Fiber Reinforced Asphalt Pavements

54th ANNUAL IDAHO ASPHALT CONFERENCE

October 23, 2014
Moscow, Idaho

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Agenda

ASU's experience in testing and evaluation of FRAC

- Fiber Reinforced Asphalt Concrete (FRAC)
- Field projects constructed
- Process and production
- Laboratory tests
- On-Going Research

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Why do we use modifiers in HMA?

- Mitigate both traffic and climate induced pavement distresses
  - Rutting Resistance
    - Stiffer asphalt binders
  - Reduce Cracking
    - Eliminate or delay cracking
    - Inhibit crack propagation
  - Reduce Surface Wear: Raveling

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Types of Modifiers

- Polymers

  Plastomers
  Elastomers
  Crumb / tire rubber

- Fillers

  Gilsonite
  Mineral fillers

- **Fibers**

  1960's Asbestos

  polyester & polypropylene, glass, carbon, cellulose Aramid (Kevlar)

  over 31+ recycled waste fibers

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Why Fibers in HMA?

- Additional tensile strength and fracture energy
- Reinforcing / load transfer element & minimize crack propagation and severity
- Favors slight increase in optimum bitumen content
- Reduce drain-down of bitumen in HMA
- Favorable cost
- Literature:
  - Increased dynamic modulus
  - Better moisture susceptibility & freeze thaw resistance
  - Rutting resistance
  - Reduce, delay or eliminate of cracking

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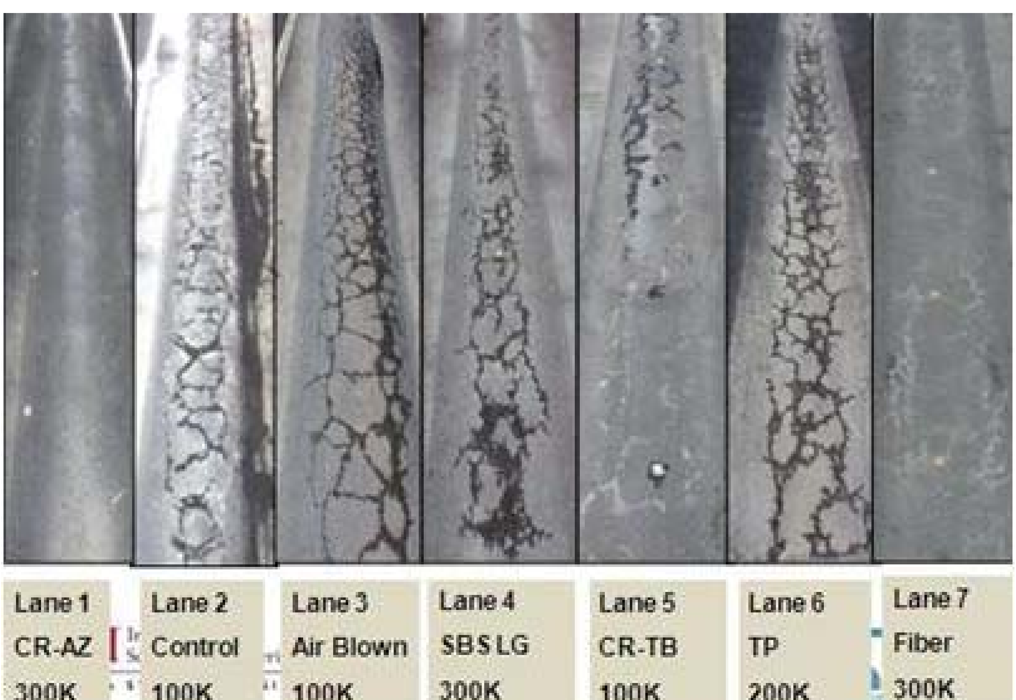
FHWA ALF Tests



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Fibers in HMA Mixtures


BoniFiber[@] Fiber


Dolanit[@] AS fiber


Lignin fiber


Asbestos Fiber

Huaxin Chen et al (2009)


(FORTA®)

Tire Fibers

Cellulose Fibers


(Chowdhary et al.)


Coconut Fibers *(Passos, 2005).*

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Tire Fibers - Early Research in Arizona

Table 9-15. AR physical properties with added tire fiber

Rubber content	16	15.9	15.5	15.0
Fiber content	0	0.1	0.5	1.0
Viscosity, 350°F, cp	1,500	1,900	2,400	2,800
Penetration, 77°F	77	84	74	72
Softening point, °F	128	130	130	134
Resilience, 77°F	11	15	17	21
Ductility, 39.2°F	19	22	15	15
Added fiber content as a proportion of CRM, %	0	0.6	3.2	6.7

Notes:
(1) Asphalt used is an AC-5, penetration=125, softening point=106°F.
(2) Materials were heated at 350±10°F for 90 minutes.

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The effect of polypropylene fibers on asphalt performance – Tapkin, ScienceDirect 2007

Physical properties of fibers

Items	Fiber type			
	BoniFiber®(polyester)	Dolanit®AS (polyacrylonitrile)	Lignin	Asbestos
Fiber diameter (mm)	0.020 + 0.0025	0.013	Mean value: 0.045	N/A
Fiber length (mm)	6.35 + 1.58	4.00–6.00	<5.00, mean value: 1.10	5.5
Length/diameter ratio (mean value)	318	385	24	N/A
Tensile strength (MPa)	517 ± 34.5	>910	N/A	30–40
Maximum tensile strain	33 ± 9	8–12	N/A	N/A
Specific gravity	1.36 ± 0.04	1.14–1.16	0.80–1.30	2.4–2.6
Melt temperature (°C)	>249	>240	>200	N/A
Asphalt drained down (%)[1]	28.00	19.13	0.00	18.25

Note: [1] drain-down experiment at 140 °C was performed and not detailed in this paper, and a higher content of drained down (separation) asphalts indicates a lower absorption of asphalts.

NYCON-G

NYCON-G
Nylon, Medium Denier, Superior Finish

PHYSICAL PROPERTIES

Filament Diameter	12 Denier (57 Microns)
Fiber Length	Well Graded < 0.75" (19mm)
Specific Gravity	1.10
Tensile Strength	44 ksi (300 MPa)
Flexural Strength	400 ksi (2.8 GPa)
Melting Point	435° F (225° C)
Color	Tan
Water Absorption	1% to 3% by Weight
Alkali Resistance	High
Concrete Surface	Not Fuzzy
Corrosion Resistance	High

https://carpetrecovery.org/wp-content/uploads/2014/04/NyconG.pdf

Rheological properties of fiber reinforced asphalt binders – Ye and Wu, Indian Journal of Engineering & Materials Sciences, 2008

Scanning Electron Microscope (SEM):

- Cellulose: flocculent material with porous and ribbon type surface (strong absorption of binder)
- Polyester and mineral fibers: round and smooth surface, much lower absorption.

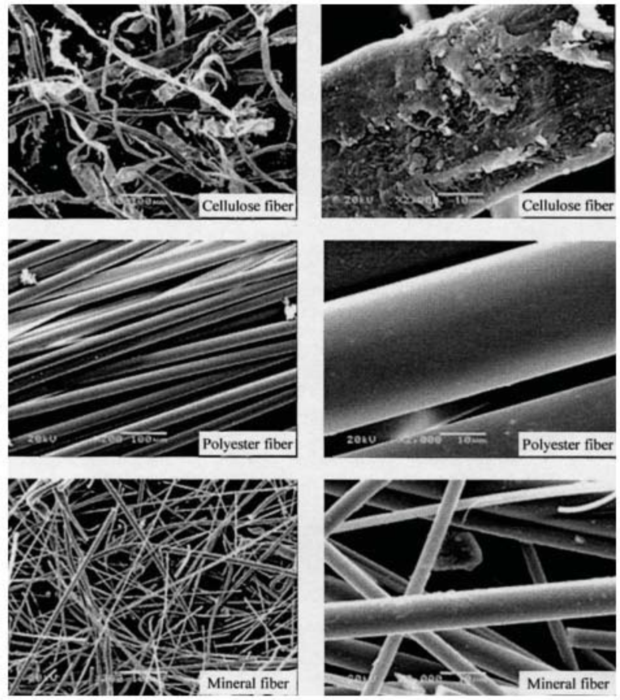
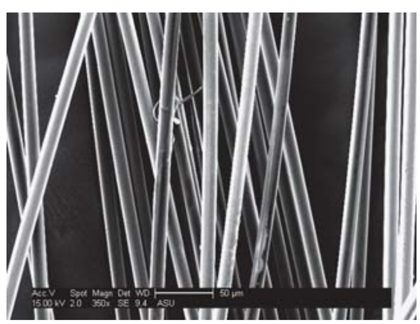
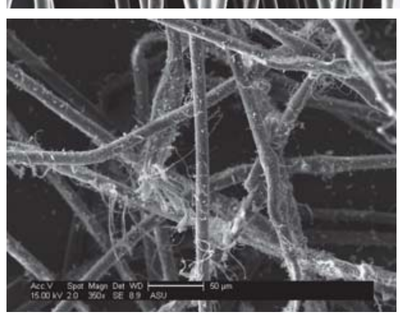


Fig. 1—Morphology of various types of fibers

Blend of collated Polypropylene and Aramid fibers

FORTA® Fibers





fibrillated

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Physical Characteristics

Materials	Polypropylene	Aramid
Specific Gravity	0.91	1.45
Tensile Strength (MPa)	483	3000
Length (mm)	19	19
Acid/Alkali Resistance	inert	inert
Decomposition Temperature (°C)	157	>450

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ASU Early Projects

- Boeing Mixture – Pilot Study
- City of Tempe – Evergreen Drive

Mix Type	Binder Mix Design Data			
	Binder Type	Design AC (%)	Target Va (%)	Gmm
FORTA Boeing PHX D-1/2	PG 70-10	5.10	7	2.4605

Mix Type	Binder Mix Design Data			
	Binder Type	Design AC (%)	Target Va (%)	Gmm
PHX C-3/4 Control	PG 70-10	5.00	7	2.428
PHX C-3/4 1 lb/Ton	PG 70-10	5.00	7	2.458
PHX C-3/4 2 lb/Ton	PG 70-10	5.00	7	2.471

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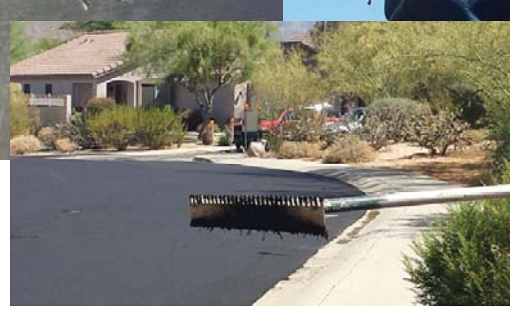

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Laboratory Tests

- Binder Tests
- Triaxial Shear Strength
- Dynamic Modulus
- Permanent Deformation
  - Repeated Load
  - Static Creep
- Beam and Axial Fatigue
- Indirect Tensile Strength and Creep
- Fracture and Crack Propagation

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Polypropylene Modified Binder

Mix time and temperature:

- Time: 30 min
- Temperature: 329 and 365 ° (165-185 ° C)

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Binder Tests

➢ Conventional Tests

- Penetration AASHTO T49-93
- Softening Point AASHTO T53-92
- Rotational Viscosity AASHTO TP48

➢ Superpave / SHRP Tests

- Dynamic Shear Rheometer (DSR): AASHTO PP1
- Bending Beam Rheometer (BBR): AASHTO TP1-98

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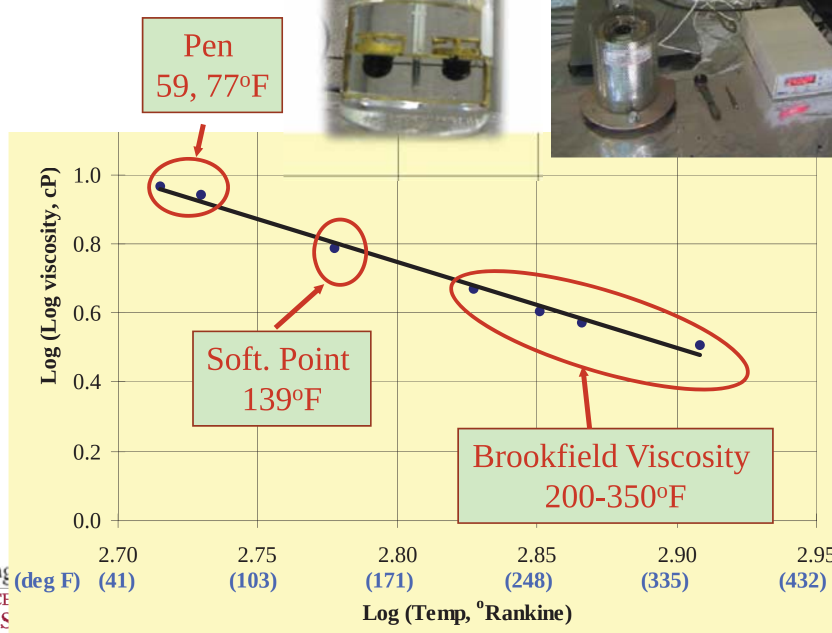
Viscosity – Temperature



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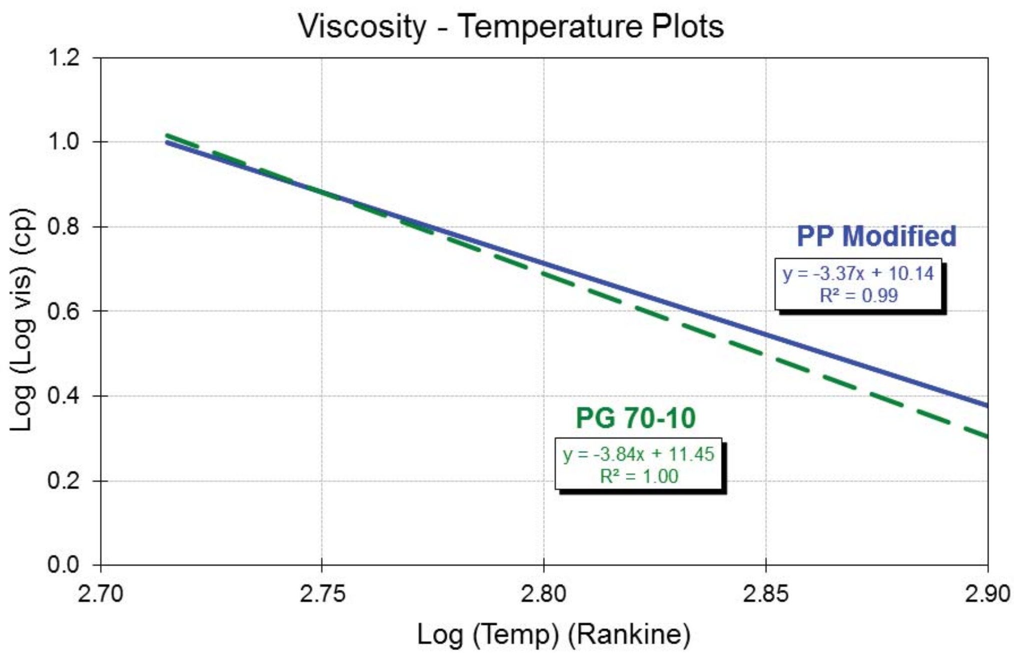
BINDER TEST RESULTS



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Laboratory Mixing Procedure

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Field → Laboratory Mixes

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Field → Laboratory Mixes

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Visual Observation

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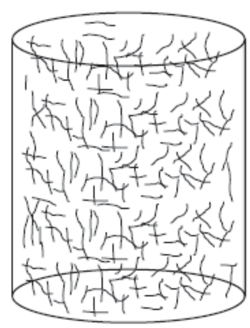
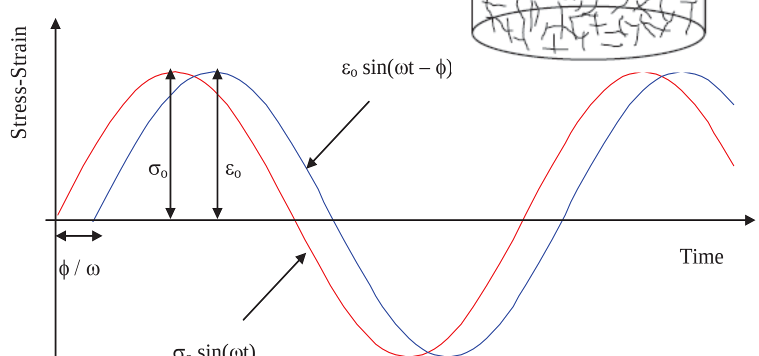
DYNAMIC COMPLEX MODULUS (E*)

- **$|E^*|$ = Dynamic Complex Modulus = σ_o / ε_o**
- **σ_o = peak dynamic stress amplitude (kPa / psi)**
- **ε_o = peak recoverable strain (mm/mm or in/in)**
- Φ = phase lag or angle (degrees) = VISCOELASTIC PROPERTY





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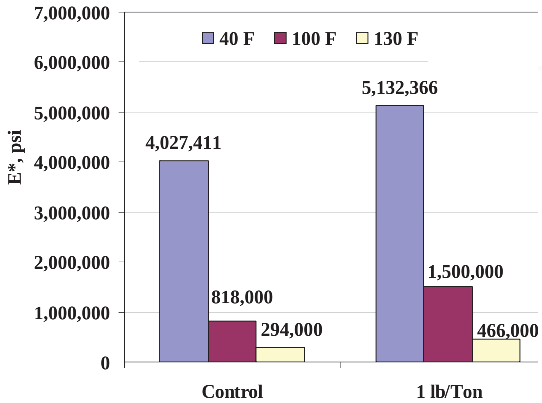
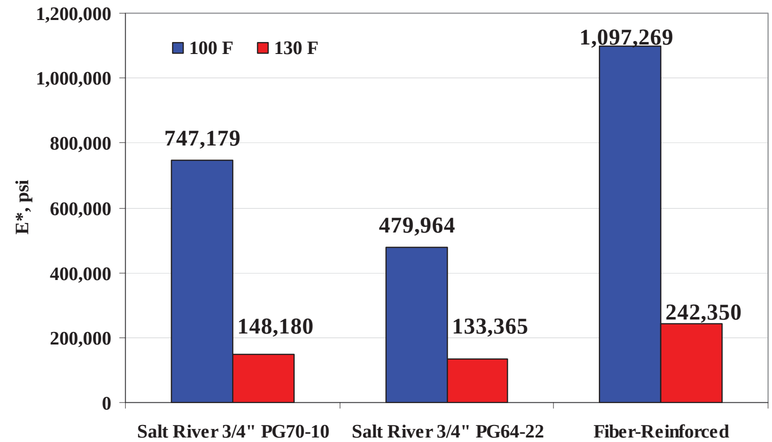
E* TEST RESULTS

Evergreen



Boeing



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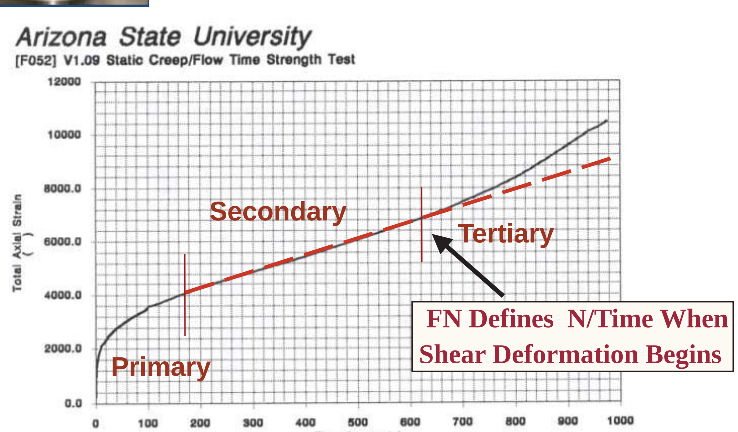
Repeated Load Permanent Deformation Tests



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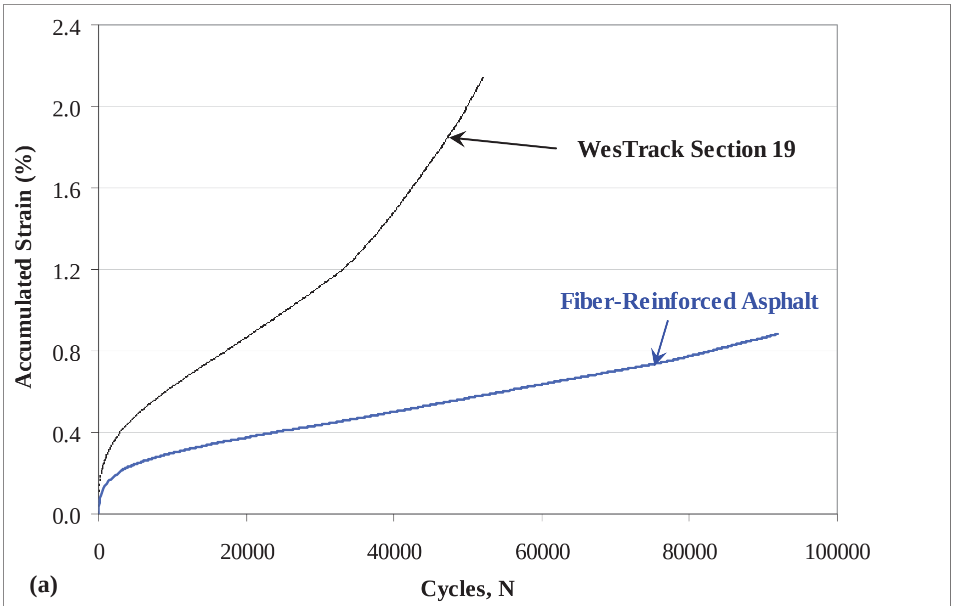
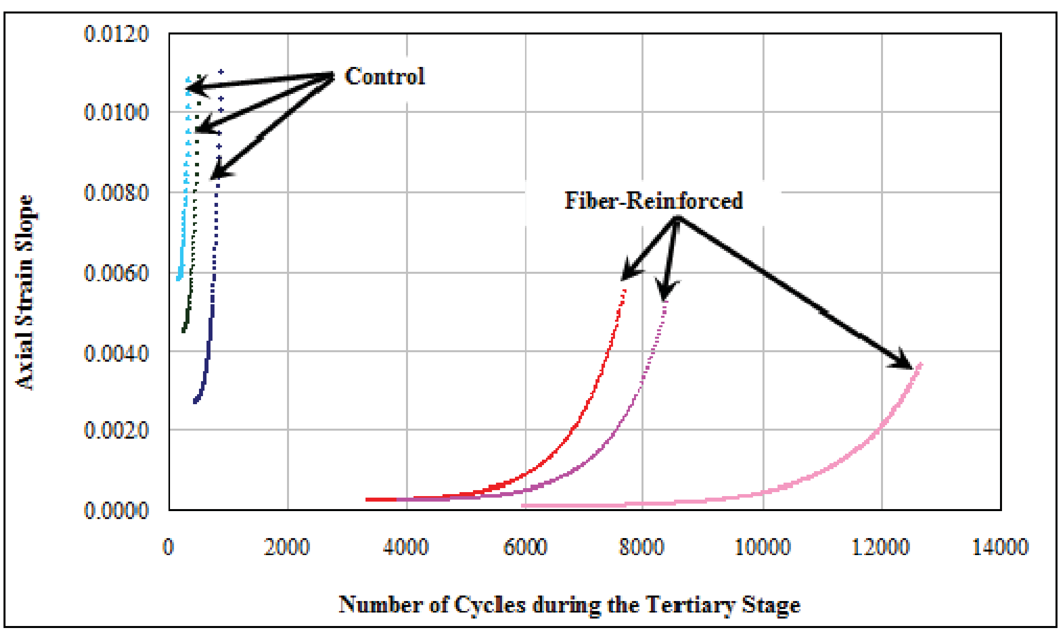
Repeated Load Permanent Deformation Test (Flow Number)-Fiber Reinforced Asphalt

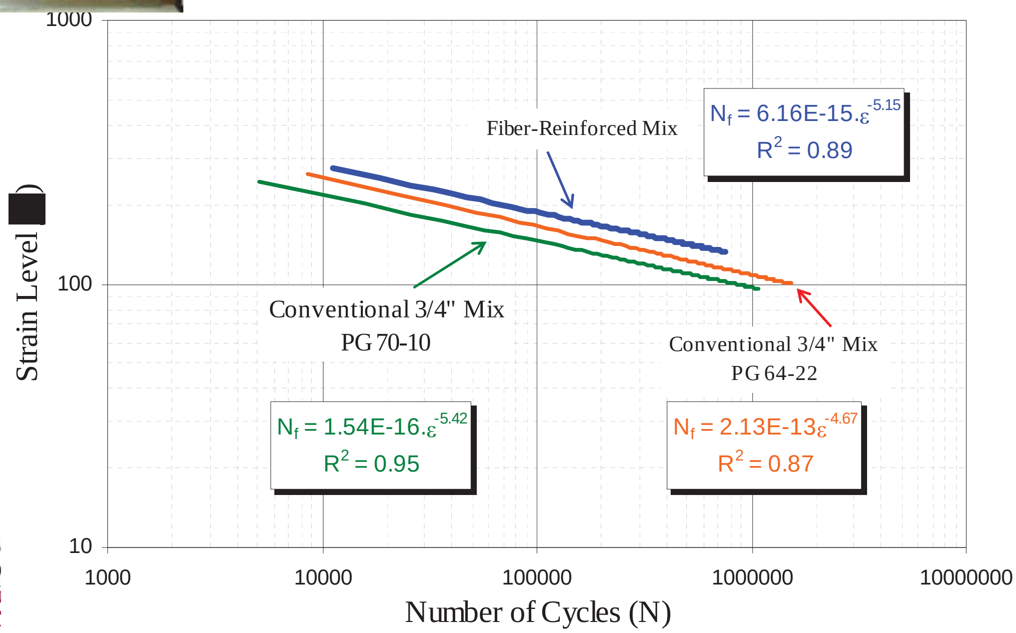
Boeing



Flow Number-Evergreen Dr.



Fatigue Test Results



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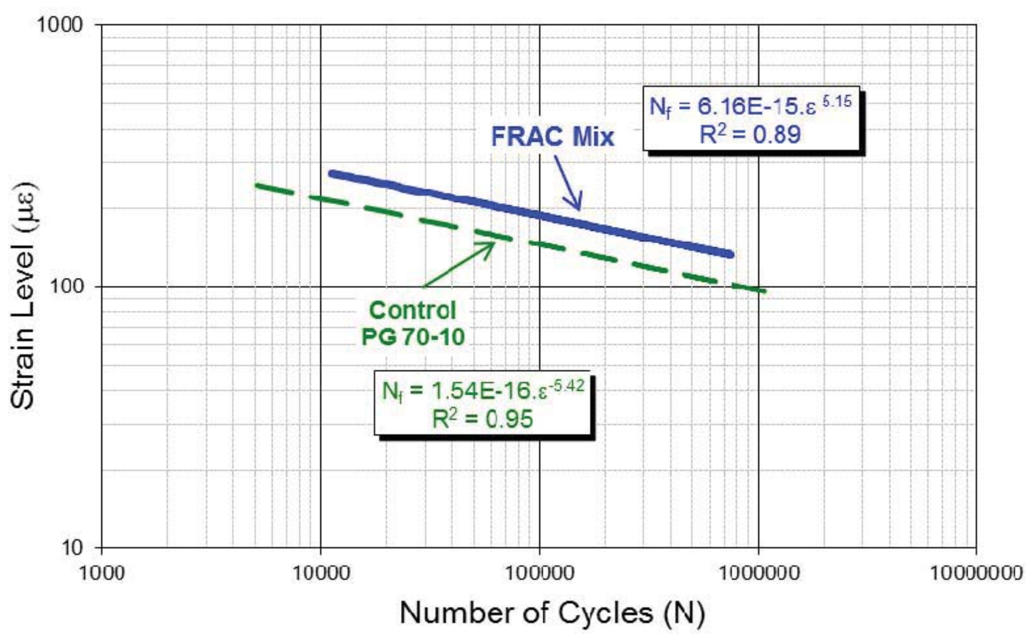
Fatigue Test Results



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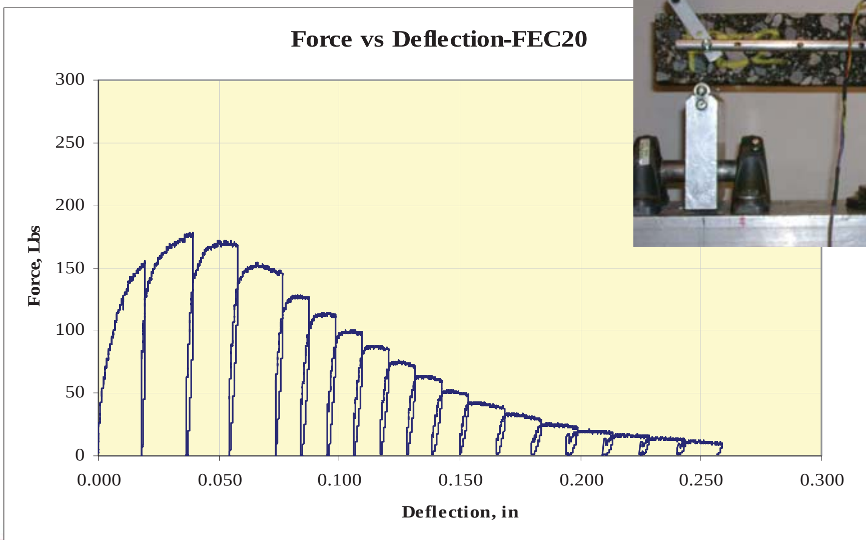
Flexural Strength and Post Peak Energy



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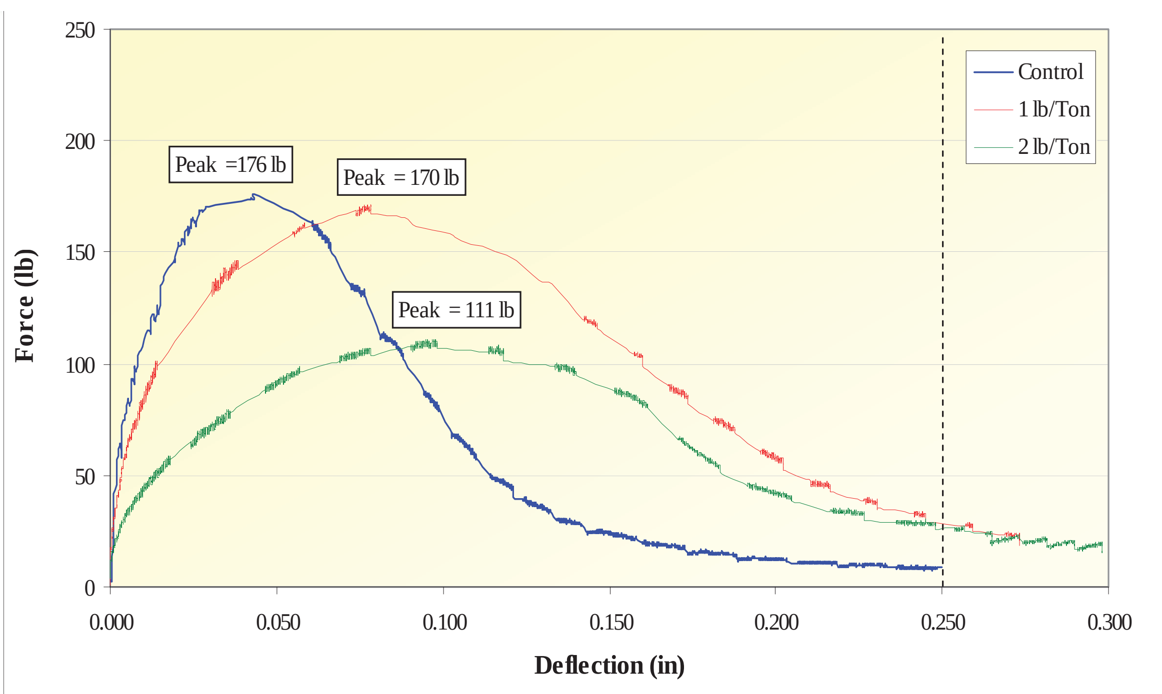
Comparative Plot – Cyclic Load



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Indirect Tension Tests

- Disk shape specimen (150 x 38 mm) with vertical and horizontal LVDTs on both sides
- **The tensile creep**
  - Three temp: 0, -10, and -20ºC
  - Static load along the diametral axis of a specimen
  - Deformations used to calculate tensile creep compliance as a function of time
- **The tensile strength**
  - Determined immediately after the tensile creep test
  - Constant rate of vertical deformation to failure

Indirect Tensile Tests Loading Frame and Specimen with LVDTs

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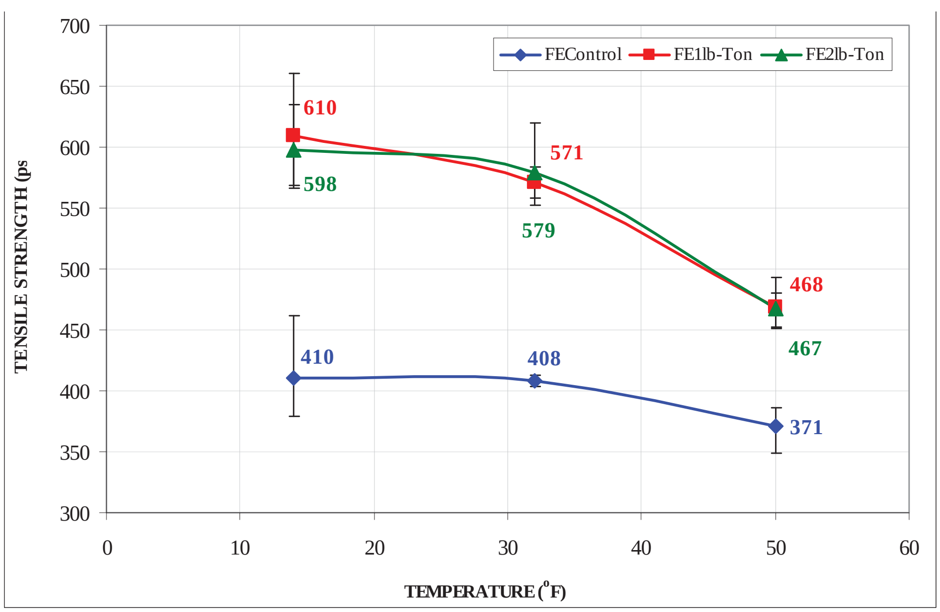
Tensile Strength - Evergreen



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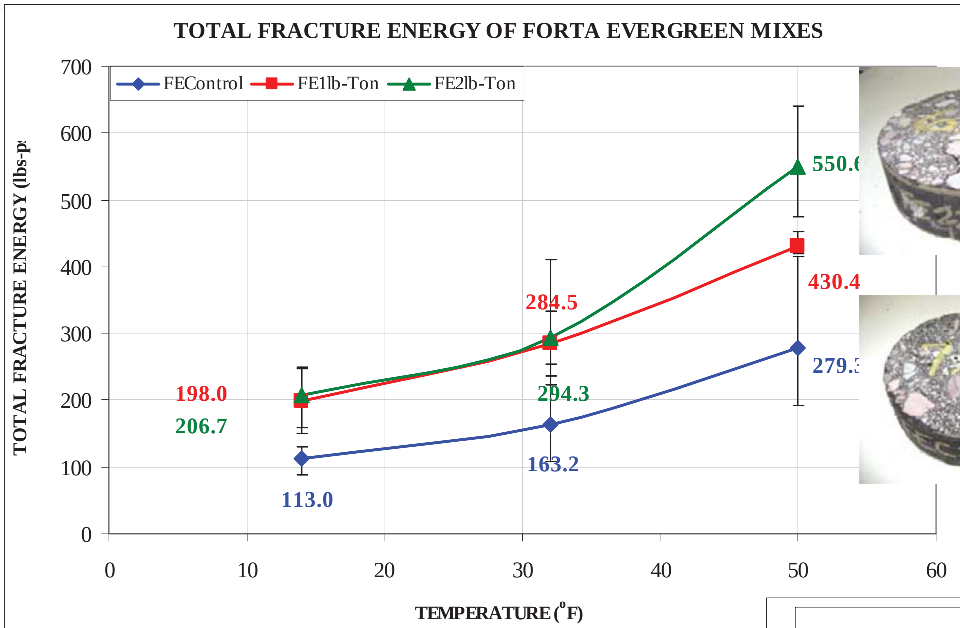
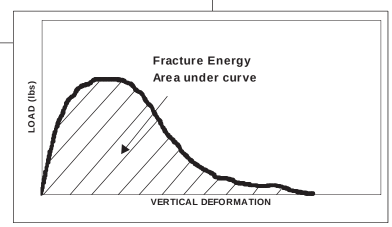
Total Fracture Energy





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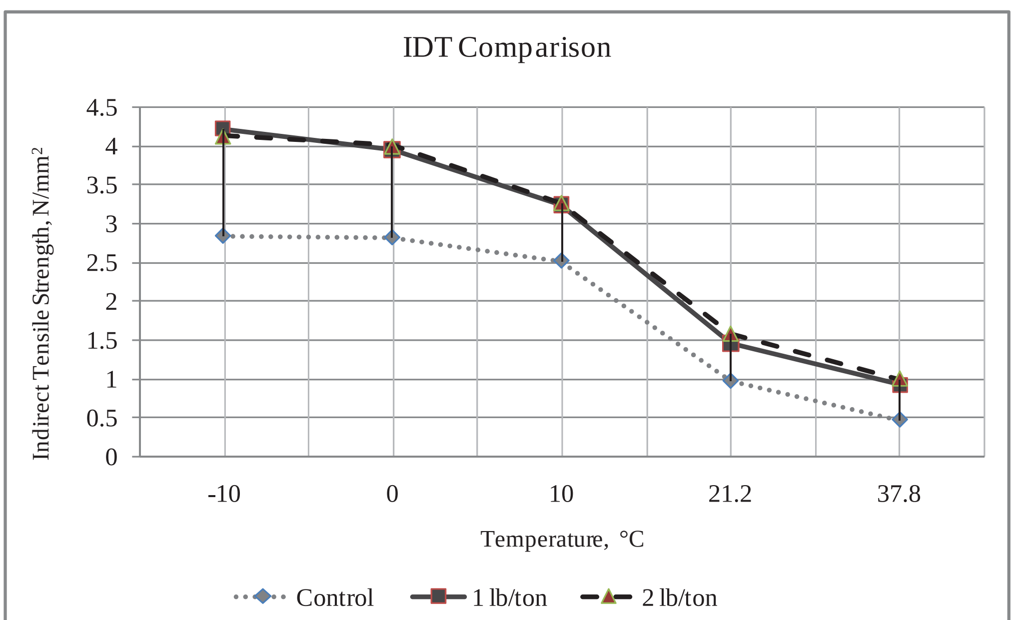
Comparison of Indirect Tensile Strength at 5 Temperatures



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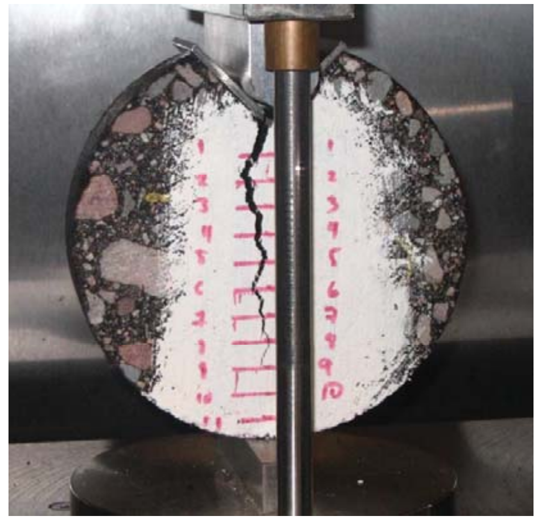
FRACTURE AND CRACK GROWTH MODEL - C* LINE INTEGRAL

- C* Line Integral–analog of the J integral where strains and displacement replaced by their rates (time dependent materials)
- Defined as the difference of 2 identically loaded bodies having incrementally differing crack lengths

$$C^* = \frac{1}{B}\frac{dU^*}{dC}$$

dU*=Change in energy rate for a load P and a crack extension dC

B=thickness



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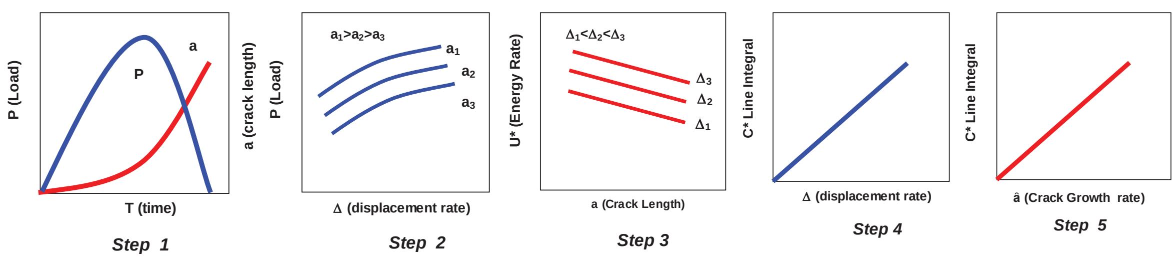
C* MULTIPLE SPECIMENS METHOD



- Specimens subjected to different constant displacement rates
- Load and crack length measured as a function of time

- Load vs displacement rate for fixed crack length
- Area under the curve= rate of work done U* per unit of crack plane thickness

- Crack growth rate are plotted versus crack length

- Area under the curve (Step 3) is plotted against crack length
- Slope of curve is C*

- Crack growth rate is plotted as a function of C*
- The higher the slope the more resistant the material

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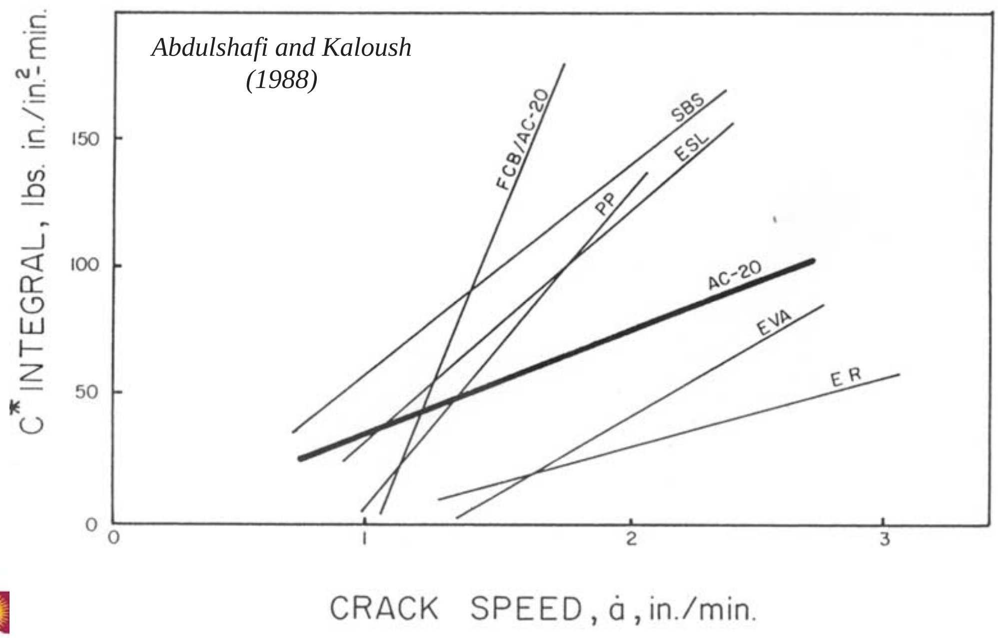
C* LINE INTEGRAL-Literature Results



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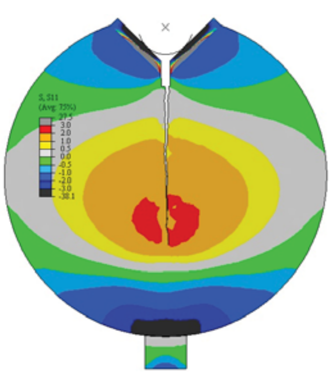
C* Fracture Test

(Jeff Stempihar, PhD 2013)

Develop test geometry, protocol, temperature and loading rate dependency, FE analysis and predictive models



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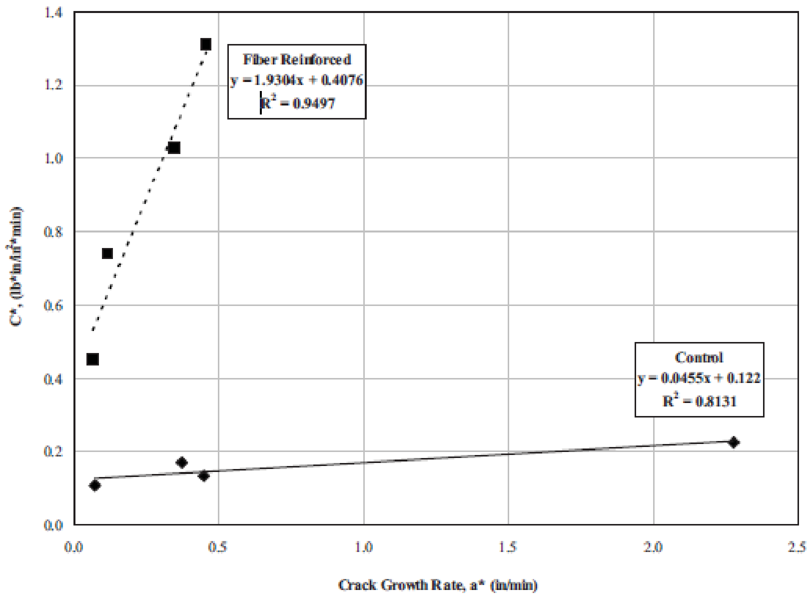
C* LINE INTEGRAL



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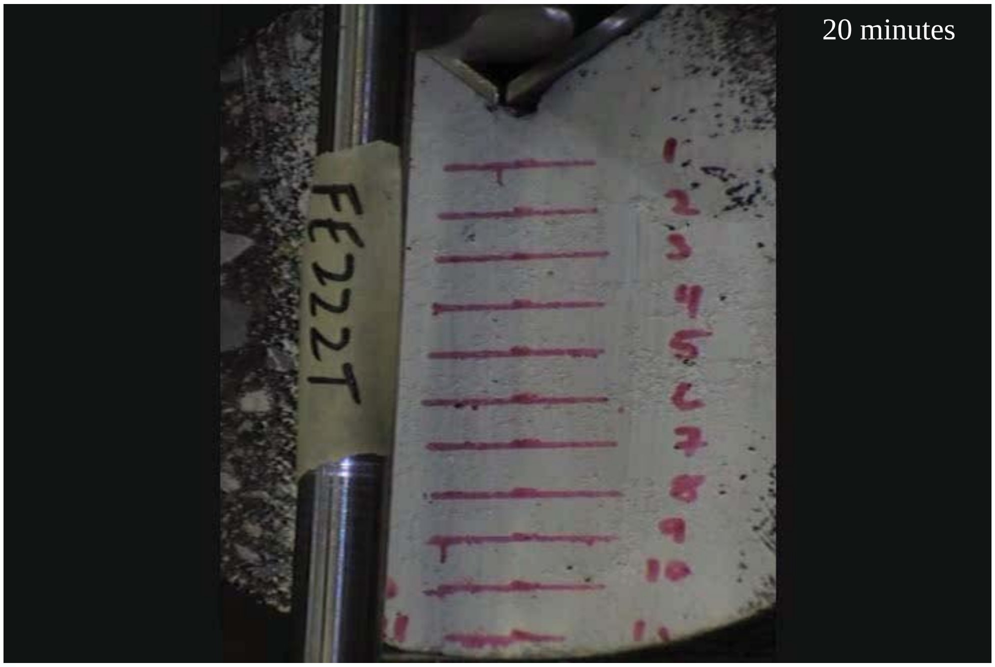
ACTUAL TEST PERFORMED



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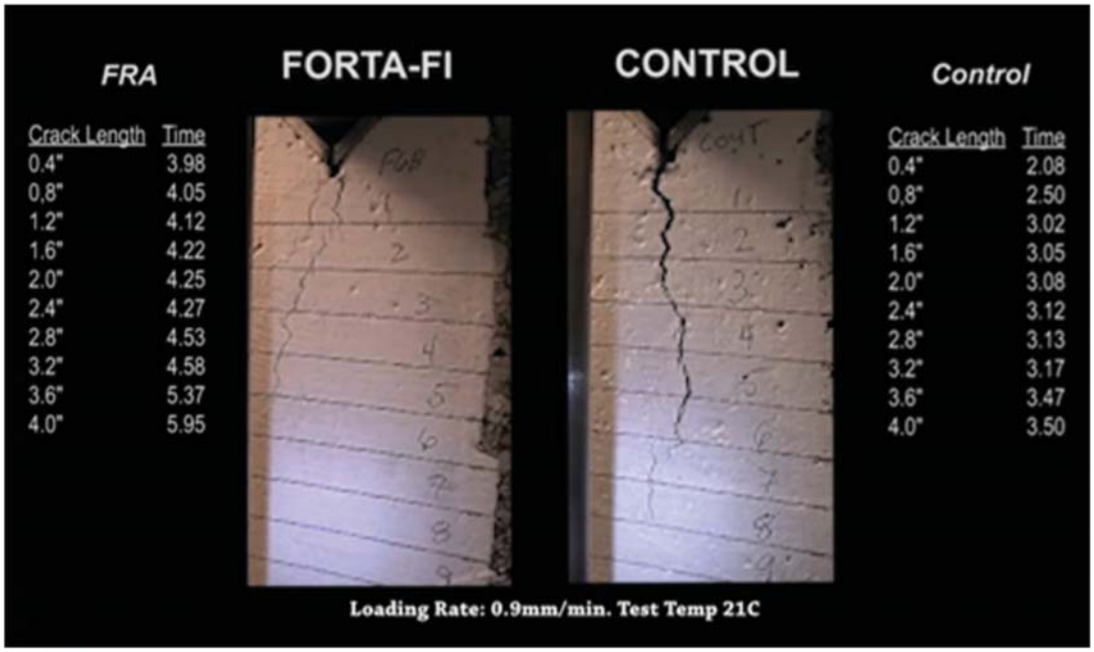
C* Fracture Test



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Post Test Failure

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What is the field telling us?

- Boeing – Mesa, AZ
  - infield placed in 2008
  - 2010, broken pipe caused a sink 2.5' W x 8' L x 2.5" D
  - Only (1) 10" crack found

Field Maintenance

- Asphalt saw-cut & removed in 2 pieces 3'W x 8'L x 2"Thick
  - One center anchor on 560lbs slab
  - Removed in one piece!

Evergreen Drive
December 2013

Fibers Extraction

xylene, toluene and trichloroethylene

Centrifuge Procedure

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Fibers Recovery

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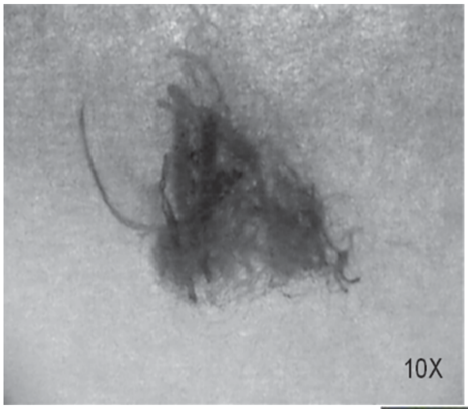
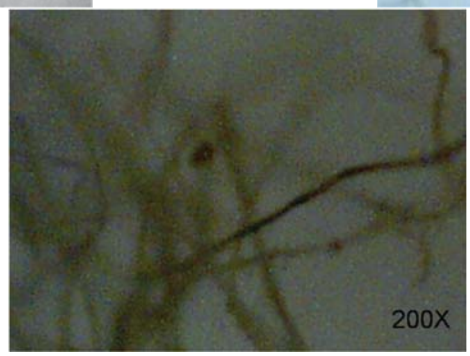
Microscopic Observations of Recovered Fibers





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Summary of Laboratory Tests (Fibers Benefits)

- The viscosity-temperature susceptibility relationship showed positive and desirable modification process.
- Higher Dynamic Modulus E* values compared to the conventional mixtures.
- Gradual accumulation in permanent strain and higher tertiary flow values => desirable properties to resist rutting.
- Higher fatigue life and fracture energy
- Higher crack propagation resistance as represented by the C* Fracture Test.
- Fiber extraction Process
  - Good estimate of actual fiber content
  - Quality Control / Quality Assurance

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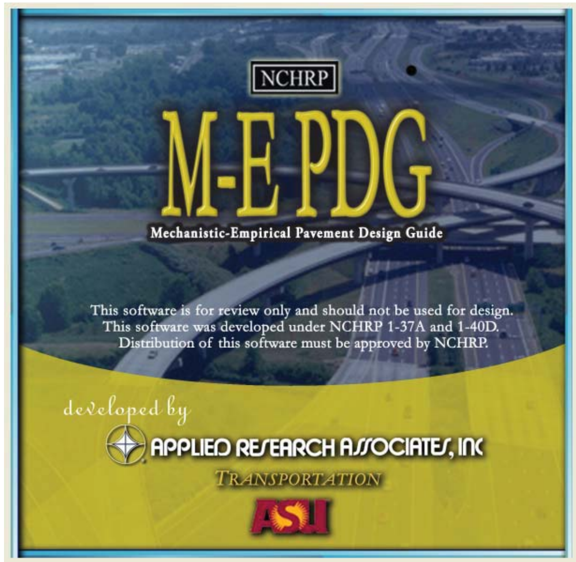
USE of Data in the MEPDG (PavementME)



Temp. °F (°C)	Freq. Hz	Dynamic Modulus, MPa - ksi (Test Values)				Modular Ratio (Average 1.44)
		Fiber-Reinforced		Conventional		
14 (-10)	25	7,029	48,463	6,059	41,775	1.16
	10	6,511	44,892	5,587	38,520	1.17
	5	6,279	43,293	5,500	37,920	1.14
	1	5,815	40,090	4,983	34,356	1.17
	0.5	5,577	38,449	4,776	32,926	1.17
	0.1	4,987	34,384	4,212	29,037	1.18
40 (4.4)	25	5,308	36,596	4,191	28,897	1.27
	10	5,132	35,387	4,027	27,768	1.27
	5	4,812	33,178	3,793	26,149	1.27
	1	4,238	29,218	3,204	22,089	1.32
	0.5	3,958	27,289	2,940	20,270	1.35
	0.1	3,325	22,927	2,357	16,247	1.41
70 (21.1)	25	3,197	22,045	2,258	15,566	1.42
	10	2,924	20,160	1,967	13,563	1.49
	5	2,669	18,403	1,760	12,137	1.52
	1	2,119	14,610	1,287	8,870	1.65
	0.5	1,853	12,773	1,108	7,637	1.67
	0.1	1,294	8,920	759	5,230	1.71
100 (37.8)	25	1,786	12,311	1,010	6,960	1.77
	10	1,500	10,341	818	5,641	1.83
	5	1,246	8,589	685	4,723	1.82
	1	814	5,611	442	3,045	1.84
	0.5	641	4,422	360	2,482	1.78
	0.1	315	2,174	235	1,623	1.34
130 (54.4)	25	616	4,249	387	2,668	1.59
	10	466	3,214	294	2,024	1.59
	5	374	2,578	247	1,702	1.51
	1	232	1,596	173	1,194	1.34
	0.5	194	1,335	156	1,076	1.24
	0.1	138	949	130	893	1.06
Average Modular Ratio						1.44

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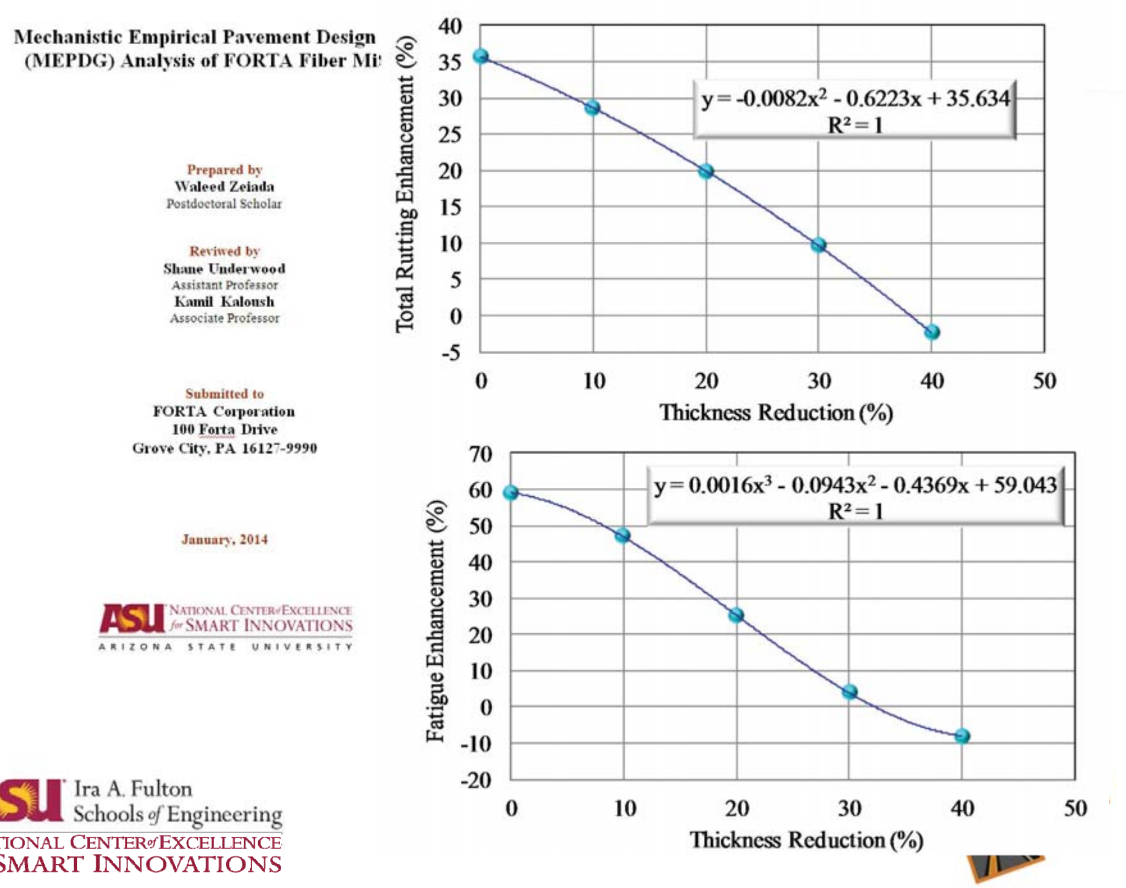

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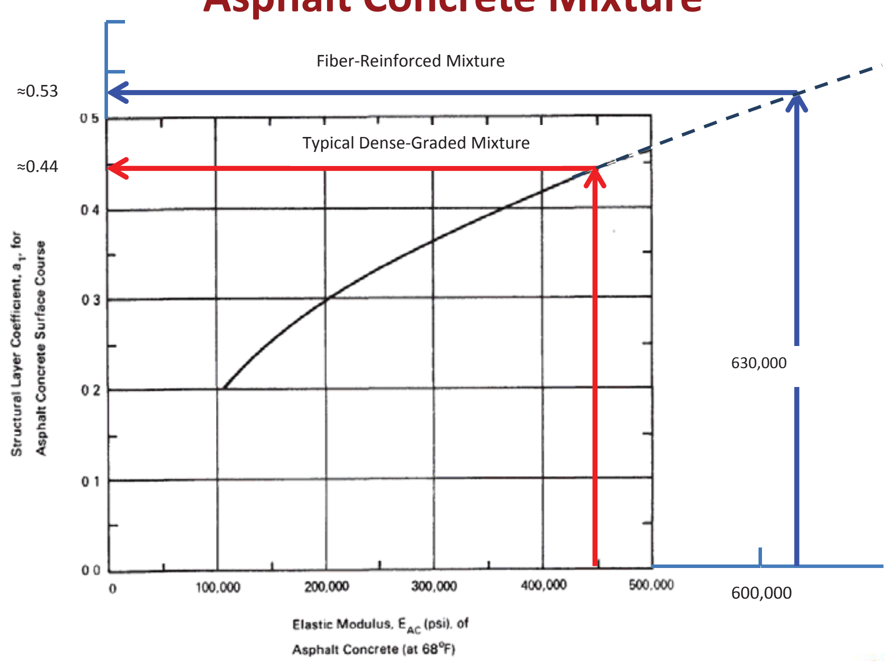
Extrapolated Layer Coefficient of Fiber-Reinforced Asphalt Concrete Mixture



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Laboratory Evaluation

Jackson Hole Airport

- Temperature changes from: -40°F to 41° F (winter) & up to 104°F in the summer
- Elevation requires higher approach speeds
- Short runway length
- Accommodates planes such as the 757 and A320
- Snow plowing caused raveling in existing pavement

Mix Property	JAC Mixture	SHR Mixture (Control)
Gradation	Open	Open
Binder	PG 64-34	PG 64-34
Asphalt Content	5.70%	5.60%
Laboratory Target Air Voids	13,15%*	15,17%*
G_{mm}	2.416	2.540
Hydrated Lime (%)	0.75%	-
Fiber Reinforcement	1 lb/ton (0.5 kg/MT)	None
Mixing/Compaction Temp, ° F (° C)	325/300 (163/149)	325/300 (163/149)

Sieve Size (US)	Sieve Size (SI)	JAC Mixture % Passing	SHR Mixture % Passing	FAA P-402 Control Points
1"	25.4	-	-	-
3/4"	19	100	100	100
1/2"	12.7	82	85	70-90
3/8"	9.5	57	52	40-65
No. 4	4.76	22	19	15-25
No. 8	2.38	12	13	8-15
No. 30	0.6	6	7	5-9
No. 200	0.074	2	2.5	1-5

Air voids for cylinder and beam samples, respectively (Corelok Method)

Raveling Test

- Cantabro Test
  - LA abrasion machine without steel balls
  - Mashall specimen size
  - Test temperature = 25° C
  - Recommend a lower test temperature for soft binders

Location	Replicate	W_i	W_f	% Loss	Average	CV
Jackson Hole Airport	1	986.8	959.6	2.8%	2.6%	16.9%
	2	970.1	940.2	3.1%		
	3	967.6	945.1	2.3%		
	4	1031.5	1009.7	2.1%		
Control	1	987.8	953.4	3.5%	3.7%	33.3%
	2	998.9	971.9	2.7%		
	3	963.5	910.9	5.5%		
	4	999.3	968.4	3.1%		

CO_2 EQUIVALENT EMMISSION COMPARISON

The transport distance was assumed to be 25 km (15.5 miles), the density of asphalt concrete was taken as 2275 kg/m^3 (142 lb/ft^3) and a runway width of 45.7 m (150 feet). The use of FRAC as the FAA P-401 surface course can result in a 33% decrease in total kg of annual CO2 equivalent per km of runway. This is based on the assumption that the dynamic modulus increases by 50% to 300,000 psi (1,723) for FRAC and is also limited by the current FAA design procedures.

Service life (Y)	Total kg Annual CO_2 Eq. / km runway (lb/mi runway)	% Change
10	128279 (455,703)	100.0%
15	85519 (303,801)	33.3%
20*	64139 (227,850)	0.0%
25	51312 (182,283)	-20.0%
30	42760 (151,902)	-33.3%

** Standard FAA design life*

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Cost Comparison

Item	Jackson Hole Airport			Sheridan County Airport		
	Unit	$/unit	Total Cost	Unit	$/unit	Total Cost
P-402 Porous Friction Course, tons	8530	48.5	$413,705	5800	58.6	$339,880
PG 64-34 Modified Binder, tons	640	1000	$640,000	520	890	$462,800
Total Cost of HMA Mixture			***$1,053,705***			***$802,680***
Cost per Ton of HMA Mixture			***$124***			***$138***

Item	Jackson Hole Airport			Sheridan County Airport		
	Unit	$/unit	Total Cost	Unit	$/unit	Total Cost
P-402 Porous Friction Course, tons	8530	50	$426,500	5800	60.4	$350,320
PG 64-34 Modified Binder, tons	640	1000	$640,000	520	890	$462,800
Fiber Reinforcement Additive, lbs	8530	7	$59,710	5800	8.35	$48,430
Total Cost of FRAC Mixture			***$1,126,210***			***$861,550***
Cost Per Ton of FRAC Mixture			***$132***			***$149***

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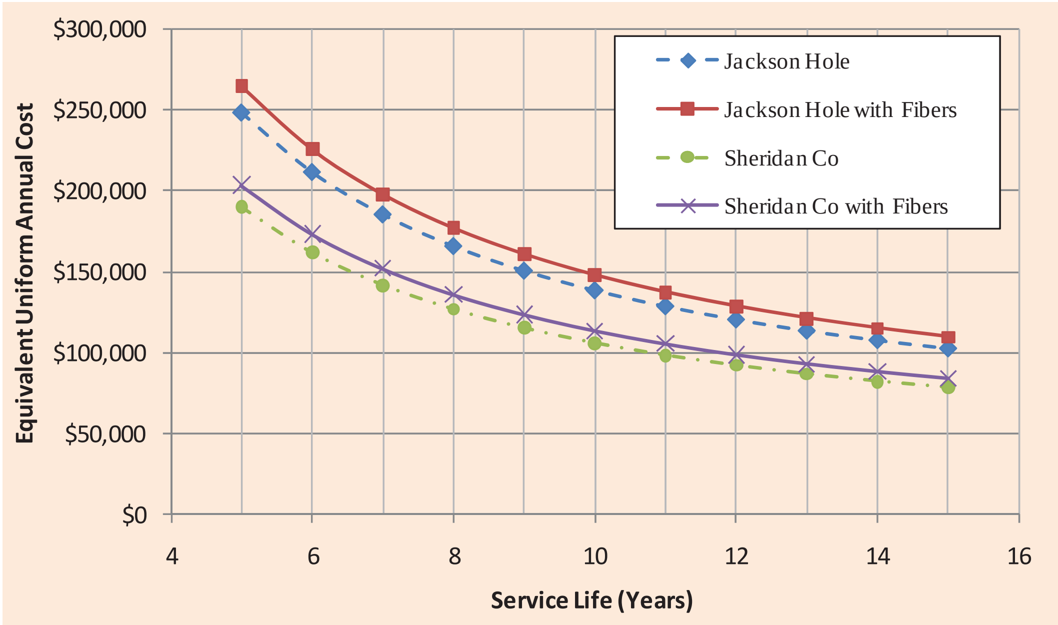
Cost Comparison

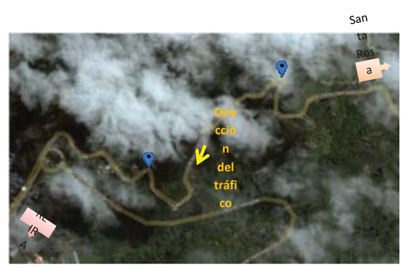


Project in Columbia

Autopistas del Café

Downhill Curves (Location: Pereira)

- Downhill curve with high traffic volume
- Raveling problems occur within 2 month and yearly repairs where required (2009, 2010 & 2011);
- In January 2013, FORTA-FI was used with a dense HMA (“MDC-2”) and a conventional 60-70 binder;
  - Work done on 2 curves: milled 5cm and repaved with 5cm;
  - 16 month later, both curves are in excellent condition;
  - No cracks, no raveling



Bus stop (Medellín)

- Bus stop on a downhill alongside Parque Villa Hermosa;
- Severe rutting within 2 years; (May 2013)
- Work done: milling of 15cm and paving a 7.5cm base MSC-1 and a 7.5 cm surface course of MDC-2 with FORTA-FI;
- 1 Year later road has no rutting

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Devimed Peaje

DeviMed highway (Medellin to Bogota): already paved more than 50km x 9m wide by 6 cm average.

Toll booth, **Peaje Guarne** is one of the most congested roads out of Medellin. Problems: reflective cracking

Paved with FORTA-FI, 7 cm thick by **PAVIMENTAR**

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Other on-going research

Characterization of Fiber Orientation and Distribution in Fiber Reinforced Asphalt Concrete

Amelia Celoza, Civil Engineering
Mentor: Dr. Kamil Kaloush, Associate Professor
School of Sustainable Engineering and the Built Environment

Research Objective: Investigate methodologies to identify internal characteristics of asphalt pavements and evaluate their applicability to imaging of fibers orientation and distribution in Fiber Reinforced Asphalt Concrete (FRAC).

Fiber Reinforced Asphalt Concrete (FRAC):

- provides benefits to sustainable pavement design and performance
- is more resistant to wear, cracking, and rutting
- is more resistant to moisture damage and aging

Figure 1. Blend of reinforcing fibers [1]

Fibers utilized in FRAC are aramid and polypropylene, as seen in Figure 1.

Fibers increase durability and performance in general. There are several methods on how they are introduced at the asphalt plant. The fibers addition are most effective when they are uniformly distributed in the asphalt mixture.

Understanding fiber orientation and distribution will aid in improving FRAC production methods.

[1] Kaloush, K.E. et al. Evaluation of fiber-reinforced asphalt mixtures using advanced material characterization tests.
[2] Kutay, M.E et al. Three-dimensional image processing methods to identify and characterise aggregates in compacted asphalt mixtures.

X-Ray Computed Tomography

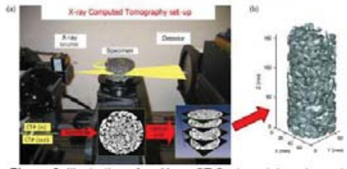

Figure 2. Illustration of an X-ray CT System: (a) equipment components and (b) reconstructed 3D image of an asphalt specimen [2]

- X-ray CT creates 2D images, or "slices," of the asphalt concrete sample
- Threshold values diff[poster_template_landscape-rschprogram.jpg] components, such as air voids, aggregate, and binder
- Digital image processing identifies components
- Three-dimensional model is constructed from two-dimensional processed images

Digital Image Processing

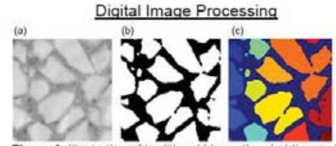

Figure 3. Illustration of traditional binary thresholding and labeling: (a) original grayscale image, (b) thresholded binary image, and (c) labeled image [2]

Expected Orientation and Distribution of Fibers

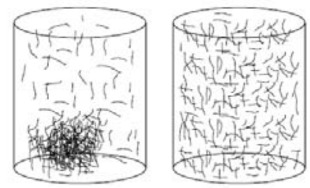

Figure 4. Illustrations of expected fiber distribution in FRAC specimens: clustered (left) and uniformly distributed (right)

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EFFECT OF AGITATION LEVEL ON FIBRILLATION OF ARAMID FIBERS

B. Shane Underwood[1], and Waleed A. Zeiada[2]
[1]Assistant Professor, [2] Postdoctoral Scholar, Arizona State University, Tempe, AZ 85287-5306, USA

Introduction

- Distribution of fibers within the mixture and the state of the fibers that are distributed are the main two key variables that believed to affect the final performance of fiber reinforced asphalt concrete (FRAC).
- In this context "state" refers to the amount of micro-fibrillation.
- The distribution and the state of the fibers are related, but provide for fundamentally different functions within the FRAC and so they can be examined separately for their individual contribution.
- Once each of these phenomena is understood, the interactions between them can be more efficiently studied.
- A small laboratory mixing and imaging experiment has been instigated to study the effects of the fiber introduction method and agitation level on the state of the fibers.
- Two methods of fiber introduction into FRAC were examined; air blown and hand fed.

Hand Feed

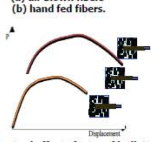
Air Blown

Agitation of Fibers

- The experiment evaluated the fiber introducing method (air blown versus hand fed) and the agitation level (2 and 4 minutes of mixing with hot aggregates) on the state of the fiber fibrillation.
- The hand fed fibers were taken directly from unopened bags of fiber and the air blown fibers were sampled from field production samples shipped to ASU by Forti-Fi.
- The Aggregates were proportioned to replicate a typical asphalt concrete mixture and thoroughly heated to a typical asphalt concrete production temperature (190ºC).
- The aggregates were then transferred to a laboratory mixer and the fibers were introduced at an equivalent rate of 1 pound per ton.
- The mixer was started and the aggregates agitated for 2 and 4 minutes.
- Some clumping was observed, but the tendency to clump was much greater with the air blown fibers than with the hand fed condition.
- The visual observations were not quantified.

Aggregate after 2 minutes of mixing;
(a) air blown fibers
(b) hand fed fibers.

- It is expected that agitation level affects the degree of fibrillation.
- It is hypothesized that increasing the degree of fiber fibrillation would increase the pond between the fibers and the asphalt mix which consequentially enhances the FRAC anticipated performance.



Hypothesized effect of micro-fibrillation degree on pull-out load

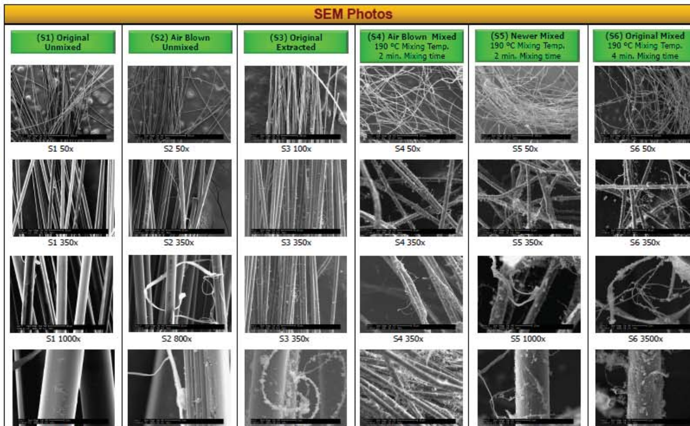
SEM Scanning

- To link the mixing observations and mechanical behavior to fiber state, a scanning electron microscope (SEM) was used to image the air blown and hand fed fibers before and after mixing.
- In total 45 different micrographs were created and the findings from these images are summarized. It should be noted that these images are all taken of only the Aramid fibers.

Summary

- The manufacturing and bundling of the fibers does not cause a substantial amount of micro-fibrillation.
- Air blowing the previously undisturbed samples causes some fibrillation, but not a substantial amount.
- The act of mechanical agitation causes fibrillation with the degree of fibrillation increasing as mixing time increased.
- Micro-fibrillation is less in the case of the air blown samples than the hand fed samples.
- These images and the results from the mixing experiment suggest that the introduction of fibers by air blowing may lead to less micro-fibrillation and less potential for dispersion during the FRAC fabrication process.
- This finding may also provide an explanation for some of the laboratory findings regarding the improvement in mechanical properties with the air blown and hand fed process.

SEM Photos



Thank You!

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