ACE XP
POLYMER FIBER
Superior Asphalt Performance

Technical Brief

Advanced Polymer Fiber Technology for Asphalt

Testing By:

Advanced Asphalt Technologies
Asphalt Institute
Hi-Tech Asphalt Solutions
Ingios Geotechnics
Ohio University (In Process)
Oregon State University
Pave-Tex
Southern Alberta Institute Technology
Texas Transportation Institute
University of California – Pavement Research Center
University of Alberta (In Process)
University of Missouri (In Process)
University of New Hampshire (In Process)
Western New England University

The following testing information has been extracted from reports and test results as performed by the testing agencies listed above and summarized here to show the improved performance of Aramid Fiber Reinforced Asphalt Concrete when reinforced by ***ACE XP Polymer Fiber****. The testing performed and summarized on the following pages was selected by the testing agency to show improved performance in cracking, rutting, and strength of the FRAC mix as compared to standard asphalt concrete mixes. The following lab and field tests were performed:*

- *The Overlay Tester (Lab)*
- *DC(T) – Disk Shaped Compact Tension Test (Lab)*
- *ID(T) – Indirect Tensile Test, Strength and Compliance (Lab)*
- *Hamburg Test (Lab)*
- *APLT – Static Creep (Field)*
- *APLT – Dynamic Modulus (Field)*
- *Chemical Extraction Test (Lab)*
- *Aramid State Dispersion Ratio Test – ADSR Test (Lab)*
- *Flow Number Testing (FN) – Rutting Resistance Test*
- *Flexibility Index Test (FI) – Fatigue Cracking Test*
- *IDEAL CT – Crack Test*
- *Bending Beam Fatigue Testing – (BBF)*
- *AMPT Repeated Loading Test – For Rutting Resistance*

Lab Testing Summary

Lab Test Description	ACE XP Results
Lab - TTI Overlay Tester *Thermal/Reflective Cracking*	+140%
Lab - DC(T) Test *Low Temperature Fracture Energy*	+21%
Lab - IDT Strength Test (@ -12 Degree C) *Low Temperature Strength @ Critical Crack Temperature (Ran both ¾" and 1 ½" ACE XP Lengths)*	+8 to 17%
Lab – IDT Strength Test (@ 25 Degree C) *High Temperature Strength run with 3 different asphalt contents, 4.5%, 5.5% and 6.5%. ACE Reinforced improved all three mixes, but 6.5% AC by 51.7%. (1 ½" ACE XP Lengths)*	Average +34.7%
Lab - IDT Creep Compliance Test *Determine Low Temperature Critical Cracking Value (Bottom PG Number)*	-4.3º C (-1 PG – Bottom Number)
Lab - Hamburg Rut Test *Determine Rut Resistance of Various Asphalt Mixes (Top PG Number)*	PG64-22 (w/ ACE) = PG70-22 (+1 PG – Top Number)
Lab - Hamburg Rut Test *Determine Rut Resistance of Various Asphalt Mixes (Top PG Number)*	PG70-22 (w/ ACE) = PG76-22 (+1 PG – Top Number)
Lab – Flow Number Test (FN) *Determine Rut Resistance of ODOT Level 3 mix vs Control (Ran both ¾" and 1 ½" ACE XP Lengths)*	+37.5%
Lab – AMPT Permanent Deformation Testing – Rut Performance *Test counts the cycle of load to reach 5% permanent deformation of the sample. Test run at both 45 and 55 Degree C. (1 ½" ACE XP Lengths)*	+46% (45 Deg C) +18% (55 Deg C)
Lab – Flexibility Index Test (FI) *Determine Fatigue Cracking Resistance of ODOT Level 3 mix vs Control (Ran both ¾" and 1 ½" ACE XP Lengths)*	+37%
Lab – IDEAL CT Cracking Test *Determine IDEAL CT Crack Index of TxDOT Dense Grade 64-22 vs Control – (1 ½" ACE XP Lengths)*	+36%
Lab – IDEAL CT Cracking Test *Determine IDEAL CT Crack Index of lab prepared TxDOT SuperPave 76-22 vs Control (1 ½" ACE XP Lengths)*	+58%
Lab – IDEAL CT Cracking Test *Determine the IDEAL CT Crack Index of a lab prepared KYTC PG64-22 Dense Grade Mix used on Medium ESAL Roads. (1x Dose – 1 ½" ACE XP Lengths)*	+30%
Lab – IDEAL CT Cracking Test *Determine the IDEAL CT Crack Index of a lab prepared KYTC PG64-22 Dense Grade Mix used on Medium ESAL Roads. (2x Dose – 1 ½" ACE XP Lengths)*	+60%
Lab – Bending Beam Fatigue Testing – (BBF) *Cyclic loading on a 4-point bending beam machine to crack failure. Failure determined at various strain levels to predict reflective crack control. (1 ½" ACE XP Lengths)*	+90% (600 Micro-Strains) +200% (900 Micro-Strains)

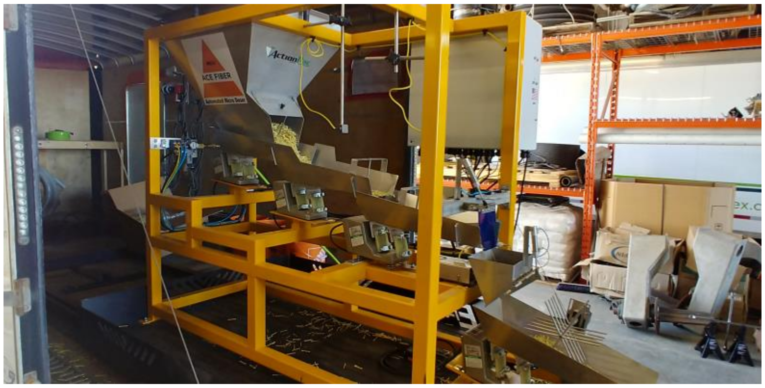
Field Testing Summary

Field Test Description	ACE XP Results
Field – APLT (Automated Plate Load Test) Static Creep *Measure Plastic Deformation of In-Place Asphalt (Rut) vs Control*	+11 to 19% Rebound Ratio over Control
Field – APLT (Automated Plate Load Test) Elastic Modulus *Measure Elastic Modulus of In-Place Asphalt w/ ACE Fiber*	+150%
Field – APLT (Automated Plate Load Test) *SN Layer Coefficient, a_1 Back Calculate SN Layer Coefficient, a_1 using Measured Elastic Modulus*	+40%
Field – APLT (Automated Plate Load Test) *ESAL Prediction Using AASHTO 93 Calculate Increase ESAL Capacity of In-Place Asphalt Reinforced w/ ACE XP Polymer Fiber*	+100% or more Depending of Depth of Asphalt
Field – APLT (Automated Plate Load Test) *Measure Plastic Deformation of In-Place Asphalt (Rut) vs Control at various simulated tire pressures ranging from 150 to 750psi*	24% to 31% Less Rutting Depth
Field – APLT (Automated Plate Load Test) *Measure Plastic Deformation of In-Place Asphalt (Rut) vs Control at constant load of 20,000 lbs. for 15 minutes*	61% Less Rutting Depth

Aramid Mix & Dispersion Lab Validation

Lab Test Description	ACE XP Results
Lab – Aramid Chemical Extraction Test (AI) *Measure the amount of Aramid Fibers in each Sample & Ton*	2.8 to 7.4 oz./ton
Lab – Aramid Chemical Extraction Test (AAT) *Measure the amount of Aramid Fibers in each Sample & Ton*	2.3 to 2.4 oz./ton
Lab – Aramid Dispersion State Ratio – ADSR (AI) *Classify the dispersion of the recovered Aramid Fibers from Extraction*	86.4%
Lab – Aramid Dispersion State Ratio – ADSR (AAT) *Classify the dispersion of the recovered Aramid Fibers from Extraction*	86.2%

The MD3+ Automated Dosing Machine Delivers the Right Dosage of ACE XP Polymer Fiber Every Time



The Overlay Tester

Developed by Texas Transportation Institute

Performed by Hi-Tech Asphalt Solutions

Test Summary:

In this test one plate is locked and the other cycles back and forth a distance of 0.025 inches, with 5 second openings and 5 second closings, which **simulates an HMA overlay over a thermally active crack or joint.** The number of complete cycles for the crack to reach the surface is recorded.

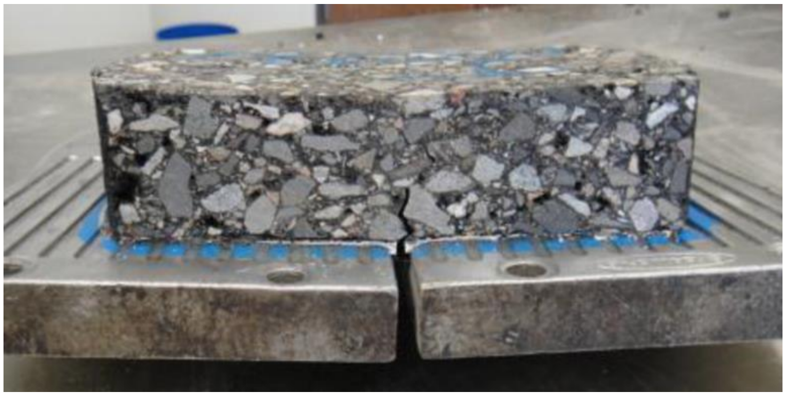
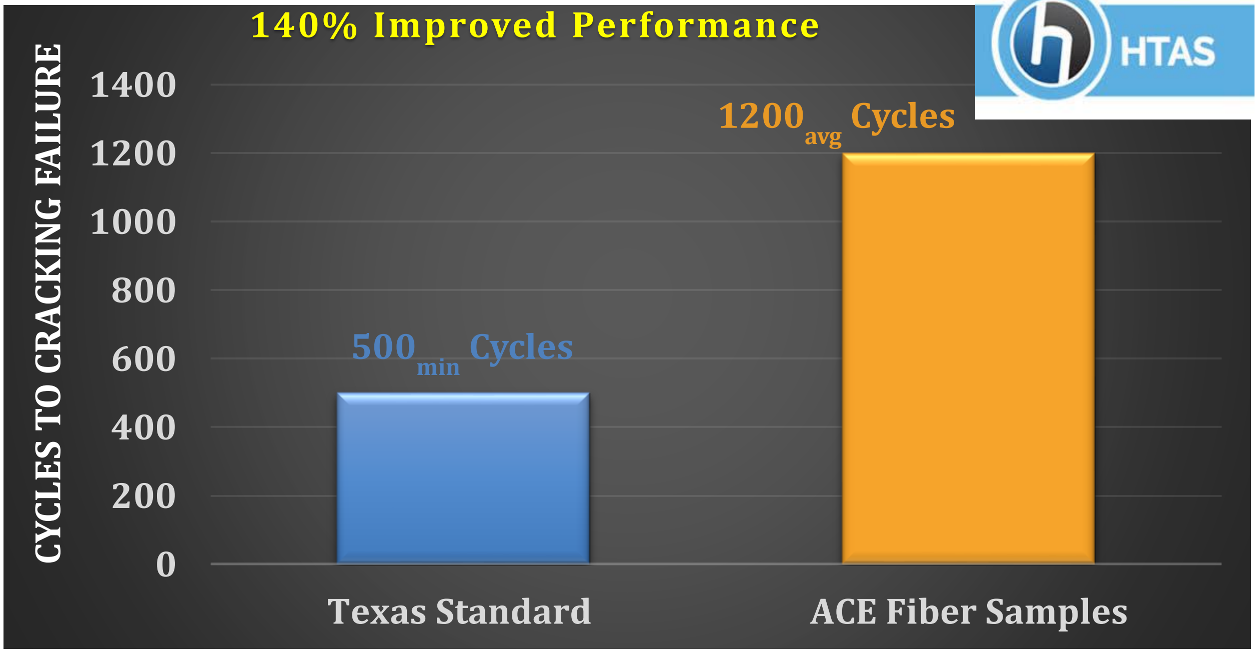


Figure 1 – Overlay Tester Apparatus

Results:

In 2014, Hi-Tech Asphalt Solutions (HTAS) ran the TTI Overlay Tester on Ace Fiber reinforced asphalt concrete samples using PG64-22 Binder. To compare the results of the FRAC samples, HTAS compared the performance to a standard adopted in the State of Texas. These standard states that all asphalt concrete mixes used as an overlay must provide a minimum of 500 cycles to failure in the Overlay Tester. HTAS prepared 6 samples of the ACE Fiber reinforced asphalt mix, and all 6 samples were run to 1200 cycles which was set as the test maximum. The results are shown in Table 1 below.

Table 1



The DC(T) Test

The Disk-Shaped Compact Tension Test

Performed by Western New England University

Test Summary:

The Disk-shaped Compact Tension test [DC(T)] was conducted in accordance with ASTM D7313-07 to assess the fracture resistance of asphalt mixtures. DC(T) tests were performed in the materials laboratory at the University of Illinois. Figure 2 shows DC(T) testing setup and Figure 3 shows the sample dimensions.

The DC(T) testing temperature was selected based on the ASTM standard that recommends testing temperature to be 10°C warmer than the PG low temperature (PGLT) of the mixture. Prepared DC(T) samples were conditioned at testing temperature for two hours prior to starting the test. The DC(T) test was conducted through applying a monotonic tensile load to the specimen such that a constant crack mouth opening displacement (CMOD) rate of 1 mm/min was achieved.

The test is completed when the post peak level has reduced to 0.1 kN. Fracture energy of the specimens was determined by calculating the normalized area under the Load-CMOD curve.

Figure 2

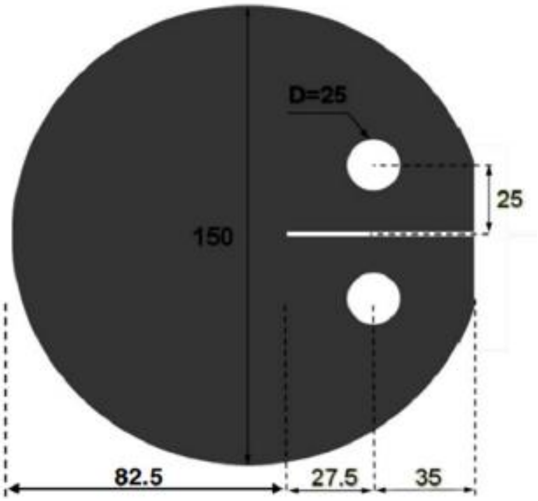


Figure 3

Results:

The DC(T) fracture energy test results of two sets of PG64-22 mixtures; each set containing four fiber mixtures with different amounts of fiber ranging from 0 to 10 (oz./ton) are presented in Table 2 and Table 3 below. DC(T) tests were performed at -12^{o}C for all samples. Results show that adding ACE fiber improved the cracking performance of mixtures by increasing the fracture energies of the material. It is observed that the higher the fiber content of the mixture, the higher its fracture energy. Moreover, the rate of increase in the mixtures' fracture energy as a result of adding fiber is also impressive. The average rate of gaining fracture resistance for the fiber mixtures is around 13.5 J/m2 per ounce of fiber added. *This test was performed by WNEU on two separate occasions; the first in July of 2016 and the second in November of 2016. The goal was to test a higher quality mix the second time around and see the results.*

Table 2 – July 2016

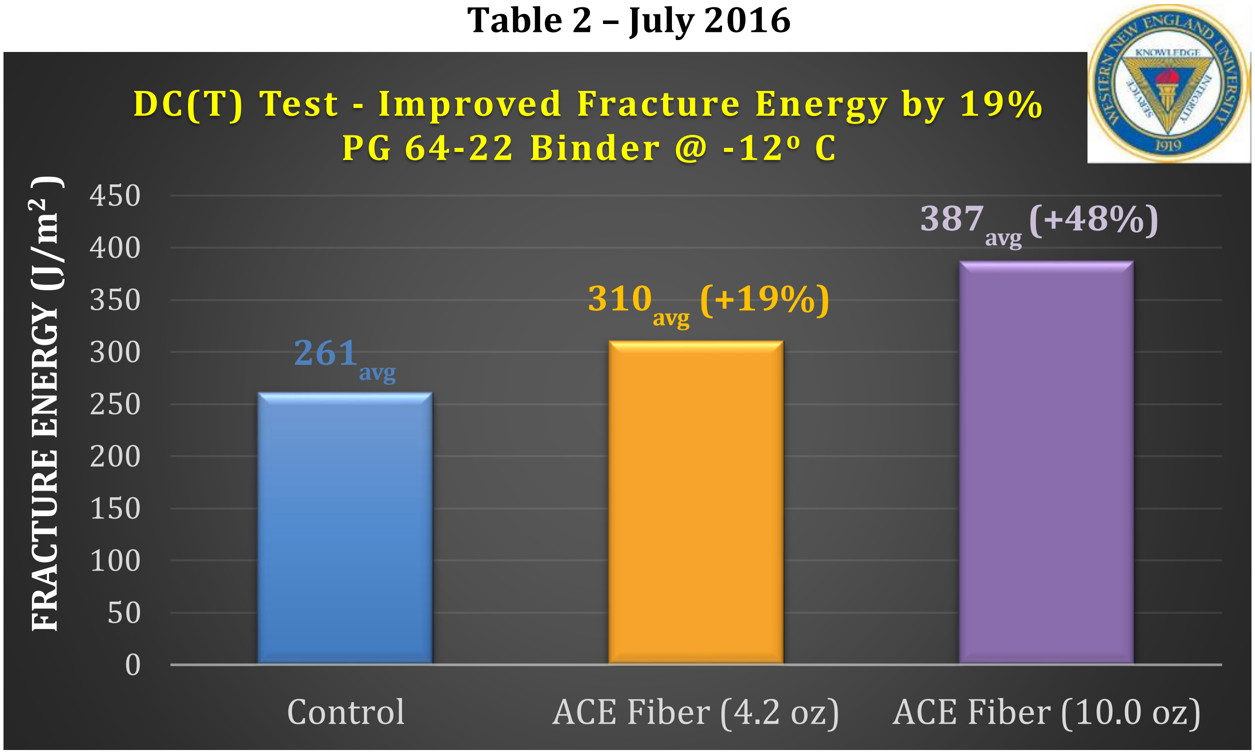
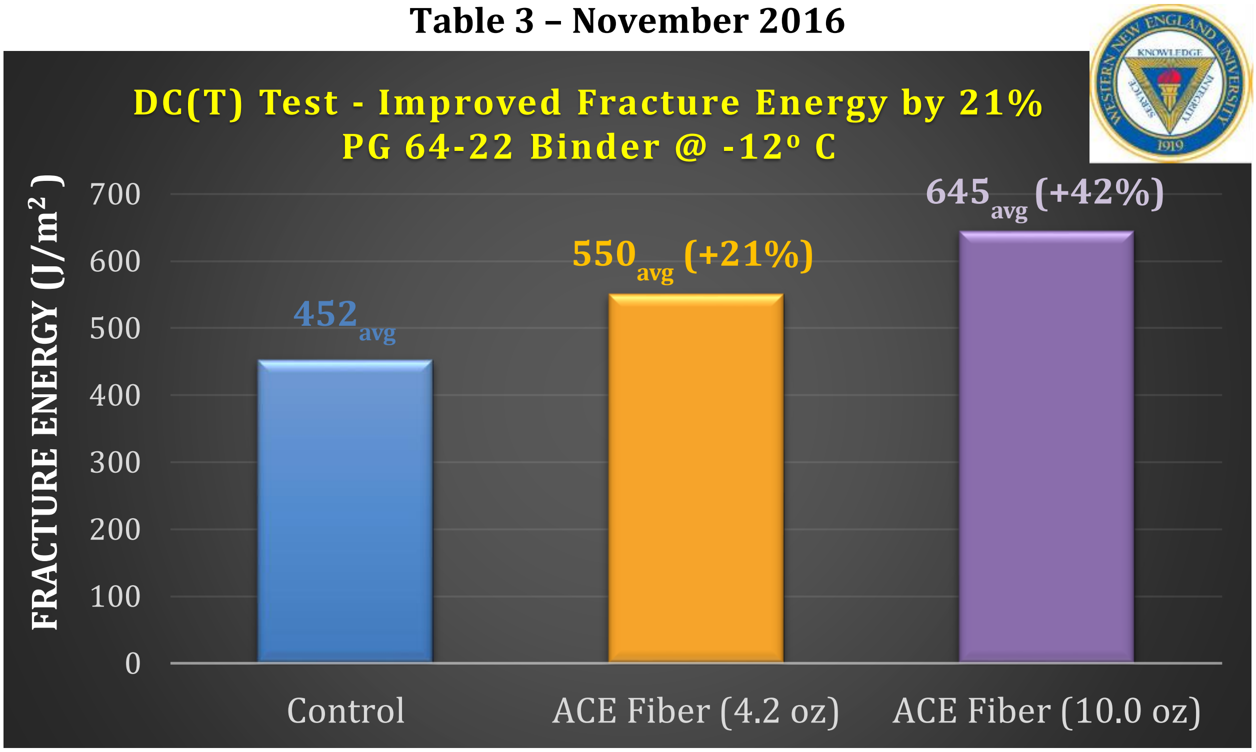


Table 3 – November 2016

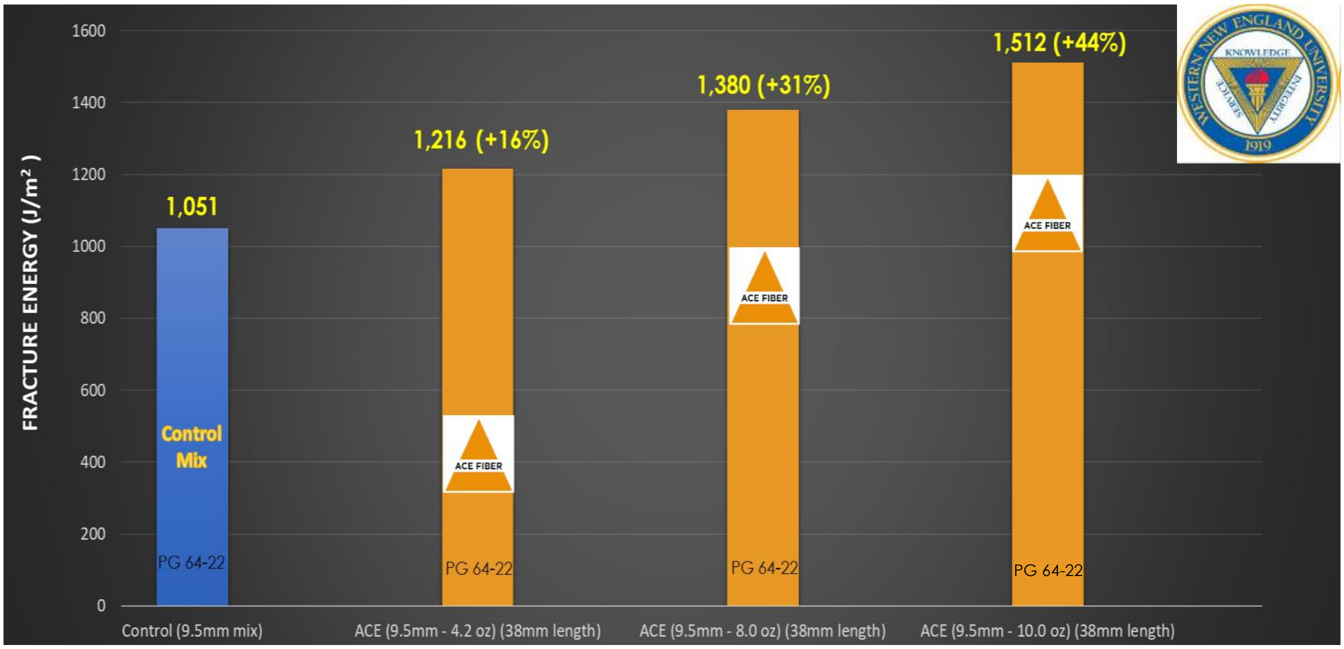


The DC(T) Test

The Disk-Shaped Compact Tension Test

Performed by Western New England University

Table 4 – November 2016, DC(T) Run at 15° C for Fatigue Cracking Using 1 ½" ACE Fiber Length vs. Control



The (IDT) Test

The Indirect Tensile & Compliance Test

Performed by Advanced Asphalt Technologies And Asphalt Institute

Test Summary:

The IDT test for critical low temperature cracking was performed to determine the low temperature critical cracking or the bottom number of the Performance Graded Asphalt Binder (PG).

Each IDT specimen was tested at three (3) temperatures: -10, -20, -30°C for Creep Compliance testing. Samples were conditioned at the test temperature for a minimum of 4 hours prior to testing. Extensometers were attached to samples to measure the indirect displacement of the sample under constant loading at each temperature. Samples were loaded into the test frame (Figure 4) and a vertical constant load was applied and indirect displacement was measured for 300 s.

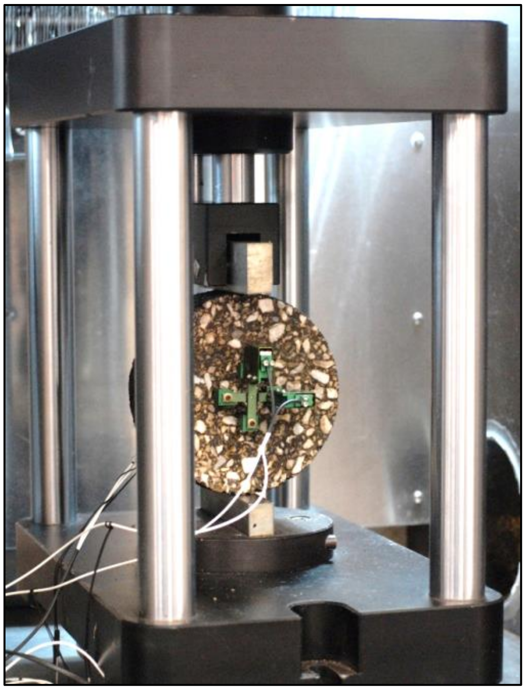


Figure 4

After Creep Compliance testing, samples were tested for tensile strength at each of the test temperatures. The static load must produce a horizontal deformation of 1.25 to 19.0 microns for 150 mm diameter specimens. Similar preconditioning of test samples was conducted prior to breaking. Samples, without extensometers, were loaded into the test frame and a load was applied at a constant rate of 12.5 mm/min. Peak load and vertical deformation was recorded and tensile strength of each specimen was determined.

Results:

The low temperature critical cracking temperature is predicted from the IDT test. To do this the relaxation (compliance) and tensile strength of the samples must be examined. This is done by shifting the isotherms (various temperature responses plotted on the same graph), Figure 5, to form a shifted compliance curve, Figure 6. From this shift, we understand the time-temperature relation of the samples that allows us to then plot the measured stress and overlay with the fracture stress of the samples. The intersection of these lines is where the asphalt sample's strength equals its thermal stress from cooling and is the predicted critical cracking temperature, shown in Figure 7 for Advanced Asphalt Technologies.

The (IDT) Test

Isotherms from Compliance Testing

Performed by Advanced Asphalt Technologies And Asphalt Institute

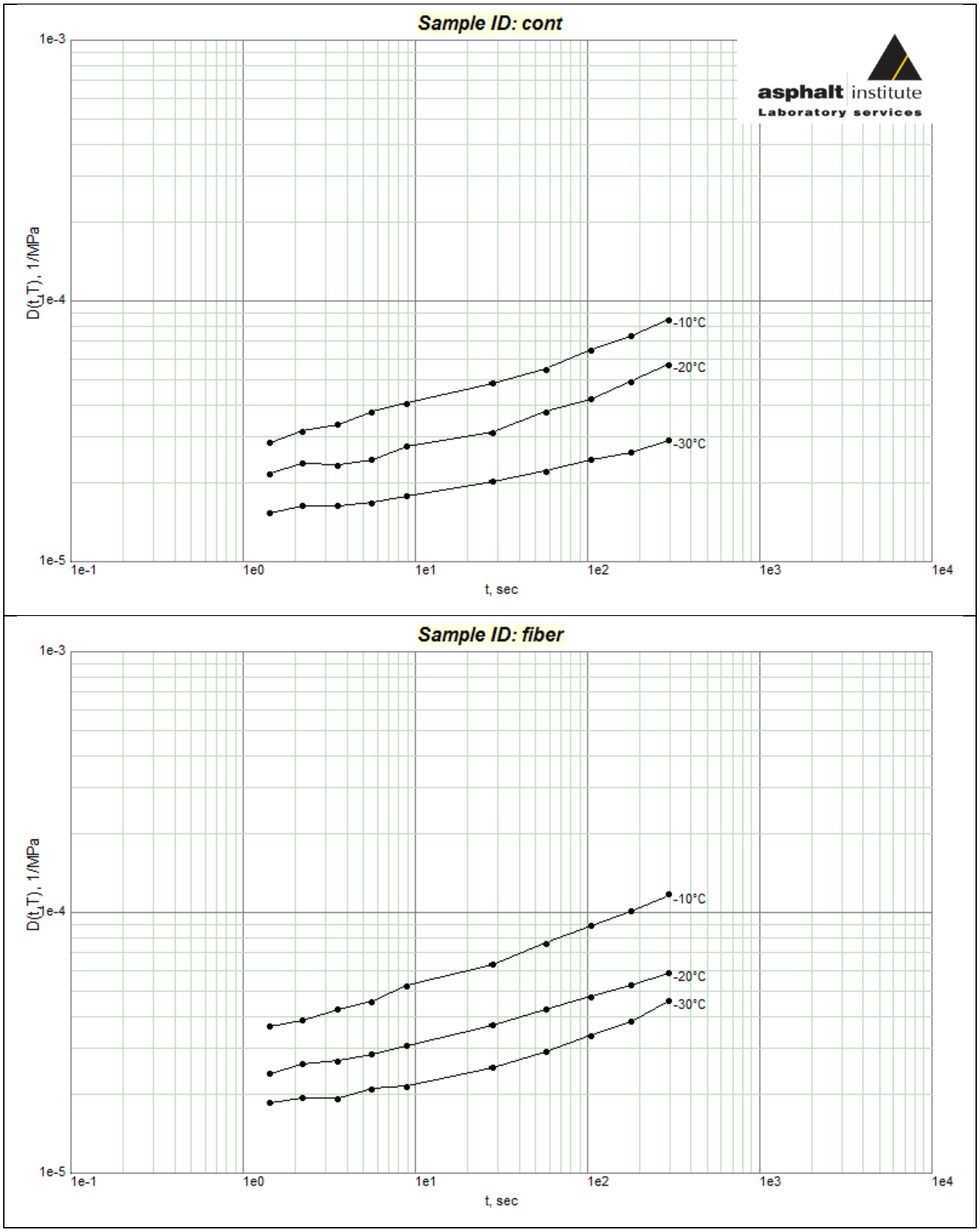


Figure 5
Isotherms from Compliance Testing of the Control and ACE Fiber Samples

The (IDT) Test

Shifted Compliance Curves (to determine time temperature shift)

Performed by Advanced Asphalt Technologies And Asphalt Institute

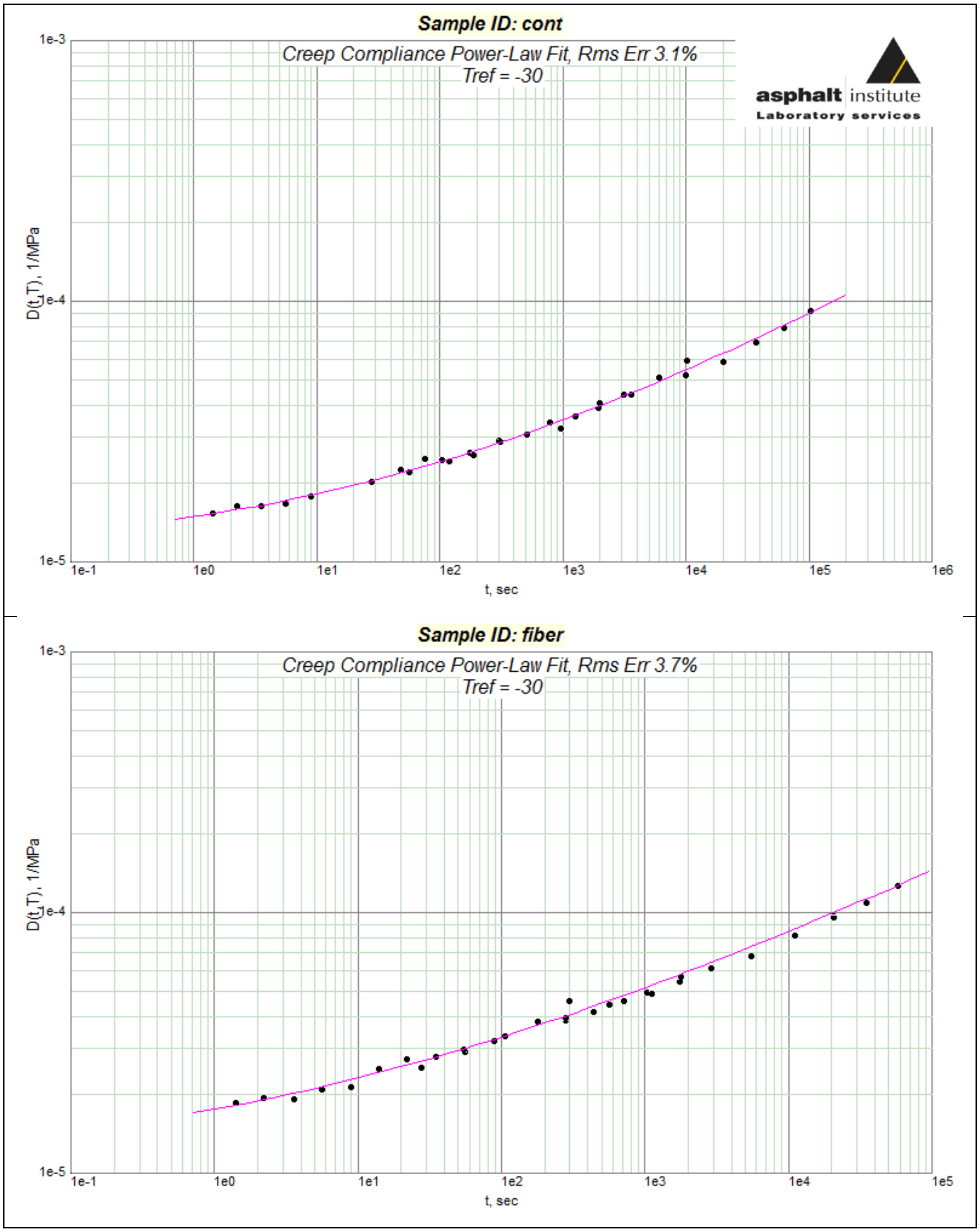


Figure 6
Shifted Compliance Curves (to determine time temperature shift) of the Control and ACE Fiber Samples

The (IDT) Test

Estimated Thermal Stress & Critical Cracking Temperature

Performed by Advanced Asphalt Technologies And Asphalt Institute

The control samples that were tested were averaged to produce a predicted low temperature critical cracking temperature:

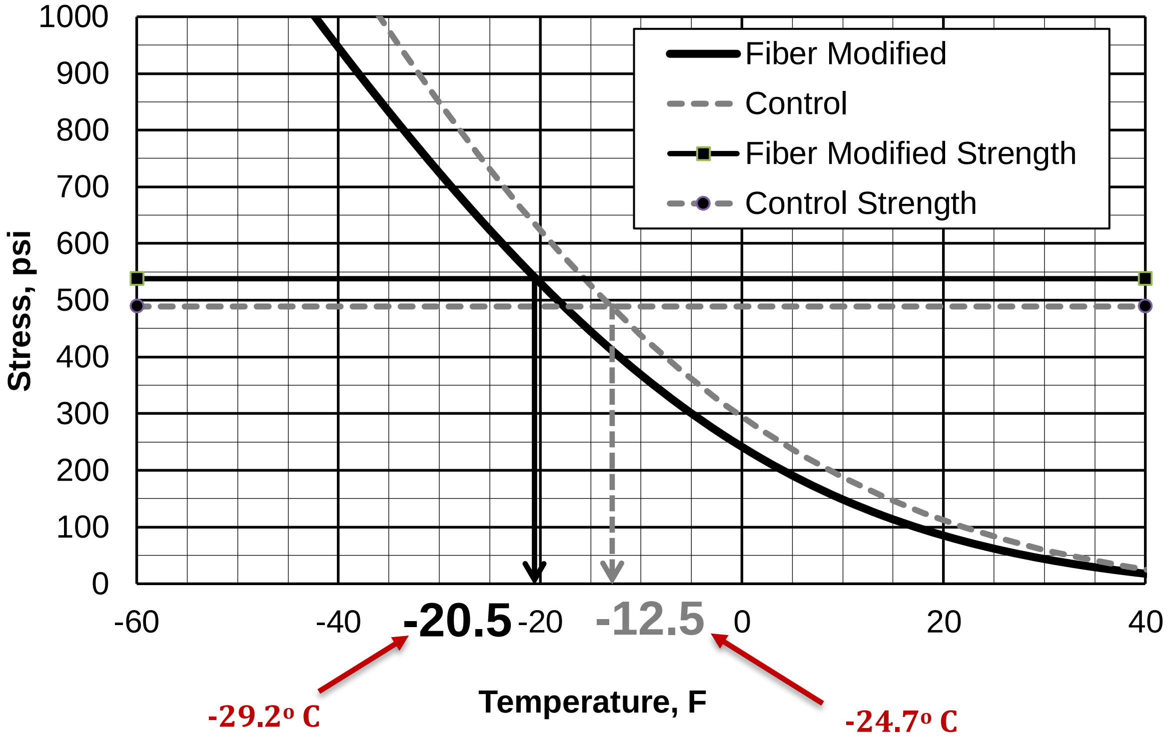
- Control sample (-24.7° C) and ACE Fiber sample (-29.2° C) – (AAT results)
- Control sample (-25.4° C) and ACE Fiber sample (-29.5° C) – (AI results)

While the ACE Fiber roots into asphalt binder making the mix stiffer, it appears that the ACE Fiber in these cases also improved the low temperature properties by -4.5° C (AAT) and -4.1 °C (AI), which is not typically shown by stiffer asphalt mixes. Essentially one could conclude that since the ACE fiber improves the low temperature properties, it is equivalent to lowering the PG low temperature grade to some extent.

This finding could lead to a cracking improvement of mixtures containing Reclaimed Asphalt Pavement (RAP) or Reclaimed Asphalt Shingles (RAS).

Figure 7
Estimated Thermal Stress

ADVANCED ASPHALT TECHNOLOGIES



The (IDT) Test Summary

The Indirect Tensile & Compliance Test

Performed by Advanced Asphalt Technologies And Asphalt Institute

Table 5 – IDT Improved Strength

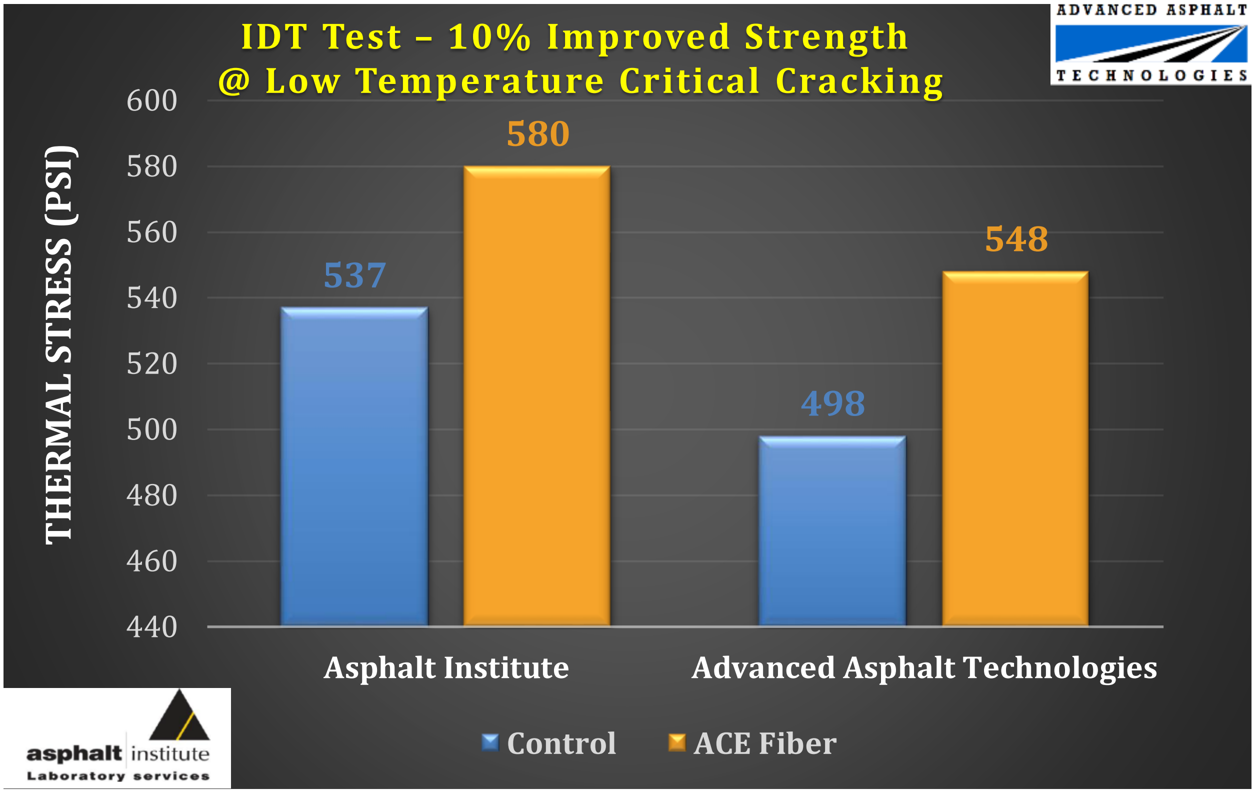
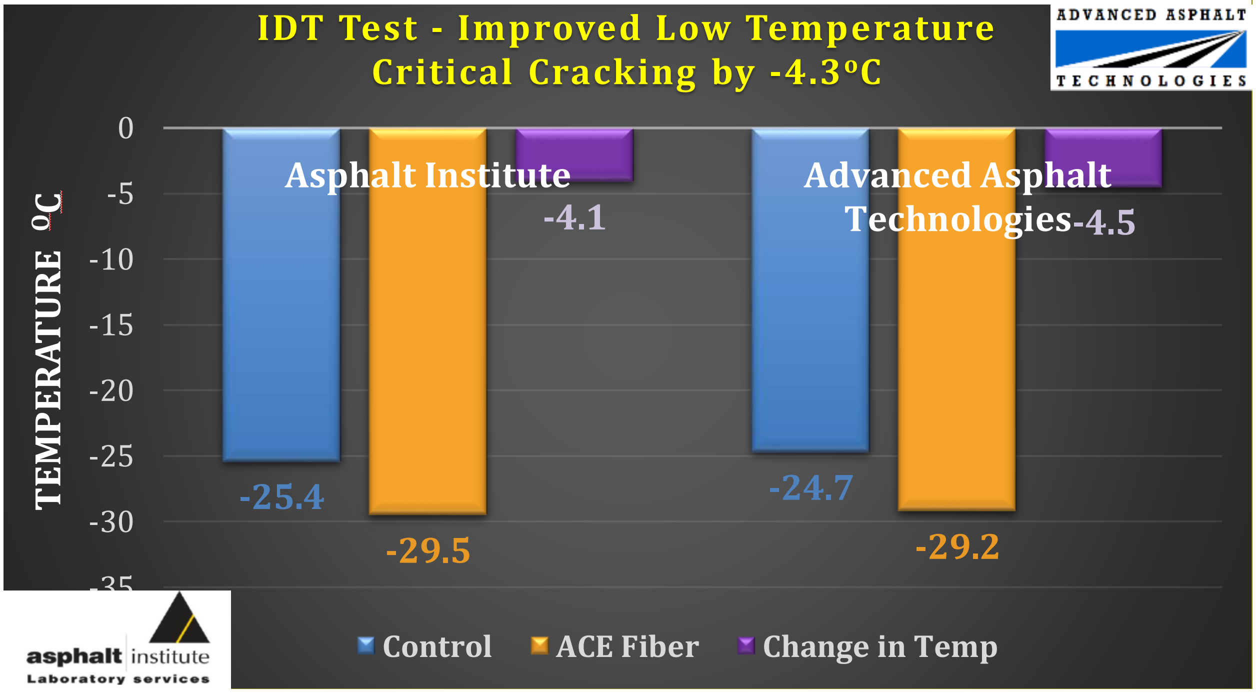


Table 6 – IDT Improved Low Temperature Cracking

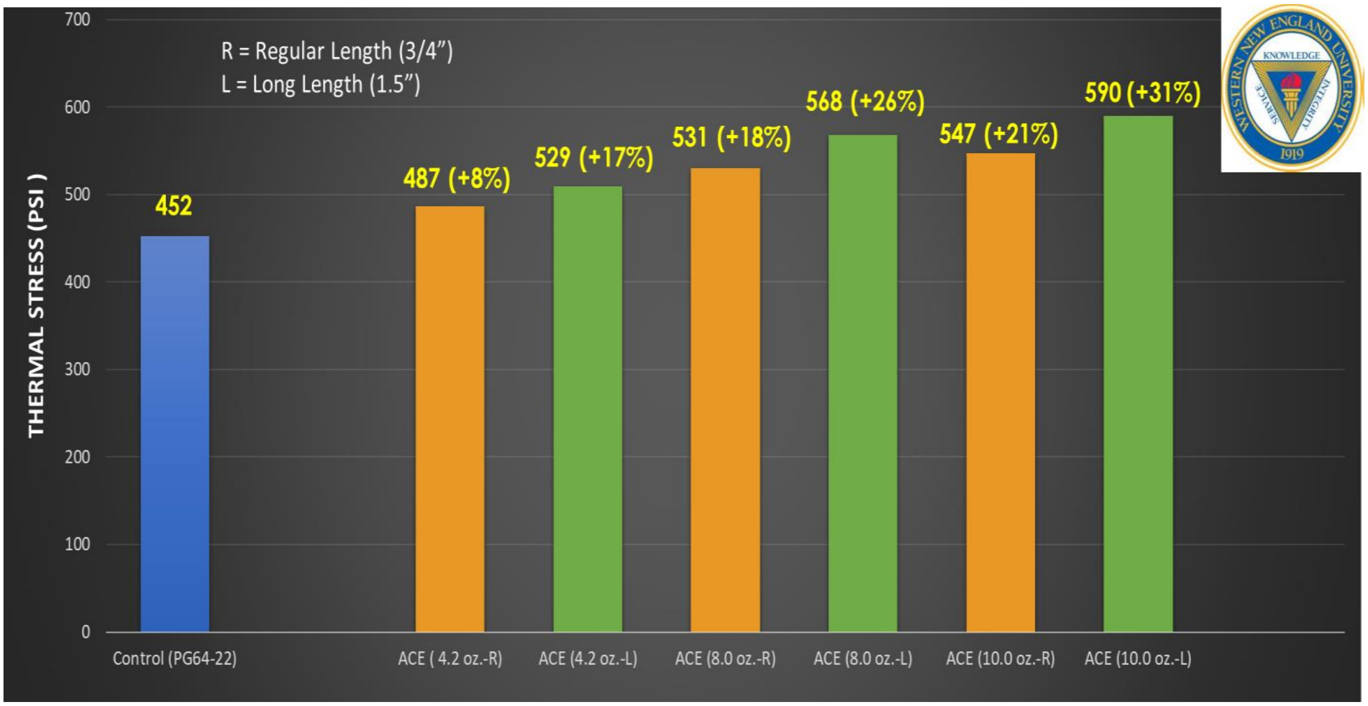


The (IDT) Test Summary

The Indirect Tensile @ -12° C

Performed by Western New England University

Table 7 – IDT Improved Low Temperature Cracking Resistance Both ¾” & 1 ½” Length ACE XP Polymer Fiber



The (IDT) Test Summary

The Indirect Tensile @ 25° C

Performed by University of Calgary

SAIT

Detailed Procedure – ASTM D6931 Indirect Tensile Strength of Asphalt Mixtures

Using a caliper, the thickness of each briquette was obtained by averaging 3 measurements equidistant from each other on the specimen face. Next the briquettes were conditioned and brought to the testing temperature of 25°C by submersion in a water bath. The specimens were taken one-by-one and placed in the IDT Strength-Loading fixture on the bottom loading strip. The top and bottom loading strips were positioned so that they were along the vertical diametric plane of the asphalt briquette. The loading fixture was then placed in the compression machine and loaded at 50±5mm/min until the maximum stress was reached.

Table 8 – IDT Improved High Temperature Cracking Resistance with 3 Different Asphalt Contents - 38mm Length ACE XP Polymer Fiber

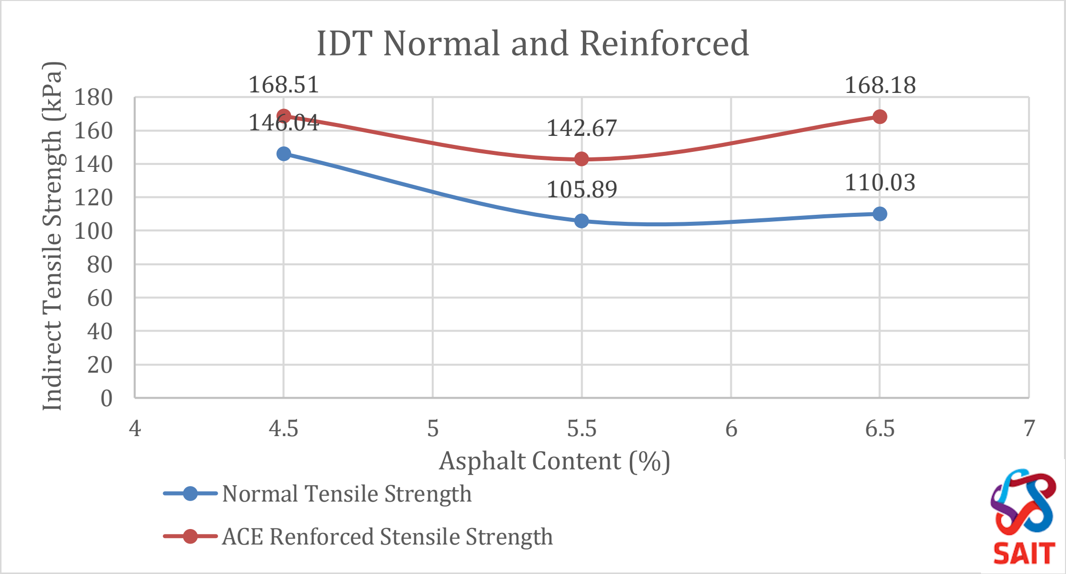


Table 9 – IDT Strength Comparisons with 3 Different Asphalt Contents - 38mm Length ACE XP Polymer Fiber

IDT			
IDT Strength Comparison Data			
AC content (%)	4.5%	5.5%	6.5%
Normal IDT Strength (kPa)	146.04	105.89	110.84
Reinforced IDT strength (kPa)	168.51	142.67	168.18
Increment	22.47	36.78	57.34
% Increase in Strength	15.4%	34.7%	51.7%

Hamburg Wheel Tracking Test

TxDOT Test Method 242F

Performed by Texas Transportation Institute
And Hi-Tech Asphalt Solutions

Test Summary:

The Hamburg Wheel Tracking Test is run under a water bath capable of controlling the test temperature within ± 2°C (4°F) over a range of 25 to 70°C (77 to 158°F). The steel wheel has a diameter of 203.6 mm (8 in.) and width of 47 mm (1.85 in.) over a test specimen. The load applied by the wheel is 705 ± 22 N (158 ± 5 lbs.). The wheel shall make approximately 50 passes across the test specimen per minute. The maximum speed of the wheel must be approximately 0.305 m/s (1.1 ft./sec).

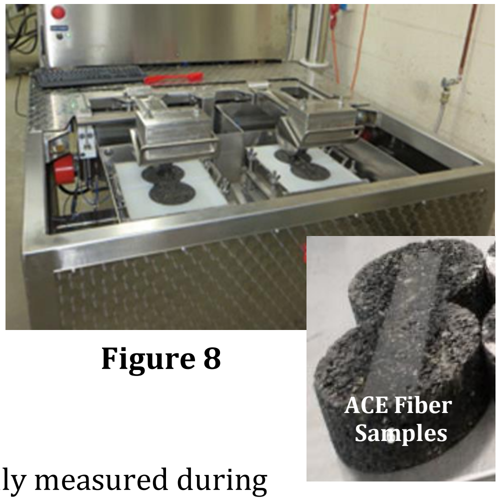


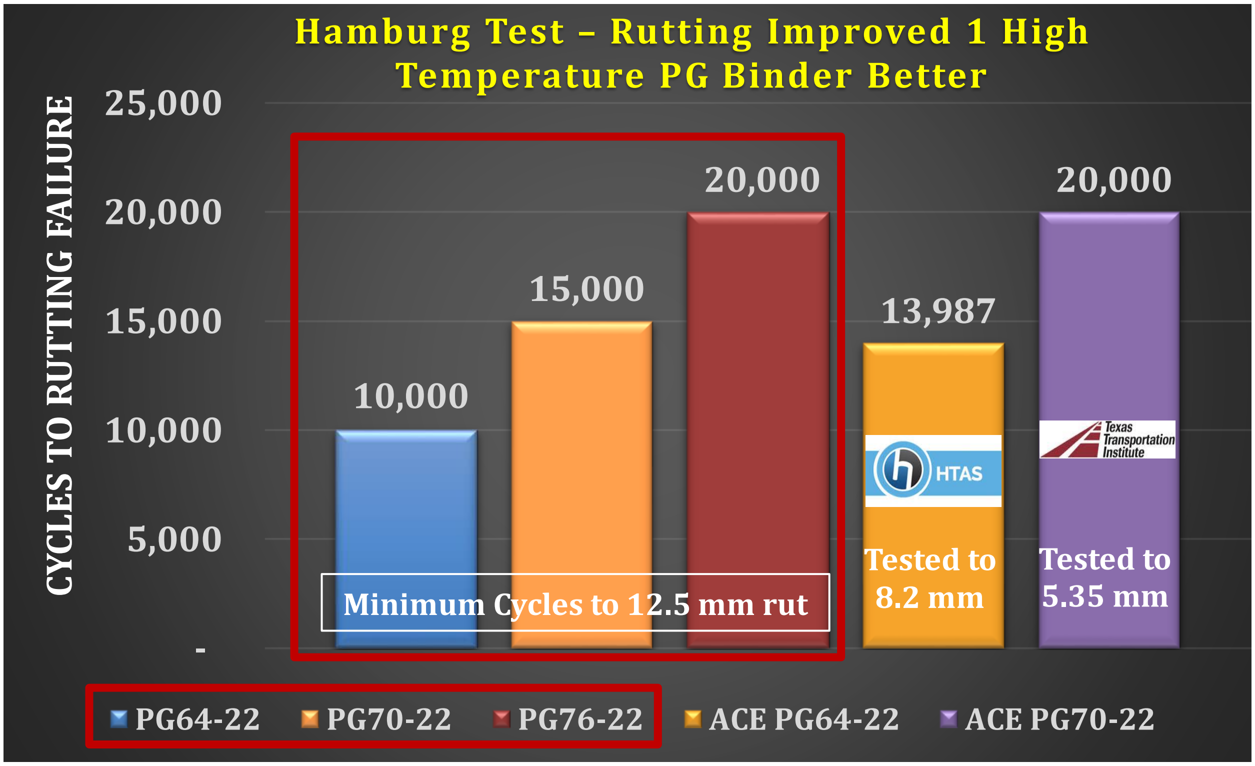
Figure 8

The rut depth induced by the steel wheel is automatically measured during the test. The test is run until the **rut depth** exceeds 12.5mm (0.50 inches). Test apparatus is shown in Figure 8.

Results:

PG64-22 with ACE Fiber tested by HTAS performed like PG70-22 & the PG70-22 with ACE Fiber tested by TTI performed like PG76-22. One Performance Grade Higher (Top Number).

Table 11 –Improved Rut Resistance



Hamburg Wheel Tracking Test

TxDOT Test Method 242F

Performed by West Texas Paving and Century Asphalt

Table 12 – Improved Rut Resistance (West Texas Paving PG64-22 Mix)

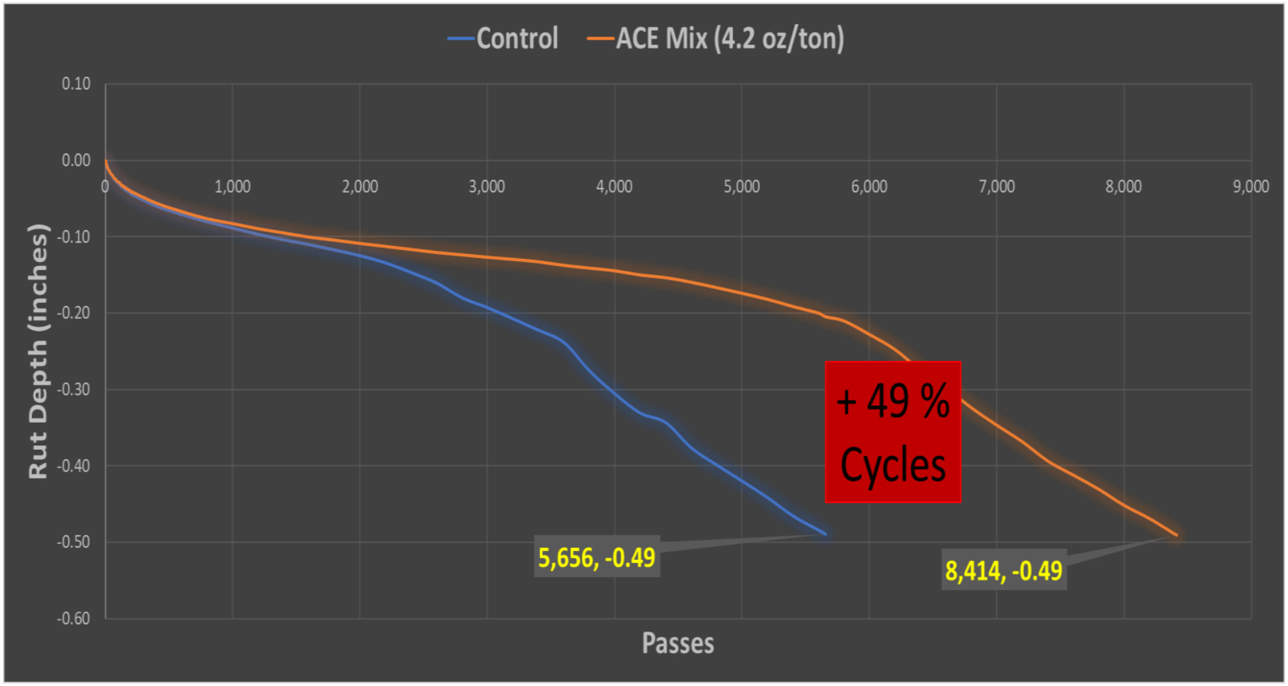
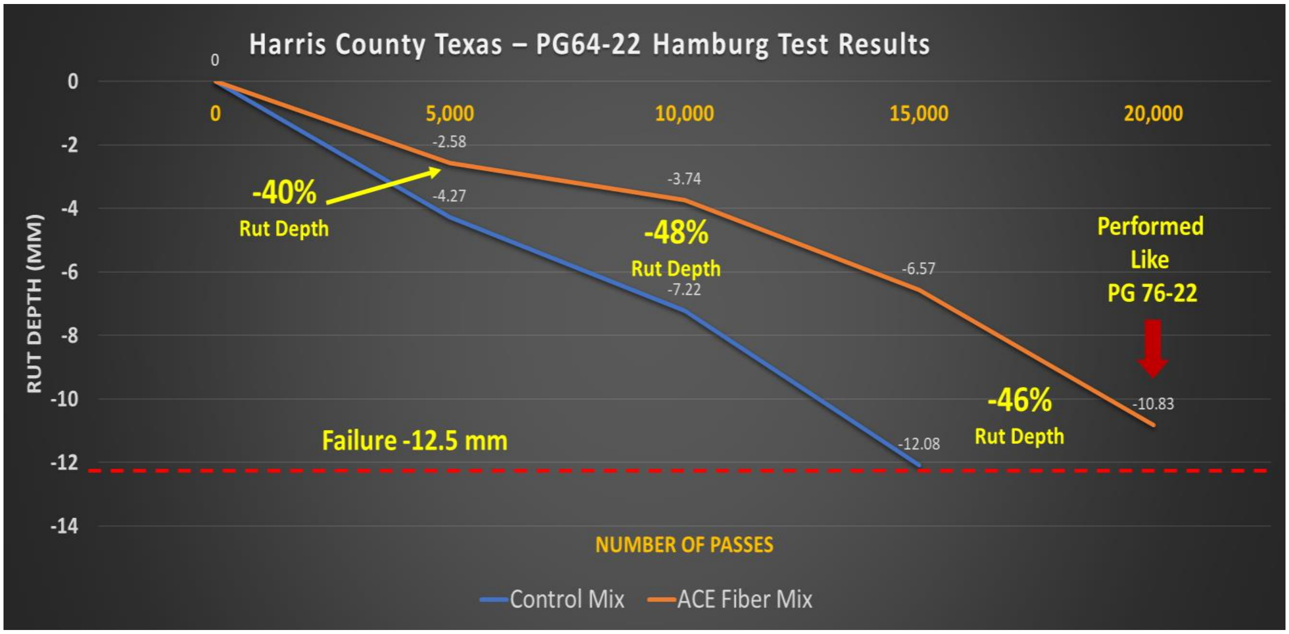


Table 13 – Improved Rut Resistance (Century Asphalt)



The (APLT) Static Creep Test

The Automated Plate Load Test

Performed by Ingios Geotechnics, Inc.

Test Summary:

The Automated Plate Load Test (APLT)

Ingios Geotechnics, Inc. has developed rapid in-situ testing using Automated Plate Load Testing (APLT) and analysis methods to characterize the in-situ **dynamic modulus (*E*)** and repeated and static load creep or permanent deformation properties of the AC layer. Equipment developed by Ingios is shown in Figure 9.

> ***"The major advantage of in-situ testing is that it does not suffer from the effects of sample preparation, sample size, equipment, and boundary conditions associated with laboratory tests"***

Figure 9

In situ testing was performed at three test locations on September 14, 2016 in a medium duty test section in the parking lot of Love's Travel Stop in Sadieville, KY. The test section consisted of 2 in. AC surface course layer, 4.5 in. of AC base course layer, 8 in. of dense graded aggregate base layer, Type 2 geogrid, and subgrade. A second Love's Travel Stop location, Greenwood, LA, was tested on March 8, 2017. This location had both an ACE Fiber Reinforced Section and a Control Section. The LA test section consisted of 2 in. AC surface course layer, 6 in. of AC base course layer, 10 in. of dense graded aggregate base layer, Type 2 geogrid, and lime stabilized subgrade.

Results:

Static creep test results showed that permanent deformation (δ_p) at the end of the static creep test with applied contract stress of 150 psi averaged about 0.14 in. Forecasting power models show that at all three test locations the number of loading cycles to achieve 0.5 inch permanent deformation (i.e., definition of "rut") are greater than 25,000 hours for all tests.

The static loading tests demonstrated resilient behavior during un-loading from 250 psi to 0 psi where the deformation after loading from 150 to 250 psi was fully recovered. This behavior suggests that the fiber reinforced AC stores energy during loading (energy is not dissipated in plastic deformation), which partially explains how the fibers can potentially help resist deformation. Tertiary flow was not observed in any of the three static tests, therefore flow time could not be calculated.

Static creep test using a 4 in. diameter spherical dome plate using 20,000 lbs. constant load was conducted which produced an indentation in the fiber reinforced AC layer. No radial tension cracks were developed around the indentation. The observation of no radial cracks in this test can be partly attributed to the improved shear resistance in the fiber reinforced AC mixtures.

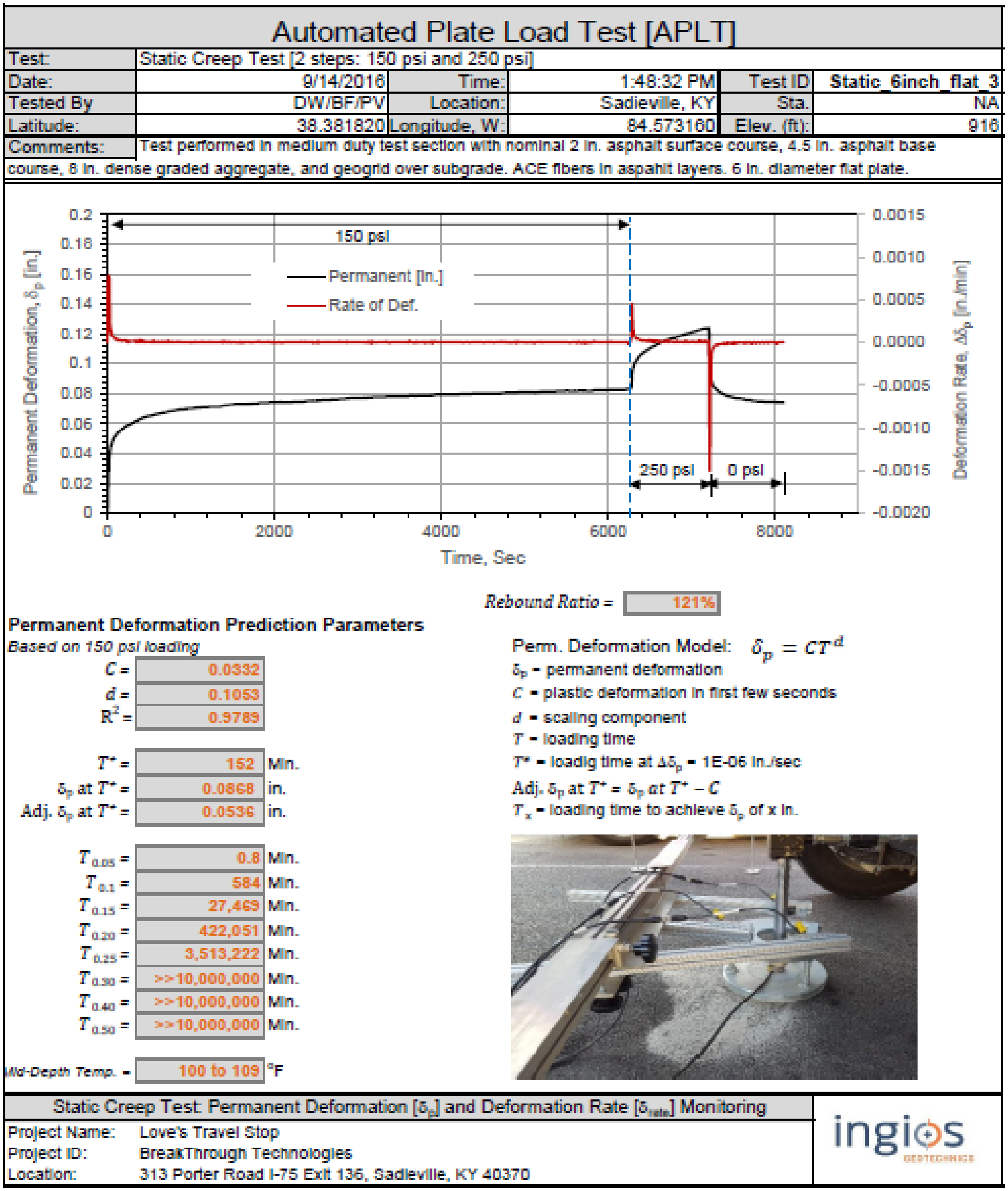
The (APLT) Static Creep Test

(6" Flat Plate)

Performed by Ingios Geotechnics, Inc.

(Kentucky Site)

Figure 10 – APLT Static Creep Test Result



Automated Plate Load Test [APLT]

Test:	Static Creep Test [2 steps: 150 psi and 250 psi]				
Date:	9/14/2016	Time:	1:48:32 PM	Test ID	**Static_6inch_flat_3**
Tested By	DW/BF/PV	Location:	Sadieville, KY	Sta.	NA
Latitude:	38.381820	Longitude, W:	84.573160	Elev. (ft):	916

Comments: Test performed in medium duty test section with nominal 2 in. asphalt surface course, 4.5 in. asphalt base course, 8 in. dense graded aggregate, and geogrid over subgrade. ACE fibers in aspahlt layers. 6 in. diameter flat plate.

Rebound Ratio = 121%

Permanent Deformation Prediction Parameters

Based on 150 psi loading

C =	0.0332	
d =	0.1053	
R^2 =	0.9789	
T^* =	152	Min.
δ_p at T^* =	0.0868	in.
Adj. δ_p at T^* =	0.0536	in.
$T_{0.05}$ =	0.8	Min.
$T_{0.1}$ =	584	Min.
$T_{0.15}$ =	27,469	Min.
$T_{0.20}$ =	422,051	Min.
$T_{0.25}$ =	3,513,222	Min.
$T_{0.30}$ =	>>10,000,000	Min.
$T_{0.40}$ =	>>10,000,000	Min.
$T_{0.50}$ =	>>10,000,000	Min.
Mid-Depth Temp. =	100 to 109	°F

Perm. Deformation Model: $\delta_p = CT^d$

δ_p = permanent deformation

C = plastic deformation in first few seconds

d = scaling component

T = loading time

T^* = loadig time at $\Delta\delta_p$ = 1E-06 in./sec

Adj. δ_p at T^* = δ_p at $T^* - C$

T_x = loading time to achieve δ_p of x in.

Static Creep Test: Permanent Deformation [δ_p] and Deformation Rate [δ_{rate}] Monitoring

Project Name: Love's Travel Stop
Project ID: BreakThrough Technologies
Location: 313 Porter Road I-75 Exit 136, Sadieville, KY 40370

The (APLT) Static Creep Test

(6” Flat Plate)

Performed by Ingios Geotechnics, Inc.

(Louisiana Site)

Figure 11 – APLT Static Creep Test Result ACE Fiber vs Control

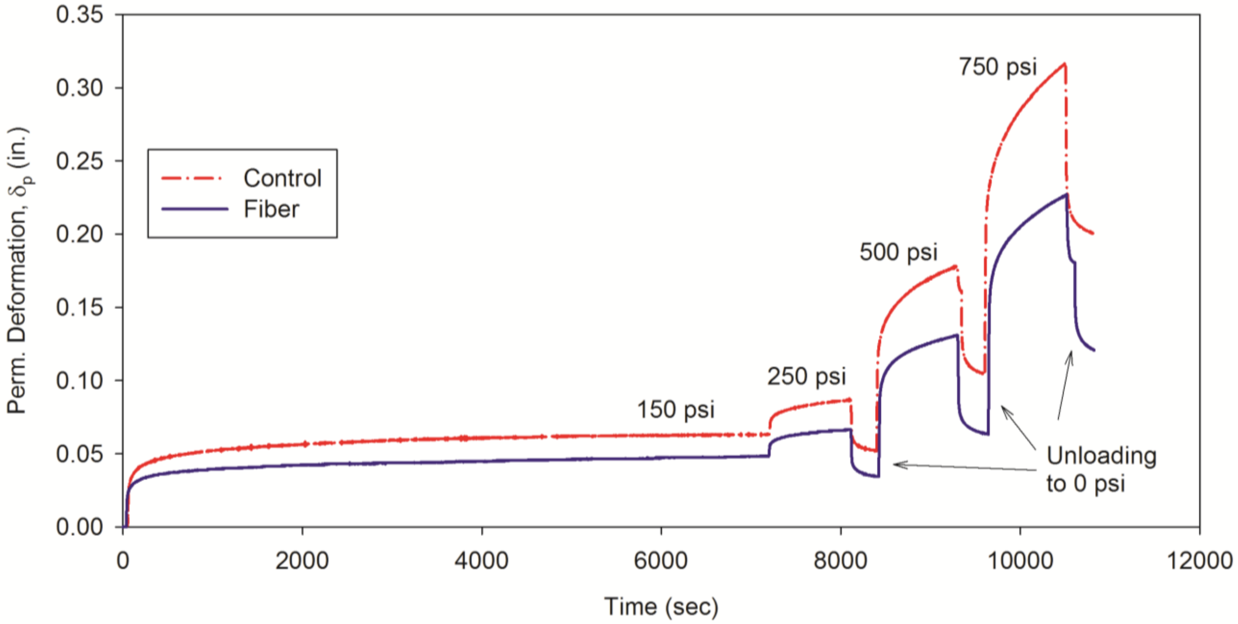
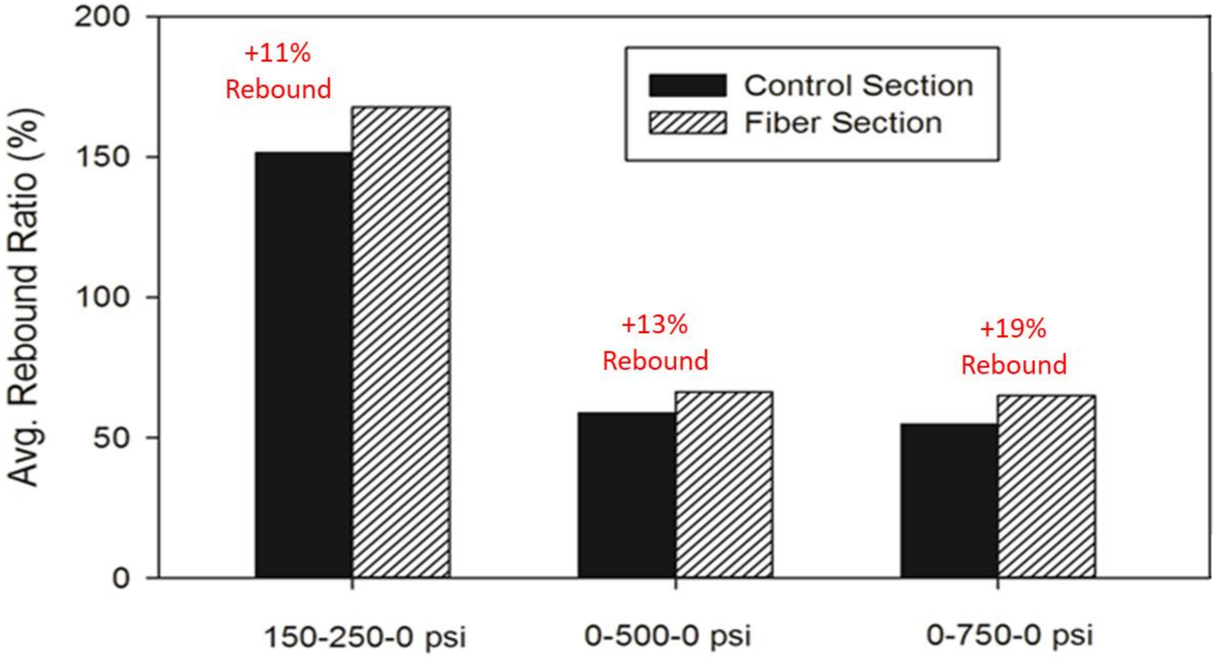


Figure 12 – APLT Static Creep Test Result ACE Fiber vs Control Rebound % Comparison



The (APLT) Static Creep Test

(6" Flat Plate)

Performed by Ingios Geotechnics, Inc.

(Louisiana Site - Continued)

Figure 13 – APLT Static Creep Test Result ACE Fiber vs Control Rut Depth Comparison

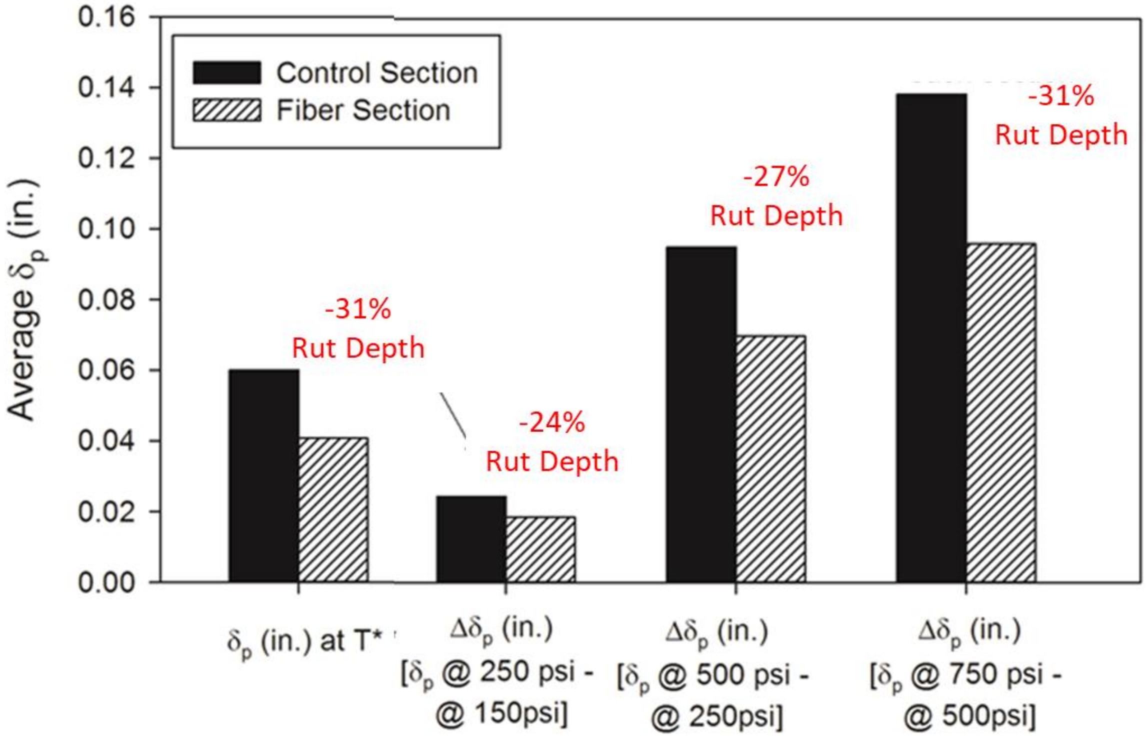


Figure 15
Permanent ACE Fiber Section Deformation after test completion

Figure 14
6 in. diameter flat plate - ***Repeated Load and Static Load Creep Test***

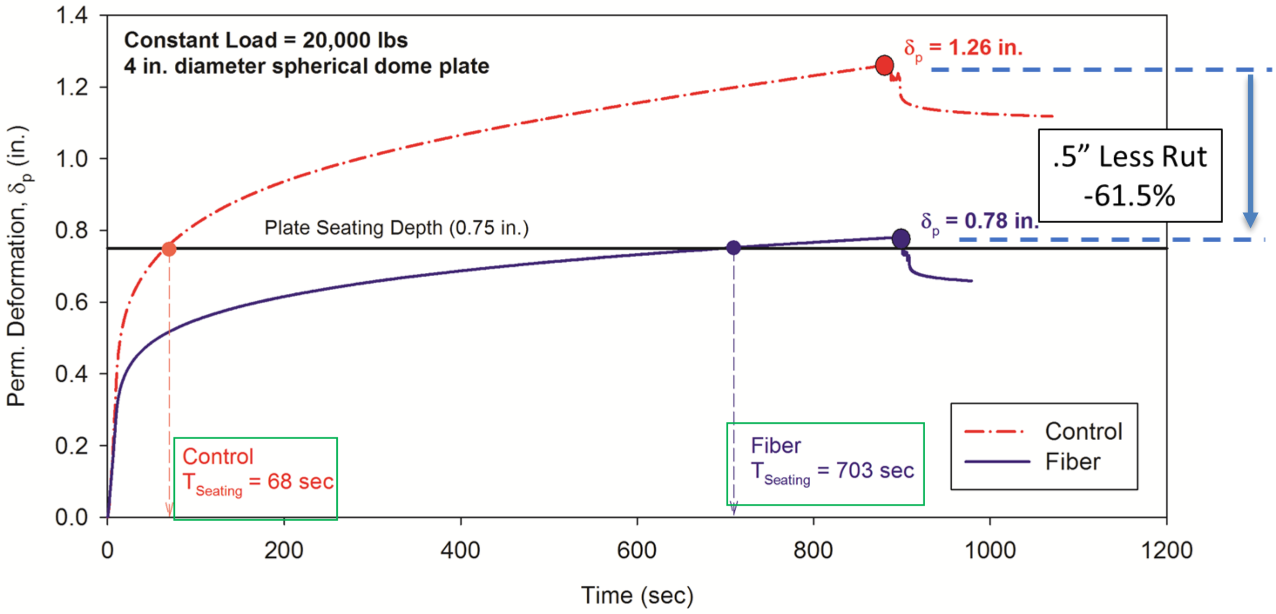
The (APLT) Static Creep Test

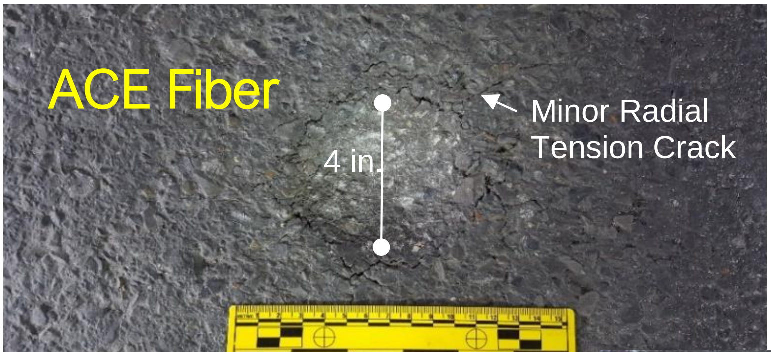
(4” Spherical Dome)

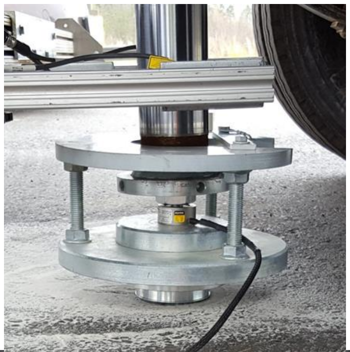
Performed by Ingios Geotechnics, Inc.

(Louisiana Site)

Figure 16 – APLT Static Creep Test Result ACE Fiber vs Control Rut Depth & Time to Rutting Comparison







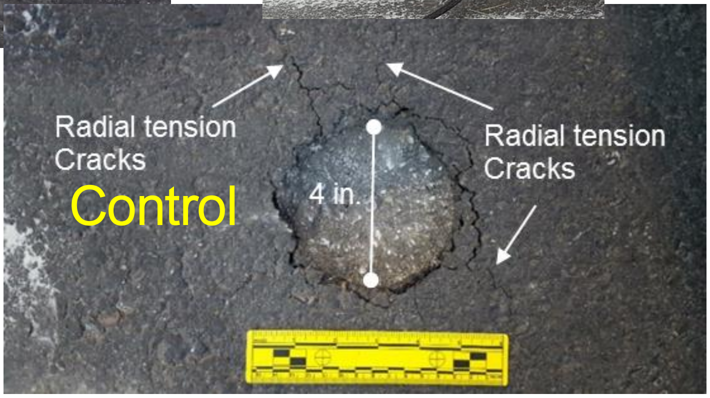


Figure 17
Radial Tension Cracks after the 4” Domed Test Completion

The (APLT) Dynamic Modulus Test

The Automated Plate Load Test

Performed by Ingios Geotechnics, Inc.

Test Summary:

The Automated Plate Load Test (APLT) Ingios Geotechnics, Inc. has developed rapid in-situ testing using Automated Plate Load Testing (APLT) and analysis methods to characterize the in-situ **dynamic modulus (*E*)** and repeated and static load creep or permanent deformation properties of the AC layer. Equipment developed by Ingios is shown in Figure 10.

"The major advantage of in-situ testing is that it does not suffer from the effects of sample preparation, sample size, equipment, and boundary conditions associated with laboratory tests"

Figure 18

In situ testing was performed at three test locations on September 14, 2016 in a medium duty test section in the parking lot of Love's Travel Stop in Sadieville, KY. The test section consisted of 2 in. AC surface course layer, 4.5 in. of AC base course layer, 8 in. of dense graded aggregate base layer, Type 2 geogrid, and subgrade. A second Love's Travel Stop location, Greenwood, LA, was tested on March 8, 2017. This location had both an ACE Fiber Reinforced Section and a Control Section. The LA test section consisted of 2 in. AC surface course layer, 6 in. of AC base course layer, 10 in. of dense graded aggregate base layer, Type 2 geogrid, and lime stabilized subgrade.

Results:

The in-situ back calculated and temperature corrected ACE Fiber reinforced AC layer moduli (E'_{AC}) values averaged between the two sites at about 1,155,000 psi for 70 psi cyclic stress and loading frequency of 1.59 Hz. Likewise an average of the control with AASHTO standard was about 469,568 psi. The ACE Fiber reinforced AC layer showed about 150% increase in Modulus between the two sites.

ESAL calculations were performed using the measured subgrade M_R values. Results and analysis from the two test sites produced an average structural layer coefficient for the fiber reinforced AC layer (a_1) of 0.59 and an average of 54.3 million ESALs.

Considering $a_1 = 0.44$ which represents an unreinforced AC layer and keeping all other input parameters constant, the number of ESALs is calculated as 12.7 million. ESAL calculations showed that compared to an unreinforced AC layer case ($a_1 = 0.44$), the ACE fiber reinforced AC layer ($a_1 = 0.59$) increased the average number of ESALs by about 4.3 times.

The (APLT) Dynamic Modulus Test

(Combined Results from both Ketucky & Louisianna Sites)

Performed by Ingios Geotechnics, Inc.

Table 14 –Improved Elastic Modulus

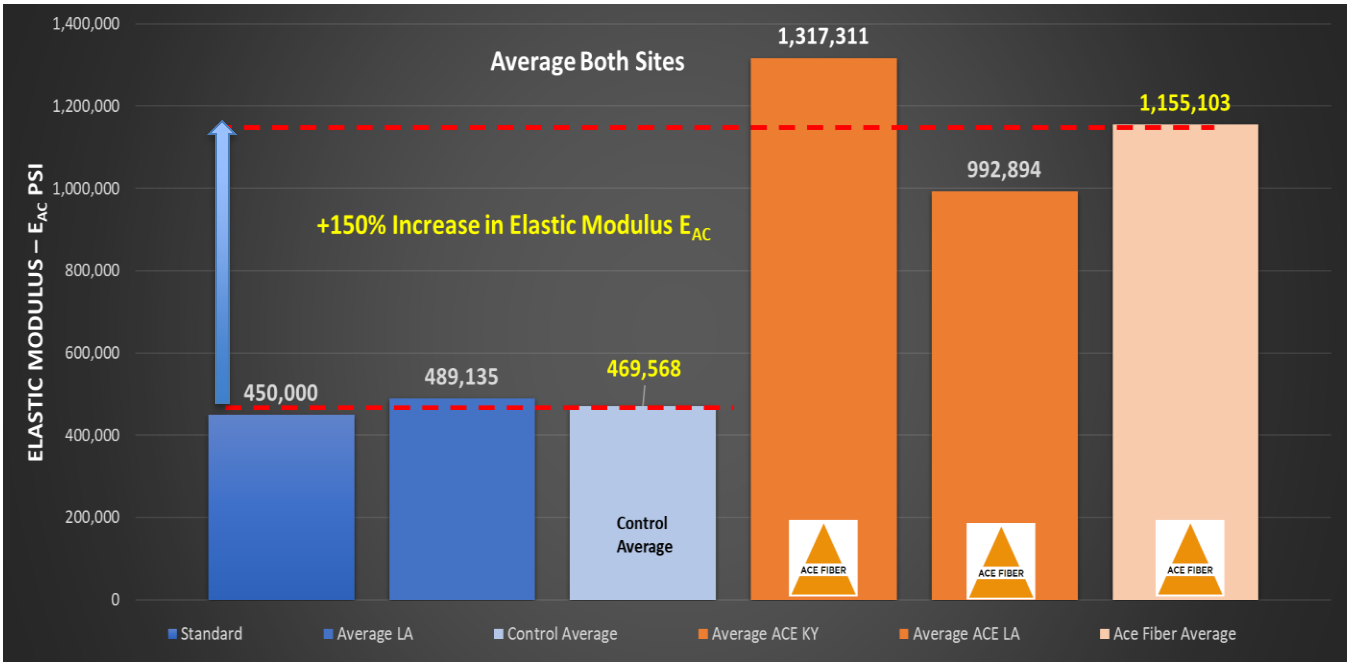
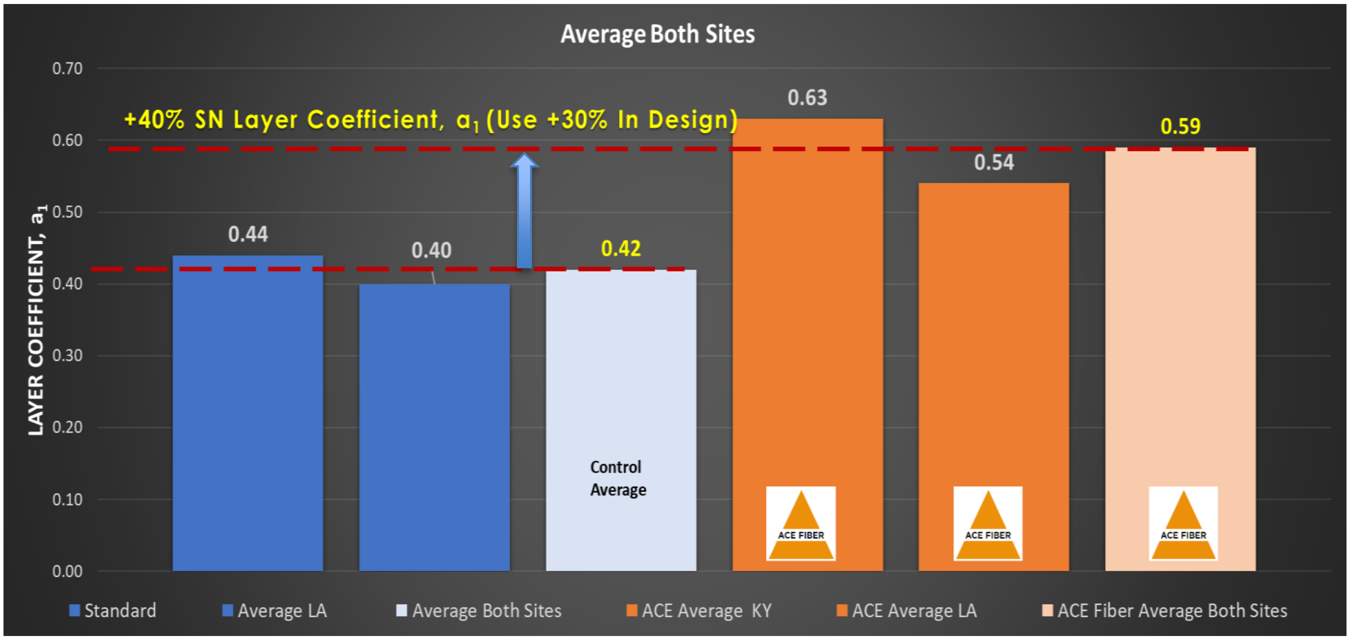


Table 15 –Improved SN Layer Coefficient

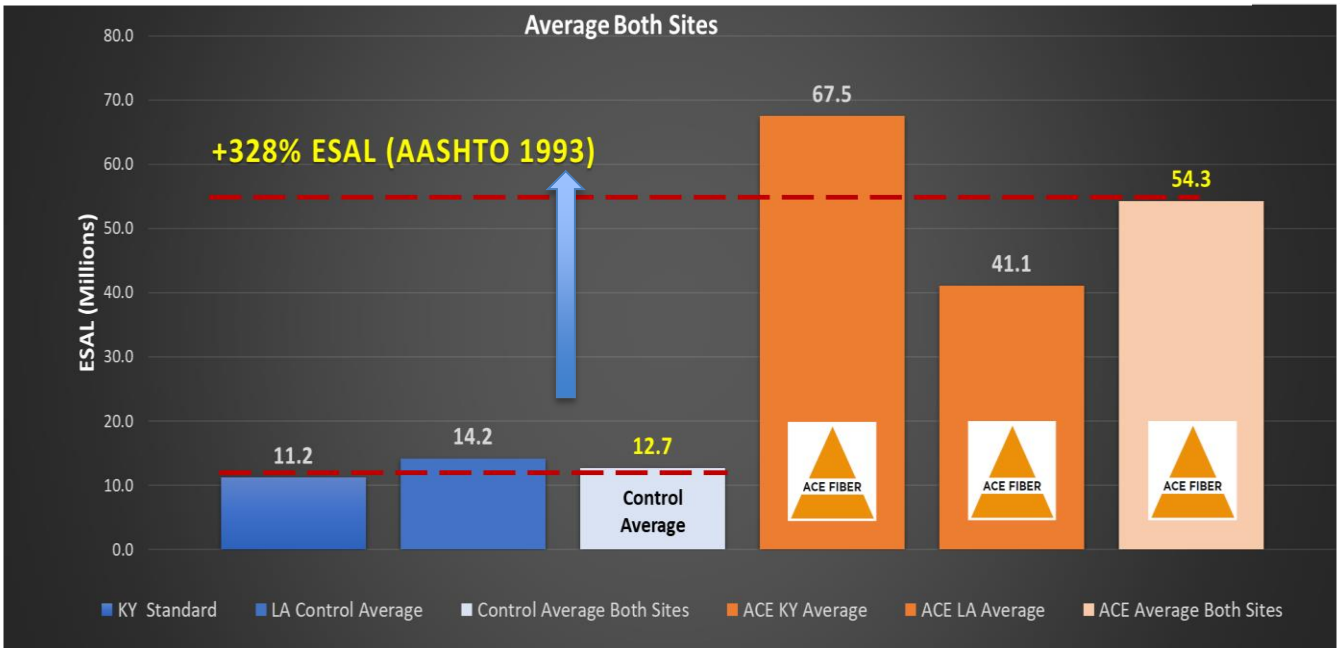


The (APLT) Dynamic Modulus Test

(Combined Results from both Ketucky & Louisianna Sites)

Performed by Ingios Geotechnics, Inc.

Table 16 –Improved ESAL Count



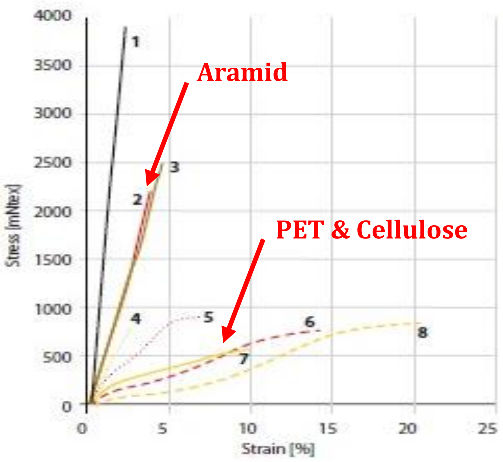
ACE XP Polymer Fiber™ is Engineered for Performance

Aramid Fibers are used extensively in many industries and applications including ballistic protection, heat & cut protection, automotive, ropes & cables, conveyor belts, etc. However, it takes a special fiber to withstand the extreme production temperatures of asphalt concrete without changes occurring to the reinforcement properties of the fiber. That is why ACE XP Polymer Fiber™ uses aramid fibers exclusively. Aramid is a unique man-made, high-strength fiber boasting high tensile strengths over 400,000 psi (5 x steel), a superior stress/strain relationship, and decomposition temperatures exceeding 800°F (well above asphalt mixing temperatures of 400°F).

Aramid Specifications

Material Property	Value
Density (g/cm3)	1.44
Tensile Strength (N/tex)	2.4-3.6
Modulus (GPa)	60-120
Elongation at Break (%)	2.2-4.4
Tenacity (N/tex)	1.65-2.5
Decomposition Temperature	800

Aramid Stress/Strain Curves



Semi-Circular Bend Test (SCB)

Flexibility Index Test (FI)

Performed by Oregon State University

Test Summary:

FI is a ratio of the fracture energy (G_f) to the slope of the line at the post-peak inflection point of the load-displacement curve and is a parameter specific to asphalt pavement, which correlates to the brittleness of the material. It has been shown in recent studies to be highly indicative of pavement cracking resistance and is considered the most comprehensive way of assessing cracking resistance.

Figure 19 – SCB Test Samples

Results:

Test results are presented below. The blue bars represent the average FI from four replicate experiments while the length of the error bar on each bar represents the variability of the measured FI for each set (error bar length = two standard deviations). The mix with 1-1/2" fibers had the highest FI compared to the other two mixtures. It was observed that there is no significant difference between FI of the control mixture and the 3/4" aramid fiber mixture. However, with the use of 1-1/2" fibers, there was an approximate 37% increase in the FI value, suggesting that longer fibers significantly improve the cracking performance of asphalt mixtures.

Figure 20 – SCB Test Set-up

Coleri et al. (2017a) tested three different ODOT Level 4 production mixes with different mix designs and obtained FI values ranging from 9 to 14. The asphalt mixture with 1-1/2" fibers in this study provided an average FI of 18.5 that is higher than the highest FI observed by Coleri et al. (2017a). However, it should be noted that mixtures from the Coleri et al. (2017a) study were different from the mixtures tested in this study and should not be used as control results.

$$FI=A*\frac{G_f}{abs(m)}$$

Where:

G_f = fracture energy (KJ/m^2),

abs(m) = absolute value of the slope at inflection point of post-peak load-displacement curve,

A = unit conversion factor and scaling coefficient.

Semi-Circular Bend Test (SCB)

Flexibility Index Test (FI)

Performed by Oregon State University

Flexibility index (FI) is the ratio of the fracture energy (G_f) to the slope of the line at the post-peak inflection point of the load-displacement curve (Figure 21). FI correlates with brittleness and it was developed for asphalt materials by Ozer et al. (2016). Lower FI values show that the asphalt mixtures are more brittle and have a higher crack growth rate (Ozer et al. 2016).

Figure 21 - Illustration of load-displacement curve and slope at inflection point (m)

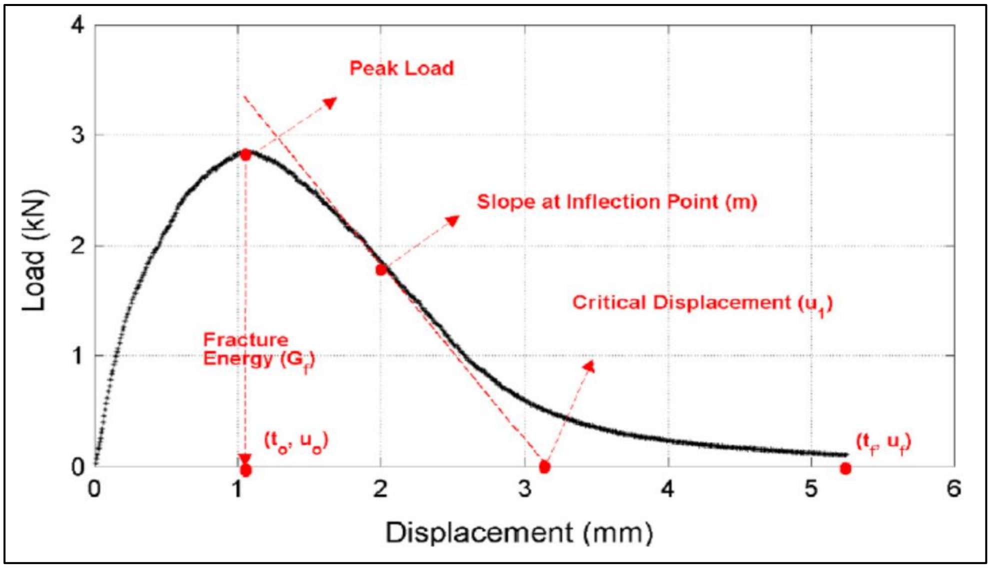
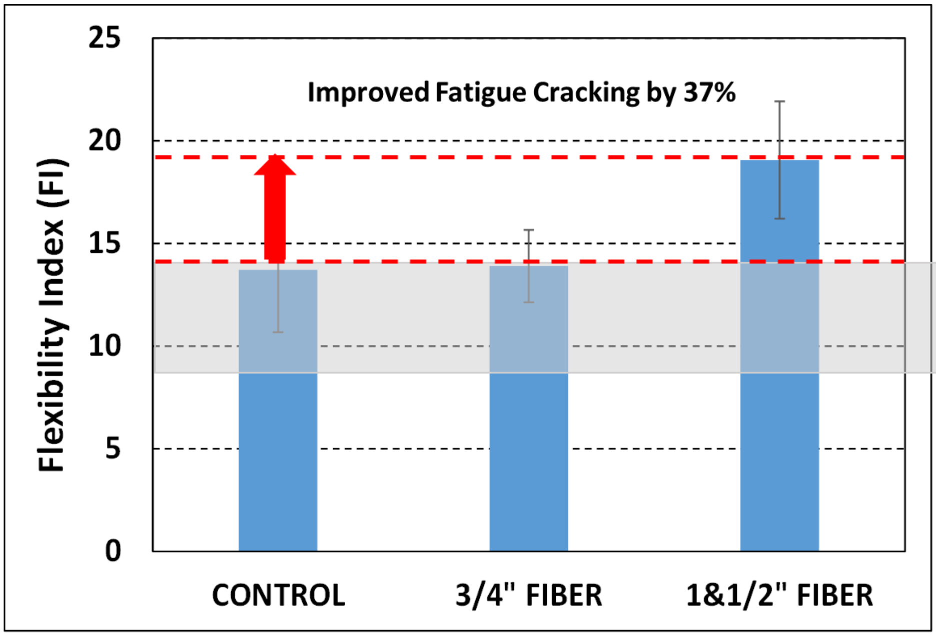


Figure 22 – ACE Fiber 1.5" Lengths improved the FI by 37% over Control



Asphalt Mix:
- 25% RAP
- PG 70-22ER
- 5.4% AC

Range of FI for Typical ODOT Level 4 Mixes

Flexibility index from SCB tests for ODOT Level 3 PMLC samples.

The Flow Number Test (FN)

Rut Resistance Index

Performed by Oregon State University

Test Summary:

The flow number (FN) test is a performance test for evaluating rutting resistance of asphalt concrete mixtures (Bonaquist et al. 2003). In this test, while a constant deviator stress is applied at each load cycle on the test sample, the permanent strain at each cycle is measured (Figure 23). Permanent deformation of asphalt pavement has three stages: 1) primary or initial consolidation, 2) secondary and 3) tertiary or shear deformation (Biligiri et al. 2007). Figure 23 shows three stages of permanent deformation. FN is taken as the loading cycle at which the tertiary stage begins following the secondary stage. Justification for selection of FN criteria is determined using the Francken model, which is discussed below.

Results:

The flow number (FN) test is a simple performance test for evaluating rutting performance of asphalt concrete mixtures (Bonaquist et al. 2003). High FN values indicate that asphalt mixtures have high rutting resistance. Since the DM test is a non-destructive test (low strain level), the same samples prepared for DM tests were used for FN tests to compare the rutting resistance of HMA mixtures. Therefore, a total of six tests were conducted (two replicate tests for each mix type). Figure 24 illustrates the FN results for all three mixes. From this figure, it can be observed that the mixture with 1-1/2" aramid fibers had the highest flow number followed by the mixture with 3/4" aramid fibers and the control mixture. It is quite evident that the use of aramid fibers significantly improved the rutting resistance of asphalt mixtures. The use of 1-1/2" fibers increased the rutting resistance by about 37.5%.

Coleri et al. (2017a) tested three different ODOT Level 4 production mixes with different mix designs and obtained FN values ranging from 400 to 750. The asphalt mixture with 1-1/2" fibers in this study provided an average FN of 560 that is within the FN range observed by Coleri et al. (2017a). However, it should be noted that mixtures from the Coleri et al. (2017a) study were different from the mixtures tested in this study and should not be used as control results.

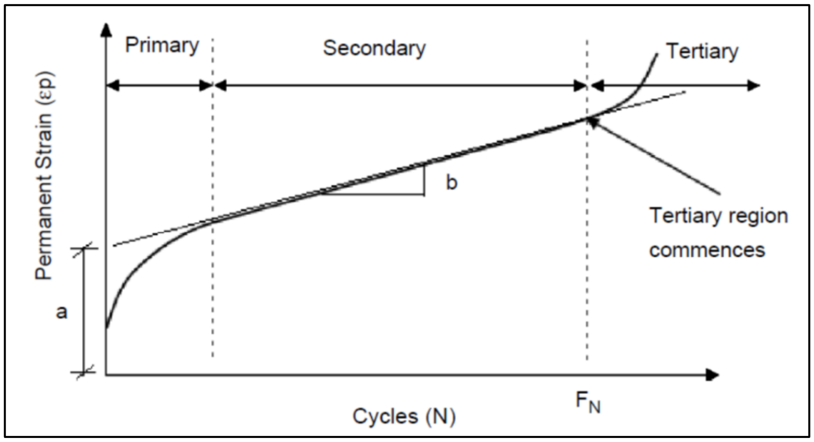


Figure 23 – Relationship between permanent strain and load cycles in FN test **(Biligiri et al. 2007)**

The Flow Number Test (FN)

Rut Resistance Index

Performed by Oregon State University

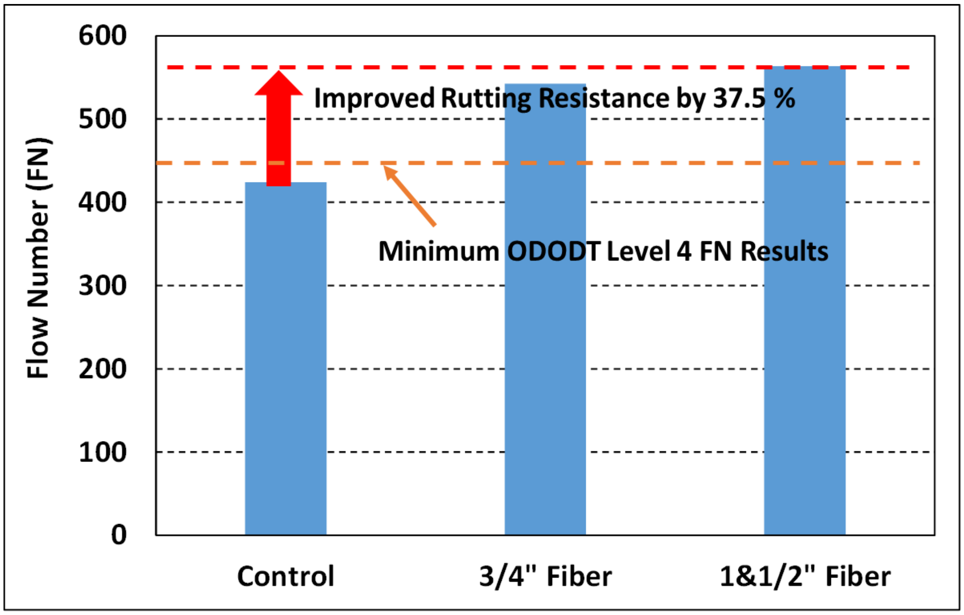
In this study, testing conditions and criteria for FN testing described in AASHTO TP 79-13 for unconfined tests were followed. The recommended test temperature, determined by LTPPBind Version 3.1 software, is the average design high pavement temperature at 50% reliability for cities in Oregon with high populations and at a depth of 20 mm (0.79 in) for surface courses (Rodezno et al. 2015). Tests were conducted at a temperature of 54.7°C with an average deviator stress of 600 kPa and minimum (contact) axial stress of 30 kPa. For conditioning, samples were kept in a conditioning chamber at the testing temperature for 12 hours prior to testing. To calculate FN in this study, the Francken model was used (discussed below).

Minimum FN values (calculated by using the Francken model) for different traffic levels recommended by AASHTO TP 79-13 are given in 12 (Rodezno et al. 2015).

Table 17: Minimum average FN requirement for different traffic levels

Traffic (million ESALs)	Minimum Average FN Requirement
<3	NA
3 to <10	50
10 to <30	190
≥30	740

Figure 24 – ACE Fiber 1.5” Lengths improved the FN by 37.5% over Control



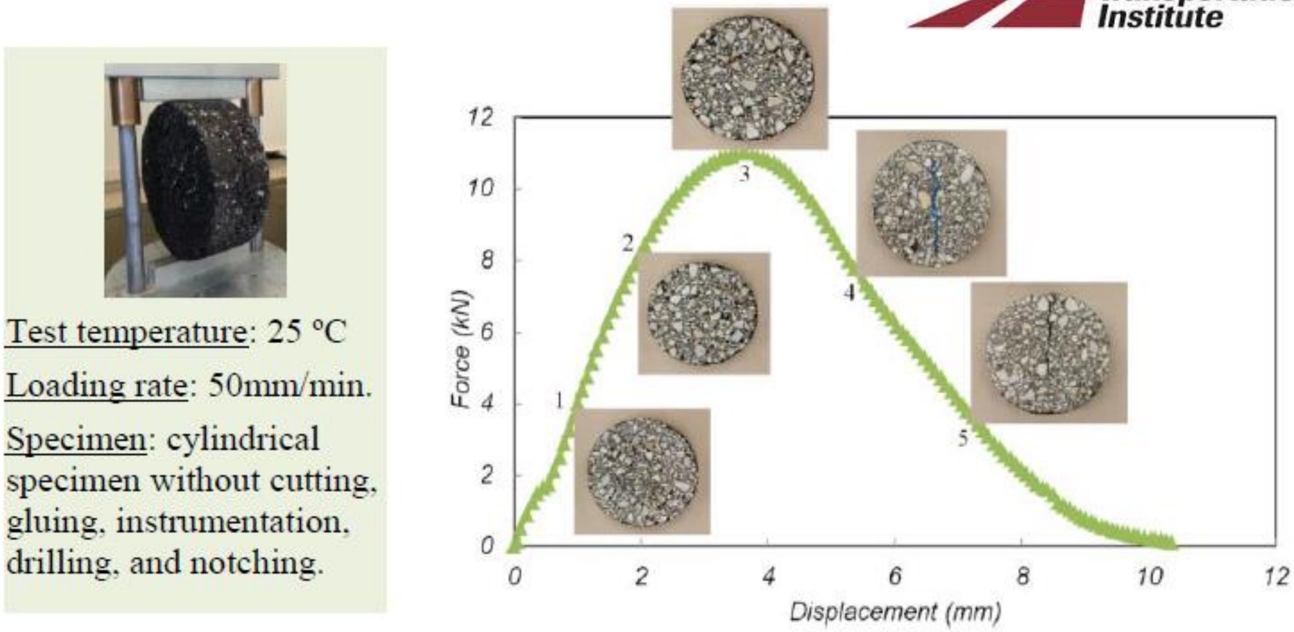
Asphalt Mix:
- 25% RAP
- PG 70-22ER
- 5.4% AC

Flow number for ODOT Level 3 PMLC samples

IDEAL CT – Crack Index Testing

Test Method Developed by TTI (2019 AASHTO Ballot)

Performed by Pave-Tex



Test temperature: 25 °C

Loading rate: 50mm/min.

Specimen: cylindrical specimen without cutting, gluing, instrumentation, drilling, and notching.

Figure 1. *IDEAL-CT: Specimen, Fixture, Test Conditions, and Typical Result*

Test Summary:

The IDEAL-CT is similar to other traditional indirect tensile strength test, and it is run at room temperature with cylindrical specimens at a loading rate of 50mm/min. in terms of cross-head displacement. Any size of cylindrical specimens with various diameters (100 or 150mm) and thicknesses (38, 50, 62, 75mm, etc.) can be tested. For mix design and laboratory QA/QC, the authors proposed to use the same size specimen as the Hamburg wheel tracking test: 150 mm diameter and 62 mm height with 7±0.5 percent air voids, since agencies are familiar with molding such specimens. Figure 1 shows a typical IDEAL-CT: cylindrical specimen, test fixture, test temperature, loading rate, and the measured load vs. displacement curve.

The purpose of the test method is to determine the cracking behavior of the asphalt sample all the way through the cracking process. This test will deliver an Indirect Tensile load as well measure the resistance of the asphalt from first crack all the way through failure. Both the load and the displacement are recorded creating a displacement curve shown in Figure 1. The work or fracture energy created by the asphalt sample is calculated by the area under the displacement curve shown in Figure 2 below.

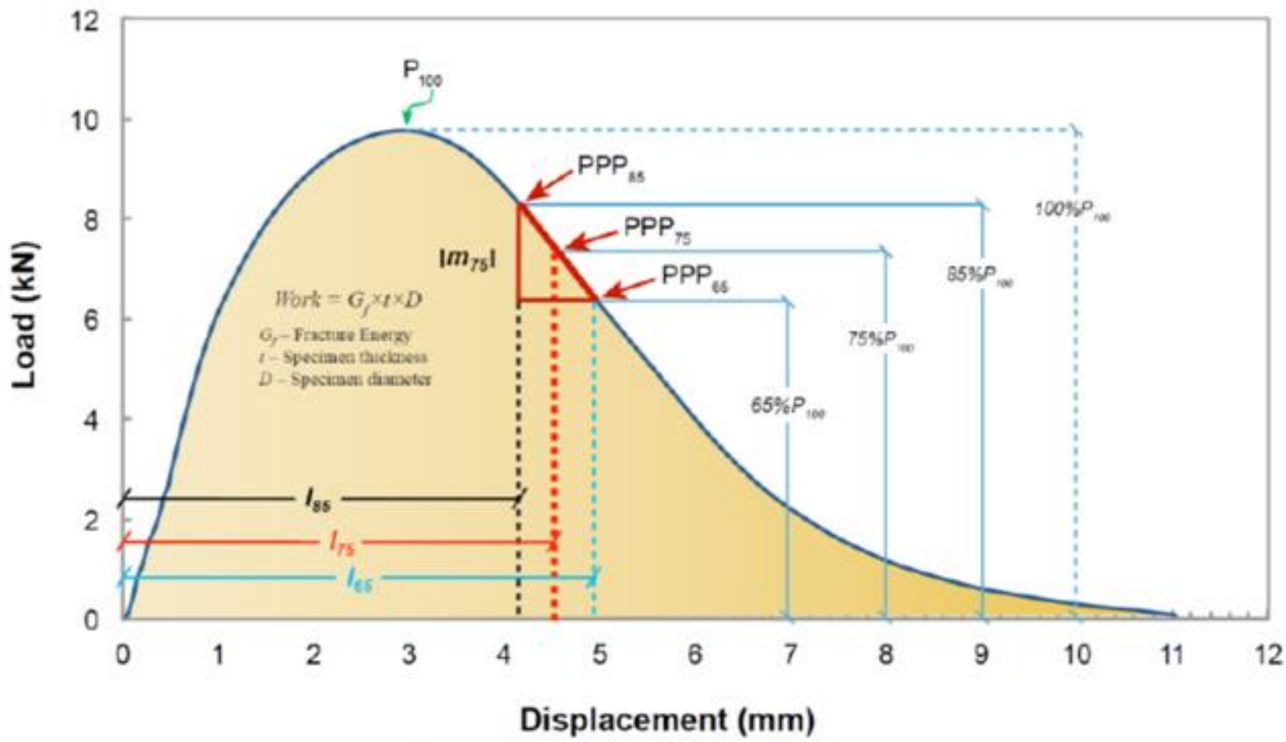
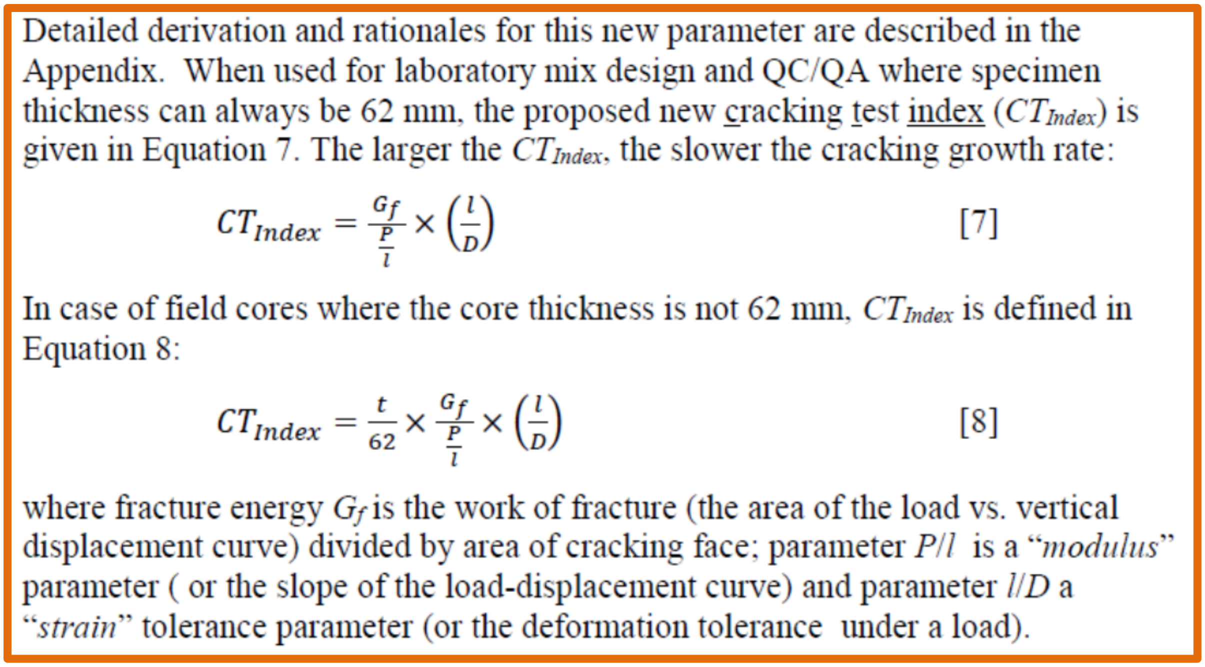


Figure 2. *Illustration of the PPP$_{75}$ Point and Its Slope* $|m_{75}|$

The Ideal CT Crack Index is calculated as follows:


Detailed derivation and rationales for this new parameter are described in the Appendix. When used for laboratory mix design and QC/QA where specimen thickness can always be 62 mm, the proposed new cracking test index (CT_{Index}) is given in Equation 7. The larger the CT_{Index}, the slower the cracking growth rate:

$$CT_{Index} = \frac{G_f}{\frac{P}{l}} \times \left(\frac{l}{D}\right) \qquad [7]$$

In case of field cores where the core thickness is not 62 mm, CT_{Index} is defined in Equation 8:

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{\frac{P}{l}} \times \left(\frac{l}{D}\right) \qquad [8]$$

where fracture energy G_f is the work of fracture (the area of the load vs. vertical displacement curve) divided by area of cracking face; parameter P/l is a "*modulus*" parameter (or the slope of the load-displacement curve) and parameter l/D a "*strain*" tolerance parameter (or the deformation tolerance under a load).

Table 18 – IDEAL CT with 2 TxDOT Mixes using 20% RAP – 38mm Length ACE XP Polymer Fiber

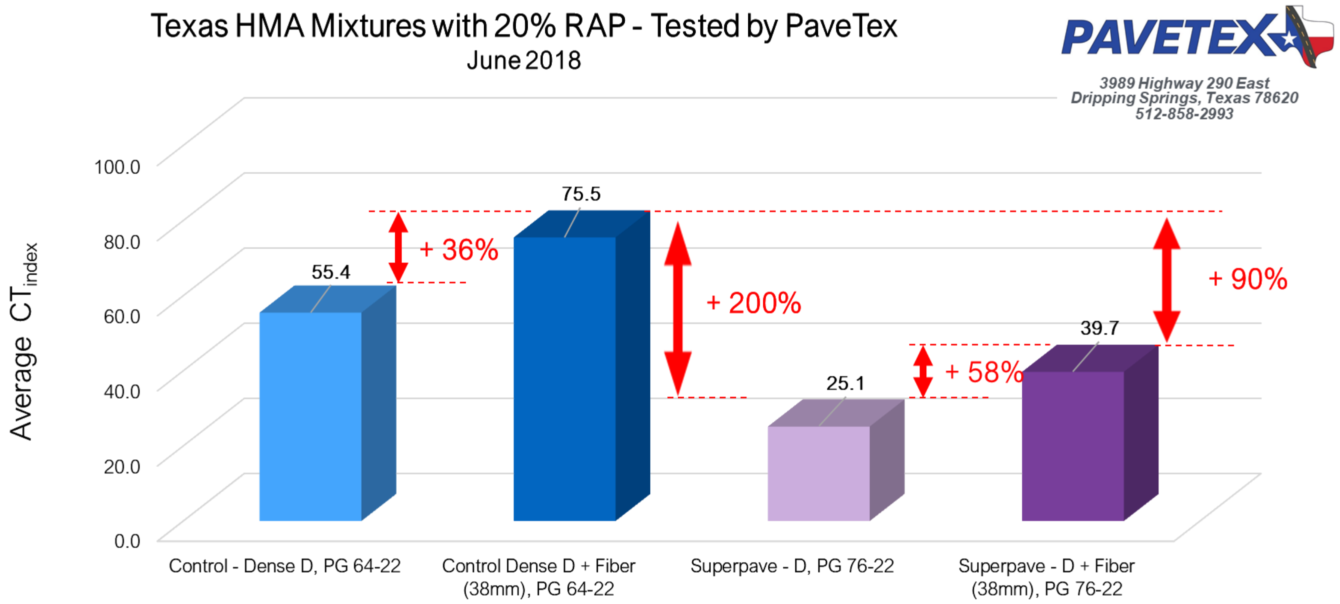


Table 19 – IDEAL CT vs Indirect Tensile Strength Results

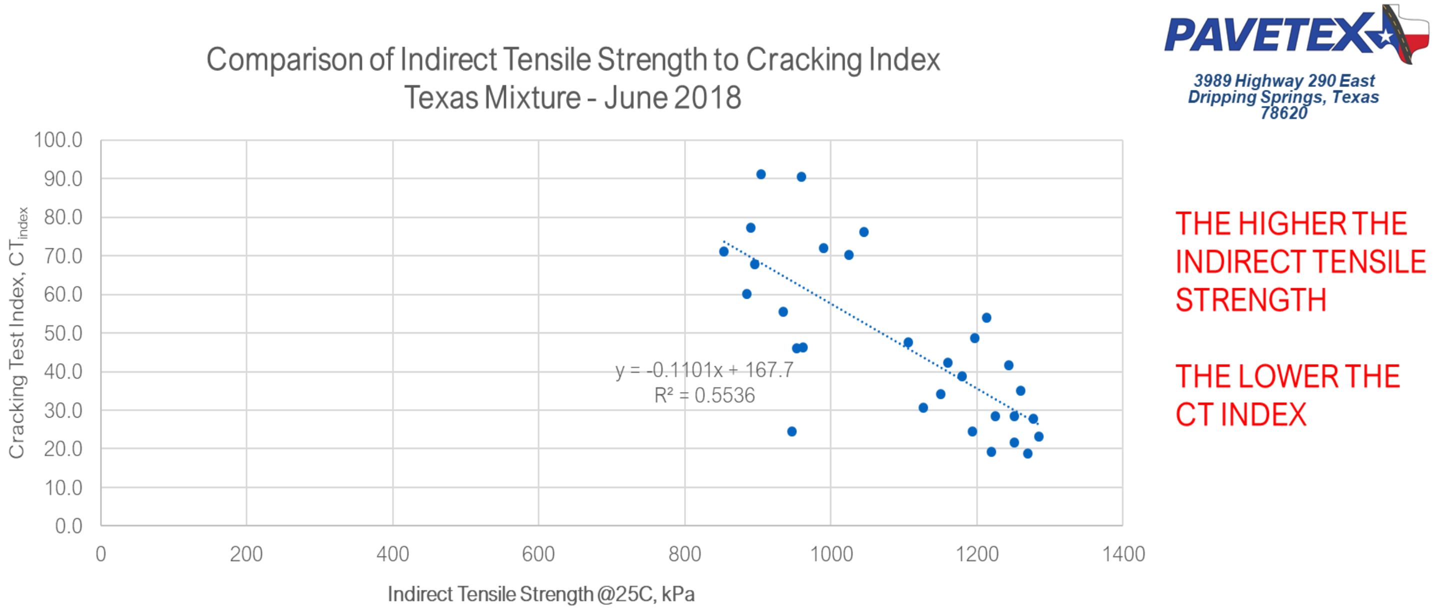
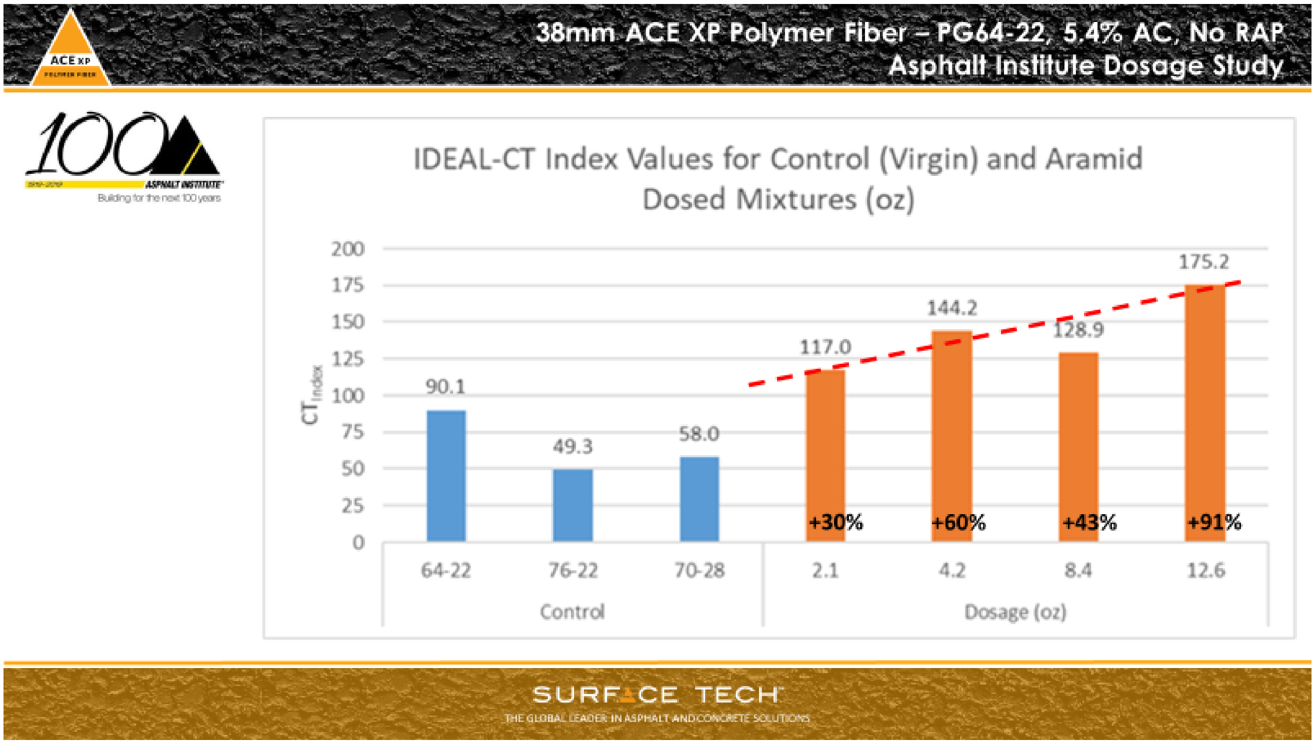
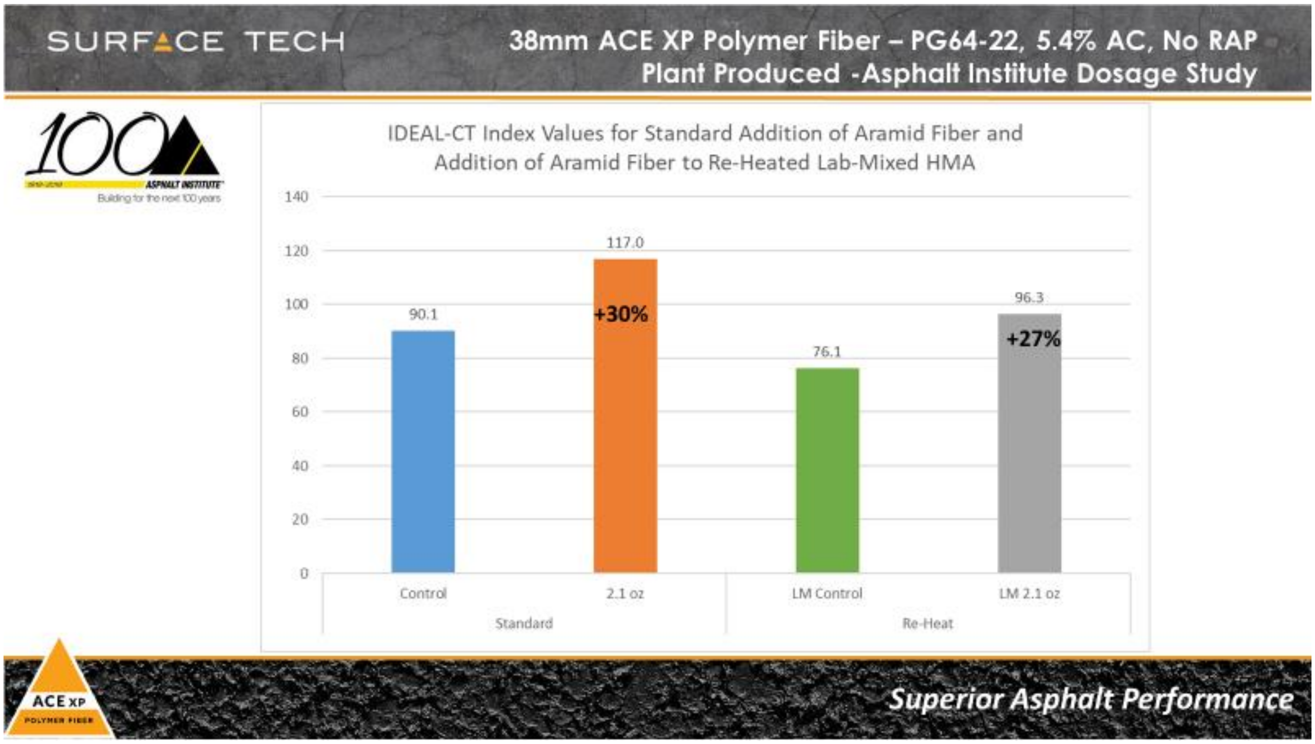


Table 20 – IDEAL CT Dosing Study for Lab Produced KYTC PG64-22 Mix Design – 38mm Length ACE XP Polymer Fiber



38mm ACE XP Polymer Fiber – PG64-22, 5.4% AC, No RAP
Asphalt Institute Dosage Study

Table 21 – IDEAL CT Dosing Study for Plant Produced KYTC PG64-22 Mix Design – 38mm Length ACE XP Polymer Fiber



38mm ACE XP Polymer Fiber – PG64-22, 5.4% AC, No RAP
Plant Produced -Asphalt Institute Dosage Study

Bending Beam Fatigue Test (BBF)

Test Method per ASTM D8237-18

Performed by University of California – Pavement Research Center

Fig. 25 – 4 Point Bending Beam Apparatus

Test Summary:

The flexural fatigue test is performed by placing a beam of HMA in repetitive four-point loading at a specified strain level. During the test, the beam is held in place by four clamps and a repeated haversine (sinusoidal) load is applied to the two inner clamps with the outer clamps providing a reaction load (Figure 25). The load rate is variable but is normally set at 1 to 10 Hz. This setup produces a constant bending moment over the center portion of the beam (between the two inside clamps). The deflection caused by the loading is measured at the center of the beam. The number of loading cycles to failure can then give an estimate of a particular HMA mixture's fatigue life. Small HMA beams (15 x 2 x 2.5 inches (380 x 50 x 63 mm)) are made and placed in a 4-point loading machine, which subjects the beam to a repeated load.

Beam fatigue testing is performed at intermediate temperatures, usually 68°F (20°C), because fatigue cracking is thought to be a primary HMA distress at these intermediate temperatures. At higher in-service temperatures (above about 100°F (38°C)) rutting is usually the HMA distress of greatest concern, while at lower temperatures (below about 40 °F (4°C)) thermal cracking is usually the HMA distress of greatest concern.

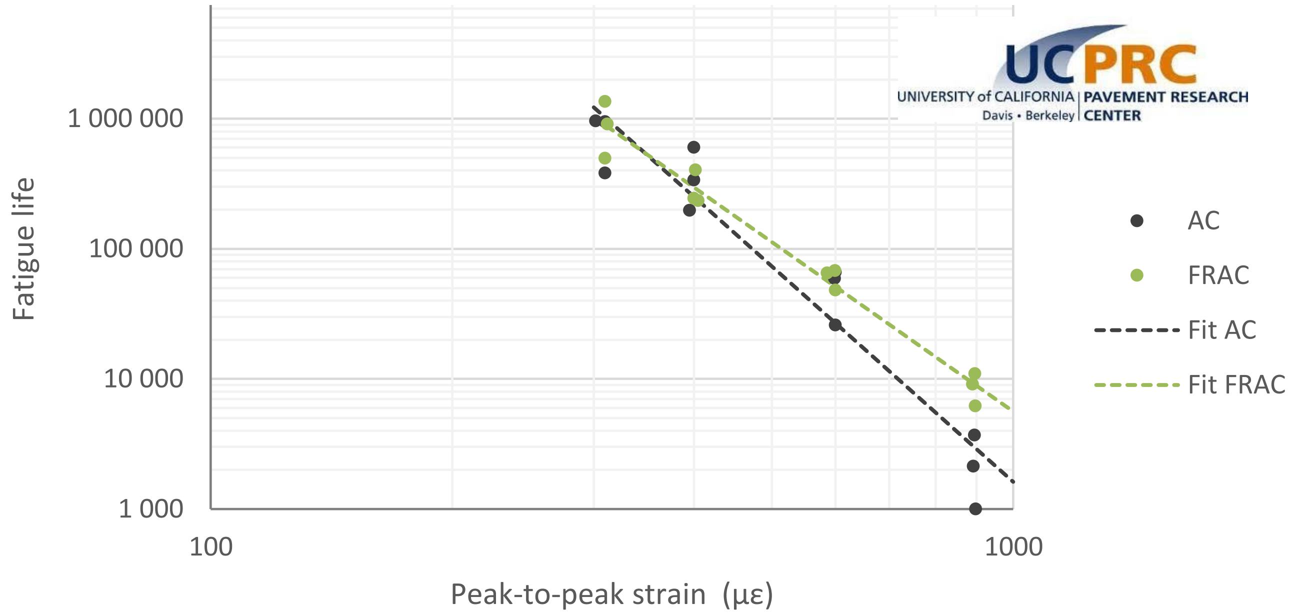
Fig. 26 – Preparation of Asphalt Concrete Beams

Fig. 27 – Typical Beam Test Sample

Results:

Three strain levels were initially applied in order to test the two mixes' fatigue resistance: 300, 400, and 600 με (peak to peak). At the two lower strain levels, 300 and 400 με, the fibers did not seem to impact the asphalt mix's fatigue life. However, figure 28 below shows that at the 600 με strain level, addition of the fibers resulted in a ***90 percent*** increase in fatigue life. After these results were obtained, a decision was made to conduct additional testing at 900 με to verify that the impact on fatigue resistance was strain-dependent. This additional testing confirmed the strain sensitivity of the fibers' reinforcing effect: at 900 με, addition of the fibers resulted in a ***200 percent*** increase in asphalt mix fatigue life. A strain level as high as this may occur in asphalt overlays of jointed concrete pavements or on overlays of pavements with considerable cracking. Importantly, this indicates that the addition of the aramid fibers to the asphalt mix should provide improved resistance to cracking when subjected to high strains in the field as seen in reflective cracking.

Figure 28: Fatigue resistance of the asphalt mixes (4PB flexural beam testing, 20°C/68°F and 10 Hz).



Stiffness & Rutting Resistance

Test Method per AASHTO T 378-17

(using the asphalt mixture performance tester, AMPT)

Performed by University of California – Pavement Research Center

Test Summary:

This test method describes procedures for measuring the dynamic modulus and flow number for asphalt mixtures.

In the flow number procedure, a specimen at a specific test temperature is subjected to a repeated haversine axial compressive load pulse of 0.1 s every 1.0 s. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function of the load cycles and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain.

Test temperature and frequency ranges for this specific stiffness tests were, respectively, 4 to 40°C (39 to 104°F) and 0.1 to 25 Hz. Rutting resistance was determined with unconfined repeated loading test at 45 and 55°C (113 and 131°F).

The test was concluded when permanent deformation of 5% was reached. The number of cycles to reach 5% was counted and compared.

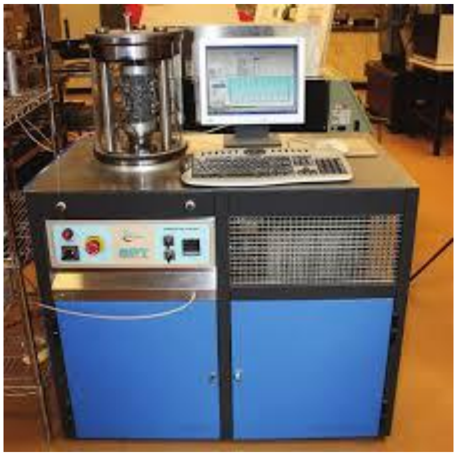


Fig. 29 – Typical AMPT Set Up

Fig. 30 – Typical AMPT Set Up

Results:

The mixes' resistance to permanent deformation was tested with the unconfined repeated loading test at 45 and 55°C (113 and 131°F). The results are shown in **Error! Reference source not found.**31. Adding the fibers increased the mix's resistance to permanent deformation considerably. At 45°C (113°F), the number of load repetitions to reach 5 percent permanent deformation increased ***46 percent*** (FRAC versus the original mix), while the increase was ***18 percent*** at 55°C (131°F). The fact that the increase was larger at 45°C than at 55°C may be related to the stronger adhesion between the fibers and binder at 45°C compared to 55°C.

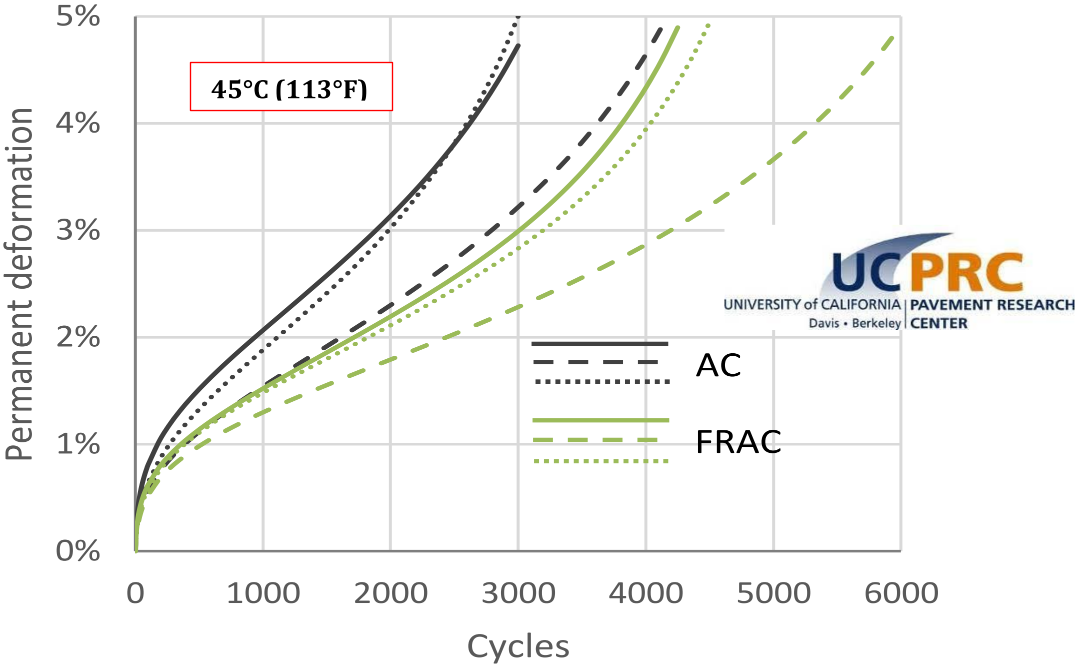
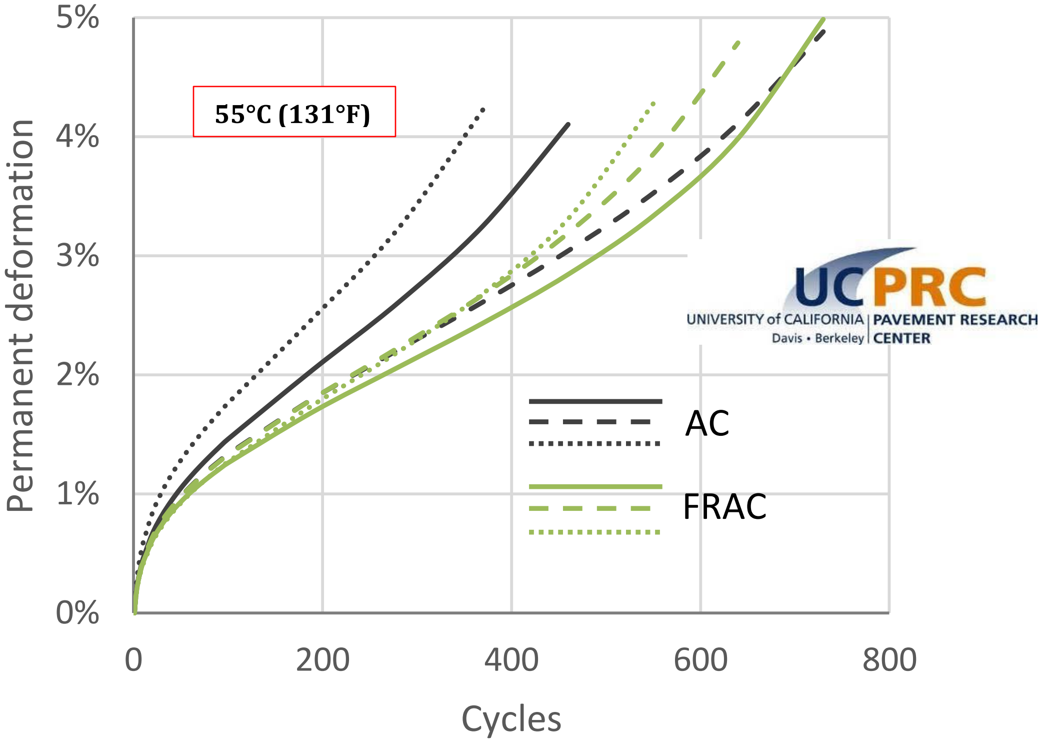


Figure 31: Permanent deformation of the asphalt mixes (AMPT repeated loading testing)



Extraction Test of Aramid Fibers

Test Method per ASTM D2172

Performed by Advanced Asphalt Technologies And Asphalt Institute

Test Summary:

The purpose of the test method is to determine the amount of recovered fiber from fiber reinforced asphalt concrete (FRAC) and calculate the Aramid Dispersion State Ratio (ADSR). The test method utilizes ASTM D2172 to extract the asphalt binder from FRAC samples. The amount of fiber remaining after extraction is measured by washing, sieving, manually removing the fiber, and recording total fiber mass. Due to the light weight nature of aramid fiber and residual AC binder present on the fiber after extraction, the extracted fiber content will measure higher than the amount of fiber added at the time of mixing. The amount of extracted fiber is reported as a percentage of total sample size. The Solvent used as part of ASTM D2172 is Trichloryl Ethylene, which was found to yield no negative reaction with the fiber produce. CAUTION should be used when handling this solvent.

Figure 31

Results:

Both Advanced Asphalt Technologies (AAT) and Asphalt Institute (AI) ran this extraction test. The samples containing ACE Fiber were individually removed from the sieves after the sieving operation. These ACE Fibers were added to the bulk ACE Fibers collected. The ACE Fibers were then soaked with solvent, washed, and dried to constant mass at 110°C and the mass of the ACE Fibers in each sample was determined. All results of the extraction of ACE Fibers from the mixture samples are listed in Table 22 Below.

Table 22 - ACE XP Polymer Fiber Extraction Test Results per ASTM

ACE Fiber Sample	Test Lab	% Extracted Fibers (%)	Weight of Fibers (oz./ton)
ACE XP Sample 1	AAT	.007	2.3
ACE XP Sample 2	AAT	.007	2.4
ACE XP Sample 3	AI	.014	4.5
ACE XP Sample 4	AI	.009	2.9
ACE XP Sample 5	AI	.008	2.4
ACE XP Sample 6	AI	.005	2.1
Average:		**.008**	**2.8**

ADSR Test of Aramid Fibers

Aramid Dispersion State Ratio

Performed by Advanced Asphalt Technologies And Asphalt Institute

Test Summary:

The purpose of the test method is to determine the amount of recovered fiber from fiber reinforced asphalt concrete (FRAC) and calculate the Aramid Dispersion State Ratio (ADSR). The test method utilizes ASTM D2172 to extract the asphalt binder from FRAC samples. The amount of fiber remaining after extraction is measured by washing, sieving, manually removing the fiber, and recording total fiber mass. Due to the light weight nature of aramid fiber and residual AC binder present on the fiber after extraction, the extracted fiber content will measure higher than the amount of fiber added at the time of mixing. The amount of extracted fiber is reported as a percentage of total sample size. The Solvent used as part of ASTM D2172 is Trichloryl Ethylene, which was found to yield no negative reaction with the fiber produce. CAUTION should be used when handling this solvent.

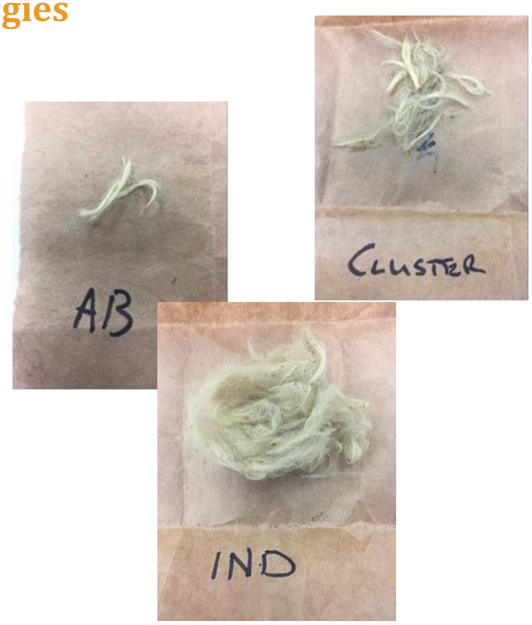


Figure 13

Results:

Both Advanced Asphalt Technologies (AAT) and Asphalt Institute (AI) ran this ADSR classification. This is a visual observation and subject to human judgement and thus not the most repeatable process. Extreme care should be taken when separating the fibers for ADSR classification. Table 23 shows the dispersion classification and % weights of each dispersion state of the extracted fiber. The *"bundled state"* is the worst case where the extracted fiber does not disperse, followed by the *"agitated bundle"*, *"cluster"*, and finally the ***"individual"*** classification, which indicates the ***best*** dispersion.

Table 23 - ACE XP Polymer Fiber ADSR Classification

ACE Fiber Sample	Test Lab	Bundled Fibers (%)	Agitated Bundle (%)	Cluster (%)	Individual (%)	ADSR (%)
ACE XP Sample 1	AAT	0.0	0.0	10.9	89.1	89.1
ACE XP Sample 2	AAT	0.0	0.0	16.8	83.2	83.2
ACE XP Sample 3	AI	0.0	0.0	20.0	80.0	80.0
ACE XP Sample 4	AI	0.0	2.2	9.2	88.6	88.6
ACE XP Sample 5	AI	0.0	0.0	14.8	85.2	85.2
ACE XP Sample 6	AI	0.0	0.0	8.2	91.8	91.8
Average:						**86.3%**