Evaluation of Fiber Reinforcement in Hot Mix Asphalt Using Advanced Material Characterization Tests

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Evaluation of Fiber Reinforcement in Hot Mix Asphalt Using Advanced Material Characterization Tests

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ABSTRACT
Quantifying the improved performance of asphalt mixtures against permanent deformation and fatigue cracking by addition of a polypropylene and aramid fiber mixture was the focus of this study. The goal of the laboratory experimental program was to conduct laboratory tests that are recommended by the National Cooperative Highway Research Program (NCHRP) 9-19 Project. The 9-19 project dealt with recommending Simple Performance Tests (SPT) for the evaluation of asphalt mixtures. The SPT included triaxial shear strength, dynamic (complex) modulus, and repeated load tests for the permanent deformation characterization of the asphalt. In addition, flexural beam tests were conducted to evaluate fatigue cracking. The data obtained from this testing program was used to compare the performance of the modified mixture of fibers and asphalt to typical conventional asphalt mixtures. The experimental results provided evidence that the presence of fibers improved the permanent deformation and fatigue cracking properties of the asphalt.

1. INTRODUCTION AND OBJECTIVE

Fibers have been used to improve the performance of asphalt mixtures against permanent deformation and fatigue cracking (Bueno et al. 2003, FORTA 2005, Lee et al. 2005). Recent development in material characterization tests in the pavement community require the re-evaluation of the fiber-reinforced asphalt mixtures using state-of-the art testing procedures to demonstrate the performance benefits, as better resistance to fatigue and permanent deformation. Since 1999, the Department of Civil and Environmental Engineering at Arizona State University (ASU) has been involved with several major asphalt mixtures characterization studies, with laboratory research being conducted at the Advanced Pavements Laboratory. These studies included the National Cooperative Highway Research Program (NCHRP) 9-19 Project (Witczak et al. 2002) which dealt with the development of Simple Performance Tests (SPT) for the evaluation of the permanent deformation and cracking potential of asphalt mixtures. The results from these advanced tests were utilized as input parameters in the newly developed Mechanistic-Empirical Pavement Design Guide (MEPDG) (flexible pavement program developed at ASU).

Previous studies regarding fiber-reinforcement were conducted using Portland cement concrete. Only a few research studies report experimental results for synthetic fibers and asphalt concrete mixtures in the technical literature. Bueno et al. (2003) studied the behavior of randomly distributed synthetic fibers on the mechanical response of a cold-mixed densely graded asphalt mixture using both the Marshal test and static and cyclic triaxial tests. The addition of fibers caused small variations in the shear strength triaxial parameters of the mixture. Lee et al. (2005) evaluated the influence of recycled carpet fibers on the fatigue cracking resistance of asphalt concrete using fracture energy. They concluded that the increase in fracture energy represents a potential for improving asphalt fatigue life.

The objective of this study was to conduct an advanced laboratory experimental program to obtain engineering material properties for fiber-reinforced asphalt mixtures using recent laboratory tests adopted by the pavement community. The results for the particular mixture of fiber and asphalt were compared and ranked among other asphalt mixtures in ASU's database to demonstrate the value-added uses for asphalt pavement containing fibers.

2. MATERIALS

2.1 Fiber Characteristics

The fiber mixture used in this experimental study is a blend of synthetic fibers designed for use in Hot Mix Asphalt (HMA) applications. The fiber mixture consists of polypropylene and aramid fibers. The mixture utilizes the tensile strength of the aramid fibers to improve fatigue and creep properties of the HMA. The typical fiber mixture contained in one bag (approximately 445.0 g), with both the aramid (yellow-colored) and the polypropylene (tan-colored) fibers evenly mixed, are shown in Figure 1. The main physical properties of both fibers used with HMA are given in Table 1. The fibers are designed to reinforce HMA pavements in all three dimensions and are typically used in the surface-course of asphalt pavements and overlays.

Figure 1. Close up of reinforced fibers: polypropylene (tan-colored) and aramid (yellow-colored).

Table 1. Physical characteristics of used fibers.

Materials	Polypropylene	Aramid
Form	Twisted Fibrillated Fiber	Monofilament Fiber
Specific Gravity	0.91	1.45
Tensile Strength (MPa)	483.00	3000.00
Length (mm)	19.05	38.10
Color	tan	yellow
Acid/Alkali Resistance	inert	inert
Decomposition Temperature (°C)	157	>450

2.2 Mixture Characteristics

As mentioned earlier, the objective of this study was to conduct a laboratory experimental program to obtain engineering material properties for the fiber-reinforced asphalt mixture. The reference air voids for the mix was 7.0%. This section provides information on the fiber-asphalt mixture characteristics. The asphalt binder used in the study was PG 70-10. The hot mix asphalt mixture was obtained as loose mix samples taken from the paver hopper during construction. The mixture properties of the project are reported in Table 2, including the maximum theoretical specific gravity (G_{mm}) that was determined at ASU. A close up of the asphalt mixture that was spread on the table for preparation of the Rice gravity test is shown in Figure 2. Fibers, as visually observed by the naked eye, were evenly distributed throughout the mix. The mix was re-heated and re-compacted into 150 x 170 mm Gyratory specimens. Cylindrical samples were cored from each gyratory plug, and the ends were cut to get final specimens of 100 mm in diameter and 150 mm in height for triaxial testing. In addition, beam specimens were prepared and compacted according to AASHTO TP8 test protocols (AASHTO T321-03; SHRP M-009).

Figure 2. Fiber modified asphalt mixture.

Table 2. Mixture Characteristic.

Mix Type	Binder Mix Design Data			
	Binder Type	Design AC (%)	Target Va (%)	G_{mm}
Conventional	PG 70-10	5.10	7.0	2.4605

3. RESULTS AND ANALYSIS

3.1 Triaxial shear strength test

The triaxial shear strength test has been recognized as the standard test for determining the strength of materials for over 50 years (Kaloush 2001). 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 accurately simulate the state of stresses existing in the pavement, provided certain specimen boundary and geometry conditions are met. In general, there has been reluctance to adopt this test as a routine test procedure because of the degree of difficulty in performing the test. However, with the improvement in testing equipment and computerized data acquisition systems, there has been an increased interest in using the triaxial strength test for more than just a research tool.

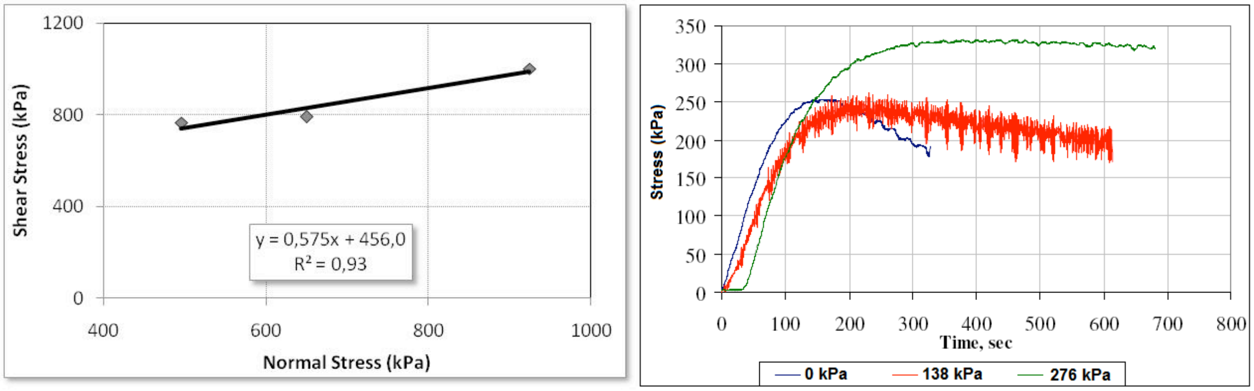
Three triaxial strength tests, one unconfined and two confined, were conducted for the fiber-reinforced mixture. These tests provided the standard cohesion, “c”, and the angle of internal friction, “ϕ”, parameters. The test were carried out on cylindrical specimens, 100 mm in diameter and 150 mm in height, prepared as described previously. The two confining pressures used were 138 and 276 kPa. The specimens were loaded axially to failure at the selected constant confining pressure, and at a strain rate of 1.27 mm/mm/min. An IPC Universal Testing Machine (UTM 100) electro-hydraulic system was used to load the specimens. The machine was equipped to apply up to 690 kPa confining pressure and 100 kN maximum vertical load. The load was measured through the load cell, and the deformations were measured through the actuator Linear Variable Differential Transducer (LVDT). Thin and fully lubricated membranes were placed on the sample ends to reduce end friction. The tests were conducted at 37°C and were conducted within an environmentally controlled chamber which could be controlled within ± 0.5°C.

The results for the triaxial strength tests for the fiber reinforced mixture are summarized in Figure 3. A plot of the Mohr-Coulomb failure envelope, represented by the cohesion “c” and angle of internal friction “ϕ” for the tested mixture, are shown in Figure 3 (a). The parameters “c” and “ϕ” are the strength indicators of the mix. The “ϕ” values are more indicative of the aggregate matrix interlock properties and the “c” values are related with the cementing action of the binder. The larger both the “c” and “ϕ” values, the larger the mix resistance to shearing stresses., and hence, the smaller the potential for permanent deformation. Typical “c” values for conventional AC mixtures are in the range of 35 and 241 kPa, but the “c” value of the fiber-reinforced mix was 456 kPa. Typical “ϕ” values have been found to be in the range between 35° and 48°, but for the fiber-reinforced mix, the value was 30°.

A comparison plot of the triaxial strength test results for the different confinement levels performed is provided in Figure 3(b). The plots illustrate both before and after peak stress development of the fiber-asphalt mixture during the test. For the confined tests, there is an extension or an endurance of the curve post peak stress, a behavior that was attributed to the influence of aramid fibers in the mix. This behavior indicates that aramid fibers provide additional reinforcement to the asphalt mix in resisting permanent deformation beyond shear failure threshold levels.

3.2 Permanent deformation test

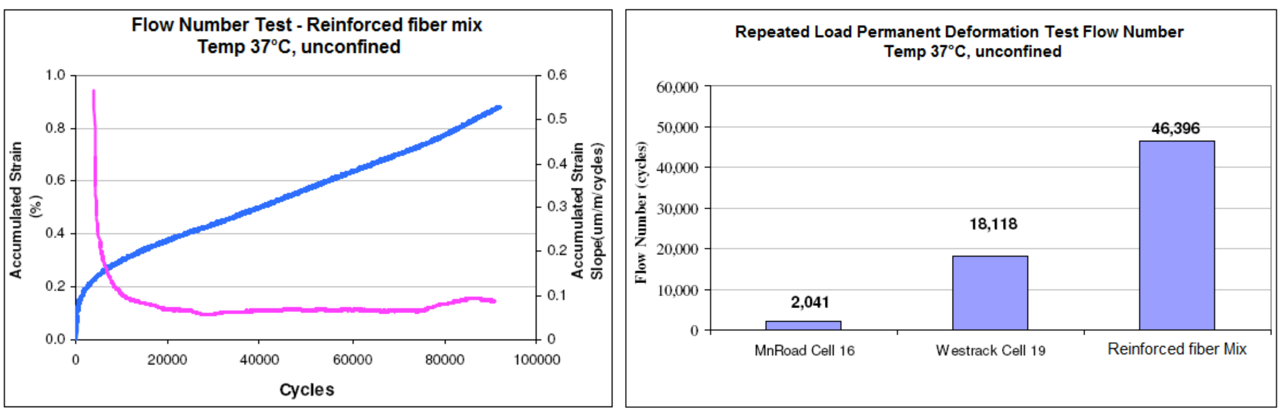
The repeated load test is a type of creep test used to determine the permanent deformation characteristics of paving materials (Flow Number). For this test, a repeated dynamic load is applied for several thousand repetitions, and the cumulative permanent deformation as a function of the number of cycles (repetitions) over the test period is recorded. The starting point, or cycle number, at which tertiary flow occurs, is referred to as the “Flow Number” (Kaloush 2001). Repeated unconfined load tests were conducted using three cylinder specimens of the mixture, 100 mm in diameter and 150 mm in height. For the tests, a haversine pulse load of 0.1 sec and 0.9 sec dwell (rest time) was applied. An IPC Universal Testing Machine (UTM 25) electro-pneumatic system was used to load the specimens. The machine is equipped to apply up to 620 kPa confining pressure and 24.9 kN maximum vertical load. The load was measured through the load cell, and the deformations were measured through six spring-loaded LVDTs. Two axial LVDTs were mounted vertically on diametrically opposite sides of the specimen. Parallel studs, mounted on the test specimen, placed 100 mm apart, and located at the center of the specimen, were used to secure the LVDTs in place. The studs were glued using a commercial 5-minute epoxy. The tests were conducted within an environmentally controlled chamber throughout the testing sequence.



(a) (b)

Figure 3. (a) Failure envelopes; (b) Comparison of fiber-reinforced mix triaxial strength test results at different confinement levels.

A typical repeated load/strain plot is shown in Figure 4(a). Two observed characteristics of this plot are the endurance of the secondary stage and the gradual (less) accumulation of permanent strain beyond tertiary flow. Both were attributed to the presence of the aramid fibers in the mix, as this behavior is not typically observed in conventional mixes. The average Flow Number value of three cylinders for the fiber reinforced mix was 46396, and the average strain was 0.65%. These results were compared with the results obtained for other mixtures under the same conditions and volumetric properties. The comparison of the Flow Number (FN) at failure for the fiber-reinforced mix, MnRoad, and WesTrack (both these mixes represent test sections from national experiments that performed well in the field and under the same laboratory test conditions) are shown in Figure 4(b). Under these conditions, the fiber-reinforced mixture has the highest FN value of the three mixtures and the second highest strain % at failure.



(a) (b)

Figure 4. (a) Typical repeated load permanent strain/slope plot; (b) Comparison of repeated load permanent deformation – flow number for different mixtures.

3.3 Dynamic modulus test

For linear viscoelastic materials such as AC mixes, the stress-strain relationship under a continuous sinusoidal loading is defined by its complex dynamic modulus (E*). This is a complex number that relates stress to strain for linear viscoelastic materials subjected to continuously applied sinusoidal loading. In the Mechanistic Empirical Pavement Design Guide (MEPDG), the modulus of the asphalt concrete at all levels of temperature and time rate of load can be determined from a master curve constructed around a reference temperature (generally taken as 21 °C). Master curves are constructed using the principle of time-temperature superposition. The data at various temperatures are shifted with respect to time until the curves merge into single smooth function. The master curve of the modulus, as a function of time, formed in this manner describes the time dependency of the material.

The NCHRP 1-37A Test Method DM-1 was followed for E* testing. For each mix, two to three specimens were prepared for testing. For each specimen, E* tests were conducted at -10, 4, 21, 37, and 54°C for 25, 10, 5, 1, 0.5, and 0.1 Hz loading frequencies. The E* tests were done using a controlled stress mode, which produced strains smaller than 150 micro-strain. This ensured, to the best possible degree, that the response of the material was linear across the temperatures used in the study. The dynamic stress levels were 69 to 689 kPa for colder temperatures (-10°C to 21°C) and 14 to 69 kPa for higher temperatures (37°C to 54°C). Similar to the new MEPDG's input Level-1 approach, E* Master Curves were constructed for a reference temperature of 21°C using the principle of time-temperature superposition. The construction of Master Curve for fiber-reinforced mix is shown in Figure 5.

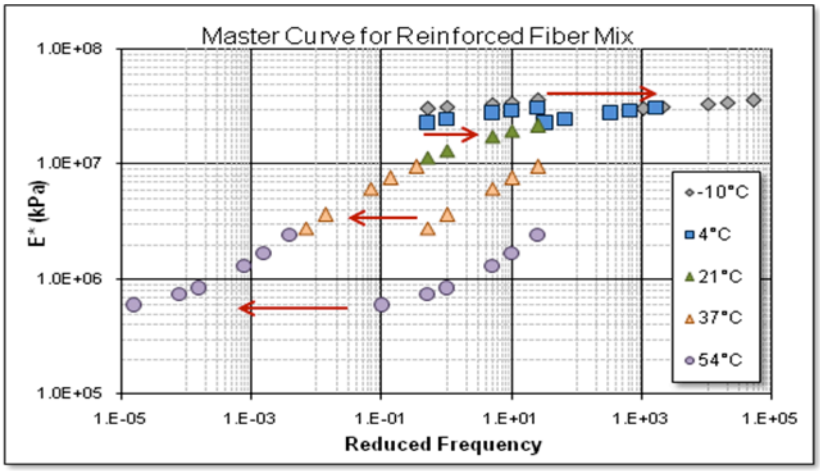
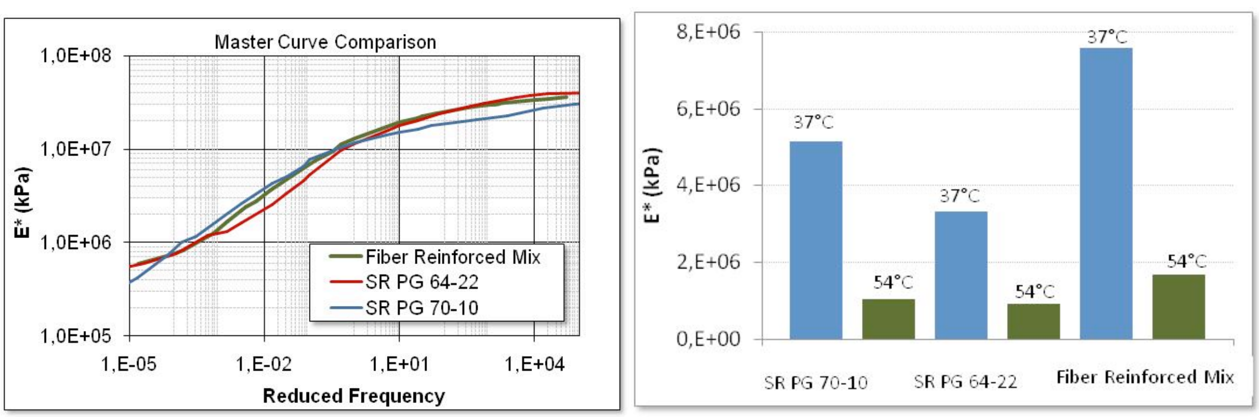


Figure 5. Construction of Master Curve base on three replicates.

Two conventional ADOT Salt River mixtures, utilizing PG 70-10 and PG 64-22 binders, were used as a comparison to the fiber-reinforced mixture. The average dynamic modulus master curves for the two Conventional ADOT mixtures, using unconfined tests and the fiber-reinforced mixture master curve are shown in Figure 6(a). The figure can be used for general comparison of the mixtures, but specific temperature-frequency combination values also need to be evaluated separately. The Salt River PG 64-22 mixture exhibits a higher modulus value at lower temperatures, followed by the fiber reinforced mix and then the by Salt River PG 70-10 mix. At room temperature, 21°C, the fiber-reinforced mix is stiffer than the other two, while at higher temperatures and lower frequencies, both the fiber-reinforced and Salt River PG 64-22 mixes have similar modulus values, followed by the Salt River PG 70-10 mix. A specific comparison for selected values of test temperatures (37 and 54°C) and loading frequency (10 Hz) are shown in Figure 6(b). All three mixes had similar air voids level of 7%. It is observed that the modulus values are more comparable at higher temperatures: 37 and 54°C, leading to the conclusion that the addition of fibers indeed enhances the properties of an asphalt mixture. In fact, at high temperatures and selected frequency, the fiber-reinforced mixture had a higher modulus (1.5 times higher) than the other two conventional mixtures. This result supports the potential field performance of the fiber-reinforced mix of having better resistance to permanent deformation at high temperatures.



(a) (b)

Figure 6. Unconfined dynamic modulus Master Curve for fiber-reinforced mix, SR PG 70-10 and SR PG 64-22 ADOT Mixtures; (b) Comparison of measured dynamic modulus values at 10 Hz.

3.4 Fatigue cracking tests

Fatigue cracking associated with loading is one of the major signs of distress occurring in flexible pavement systems. The cracking is a result of traffic-induced tensile and shear stresses in the bound layers caused by the repeated loading.

The cracking results in an eventual loss in the structural integrity of a stabilized layer material. Fatigue initiated cracks will appear at points where critical tensile strains and stresses occur. Additionally, the critical strain is also a function of the stiffness of the pavement. Since the stiffness of an asphalt mix in a pavement layered system varies with depth, these changes will effect the location of the critical strain and which initiates fatigue damage. Once the crack initiates at the critical location, the cyclic traffic loading eventually causes the cracks to propagate through the entire bound layer.

The most common model used to predict the number of load repetitions until the initiation of fatigue cracking is a function of the tensile strain and mix stiffness (modulus). The basic structure for almost every fatigue model developed and presented in the literature for fatigue characterization is of the following form (SHRP-A-404 1994):

$$N_f = K_1 \cdot \left(\frac{1}{\varepsilon_t}\right)^{K_2} \cdot \left(\frac{1}{E}\right)^{K_3} \qquad [1]$$

where:

N_f = numbers of repetitions to fatigue cracking;
ε_t = tensile strain at critical location;
E = stiffness of the material;
K_1, K_2, K_3 = laboratory calibration parameters.

Flexural fatigue tests are performed according to the AASHTO TP8 and SHRP M-009. The flexural fatigue test has been used by various researchers to evaluate the fatigue performance of pavements (SHRP-A-404 1994; Harvey and Monismith 1993; Tayebali et al. 1995; Witczak et al. 2001). The flexural fatigue apparatus is show in Figure 7. The device is typically placed inside an environmental chamber to control the temperature during the test. The fiber-reinforced mixture was heated to 146°C. The mold was heated separately for one hour at the same temperature as the mix. The mixture was placed in the mold in one load. The mold was then placed on the bottom plate of the loading machine, and the top platen was lowered to compact the mixture. A small load of 1.4 kPa was then applied to seat the specimen. A stress-controlled sinusoidal load was then applied with a frequency of 2 Hz and a peak-to-peak stress of 2.8 MPa for the compaction process. Since the height of the specimen after compaction was fixed, the weight of the mixture required to reach a specified air void value was pre-calculated. With the maximum theoretical specific gravity and the target air voids determined, the weight of the mixture was determined. During compaction, the loading machine was programmed to stop when the required specimen height was reached.

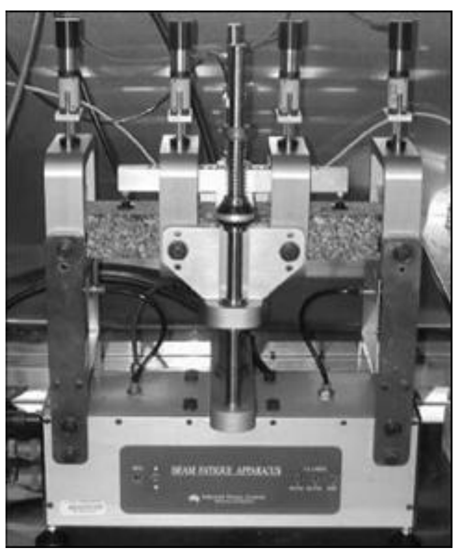


Figure 7. Flexural Fatigue Apparatus.

The test was done using only controlled strain loading, at 5 different strain levels and at 21°C. One of the most difficult tasks is to compact beams from field mixes so that they all have the same or a tight range of air void levels. This might be possible, but would require a large amount of materials and many trials. Because of the variable strain levels selected and consequent regression analysis conducted, the air void variation was relaxed to accept samples that are within 1-2% range. 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. The loading on most specimens was extended to reach a final stiffness of 30% of the initial stiffness instead of the 50% required by AASHTO TP8 and SHRP M-009. The control and acquisition software load and deformation data were reported at predefined cycles spaced at logarithmic intervals.

Fatigue relationships (flexural strain versus the number of loading cycles) for the fiber-reinforced mixture are shown in Figure 8. Also, two different conventional mixtures are plotted. These plots were obtained from controlled strain tests conducted at 21°C. The regression equations for each temperature ($N_f = K_1.\varepsilon^{K_2}$) are also shown on the plot along with the coefficient of determination (R^2) for each relationship. As can be observed, fiber-reinforced mixtures produce higher fatigue for the strain level compared with the two other mixtures, even though they have the same initial flexural stiffness as the PG 70-10 conventional mixture (Figure 9).

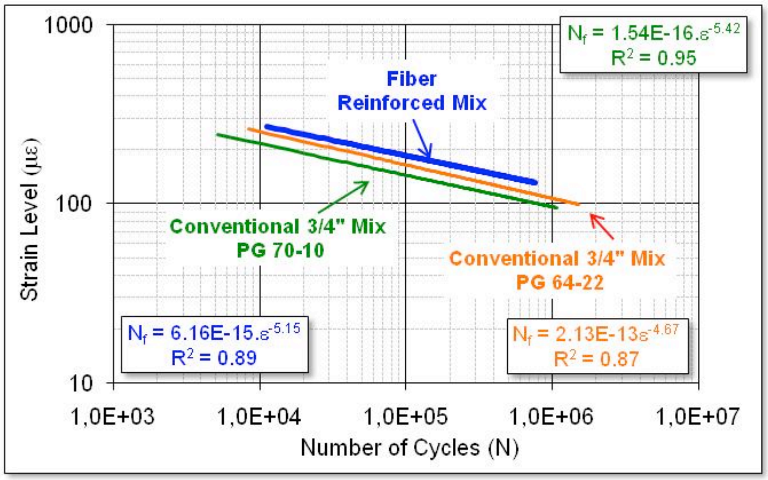


Figure 8. Controlled strain fatigue relationships for fiber reinforced mix and Salt River conventional mixtures.

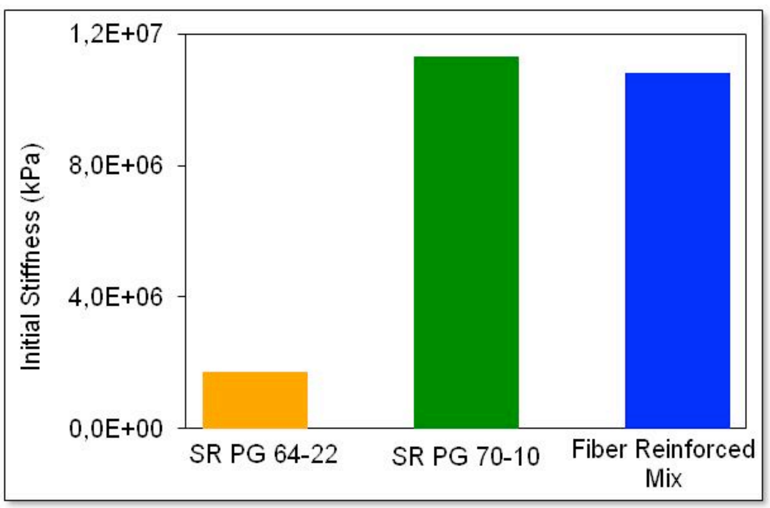


Figure 9. Initial flexural stiffness comparison for fiber reinforced mix and Salt River conventional mixtures.

4. CONCLUSIONS

Post peak failure for the fiber-reinforced asphalt mixture tested with triaxial tests showed a gradual drop in strength, a desirable effect that was attributed to the influence of the aramid fibers in the mix. Similar to triaxial results, permanent deformation tests also showed gradual accumulation in permanent strain, a desirable property that was also attributed to the role of the aramid fibers in the mix. The measured Dynamic Modulus E* values at high temperatures (37 and 54°C) and loading frequency of 10 Hz, were 1.5 to 1.6 higher than those of the conventional mixtures used in this research.

Higher moduli at high temperatures are indicative of better resistance to permanent deformation or rutting. A comparison was made between the fatigue life obtained for the fiber reinforced mix and an ADOT PG 70-10 conventional dense graded mix. The fatigue life was found to be higher for fiber-reinforced mix, even though both have the same initial flexural stiffness.

5. ACKNOWELDGEMENT

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