EVALUATING THE PERFORMANCE OF FIBER REINFORCED ASPHALT MIXTURES COMPARED TO CONVENTIONAL MIXTURES.

1. INTRODUCTION

Fibers have been used to improve the performance of asphalt mixtures against permanent deformation and fatigue cracking. By controlling thermal, reflective and fatigue cracking, as well as rutting, synthetic fibers provides the benefit of immediate cost savings through reduced asphalt thickness or extended asphalt life, or both. These fibers contain aramid and polyolefin fibers and other materials, known for their strength, durability, and binding properties. The objective of this study was to evaluate the performance of the conventional unmodified (control) and polypropylene/aramid fibers reinforced asphalt mixtures using laboratory tests. The main goal was to determine the properties of fiber reinforced asphalt mixtures in stiffness, permanent deformation, and cracking characteristics compared to unmodified mixtures. Wheel track rutting, resilient modulus, dynamic creep and indirect tensile fatigue tests were used to evaluate these properties. The fibers were added to the mixture in the laboratory and in batch asphalt plant. Both laboratory and plant mixed asphalt mixtures were compacted in the laboratory in to different test specimens and were tested to determine performance.

2. MATERIALS

2.1. Fiber

The fibers used in this study were a blend of synthetic fibers named Forta-fi that are designed for use in hot mix asphalt applications. The fibers are designed to reinforce the HMA in three dimensions and provided by *FORTA Corporation*. Table 1 shows the physical properties of fibers. Fibers were added at a content of 1.0 pound per ton of asphalt mixture at the laboratory and at two contents of 1.0 and 2.0 pounds per ton at the batch asphalt plant. A laboratory mixer with a minimum working capacity of 10 kg was used to prepare asphalt mixtures and to distribute the fibers uniformly in the mixture. The fibers were also added to the mixture in the asphalt plant, while still in the bag, before the addition of asphalt binder.

Table1. Fibers physical properties

Materials	Polyolefin	Aramid
Form	Twisted fibrillated& Monofilament	Monofilament
Specific gravity	0.91	1.44
Tensile strength (psi)	70000	400000
Length (mm)	19	19
Color	Tan, Black	Yellow
Acid/alkali resistance	Inert	Inert
Melt temperature (°C)	100	427

2.2. Laboratory mixed asphalt mixtures

2.2.1. Asphalt binder

The 60/70 penetration grade asphalt cement from *Pasargad Oil Company* was used in this study which is widely used in Iran. The physical properties are provided in Table 2.

Table2. Asphalt cement 60/70 physical properties

Property	Test method	Result
Penetration at 25°C, 100 g, 5 s, 0.1 mm	ASTM D5	66
Softening point, °C	ASTM D36	49
Ductility at 25°C, 5 cm/min, cm	ASTM D113	> 100
Solubility in trichloroethylene, (wt)%	ASTM D2042	99.5
Flash Point, °C	ASTM D92	304
Kinematic viscosity at 135°C, centistokes	ASTM D2170	446
Loss on heating, (wt)%	ASTM D1754	0.01
Penetration at 25°C after thin-film oven test, 0.1 mm	ASTM D5	50
Ductility at 25°C after thin film oven test, cm	ASTM D113	> 50

2.2.2. Aggregates

Four aggregate size fractions (two coarse, one fine) and mineral filler sampled from hot bins of asphalt plant and utilized in this study, were crushed stone aggregates from Tehran in Iran and provided by *AljPars company*. The aggregate fractions were sieve analyzed following ASTM D136 standard test method and blended in the proportions that the resulting mixture met the grading of the mix design. The mix designation D5 from ASTM D3515 standard specifications for dense graded hot mixed asphalt mixtures was selected as asphalt mixture gradation. The mix gradation and specific gravity of aggregates are presented in tables 3 and 4.

Table3. Mix gradation

Sieve	Specification limits	Percent passing
19 mm	100	100
12.5 mm	90-100	95
4.75 mm (No.4)	44-74	63
2.36 mm (No.8)	28-58	38
0.3 mm (No.50)	5-21	12
0.075 mm (No.200)	2-10	6

Table4. Specific gravity and absorption of aggregates

Aggregate size fraction	Specific gravity	
	bulk	apparent
aggregate remain on sieve No.8	2.435	2.628
aggregate pass sieve No.8 and remain sieve No.200	2.412	2.688
aggregate pass sieve No.200	2.630	
Total aggregate (mix)	2.437	

2.2.3. Mix design

Asphalt mix design was performed through the Marshall method as specified in ASTM D1559. The optimum asphalt content was chosen in accordance with Asphalt Institute's Manual Series No.2. Optimum asphalt content, volumetric parameters and mechanical properties of asphalt mixture are shown in Table 5.

Table5. Laboratory mixed asphalt mixture properties at optimum asphalt content

Mixture property	Value	Mix design criteria
Optimum asphalt content	5.5	---
Unit weight of compacted specimen (Gmb), kg/m^3	2205	---
Air voids (Va), %	4.1	3-5
Voids filled with asphalt (VFA), %	79	65-75
Voids in mineral aggregates (VMA), %	14.6	> 14
Stability, kgf	1350	> 800
Flow, 0.25mm	13.2	8-14

2.3. Plant mixed asphalt mixtures

The mix designation D5 of ASTM D3515 specification with nominal maximum aggregate size of 1/2 in. from *Macadam Shargh Company* was used. The 60/70 penetration grade asphalt cement from *Pasargad Oil Company* was used in the mixture as asphalt binder. The bulk specific gravity of aggregates and theoretical maximum specific gravity of the mixture were 2.508 and 2.375, respectively. The design asphalt cement content was 4.6 % for the control mixture and it was kept the same for the fiber-reinforced asphalt mixtures. The same compaction procedure was also used for preparing both control and fiber modified specimens. The mix gradation (job mix formula) and the specification limits are presented in tables 6.

Table6. Plant mixed aggregate gradation

Sieve	Specification limits	Percent passing
19 mm	100	100
12.5 mm	90-100	96
4.75 mm (No.4)	44-74	64
2.36 mm (No.8)	28-58	30
0.3 mm (No.50)	5-21	9
0.075 mm (No.200)	2-10	5

3. LABORATORY TESTS

3.1. Wheel track rutting test

The rutting test was performed on unmodified and fiber reinforced asphalt mixtures in accordance with AASHTO T324 standard test method employing the Hamburg Wheel Tracking device shown in figure 1. In this test, a rubber Wheel, 50 mm wide, is rolled across a compacted hot mix asphalt slab and the load which is applied to the wheel is 705 ± 5 N. The test path is 230 ± 10 mm long and the average speed of wheel is approximately 0.305 m/s (50 ± 5 wheel passes per minute). Laboratory mixed and plant mixed asphalt mixtures compacted by the roller compactor. The slab specimens for unmodified and fiber reinforced asphalt mixtures were fabricated with the height of 50 mm using roller compactor. These specimens were compacted to an air void content of 6±0.5% and tested under dry condition at 50ºC.

Fig.1. Hamburg wheel track rutting test device and control unit

3.2. Dynamic creep test

The uniaxial repeated load (dynamic creep) test was carried out on cylindrical specimens of unmodified and fiber reinforced asphalt mixtures using UTM apparatusin accordance with BS: DD226 draft test method. UTM apparatus and the test loading frame are shown in figure 2. Specimens 4 inch in diameter were prepared for laboratory mixed asphalt mixtures using Marshall compaction apparatus according to ASTM D1559 standard method and 6 in. diameter specimens were prepared for plant mixed asphalt mixtures using modified Marshall apparatus according to ASTM D5581 standard method. 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. The dynamic creep test is a test that applies a repeated pulsed uniaxial stress on an asphalt specimen and measures the resulting deformations in the same direction using linear variable differential transducers. Three stages of creep behavior can be identified. In the primary stage, the rate of deformation increases rapidly. In the secondary stage, the deformation rate becomes constant. In the last stage, the deformation increases rapidly and failure is reached. The tests were conducted at 50ºC using a 100 kPa square pulse load of 1.0 s and a rest time of 1.0 s before the application of the next pulse.

Fig.2. UTM apparatus and dynamic creep test frame

3.3. Resilient modulus test

The five pulse indirect tensile resilient modulus test of unmodified and fiber reinforced asphalt mixtures was performed at 25ºC and 0.1 Hz loading frequency on 4 in. cylindrical specimens according to ASTM D4123 standard test method. In this test, a pulsed diametral loading force is applied to the specimen and the resulting total recoverable diametral strain is measured from axes 90 degrees from the applied force. Strain in the same axes is not measured, thus an assumed value of poisson's ratio is used as a constant. The test sequence consists of the application of 100 conditioning pulses followed by 5 pulses where data acquisition takes place. The conditioning pulses ensure that the loading platens are seated onto the specimen for consistent results. The test frame and accessories are shown in figure 3. Both laboratory-mixed and plant-mixed asphalt mixtures were tested for a load pulse period of 1000 ms, pulse width of 100 ms, Haversine waveform and 0.35 poisson's ratio.

Fig.3. Resilient modulus test frame and accessories

3.4. Indirect tensile fatigue test

There are three main methods used to evaluate and predict the fatigue characteristics of asphalt mixes. They are initial strain-fatigue life, dissipated energy-fatigue life and fracture mechanics. Indirect tension fatigue test uses the fracture mechanics. The horizontal deformation during the indirect tension fatigue test is recorded as a function of load cycle. Fatigue life (Nf) of a specimen is number of cycles to failure for asphalt concrete mixtures. Fatigue cracking is a pavement distress that typically occurs at intermediate temperatures and so 20 °C is chosen as test temperature to characterize the fatigue lives of asphalt concrete mixtures. In this test a compressive load acts parallel to and along the vertical diametric plane. This loading configuration develops a reasonably uniform tensile stress in the specimen perpendicular to the direction of the applied load and along the vertical diametric plane. The procedure for indirect tensile fatigue test is described in details in the European Standard EN12697-24. Two types of controlled loading can be applied: control stress and control strain. In the control stress test, the stress remains constant but the strain increases with the number of repetitions. In the control stress test, the strain kept constant and the load or stress is decreased with the number of repetitions. The use of constant stress has the further advantage that failure occurs more quickly and can be more easily defined. Controlled stress indirect tensile fatigue test was done at 20ºC which used to determine number of cycles to fracture for asphalt mixtures. Number of load cycles to the specimen failure is defined as fatigue life (Nf) for asphalt mixtures. The loading pattern used in the test is a haversine load and the 4 in. cylindrical specimens were subjected to a stress of 300 kPa. The loading time and the subsequent rest period were 0.25 s and 1.25 s, respectively. The indirect tensile fatigue test frame and loading apparatus are shown in figure 4.

Fig.4. Indirect tensile fatigue test frame and load cell

4. RESULTS AND DISCUSSION

4.1. Wheel track rutting test

The rutting test was performed at 50ºC in accordance with AASHTO T324 standard test method employing the Hamburg Wheel Tracking device. The rut depth was recorded after each loading cycle and plotted for laboratory mixed and plant mixed asphalt mixtures as a function of the number of loading cycles in Figure 5 and Figure 6, respectively. The maximum rut depths of these mixtures after 10000 loading cycles are presented in table 7. The results show that the permanent deformation (rutting) resistance of fiber reinforced asphalt mixtures is superior to that of unmodified asphalt mixture, so that the rut depth of 1 and 2 lb/t fiber reinforced plant mixed asphalt mixtures are 4.5 and 14 times lower than that of base control asphalt mixture. The rut depth of 1 lb/t fiber reinforced laboratory mixed asphalt mixture is also 1.3 times lower than that of base asphalt mixture. Comparing the results of laboratory mixed and plant mixed asphalt mixtures reveals that addition of synthetic fibers in batch asphalt plant is more effective than laboratory mixing of fibers with asphalt mixture, and plant mixing can uniformly and completely distribute the fibers in the mixture that leads to three-dimensionally reinforcing asphalt mixture. The results of plant mixed asphalt mixtures indicate that increasing the fibers content from 1lb/t by 1 pound per ton of asphalt mixture decreases the rut depth of asphalt mixture by a factor of 3 and effectively enhances the permanent deformation resistance of asphalt mixture. Furthermore, the lower resistance of plant mixed asphalt mixtures compared to laboratory mixtures can be related to the mix gradation. Inspecting the mix gradations show that the asphalt mixture produced in the asphalt plant has less fines and poor gradation respect to the permanent deformation resistance compared to laboratory mixed asphalt mixture.

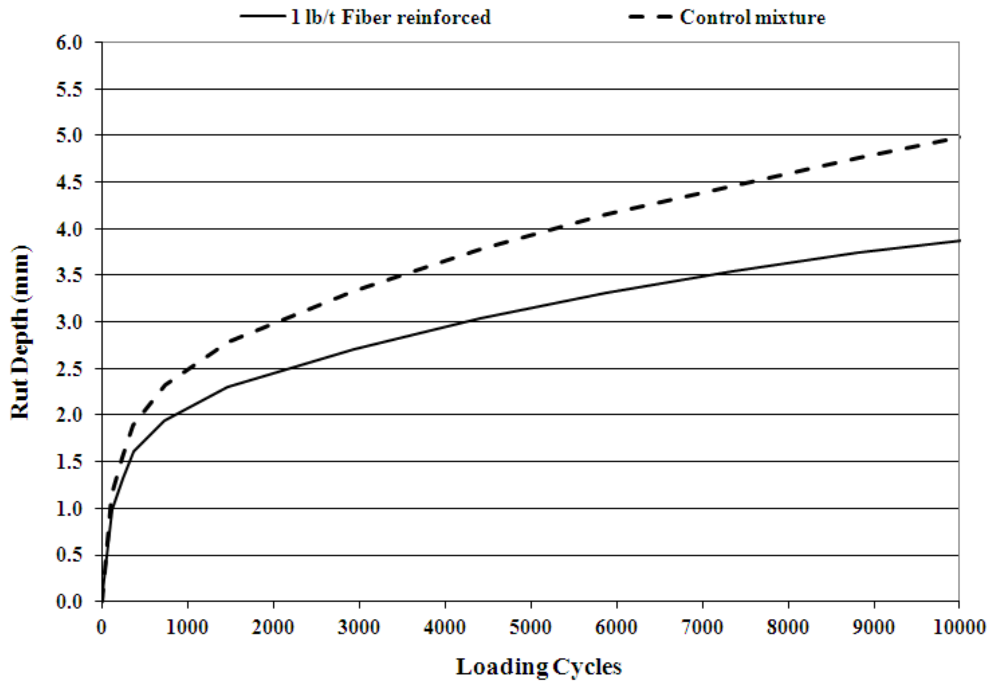

Fig.5. Rut depth versus number of load cycles for laboratory mixed asphalt mixtures

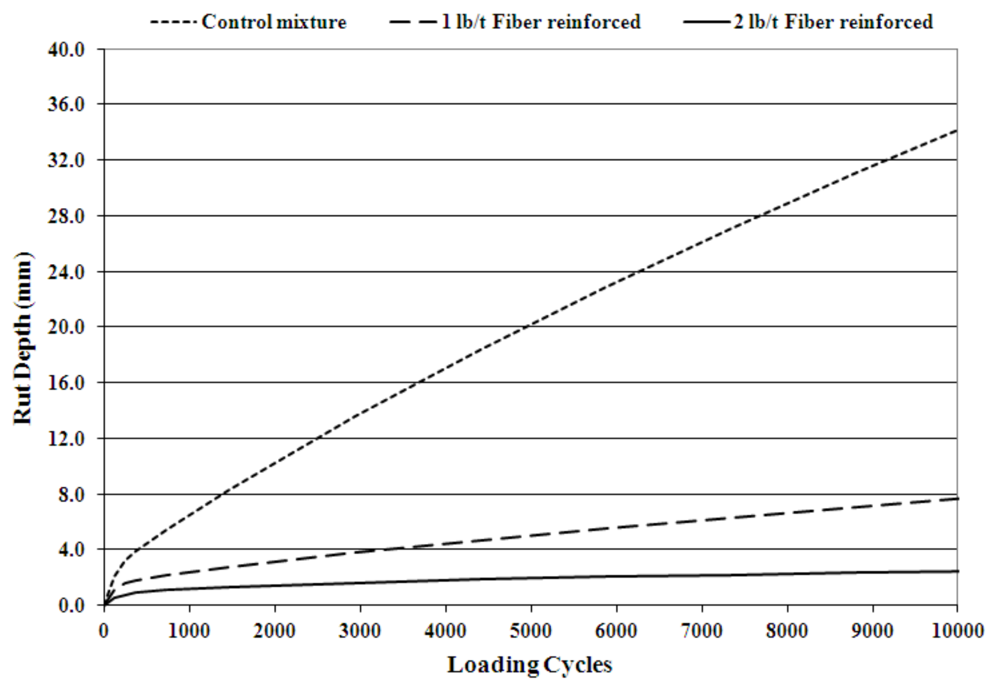

Fig.6. Rut depth versus number of load cycles for plant mixed asphalt mixtures

Table7. Wheel track rutting test results

Mixing procedure	Mix type	Rut depth (mm)
laboratory mixed	control	4.98
	fiber reinforced	3.87
plant mixed	control	34.20
	1 lb/t fiber reinforced	7.64
	2 lb/t fiber reinforced	2.44

4.2. Dynamic creep test

The dynamic creep test was carried out on unmodified and fiber reinforced asphalt mixtures according to BS: DD226 test method. The flow number and the corresponding cumulative permanent strain as a function of the number of loading cycles over the test period was recorded for laboratory mixed and plant mixed asphalt mixtures. The average results for these mixtures are presented in table 8. The results show that reinforcing the asphalt mixtures by synthetic fibers improved permanent deformation resistance of asphalt mixtures, so that the flow times (FN) of 1 and 2 lb/t fiber reinforced plant mixed asphalt mixtures are 2.3 and 40 times lower than that of control mix. The flow number of 1 lb/t fiber reinforced laboratory mixed asphalt mixture is also 1.5 times lower than that of laboratory mixed control mixture. Inspecting the results of creep test reveals that flow-time has good correlation with rut depth in wheel track rutting test and the results are rational in that the flow time decreased as the rut depth increased. Poor performing mixtures had the lowest flow time (shortest time to failure) and good performing mixtures had the largest flow time (longest time to failure). Surveying dynamic creep test results shows that the rutting parameter, FN, is compatible with rutting performance of asphalt mixtures in Hamburg Wheel Track Rutting Tester. Dynamic creep test results also indicate that fiber reinforcing of asphalt mixtures in asphalt plant is more effective than laboratory reinforcing of asphalt mixtures and plant mixing can completely distribute the fibers in the mixture. It can be seen from the results that increasing the fibers content from 1lb/t by 1 pound per ton of asphalt mixture increased the flow time by a factor of 18 and the deformation resistance of asphalt mixture increased incredibly. Furthermore, the lower resistance of plant mixed asphalt mixtures compared to laboratory mixtures is evident and related to poor mix gradation of plant mixed asphalt mixture.

Table8. Dynamic creep test results

Mixing procedure	Mix type	Flow Number (cycles)	Permanent strain at failure (%)
laboratory mixed	control	1067	1.74
	fiber reinforced	1633	1.90
plant mixed	control	250	1.13
	1 lb/t fiber reinforced	560	1.11
	2 lb/t fiber reinforced	10150	1.57

4.3. Resilient modulus test

The resilient modulus of unmodified and fiber reinforced asphalt mixtures at 25ºC was determined according to ASTM D4123 test method. The average results for laboratory mixed and plant mixed asphalt mixtures are presented in table 9. Modulus of resilience or stiffness modulus is directly related to the load spreading ability of a material and is the relationship between stress and strain and shows how much a material will deform under load. It can be observed from the results that fiber reinforcing of plant mixed asphalt mixtures increased the resilient modulus by a factor of 1.3 and 2.3 for 1 lb/t and 2 lb/t fiber contents, respectively. The Mr of 1 lb/t fiber reinforced laboratory mixed asphalt mixture is also 1.3 times higher than that of control mix.

The resilient modulus values can be utilized to analyze the response of the pavement structure due to the application of traffic loads. The resilient modulus is also the most important variable to mechanistic design approaches for pavement structures and an important parameter to predict the pavement performance and to analysis the pavement response to traffic loading. The stiffer pavements have greater resistance to permanent deformation and it is important not to ignore that high stiffness at low temperature tend to crack earlier than more flexible mixtures.

The fiber reinforced asphalt mixtures consistently exhibited higher resilient modulus values than control mixtures and 1 lb/t increase in fiber content produced a considerable increase in the elastic properties of the control mixtures. These findings indicate that using synthetic fibers produces asphalt mixtures with greater stiffness and thus higher load bearing capacity and decreases asphalt pavement design thickness.

Table9. Resilient modulus test results

Mixing procedure	Mix type	Mr (MPa)
laboratory mixed	control	1813
	fiber reinforced	2324
plant mixed	control	2646
	1 lb/t fiber reinforced	3330
	2 lb/t fiber reinforced	6136

4.4. Indirect tensile fatigue test

Controlled stress indirect tensile fatigue test was done at 20ºC according to EN12697-24 standard test method. Number of load cycles to the specimen failure (N_f) was recorded for plant mixed asphalt mixtures. The average results are presented in table 10. Because of the poor performance of laboratory mixed fiber reinforced asphalt mixtures compared to plant mix reinforced mixtures, fatigue test on laboratory mixed asphalt mixtures was cancelled. The relations between vertical deformations versus number of load cycles to failure are presented in figures 7 to 9 for plant mixed asphalt mixtures. The results show that fatigue behavior of fiber reinforced mixtures significantly improved compared to control mixture. Based on indirect tensile fatigue test results, fatigue life of 1 and 2 lb/t fiber reinforced plant asphalt mixtures are 2.0 and 34 times higher than that of control mix. Besides, the increasing of fibers content by 1 lb/t of asphalt mixture leads to a considerable improvement of fatigue behavior. The fatigue test results can be related to the three-dimensionally reinforcement of asphalt mixture by synthetic fibers. Test results reveal that plant mixing of fibers into the asphalt mixture completely distributes the fibers throughout the mixture and develops strength and durability.

Table10. Indirect tensile fatigue test results for plant mixed asphalt mixtures

Mix type	N_f
control	2555
1 lb/t fiber reinforced	5125
2 lb/t fiber reinforced	87259

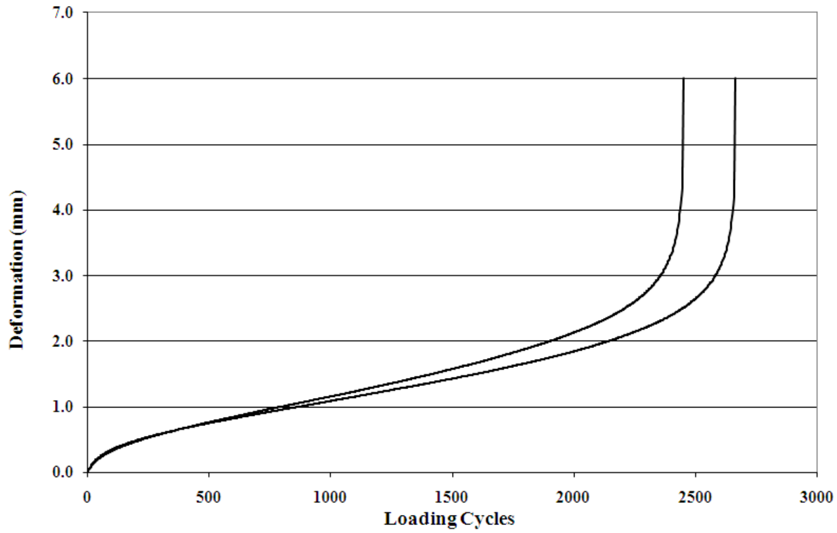

Fig.7. vertical deformation versus number of load cycles for control mixtures

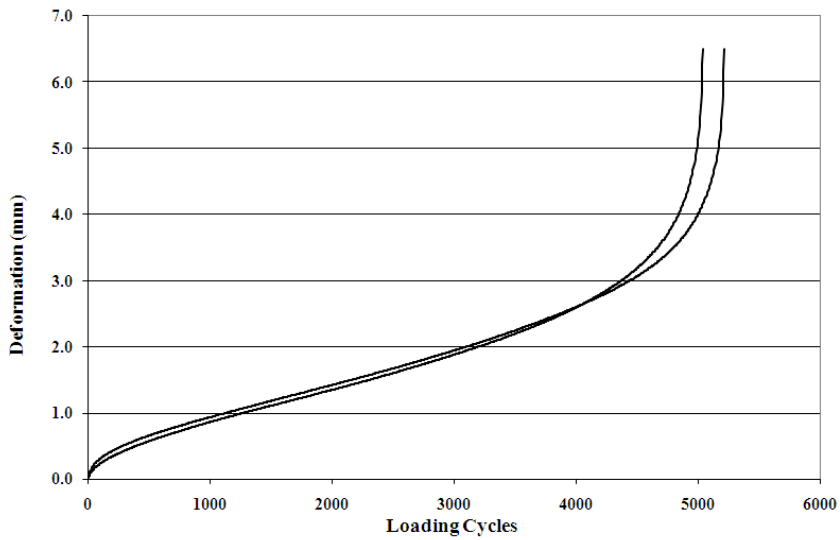

Fig.8. vertical deformation versus number of load cycles for 1 lb/t fiber reinforced mixtures

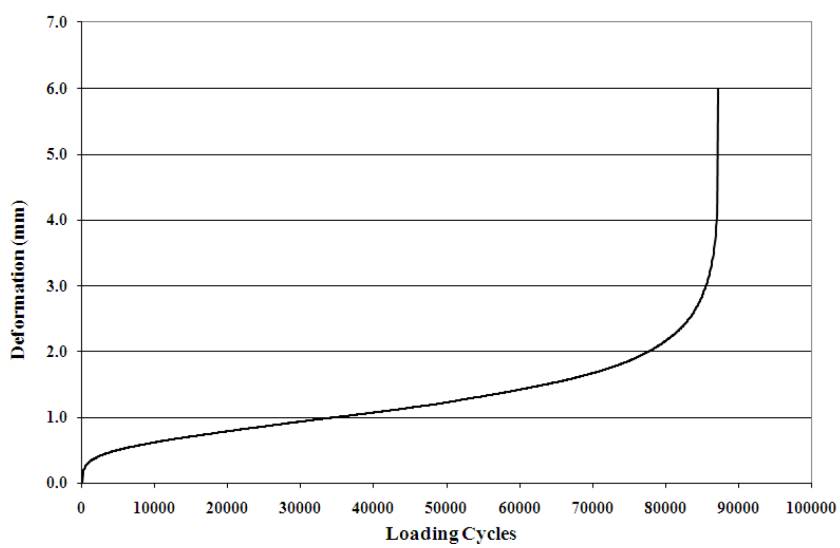

Fig.10. vertical deformation versus number of load cycles for 2 lb/t fiber reinforced mixture

5. CONCLUSION

- Rutting resistance of fiber reinforced asphalt mixtures is superior to that of unmodified asphalt mixture. The rut depth of 1 and 2 lb/t fiber reinforced plant mixed asphalt mixtures were 4.5 and 14 times lower than that of base control asphalt mixture.
- The rut depth of 1 lb/t fiber reinforced laboratory mixed asphalt mixture was 1.3 times lower than that of base asphalt mixture.
- Fibers reinforcing of asphalt mixtures improved creep behavior of asphalt mixtures, so that the flow times (FN) of 1 and 2 lb/t fiber reinforced plant mixed asphalt mixtures were 2.3 and 40 times lower than that of control mix.
- The flow number of 1 lb/t fiber reinforced laboratory mixed asphalt mixture was 1.5 times lower than that of control mix.
- Increasing the fibers content from 1lb/t to 2 lb/t decreased the rut depth in the wheel track test by a factor of 3 and increased the flow time in the creep test by a factor of 18 and the permanent deformation resistance of asphalt mixture increased incredibly.
- Fiber reinforcing of asphalt mixtures increased the resilient modulus by a factor of 1.3 and 2.3 for 1 lb/t and 2 lb/t fiber contents, respectively. The stiffer pavements have greater resistance to permanent deformation. Using synthetic fibers produces asphalt mixtures with greater stiffness and thus decreases asphalt pavement design thickness.
- Fatigue behavior of fiber reinforced mixtures significantly improved compared to control mixture. Fatigue life of 1 and 2 lb/t fiber reinforced asphalt mixtures in the indirect tensile repeated load test were 2.0 and 34 times higher than that of control mix.
- Addition of fibers in asphalt plant is more effective than laboratory mixing. Plant mixing of fibers into the asphalt mixture completely distributes the fibers throughout the mixture and develops strength and durability.

On the whole, fiber reinforcing asphalt mixtures by a minimum dosage rate of 1 lb/t of asphalt mixture considerably enhances permanent deformation, elastic and fatigue cracking behavior of asphalt mixtures. Furthermore, the best results are achieved by 2 lb/t fiber-reinforced plant-mixed asphalt mixture in the laboratory.