing equation 6, the cost of cycles of rutting life per pavement mile (1.6 km) were determined and is observed that the cost of unmodified mixture is higher than the fiber-reinforced mixtures per cycle of rutting life. The fiber reinforced mixture costs 4.05 times less than the unmodified mixture.

8 Cost- Effectiveness Analyses

The technique of comparing the amount paid to the benefit obtained is referred as cost-effectiveness analysis. The following equation 7 provides the measure for cost-effectiveness of fiber-reinforced and original mixture.

$$\text{Cost} - \text{Effectiveness} = \frac{Number\ of\ Fatigue\ or\ Rutting\ Cycles}{Cost\ of\ 1.6\ km} \quad (7)$$

The cost-effectiveness analysis referred as the ratio of the benefit to the cost paid provides the alternative economic evaluation techniques. In this paper, the cost considered is only the material initial cost but not the maintenance cost. Cost effectiveness in terms of cycles/cost of 1.6 km (one mile) is presented as the expected performances, predicting the number of fatigue and rutting cycles to the given mixture of pavement thickness and speed divide the cost.

In an overlay pavement structure, NF cycles of fatigue analysis and NR cycle of rutting analysis were divided by the cost of pavement materials resulting in the cost-effectiveness analysis. The analysis details on cost-effectiveness of rutting and fatigue is presented in the table followed.

Table 9-Cost-Effectiveness of Original and Fiber-Reinforced Mixtures in Terms of Fatigue for Overlay Pavement Structures

Pavement Layer Thickness	**Speed (kph)**	**Temp. (˚C)**	**Unmodified Original Mixture**		**Fiber-Reinforced Mixture**		**Average Cost-Effectiveness Ratio**
			Cost-Effectiveness	Average Cost-Effectiveness	Cost-Effectiveness	Average Cost-Effectiveness	
Thin	16	-12	1089.70	602.63	3958.92	2671.14	4.4
		22	19.39		78.94		
		38	2.28		3.59		
	72	-12	1296.19		4982.84		
		22	38.55		190.87		
		38	3.81		9.63		
	120	-12	1701.82		5609.27		
		22	60.71		313.33		
		38	6.19		17.68		
Thick	16	-12	1704.38		9135.76		
		22	17.59		108.87		
		38	1.31		2.66		
	72	-12	2123.39		10589.45		
		22	40.48		290.08		
		38	2.74		9.20		
	120	-12	2672.61		12320.43		
		22	61.68		443.39		
		38	4.62		15.61		

It is noticed that the cost-effectiveness increased with the increase in the speed of the vehicles and thickness of pavement. Overall, the cost-effectiveness ratio of fiber-reinforced mixture was 4.4 times higher than that of unmodified original mixture in fatigue analysis.

Similarly, in terms of rutting analysis cost-effectiveness increased with increasing speed and pavement thickness. Fiber-reinforced mixture had 4.1 times higher average cost-effectiveness than that of unmodified original mixture.

Table 10 - Cost-Effectiveness of Original and Fiber-Reinforced Mixtures in Terms of Rutting for Overlay Pavement Structures

Pavement Layer Thickness	Speed (kph)	Temp. (˚C)	Unmodified Original Mixture		Fiber-Reinforced Mixture		Average Cost-Effectiveness Ratio
			Cost-Effectiveness	Average Cost-Effectiveness	Cost-Effectiveness	Average Cost-Effectiveness	
Thin	16	-12	0.00031	0.00035	0.00136	0.00143	4.1
		22	0.00058		0.00222		
		38	0.00083		0.00342		
	72	-12	0.00028		0.00126		
		22	0.00052		0.00200		
		38	0.00076		0.00315		
	120	-12	0.00024		0.00118		
		22	0.00049		0.00187		
		38	0.00073		0.00291		
Thick	16	-12	0.00010		0.00039		
		22	0.00020		0.00073		
		38	0.00029		0.00117		
	72	-12	0.00009		0.00035		
		22	0.00017		0.00070		
		38	0.00026		0.00105		
	120	-12	0.00008		0.00035		
		22	0.00016		0.00064		
		38	0.00024		0.00100		

9 Conclusions and Recommendations

The calculated N_F and N_R cycles illustrated the life of a pavement with fiber-reinforcement is higher than the unmodified mixtures with respect to both fatigue and rutting mechanistic analyses. In addition, fiber reinforced mixture indicated more cost effectiveness than the unmodified mixture in terms of cost analysis. The following conclusion can be drawn based on the results.

The fatigue performance (N_F) of fiber-reinforced mixture was 4.8 times greater than that of the unmodified mixture in an overlay. Similarly, the rutting performance (N_R) based on flow number of fiber-reinforced mixtures was 4.7 times greater than the original unmodified mixture.

The cost of fiber-reinforced mixture per 1000 cycles of fatigue life per 1.6 km (1 mile) was $56.92, whereas for the unmodified mixture it was $133.39 for overlay pavement structures.

For overlay pavement structures, the cost of fiber-reinforced modified mixture per cycles of rutting life per 1.6 km (1 mile) was $1,132, while the cost for the unmodified mixture was $4,588.

Thick overlay had lower cost of pavement compared with thinner overlay pavements as related to their cost of cycles of fatigue and rutting.

According to fatigue analysis, the cost effectiveness of the fiber reinforced mixture was 4.4 times higher than that of unmodified controlled mixture.

According to the rutting analysis, the cost effectiveness of the fiber-reinforced mixture was 4.1 times higher than the unmodified controlled mixture.

Generally, thinner overlay pavement loaded with lower speed was less cost-effective than the thicker overlay pavement with higher speed vehicles for the same mixture.

The results of this study and the summarize points mentioned above conclude that the use of fibers in HMA overlay will enhance and improve the pavement performance in terms of fatigue and rutting. Similarly, addition of fibers lead to the cost-efficient option for thick overlay structures under high traffic volumes. Therefore, it is recommended to determine the most cost-efficient fiber contents for different traffic loading conditions and pavements thickness as a further research.

REFERENCES

[1]- M. Panda, A. Suchismita, J. Giri, Utilization of Ripe Coconut Fiber in Stone Matrix Asphalt Mixes. Int. J. Transp. Sci. Tech. 2(4) (2013) 289-302. doi:10.1260/2046-0430.2.4.289

[2]- K. Kaloush, K.P. Biligiri. W.A. Zeiada, M.C. Rodezno, J.X. Reed, Evaluation of FORTA Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests. J. Test. Eval. 38(4) (2010).

[3]- AASHTO Designation: T321-03, Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending, Washington D.C., 2003.

[4]- B.J. Putman, Effects of Fiber Finish on the Performance of Asphalt Binders and Mastics. Appl. Mech. Mater. ID 172634 (2011). doi:10.1155/2011/172634

[5]- H.L. Von Quintus, J. Mallela, M. Buncher, Quantification of the Effect of Polymer Modified Asphalt on Flexible Pavement Performance. Transp. Res. Record. 2001(1) (2007) 141-154. doi:10.3141/2001-16

[6]- L. Severo, P. Ruwer, F. Pugliero Gonçalves, J.A. Pereira Ceratti, A. Morilha, Performance of Asphalt-Rubber Hot Mix Overlays at Brazilian Highway.

[7]- J.M. Lee, S.B. Baek, K.H. Lee, J.S. Kim, J.H. Jeong, Long-term Performance of Fiber Grid Reinforced Asphalt Pavements Overlaid on Old Concrete Pavements. Int. J. Highway. Eng. 19(3) (2014) 31-43. doi:10.7855/IJHE.2017.19.3.031

[8]- P. Jaskula, M. Stienss, C. Szydlowski, Effect of Polymer Fibres Reinforcement on Selected Properties of Ashpalt Mixtures. Procedia Engineer. 172 (2017) 441-448. doi:10.1016/j.proeng.2017.02.026

[9]- J.B. Echols, New Mix Method for Fiber-Reinforced Asphalt. J. Trans. Res. B. 119(3) (1989) 72-73.

[10]- R. Mc Daniel, A. Shah, Asphalt Additives to Control Rutting and Cracking, Publication FHWA/ IN/JTRP-2002/29. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2003. doi:10.5703/1288284313147

[11]- H. Noorvand, R. Salim, J. Medina, J. Stempihar, B.S. Underwood, Effect of Synthetic Fiber State on Mechanical Performance of Fiber Reinforced Asphalt Concrete. J. Trans. Res. B. 2672(28) (2018) 42-51. doi:10.1177/0361198118787975

[12]- E. Coleri, Y. Zhang, B.M. Wruck, Mechanistic-Empirical Simulations and Life Cycle Cost Analysis to Determine the Cost and Performance Effectiveness of Asphalt Mixtures Containing Recycled Materials. J. Trans. Res. B. 2672(40) (2018) 143-154. doi: 10.1177/0361198118776479

[13]- M.I. Souliman, M. Mamlouk, A. Eifert, Cost-Effectiveness of Rubber and Polymer-Modified Asphalt Mixtures as Related to Fatigue Performance. Procedia Engineer. 145 (2016) 404-411. doi:10.1016/j.proeng.2016.04.007

[14]- R.V. Siddharthan, J. Yao, P.E. Seebaly, Pavement Strain From Moving Dynamic 3D Load Distribution. J. Transp. Eng. 124(6) (1998). doi:10.1061/(ASCE)0733-947X(1998)124:6(557)

[15]- I.M. Souliman, A. Tripathi, M. Isied, Mechanistic Analysis and Economic Benefits of Fiber-Reinforced Asphalt Mixtures. J. Mater. Civil Eng. 31(8) (2019). doi:10.1061/(ASCE)MT.1943-5533.0002755

[16]- Texas Department of Transportation, Average Low Bid Unit Prices, 2019.

[17]- ERES consultants division, Guide for Mechanistic Empirical Design of New and Rehabilitated Pavement Structure, NCHRP 1- 37A report, Transportation Research Board, National Research Council, 2004.