Evaluation of Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests

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ABSTRACT: The objective of this study was to evaluate the material properties of a conventional (control) and fiber reinforced asphalt mixtures using advanced material characterization tests. The laboratory experimental program included: triaxial shear strength, dynamic (complex) modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. The data was used to compare the performance of the fiber modified mixture to the control. The results showed that the fibers improved the mixture's performance in several unique ways against the anticipated major pavement distresses: permanent deformation, fatigue cracking, and thermal cracking.

KEYWORDS: *Asphalt mixture, Polypropylene Fibers, Aramid Fibers, Dynamic Modulus, Permanent Deformation, Flow Number, Fatigue Cracking, Thermal Cracking, Crack Propagation.*

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Paper # 200903AT102

Introduction

Fibers have been used to improve the performance of asphalt mixtures against permanent deformation and fatigue cracking [1, 2]. Recent development in materials characterization laboratory tests in the pavement community was the motivation for this study to re-evaluate the performance of synthetic fibers in asphalt mixtures. The fibers consisted of a blend of polypropylene and aramid fibers. Of particular interest were laboratory tests that were included as part of the National Cooperative Highway Research Program (NCHRP) 9-19 Project and the Mechanistic-Empirical Pavement Design Guide [3, 4].

Few research studies reporting on experiments using synthetic fibers in asphalt concrete have been found in the literature. Bueno et al studied the addition of randomly distributed synthetic fibers on the mechanical response of a cold-mixed, densely graded asphalt mixture using the Marshall test, as well as static and cyclic triaxial tests [1]. The results showed that the addition of fibers caused small variations in the mixture's triaxial shear strength parameters. Lee et al evaluated the influence of recycled carpet fibers on the fatigue cracking resistance of asphalt concrete using fracture energy [2]. It was found that the increase in fracture energy represents a potential for improving the asphalt mixture's fatigue life.

A research study by Fitzgerald reported that the addition of carbon fibers to an asphalt mixture may have beneficial properties ranging from improved mechanical properties to reduced electrical resistance using the electric resistivity testing methodology [5]. However, the study did not involve extensive laboratory mechanical testing on the carbon-fiber-modified mixtures. Cleven subjected carbon fiber-reinforced asphalt mixtures to mechanical testing, which included diametral resilient modulus, repeated load permanent deformation, flexural beam fatigue tests and indirect tensile strength tests [6]. The modified asphalt mixtures were observed to be stiffer, more resistant to permanent deformation, and had higher tensile strength at low temperatures. However, the carbon fiber modified samples showed no improvement in fatigue behavior as measured by the four-point beam test or cold temperature creep compliance test. Jahromi and Khodai also investigated the characteristics and properties of the carbon fiber-reinforced asphalt mixtures through laboratory tests such as Marshall stability, indirect tension, creep, and repeated load indirect tensile test to characterize the fatigue resistance [7]. They reported that the addition of carbon fibers showed an increase in the mix's stability, decrease in flow value, and an increase in voids in the mix. They also found that the addition of fibers improved the fatigue life and permanent deformation of the mixtures.

Mahrez and Karim utilized glass fibers in a Stone Mastic Asphalt (SMA) mixture. They found that the use of glass fiber in asphalt mixtures showed variable Marshall stability results, and that the addition of glass fibers actually decreased the mixtures' stability and stiffness [8]. In a different study by Mahrez and Karim in 2007, they used the wheel-tracking test to characterize the creep and rutting resistance of glass fiber reinforced asphalt mixtures [9]. They reported that the inclusion of glass fibers resulted in higher resilient modulus, higher resistance to permanent strain and rutting. Putman and Amirkhanian studied the feasibility of utilizing waste tire and carpet fibers in SMA mixtures [10]. The study compared the performance of SMA mixtures containing waste tire and carpet fibers with mixes made with commonly used cellulose and other polyester fibers. No significant difference in permanent deformation or moisture susceptibility was found in mixtures containing waste fibers compared to cellulose or polyester. However, they reported that the tire, carpet, and polyester fibers significantly improved the toughness of the mixtures compared to the cellulose fibers.

Chowdhury et al evaluated two types of recycled tire fibers to determine whether they can be used in different types of asphalt mixtures as a replacement of the currently used cellulose or mineral fibers [11]. The researchers tested three different types of mixtures: SMA, Permeable Friction Course (PFC), and Coarse Mix High Binder (CMHB) mixtures with two different types of recycled tire fibers, one cellulose fiber, and a control mix with no fibers. The laboratory tests used to evaluate the mixtures were: drain-down, dynamic modulus, indirect tensile strength, and Hamburg wheel tracking tests. Mixtures containing tire fibers, in most cases, outperformed the mixtures containing cellulose fiber and mixtures with no fiber. The drain-down test results clearly revealed that the recycled tire fiber can be used in SMA and PFC mixtures as a replacement for cellulose fibers to prevent asphalt drain-down during construction.

Wu et al examined the dynamic characteristics of three fiber-modified asphalt mixtures: cellulose, polyester and mineral fibers at dosages of 0.3%, 0.3%, 0.4% respectively [12]. The experimental results showed that fiber-modified asphalt mixtures had higher dynamic modulus compared with the control mixture.

Study Background

In this study, a small pavement rehabilitation project was identified and coordinated with the City of Tempe, Arizona. The rehabilitation involved constructing experimental sections of a control asphalt mixture overlay as well as a mixture reinforced with synthetic fibers. A conventional dense graded asphalt concrete mixture was selected for paving on Evergreen Drive located east of the Loop 101 and north of University Drive in Tempe, Arizona. The designated road section had two asphalt mixtures: a control mix with no fibers, and a mixture that contained one pound of fibers per one ton of mix. The fibers were a propriety blend of polypropylene and aramid provided by the manufacturer in Pennsylvania. The addition of fibers was done at a batch asphalt plant in Phoenix. Fig. 1 shows the road section condition before it was overlaid. Basically, no repair work was done and the 2-inch overlay was placed on a much deteriorated section of Evergreen Drive. Only the edge of the pavement was milled off to match the final overlay grade with the curb. Test sections with and without fibers were staggered on the road to allow for direct field performance comparisons considering traffic flow and loading types (e.g., buses). About 1500 lbs of each mixture were brought back to the Arizona State University (ASU) laboratories. Sample preparation included compaction of 150 mm diameter gyratory specimens for triaxial testing. In addition, beam specimens were prepared and compacted according to AASHTO TP8 test protocols [13-15]. The performance of both mixtures was assessed using the advanced material characterization tests that included: triaxial shear strength, dynamic modulus, repeated load for permanent deformation characterization, flexural beam tests for fatigue, C* line integral for fracture energy and crack propagation, and indirect diametral tensile test for thermal cracking evaluation.

Study Objective

The objective of this study was to evaluate the material properties of the conventional (control) and polypropylene /aramid fibers reinforced asphalt mixtures using the most current laboratory tests adopted in the pavement community [4]. The goal was to assess how the material properties for the fiber reinforced mixture differs in stiffness, permanent deformation, and cracking characteristics.

Materials

Fibers Characteristics

As mentioned earlier, the fibers used in this study were a blend of synthetic fibers designed for use in Hot Mix Asphalt (HMA) applications. Fig. 2 (a) shows typical fibers contained in one-lb bag (approximately 445.0 g), a blend of the aramid and the polypropylene. Table 1 shows the physical properties of both fibers. The fibers are designed to reinforce the HMA in three-dimensions.

Mixture characteristics

A City of Phoenix designated asphalt mixture specification (PHX C-3/4) with nominal maximum aggregate size of ¾-in was used. The asphalt binder used in the mix was a PG 70-10. The theoretical maximum specific gravity of the control and fiber-reinforced mixtures were 2.428 and 2.458, respectively. The design asphalt cement content was 5.0% for the control mixture, and it was kept the same for the fiber reinforced asphalt mixture. The reference air voids for both the control and fiber-reinforced asphalt mixtures was 7.0%. Figure 2 (b) shows a close up of a loose asphalt mixture that was spread on the table for preparation of the Rice gravity test. Fibers were seen by the naked eye with good distribution throughout the mix. The mixes were re-heated and re-compacted into 150 x 170 mm Gyratory specimens. Cylindrical samples were cored from each gyratory plug, and the ends were sawed to get final specimens of 100 mm in diameter and 150 mm in height for triaxial testing. In addition, beam specimens were prepared for fatigue cracking evaluation. For thermal cracking evaluation, disc specimens were prepared according to the "Test Method for Indirect Tensile Creep Testing of Asphalt Mixtures for Thermal Cracking" reported in NCHRP Report 465 [4]. Similar disc specimens were prepared for the C* crack propagation tests.

Laboratory Tests, Results and Analyses

Triaxial Shear Strength Tests

The triaxial shear strength test has been recognized as the standard test for determining the strength of materials for over 50 years. The results from these tests provide a fundamental basis which can be used in analyzing the stability of asphalt mixtures. This is because the stresses acting on the laboratory specimen during the test simulate the state of stresses existing in the pavement, given certain specimen boundary and geometry conditions are met.

Three triaxial strength stress states, one unconfined and two confined, were conducted for the control and fiber-reinforced asphalt concrete mixtures. Tests were carried out on cylindrical specimens, 4 inches (100 mm) in diameter and 6 inches (150 mm) in height. The tests were conducted at 130 °F (54.4 °C). The confining pressures used were 20 psi (138 kPa) and 40 psi (276 kPa). Two replicates were used at each confinement level. The specimens were loaded axially to failure at a strain rate of 1.27 mm/mm/min.

Fig. 3 (a) shows a plot of the Mohr-Coulomb failure envelope represented by the cohesion “c” and angle of internal friction “ϕ” for the tested mixtures. Classically, the parameters “c” and “ϕ” are the strength indicators of the mixtures. The larger the “c” value, the larger the mix resistance to shearing stresses. In addition, the larger the “ϕ”value, the larger the capacity of the asphalt mixture to develop strength from the applied loads, and hence, the smaller the potential for permanent deformation. The “c” value of the fiber-reinforced mix was higher (34.3 psi) than that of the control mixture (27.4 psi). The effect of fibers on the “ϕ” value was less, 48° for the fiber-reinforced mix versus 47° for the control mixture. Since the "ϕ" value is an aggregate property, therefore no significant variation was expected since both mixtures had the same aggregate gradations.

Fig. 3 (b) presents a comparison example of the tests conducted for both mixtures at the 20 psi (138 kPa) confinement level. The plots represent before and after peak stress development during the test. For the fiber-reinforced mixture, it is observed that the peak stress developed and the time of its occurrence are higher when compared to those of the control mixture, a behavior that was attributed to the influence of the fibers in the mix. The fibers provide this additional reinforcement to the asphalt mix in resisting permanent deformation and retard the occurrence of shear failure. In addition, cumulative areas under the curve for the tested mixtures were calculated; the value of these areas can be interpreted as indicators of the mixes' residual energy in resisting crack propagation post peak stress. In all tests, the fiber reinforced mixture showed higher residual energy than the control mixture.

Repeated load permanent deformation test

The repeated load or Flow Number (FN) test is a dynamic creep test used to determine the permanent deformation characteristics of paving materials. It has been thoroughly documented in the NCHRP Report 465 study [4]. In this test, a repeated dynamic load is applied for several thousand repetitions, and the cumulative permanent deformation, including the beginning of the tertiary stage (FN) as a function of the number of loading cycles over the test period is recorded. Tests were carried out on cylindrical specimens, 4 inches (100 mm) in diameter and 6 inches (150 mm) in height. A haversine pulse load of 0.1 sec and 0.9 sec dwell (rest time) is applied.

Table 2 presents a master summary of the FN test results conducted at 130 °F. The FN values of fiber-reinforced mixtures were found to be 15 times higher than the control mixture. The average permanent axial strain values were 0.78% and 0.51% for the control and fiber-reinforced mixtures, respectively. Two characteristics were observed for the fiber-reinforced mixture in these tests: an extended endurance period in the secondary stage, and the gradual (less) accumulation of permanent strain beyond tertiary flow. Fig. 4 presents the values of strain slope for both mixtures during the tertiary stage. It can be observed that the control mix has higher strain slopes compared to the fiber-reinforced mixture. Lower values of strain slope during the tertiary stage means more energy is stored in the sample, and that the mix has higher potential to resist shear failure and further development of permanent deformation.

E Dynamic Modulus Test*

The stress-to-strain relationship for an asphalt mixture under a continuous sinusoidal loading is defined by its complex dynamic modulus (E*). In the Mechanistic Empirical Pavement Design Guide (MEPDG), the E* Dynamic Modulus of an asphalt mixture is determined per AASHTO TP 62-03. For each mix, three specimens, 4 inches (100 mm) in diameter and 6 inches (150 mm) in height, were tested at 14, 40, 70, 100, and 130 °F (-10, 4.4, 21, 37.8 and 54.4 °C) and 25, 10, 5, 1, 0.5, and 0.1 Hz loading frequencies. The E* tests were done using a controlled sinusoidal stress that produced strains smaller than 150 micro-strain. A master curve was constructed at a reference temperature of 70 ºF (21 °C).

Fig. 5 (a) shows the average E* master curves for both the control and fiber-reinforced asphalt concrete mixtures. The figure can be used for general comparison of the mixtures, but specific comparison of temperature-frequency combination values need to be evaluated separately. That is, one can not compare direct values on the vertical axis for a specific log reduced time values. As shown in the figure, the fiber-reinforced mixture had higher moduli values than the control mixture at all test temperatures and frequencies. The difference is less at the lowest temperature due to dominant effect of the binder. At higher temperatures, the binder becomes softer and the aggregates dominate the elastic behavior of the asphalt mixtures, and the reinforcement effect of the fibers can enhance the modulus values at higher temperatures. In addition, the aramid fibers have a unique negative thermal coefficient value, in that they contract at higher temperatures and therefore play a positive role in resisting deformation. Fig. 5 (b) shows direct comparisons for selected values of test temperatures, 40, 100, and 130 °F (4.4, 37.8 and 54.4 °C) and loading frequency of 10 Hz. It is observed that the modulus values for the fiber-reinforced mixture are higher than the control mixture. Especially at high temperature conditions, the potential field performance to resist rutting would be better for the fiber-reinforced mix compared to the control mixture.

Fatigue Cracking Test

Load-associated fatigue cracking is one of the major distress types occurring in flexible pavement systems. The action of repeated loading, caused by traffic induced tensile and shear stresses in the bound layers, will eventually lead to a loss in the structural integrity of a stabilized layer material. Fatigue will induce cracks at points where critical tensile strains and stresses occur. The most common model form used to predict the number of load repetitions to fatigue cracking is a function of the tensile strain and mix stiffness (modulus) as follows [13]:

$$N_f = K_1\left(\frac{1}{\varepsilon_t}\right)^{k_2}\left(\frac{1}{E}\right)^{k_3} = K_1(\varepsilon_t)^{-k_2}(E)^{-k_3}$$

Where:

N_f = number of repetitions to fatigue cracking

ε_t = tensile strain at the critical location

E = stiffness of the material

K_1, K_2, K_3 = laboratory calibration parameters

In this study, beam specimens were prepared for the four point bending fatigue tests. The beams were compacted in the laboratory to the required density (7% air voids). They were saw cut to the required dimensions of 2.5 inches (63.5 mm) wide, 2.0 inches (50.8 mm) high, and 15 inches (381 mm) long. A full testing factorial was used for each mixture: constant strain, 6 to 8 levels, and one replicate for each test temperature. Three temperature levels, 40, 70, 100 ºF, (4.4, 21, and 38.8 °C) were used. Initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure under control strain was defined as the number of cycles corresponding to a 50% reduction in the initial stiffness as required by AASHTO TP8 and SHRP M-009 [14, 15].

Fatigue relationships for both mixtures were developed. The regression equations for each temperature ($N_f = K_1.\varepsilon^{K_2}$) were also computed along with the coefficient of determination (R^2) for each relationship. Fig. 6 shows a comparison of fatigue relationships for the control and fiber-reinforced asphalt concrete mixtures at 70 ºF. It is observed that the fatigue life is higher for the control mixture at high strain values while the fiber-reinforced mixture has higher fatigue life at lower strain values.

Table 3 summarizes the K_1, K_2, and K_3 Coefficients of the generalized fatigue model for both mixtures (at 50% reduction of the initial stiffness). The initial stiffness was measured at N =

50 cycles. These generalized fatigue relationships show excellent measures of accuracy for both mixtures.

An example comparing the fatigue life for both mixtures was calculated using the regression coefficients K_1, K_2, and K_3 at 40, 70, and 100 ºF and for two different strain levels. The results are shown in Fig. 7 (a, b). At 150 micro-strains level (Figure 7 (a)), the fiber-reinforced mixture shows approximately 1.5 to 2.5 times higher fatigue life compared to the control mixture at different test temperatures; while at 200 micro-strains level (Figure 7 (b)), the control mixture shows approximately 1.5 to 2.5 times higher fatigue life compared to the fiber-reinforced mixture. The shift in predicted fatigue life suggests that the fiber-reinforced mix will perform better in roads where traffic speeds are higher. In addition, this type of constant strain fatigue testing may be a disadvantage for a stiffer material like the fiber-reinforced mixture.

Thermal Cracking Test

Standard test method for determining the creep compliance and strength of HMA using the indirect tensile test device per AASHTO TP9-02 was utilized to evaluate the low temperature thermal cracking performance of the control and the fiber-reinforced asphalt concrete mixtures [16, 17]. Fig. 8 shows the tensile strength test results for both mixtures. The fiber-reinforced asphalt mixture has 1.5 times higher strength than the control mixture. Higher thermal cracking would be expected for mixtures with lower tensile strength values [4]. In essence, the fibers in the mix are believed to play a vital role in resisting thermal cracking in the HMA mixture.

The consideration of the total fracture energy is another useful comparison from this test. The results are shown in Fig. 9. The fracture energy increased with increasing temperature for both mixtures. At all test temperatures, the fiber-reinforced asphalt mixture had consistently higher fracture energy than the control mix. Generally, lower thermal cracking should be expected as the fracture energy is increased [4].

Crack Propagation - C Line Integral Test*

Fracture mechanics provides the underlying principles which govern initiation and propagation of cracks in materials. Sharp internal or surface notches which exist in various materials intensify local stress distribution. If the energy stored at the vicinity of the notch is equal to the energy required for the formation of new surfaces, then crack growth can take place. Material at the vicinity of the crack relaxes, the strain energy is consumed as surface energy, and the crack grows by an infinitesimal amount. If the rate of release of strain energy is equal to the fracture toughness, then the crack growth takes place under steady state conditions and the failure is unavoidable [18].

The concept of fracture mechanics was introduced to asphalt concrete by Majidzadeh [19]. Abdulshafi O. applied the energy (C*-Line Integral) approach to predicting the pavement fatigue life using the crack initiation, crack propagation, and failure [20]. Follow up studies used notched disk specimens to apply J-integral concept to the fracture and fatigue of asphalt pavements [20, 21].

C Parameters*

The relation between the J-integral and the C* parameters is a method for measuring it experimentally. J is an energy rate and C* is an energy rate or power integral. An energy rate interpretation of J has been discussed by Rice; and Begley and Landes [22, 23]. J can be interpreted as the energy difference between the two identically loaded bodies having incrementally differing crack lengths.

$$J = -\frac{dU}{da}$$

Where,

U = Potential Energy

a = Crack Length

C* can be calculated in a similar manner using a power rate interpretation. Using this approach C* is the power difference between two identically loaded buddies having incrementally differing crack lengths.

$$C^* = -\frac{\partial U^*}{\partial a}$$

Where U* is the power or energy rate defined for a load p and displacement u by:

$$U^* = \int_0^u p\,du$$

Method for C Determination*

Disc samples were prepared from gyratory plugs similar to the IDT specimen preparation process. For each disc, a right-angle wedge was cut into the specimen to accommodate the loading device as shown in Fig. 10. Tests were conducted at 70 ^{o}F (21 °C).

The load applied at a constant displacement rate and the crack length over time was measured for each test specimen. The displacement rates used were 0.005, 0.01, 0.015, 0.02, and 0.025 in/min for both the control and fiber-reinforced mixtures. The data was used to determine the load as a function of displacement rate for various crack lengths. The power of energy rate input, U*, was measured as the area under the load displacement rate curve. The energy rate, U*, was then plotted versus crack length for different displacement rates and the slopes of these curves constituted the C*-integral. The C*-integral was plotted as a function of the displacement rate. Finally, the C* integral data were plotted as a function of the crack growth rate as shown in Fig. 11. In this figure, it is observed that the fiber-reinforced mixture has much higher C*-integral and slope values compared to the control mixture. This is an indication that the fiber-reinforced mixture has much higher resistance to crack propagation. A unique observation of the fiber reinforced mix specimens after the test was that the samples never split and they were difficult to split them apart by hand; whereas most of the control mixture samples split at the end of the test.

Pavement Thickness Design and Consideration

The results of the previous laboratory tests were used as input into the Mechanistic Empirical Pavement Design Guide (MEPDG) computer program [3]. This was done to predict field performance per the MEPDG, and to evaluate the impacts on varying pavement design thicknesses. A total of 10 runs were performed for each of the control and fiber reinforced asphalt mixtures for the following conditions.

- Two traffic levels, 1500 and 7000 Annual Average Daily Traffic (AADT), representing an intermediate and high traffic levels.
- Five Asphalt Concrete (AC) layer thicknesses, 2 to 6 inches (50 to 150 mm) over a constant thickness base of 8 inches (200 mm).
- Climatic conditions: Phoenix, Arizona, USA
- Design life: 10 years

The distresses evaluated as output were rutting and fatigue cracking. Distress versus thickness trends for the two traffic levels were very similar but with different magnitude. Fig. 12 shows the relationship between total rutting and thickness for both mixtures at the 7000 AADT (~ 50 million ESALs). It can be observed that for a rutting criterion not to exceed 0.4 inches during the design period of 10 years, the control mixture AC pavement thickness needed is 5.5 inches; whereas the fiber reinforced mixture AC layer thickness needed would be 3.5 inches; a saving of 2 inches in the total AC layer thickness. This saving was 1.5 inches for the lower traffic level of 1500 AADT. Figure 13 shows the fatigue cracking predicted by the MEPDG. The results show similar trends, in that lower fatigue cracking is predicted for the fiber-reinforced mixture. However, the results are also dependent on the AC layer thickness. As the AC layer thickness increases beyond the 2-inch, the fatigue cracking increases to a maximum value between 3 and 4 inches. The fatigue cracking is reduced beyond the 4-inch thickness because of the reduced tensile strains anticipated at the bottom of the AC layer. The plot agrees with observations in the MEPDG manual, where for very thin AC layer pavement system, fatigue cracking may not be of a concern due to the compressive nature of strains throughout the AC layer [3].

Conclusions

The laboratory test results in this study showed that the use of polypropylene and aramid fibers blend in the asphalt mixture improves the mixture's performance in several unique ways as summerized below:

- The fiber reinforced asphalt mixture showed better resistance to shear deformation as shown by the triaxial shear strength test results. Notably, post peak failure for the fiber reinforced asphalt mixture showed higher residual energy and gradual drop in strength, an effect that was attributed to the influence of the fibers in the mix.

- Permanent deformation tests for the fiber reinforced mixture showed lower permanent strain accumulation compared to the control mix. The flow number results, or the beginning of tertiary stage, were 15 times higher than the control mixture. Two characteristics were observed for the fiber-reinforced mixture in these tests: an extended endurance period in the secondary stage of the permanent deformation curve, and the gradual (less) accumulation of permanent strain beyond tertiary flow. Both of these characteristics were attributed to the presence and mobilization of the fibers distributed in the mix.
- The measured Dynamic Modulus E* values were higher for the fiber reinforced mix. The difference between the two mixtures was less at the lowest temperature (20% increase), due to dominant effect of the binder and less contribution of the role of fibers. The largest difference was observed at 100°F (80% higher), where the reinforcement effect of the fibers is observed to be the highest. At 130°F, the increase in modulus was also substantial at about 50%.
- The fatigue cracking test was different in that, unlike the other tests, the strain level was held constant. The fatigue life was higher for the control mixture at high strain values while the fiber-reinforced mixture had higher fatigue life at lower strain values. The shift in predicted fatigue life suggests that the fiber-reinforced mix will perform better in roads where traffic speeds are higher. This result was confirmed by running the Mechanistic Empirical Pavement Design Guide (MEPDG) computer program.
- The tensile strength and fracture energy measured from the IDT test showed that at all test temperatures, the fiber-reinforced mix exhibited the highest values; an increase of 25

to 50% for the tensile strength, and 50 to 75% for the fracture energy. Lower thermal cracking would be expected as the tensile strength and fracture energy are increased.

- The relationships between crack growth rates and C* line integral values showed that the fiber-reinforced mix had about 40 times higher resistance to crack propagation than the control mix.
- The results of the advanced laboratory tests conducted were used as input into the MEPDG. The MEPDG runs demonstrated that the improved properties and mixture performance results in savings of the asphalt layer thickness. The fiber-reinforced asphalt resulted in lower rutting and fatigue cracking. For the rutting distress criteria, a reduced AC layer thickness of about 30 to 40% can be achieved when using the fiber reinforced asphalt mixture. This value will vary slightly depending on the traffic level used in the analysis. The analysis also confirmed that fatigue cracking may not be of a concern due to thin AC layer structure used. However, the greatest potential in reduced fatigue cracking can be seen in AC pavement layers that are typically in the 3 to 5 inches thickness range.

As anticipated, due to the little pavement preparation before the asphalt overlay, some cracks were present in both pavement test section. A field condition survey after approximately two years (with two summer periods included) revealed that the control test sections had about three times the amount of low severity cracks compared to the fiber reinforced test sections.

Acknowledgements

The authors would like to acknowledge FORTA Corporation and Teijin Aramid BV for their financial support and providing the fibers. Acknowledgements are also due to CEMEX (formally Rinker West, Central Region) for their assistance in the production and construction of the test section. City of Tempe engineering department and personnel for their invaluable assistance in providing the field test section at Evergreen Drive and for their help in coordinating the construction activities. Special thanks are also due to Mr. Kenny Witczak, Supervisor of the Advanced Pavement Laboratory at ASU for the production and preparation of the laboratory test specimens.

References

1. Bueno, B. S., Silva, W. R., Lima, D. C., Minete, E. (2003). Engineering Properties of Fiber Reinforced Cold Asphalt Mixes. Technical Note, *Journal of Environmental Engineering*, ASCE, Vol. 129, N. 10.
2. Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y. R., Borden, R. H. (2005). Fatigue Cracking Resistance of Fiber-Reinforced Asphalt Concrete. *Textile Research Journal*, Vol. 75, N. 2, pp. 123-128.
3. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report. NCHRP, National Research Council, Washington, D. C., March 2004.
4. Witczak, M. W., Kaloush, K. E., Pellinen, T., El-Basyouny, M., & Von Quintus, H. (2002). Simple Performance Test for Superpave Mix Design. *NCHRP Report 465*. Transportation Research Board. National Research Council. Washington D.C.
5. Fitzgerald, R. L. (2000) Novel Applications of Carbon Fiber for Hot Mix Asphalt Reinforcement and Carbon-Carbon Pre-forms, M. S. Thesis, Department of Chemical Engineering, Michigan Technological University, 2000.
6. Cleven, M. A. (2000) Investigation of the Properties of Carbon Fiber Modified Asphalt Mixtures M. S. Thesis, Department of Chemical Engineering, Michigan Technological University, 2000.
7. Jahromi, S. G., and Khodai, A. (2008) Carbon Fiber Reinforced Asphalt Concrete, The Arabian Journal for Science and Engineering, Volume 33, Number 2B, October 2008, pp. 355-364.

8. Mahrez, A., Karim, M. R., and Katman, H. A. (2003) Prospect of Using Glass Fiber Reinforced Bituminous Mixes, Journal of the Eastern Asia Society for Transportation Studies, Vol.5, October, 2003
9. Mahrez, A., and Karim, M. R., (2007) Rutting Characteristics of Bituminous Mixes Reinforced with Glass Fiber, Proceedings of the Eastern Asia Society for Transportation Studies, Vol.6, 2007.
10. Putman, B. J., and Amirkhanian, S. N. (2004) Utilization of Waste Fibers in Stone Matrix Asphalt Mixtures, Journal of Resources, Conservation and Recycling, Recycled Materials in Highway Infrastructure, Volume 42, Issue 3, October 2004, pp. 265-274.
11. Chowdhury, A., Button, J. W., and Bhasin, A. (2006) Fibers from Recycled Tire as Reinforcement in Hot Mix Asphalt, Texas Transportation Institute, Texas A&M University System, Report No. SWUTC/06/167453-1, April 2006.
12. W. Shaopeng., Y. Qunshan., L. Ning., and Y. Hongbo. (2007) Effects of Fibers on the Dynamic Properties of Asphalt Mixtures, Journal of Wuhan University of Technology-Materials Science Edition, China, December 2007.
13. AASHTO Designation: T321-03. Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending.
14. SHRP Designation: M-009. Standard Method of Test for Determining the Fatigue Life of Compacted Bituminous Mixtures Subjected to Repeated Flexural Bending.
15. SHRP-A-404. Fatigue Response of Asphalt-Aggregate Mixes. Asphalt Research Program, Institute Of Transportation Studies, University Of California, Berkeley. Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

16. Witczak, M.W., “Harmonized Test Methods for Laboratory Determination of Resilient Modulus for Flexible Pavement Design, Volume II - Asphalt Concrete Material”, Final Project Report, NCHRP Project No. 1-28A, May 2003.
17. Roque et al, “Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device”, Draft Test Protocol, AASHTO TP9-02, 2002.
18. Mamlouk, M. S. and Mobasher, B. (2004). “Cracking Resistance of Asphalt Rubber Mix versus Hot-Mix Asphalt”, International Journal of Road Materials and Pavement Design. V.5., 4, pp. 435-452.
19. Majidzadeh, K. (1976). “Application of Fracture Mechanics for Improved Design of Bituminous Concrete,” Volumes 1 and 2, Report FHWA-RD-76-91, Federal Highway Administration, Washington, D.C.
20. Abdulshafi, O., (1983). “Rational Material Characterization of Asphaltic Concrete Pavements,” Ph.D. Dissertation, the Ohio State University, Columbus, OH, 1983.
21. Abdulshafi, A. and K.E. Kaloush. "Modifiers for Asphalt Concrete." ESL-TR-88-29, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, 1988.
22. Rice. J. R., (1968). Journal of Applied Mechanics, American Society of Mechanical Engineers, Volume 35, pp. 379-386.
23. Begley, J. W. and Landes, J. D., (1972). Fracture Toughness, Processing of the 1971 National Symposium on Fracture Mechanics. Part II, ASTM STP 514, American Society for Testing Materials pp. 1-20.

Table 1. Physical Characteristics of the Fibers.

Materials	Polypropylene	Aramid
Form	Twisted Fibrillated Fiber	Multifilament Fiber
Specific Gravity	0.91	1.45
Tensile Strength (MPa)	483	3000
Length (mm)	19.05	19.05
Color		
Acid/Alkali Resistance	inert	good
Decomposition Temperature (°C)	157	>450

Table 2. Master Summary of the Repeated Load Permanent Deformation Test Results

Mix Type	σ_d (psi)	Flow Number (Cycles)	Axial Permanent Strain ε_p [%] at Failure
Control	15	436	0.84
	15	241	0.56
	15	166	0.95
	Average	281	0.78
	Standard Deviation	139	0.20
	% Coefficient of Variation	49.6	25.8
Fiber-Reinforced	15	3336	0.47
	15	3466	0.60
	15	5916	0.46
	Average	4,239	0.51
	Standard Deviation	1,453	0.08
	% Coefficient of Variation	34	15.3

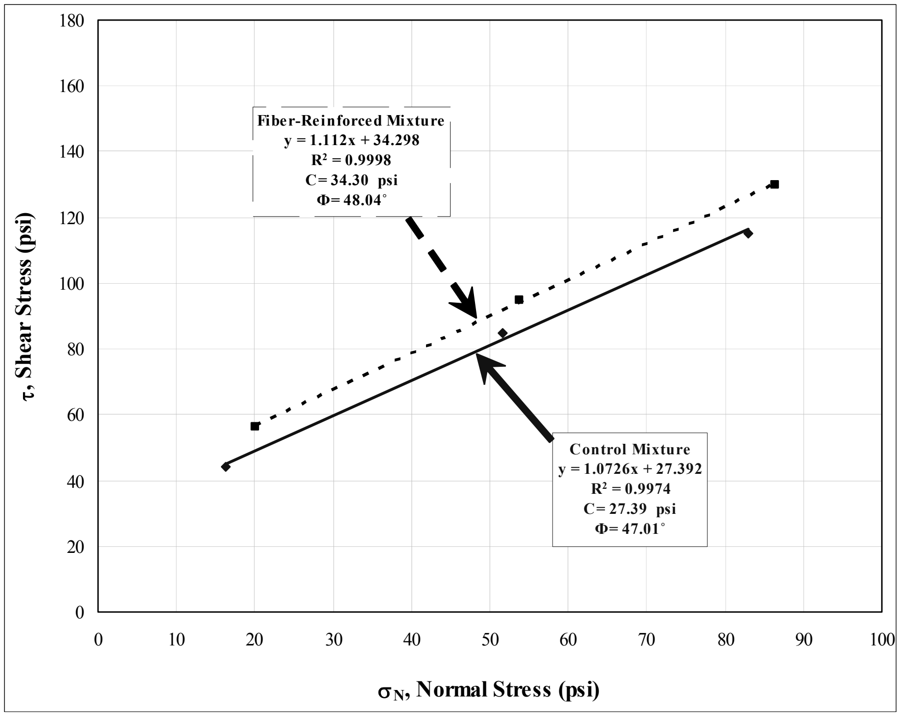
Table 3. Summary of the Regression Coefficients for the Generalized Fatigue Equation

Mixture Type	50% of Initial Stiffness, E_o @ N=50 Cycles			
	K_1	K_2	K_3	R^2
Control	2.3496	2.3601	1.3853	0.914
Fiber-Reinforced	6.48E-22	7.8357	1.0839	0.988

* $N_f = K_1 * (1/\varepsilon_t)^{K_2} * (1/E_o)^{K_3}$

Fig. 1. (a) Pavement Condition Before the Overlay; (b) Surface Preparation by Milling off the Edge of the Pavement.

Fig. 2. (a) Close up of Reinforced Fibers: Polypropylene and Aramid (b) A Close-Up of the Fiber-Reinforced Asphalt Mixture.



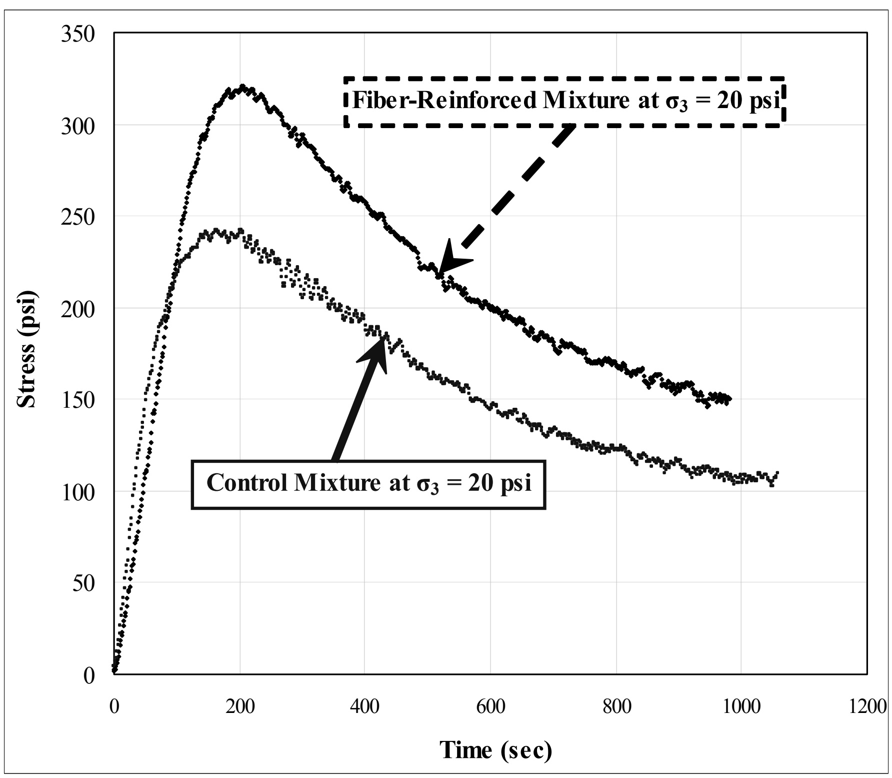


Fig. 3. Comparison of (a) Mohr-Coulomb Envelopes (b) Stress-Time Plots at 20 psi Confinement Level.

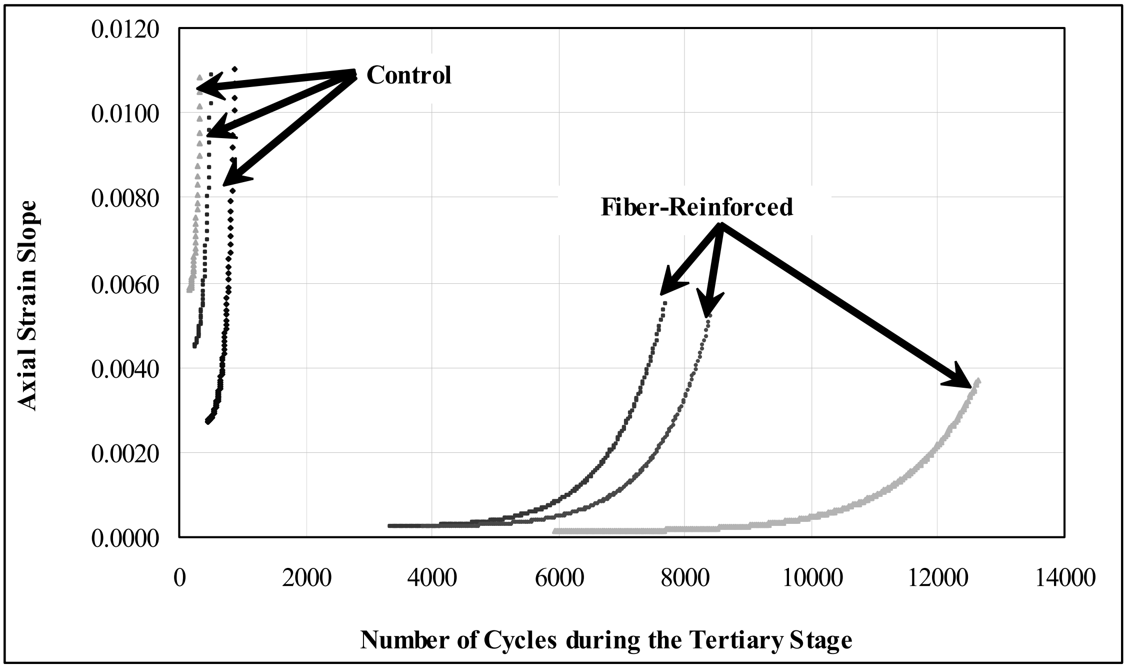
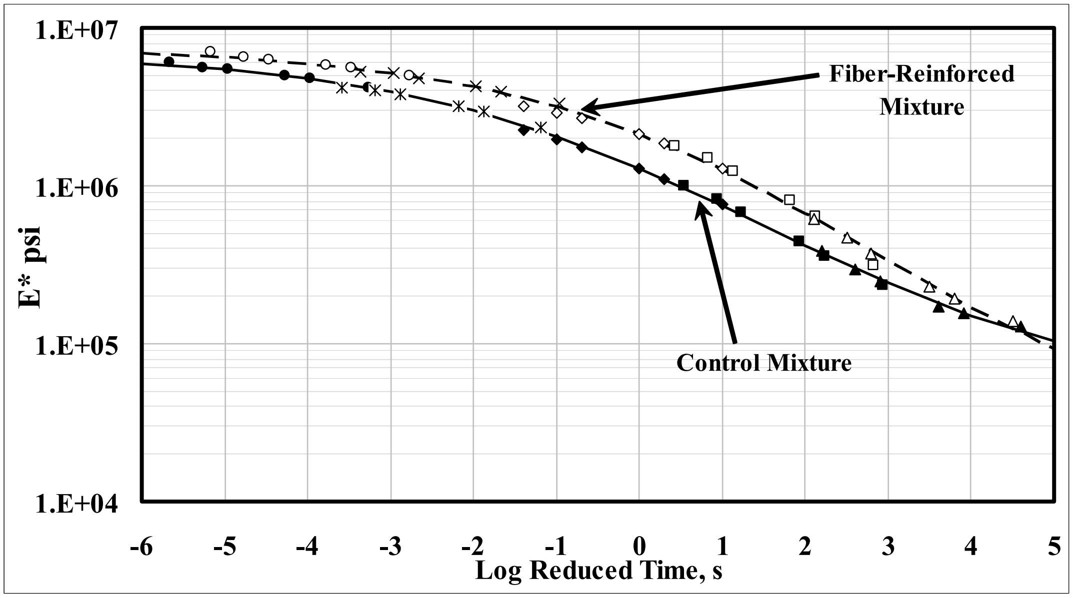


Fig. 4. Axial Strain Slope during the Tertiary Stage for Control and Fiber-Reinforced Mixtures.



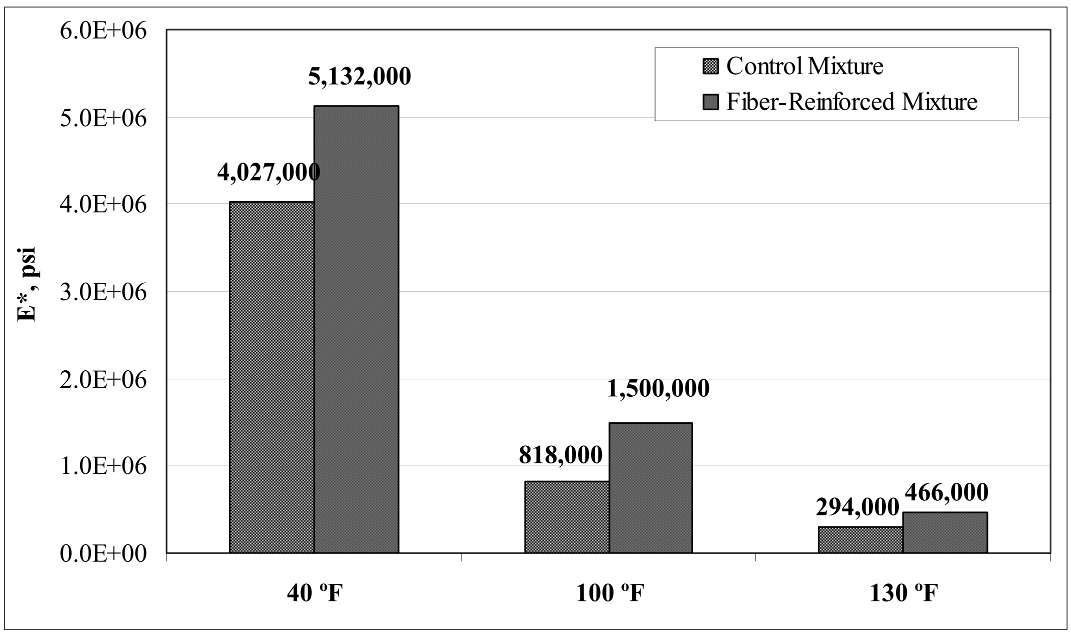


Fig. 5. (a) Unconfined Dynamic Modulus Master Curves; (b) Comparison of Measured Dynamic Modulus Values at 10 Hz.

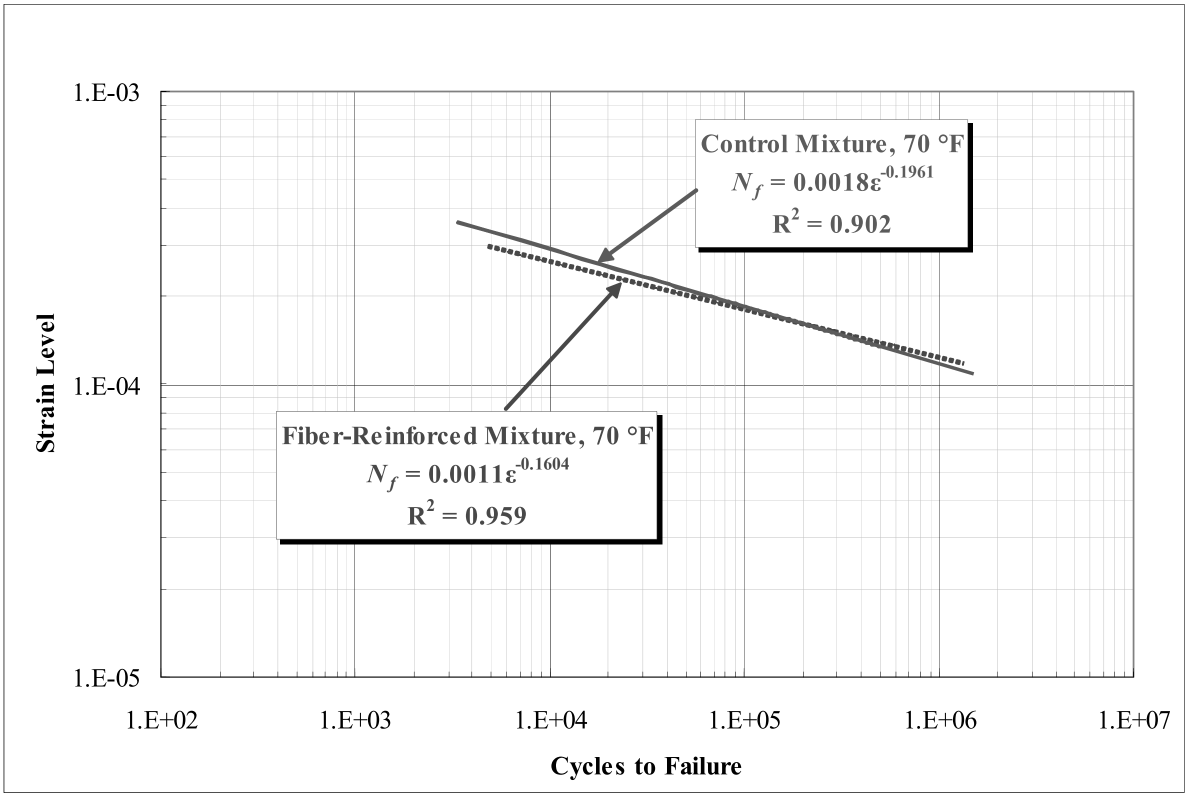
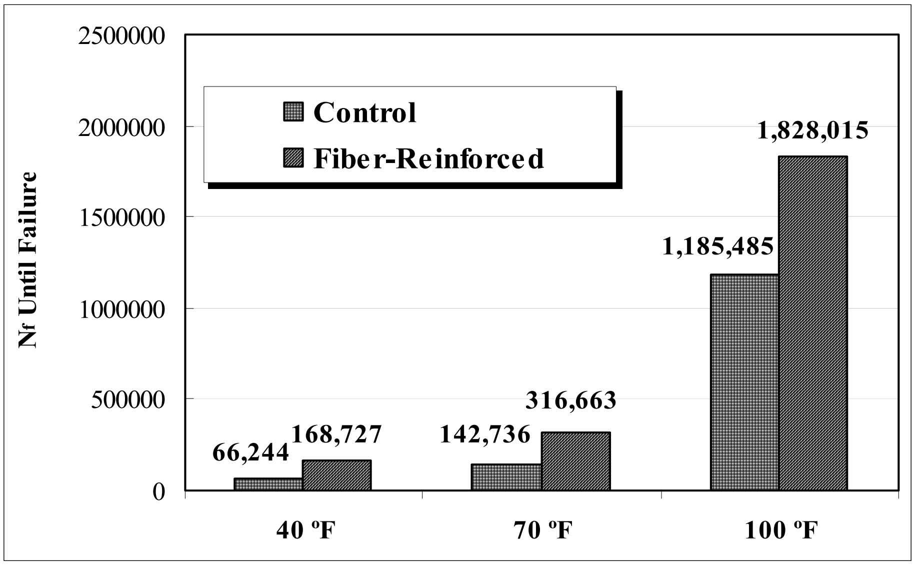


Fig. 6. Comparison of Fatigue Relationships for both Mixtures at 70 ºF.



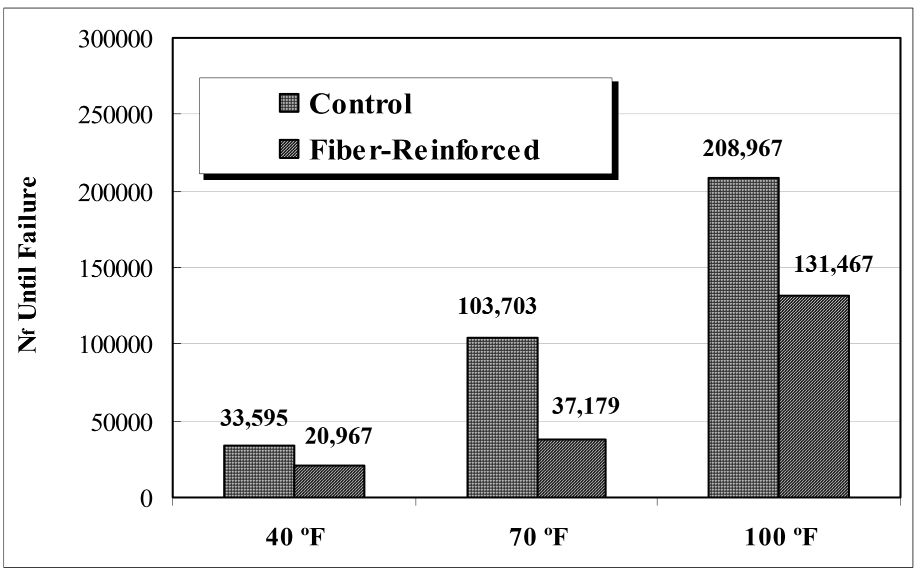


Fig. 7. Number of Cycles to Failure Predicted for Both Mixtures All Test Temperature, (a) 150 micro-strains and (b) 200 micro-strains.

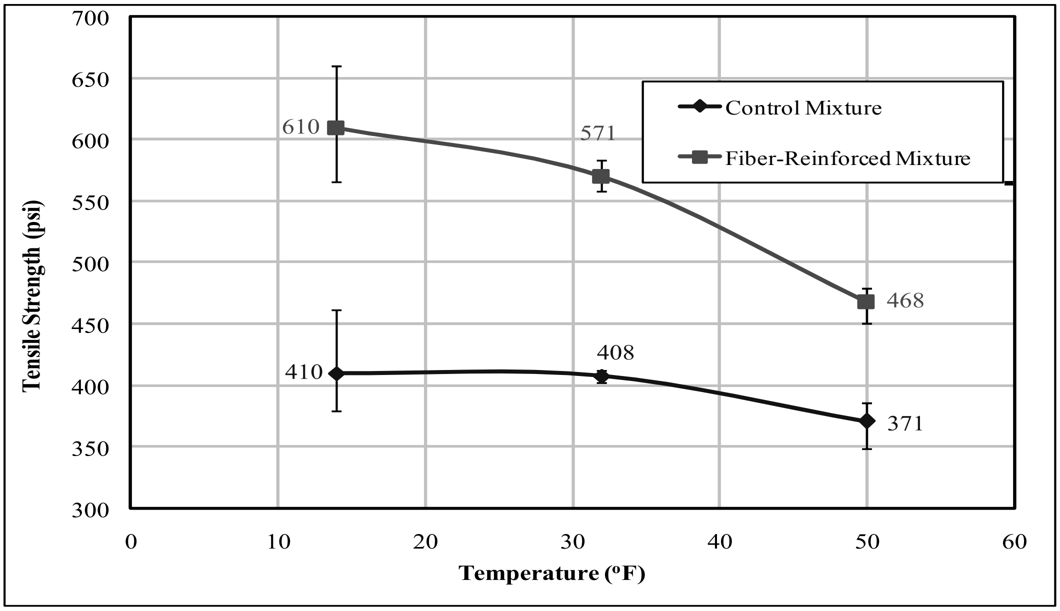


Fig. 8. Comparison of the Tensile Strength Results.

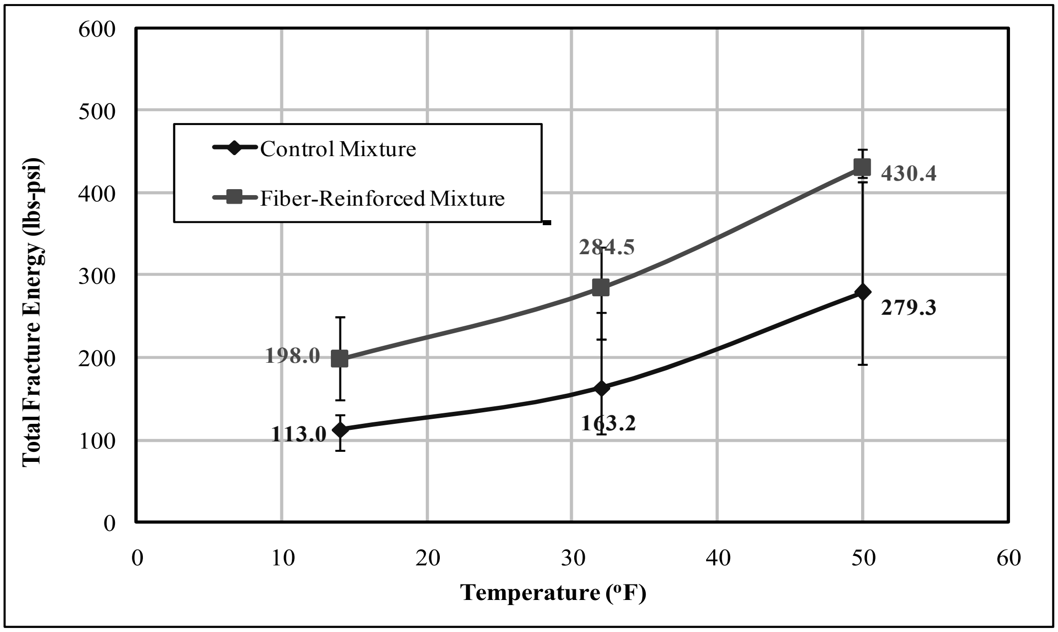


Fig. 9. Comparison of the Total Fracture Energy Results.

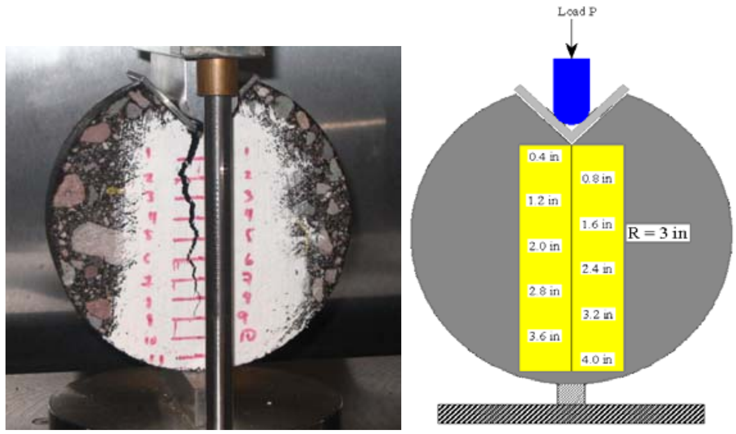


Fig. 10. Typical C* Test Setup.

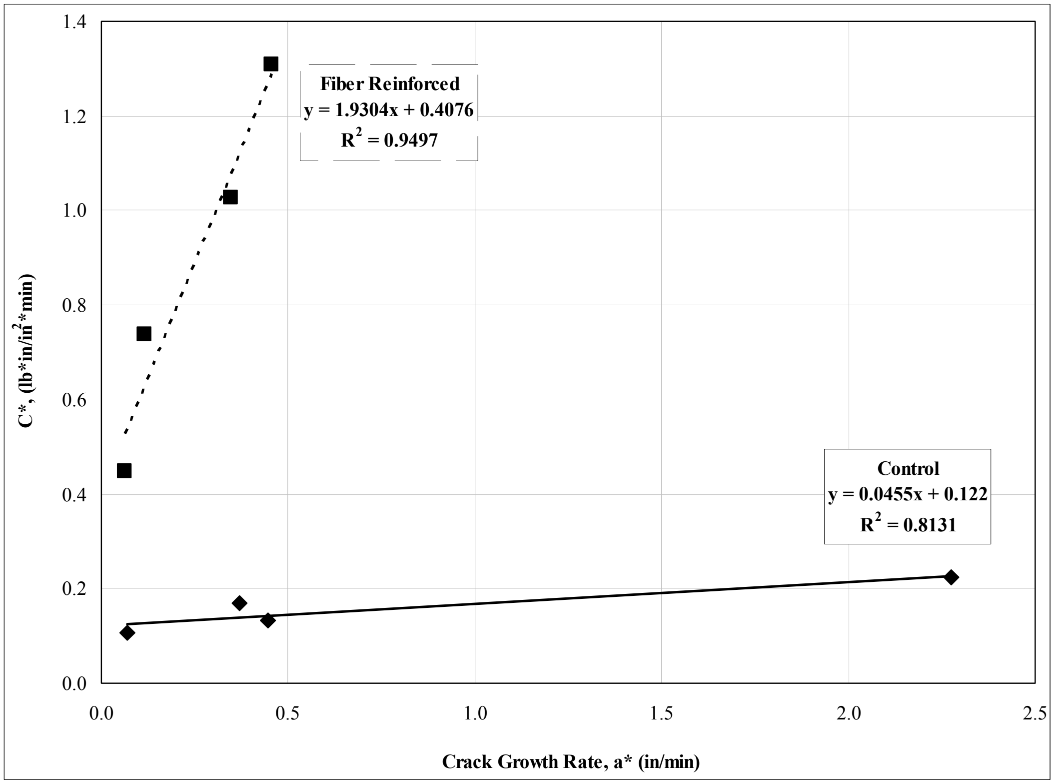


Fig. 11. C* Line Integral versus Crack Growth Rate.

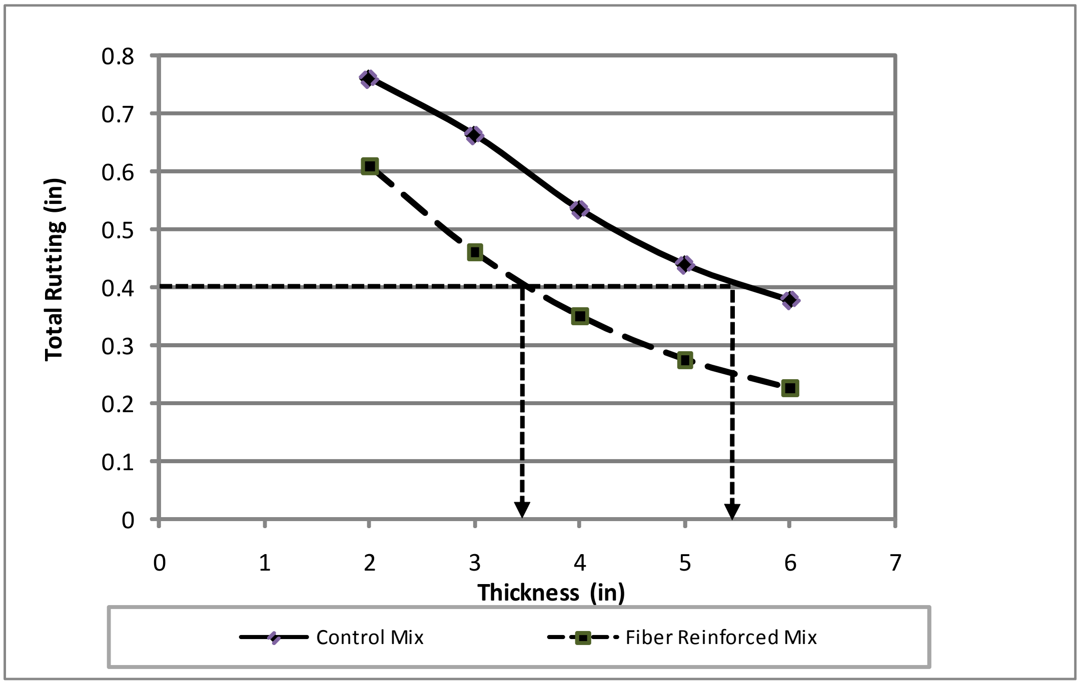


Fig. 12. Pavement Rutting Evaluation using the Mechanistic-Empirical Pavement Design Guide.

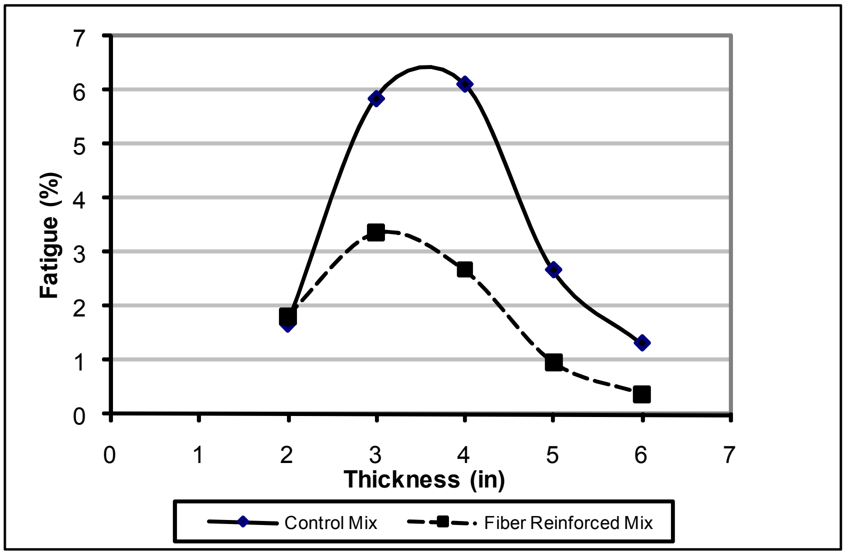


Fig. 13. Pavement Fatigue Cracking Evaluation using the Mechanistic-Empirical Pavement Design Guide.