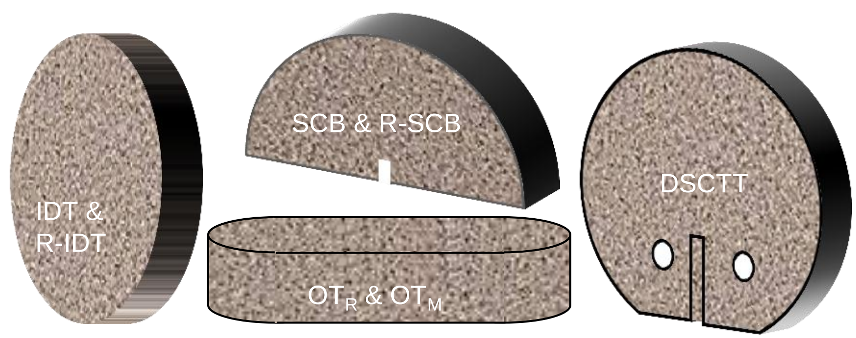
Project 0-6607

Search for a Test for Fracture Potential of Asphalt Mixes

CLOSE OUT MEETING



by

LUBINDA, ABU, & TOM

Cedar Park - Austin

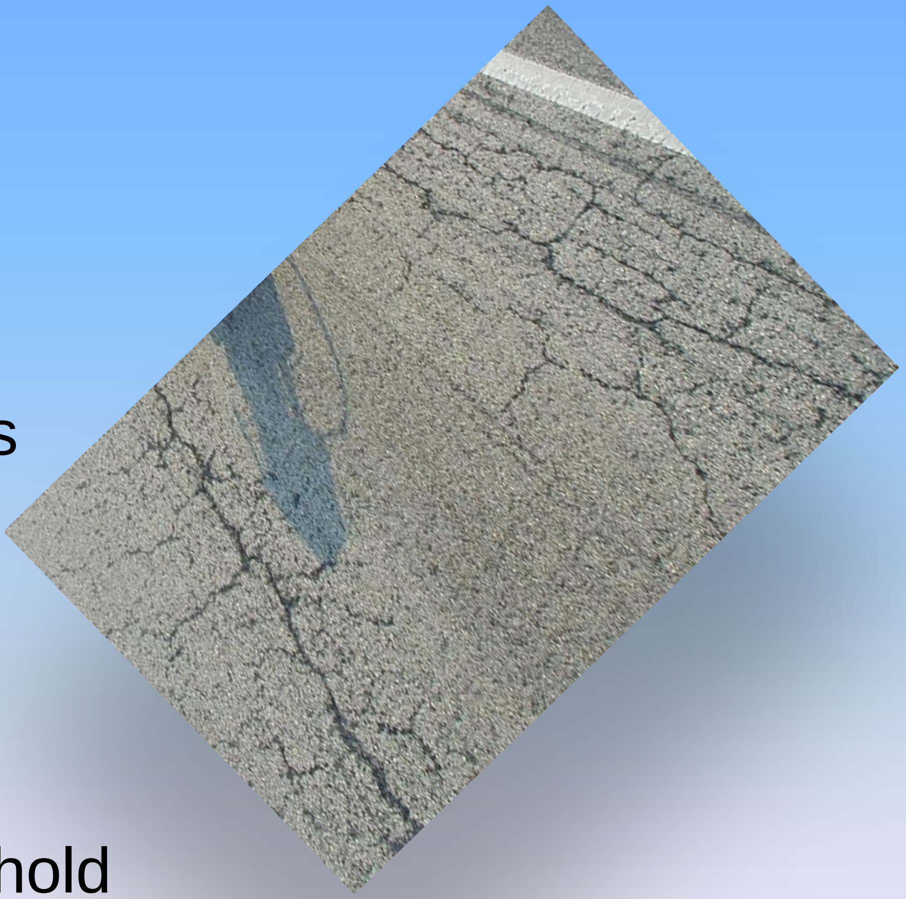
Thursday August 23rd 2012

Presentation Outline

1) Part A – Introduction
2) Part B – The OT test method
3) Part C – Surrogate crack tests (6 No.)
4) Part D – Comparison of the crack test methods
5) Part E – Summary & recommendations
6) Miscellaneous & discussions

Part A: Introduction

1) Research team
2) Problem statement
3) Objectives & work plans
4) Research tasks & product deliverables
5) HMA mixes evaluated
6) Variability & COV threshold



Texas Transportation Institute

Research Team

TxDOT	TTI
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Problem Statement

1) Increased premature pavement cracking

2) Poor HMA mix crack-performance

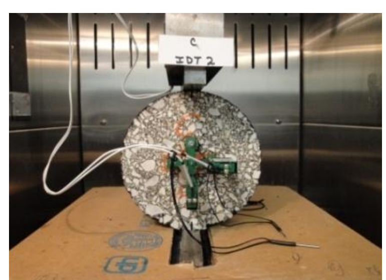
3) Concern about OT severity & variability

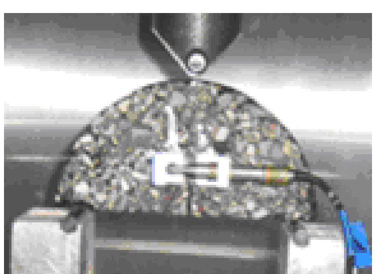
4) Need for a robust, reliable, & repeatable laboratory cracking test:

   - Routine HMA mix screening in the lab
   - Practical & easily implementable
   - Easy sample preparation with potential to test lab molded & field cores
   - Reasonable test duration (≤ 1 day)
   - Acceptable level of variability & reproducibility

Objectives & Work Plan

1) Evaluate current OT procedure
2) Address OT repeatability & reproducibility
3) Update Tex-248-F specification
4) Develop surrogate crack tests
5) Develop test procedures, specifications, & technical recommendations





Status of Research Tasks

Status of Product Deliveries

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HMA Mixes Evaluated

#	Mix Type	Materials	Cracking Resistance (OT Cycles)
1	CAM (FM 158)	6.7% PG 76-22 + Limestone + 1% Lime	**Very good** (>700)
2	CAM (SH121)	7.0% PG 64-22 + Igneous/Limestone	
3	Type F (US 271)	7.4% PG 76-22 + Sandstone	
4	Type D (Chico)	4.5 - 5.5% PG 70-22 + Limestone	**Good** (200 to 700)
5	Type D (ATL)	5.0 - 6.2% PG 64-22 + Quartzite + 20% RAP	
6	SMA (IH 35)	6.0% PG 76-22 + Limestone + 5% Filler + 1% Lime + 12% RAP	
7	Type B (WAC)	PG 64-22 + Limestone	**Marginal** (< 200)
8	Type C (LRD)	5.0 – 5.2 % PG 64-22 + Crushed Gravel + 1% Lime + 20% RAP	
9	Type D (CHS)	4.9% PG 58-28 + Granite + 1% Lime + 20% RAP	
10	Type C (FW)	4.6% PG 70-22 + Granite + 1% Anti-strip + 15% RAP	
11	Type C (Odessa)	5.8% PG 70-22 + Limestone	
12	Type C (WAC)	5.0% PG 70-22 + Limestone + 1% Lime+ 16% RAP + 3% RAS	

Sample type = Raw-materials, plant-mix, & cores | Sample replicates = 5 per mix per test per variable
Sample target AV = 7±1% | PFC = 20±2%

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Crack Test Variability

1) Repeated load crack tests – inherently very variable by their nature

	Flexural Beam Fatigue	Flexural Trapezoidal Fatigue	Diametral Fatigue
Stiffness			
Coefficient of Variation (%)	12.3	11.4	19.7
Sample Variance (ln psi)	0.010	0.014	0.015
Cycles to Failure			
Coefficient of Variation (%)	98.7	171.8	65.5
Sample Variance (ln cycles to failure)	0.282	1.696	0.213

SHRP, 1994 (Monismith)

2) For this study: used COV $\leq$ 30% as reference for acceptable variability

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Part B: The OT Test Method

1) OT sensitivity evaluation
2) OT Round-robin testing
3) Updates to Tex-248-F
4) Tex-248-F Video demo
5) OT software updates
6) OT calibration & service maintenance – manuals
7) Key findings

OT Sensitivity Evaluation

#	Factor	Variables Investigated	Key Finding	Recommendation
1	Sample replicates	3, 4, & 5	Test 5 or 4 specimens & pick the best 3 – macro	Test 5 or 4 & pick best 3 Items 5.1.1 & 6.2
2	Drying method after cutting samples	Air (room), Oven (104 °F), & Core dryer (room)	Oven @ 104 °F best followed by Core Dryer	Use Oven @ 104 °F (≥ 12 hrs) Item 5.2.3
3	Sample mold size	5” (2), 4.5” (1), 4.5” (2), & 2.5” (1)	Use 5” (2) or 2.5” (1)	Items 4.1 & 5.1.1 Use 5″ cut 2
4	Sample sitting time from day of molding	3, 5, 7, 9, 11, 15, & 20 days	Test within 5 days → more consistent results	Test within 5 days Items 4.1 & 5.7.2
5	Glue type (3 types evaluated)	(1) Devcon plastic steel putty, (2) Devcon high strength epoxy, & (3) Devcon 2-ton epoxy; all two-part	Use Devcon 2-ton 2-part epoxy (2500 psi & 8 hrs curing time to full strength) → better	Item 5.3.3: Use 2500 psi strength epoxy or gluing compound with ≤ 8 hrs curing time to full strength
6	Glue quantity (2 ton 2-part epoxy)	12, 14, 16, & 18 grams	Old plates = 15±1 g New plates = 13±1 g	Use 14±2 g (12 -16 mils) Item 5.3.3
7	Plates/sample gap width (teflon/metal strips)	6.25 mm (tape vs. metal bar)	New ha[illegible]	Item 3.3: Use new plates, but be careful with metal space bar
8	Test loading parameters	0.015 , 0.02, & 0.025 inches	[illegible] not impro[illegible]ability	Items 2.1 & 5.7: Continue using 0.025″ 77 °F @ 10 sec/cycle
9	Test temperature differential	73, 75, 77, 79, & 81 °F	High variability for > 2 °F temperature differential	Use ≤ ±2 ºF tolerance (±0.5 °F) Item 5.7.1
10	AV uniformity effect	5%, 6%, 7%, 8%, & 9% (±0.5, ±1, ±1.5%, etc)	7±0.5% gives more consistent results	Use 7±1% for practicality, but target 7±0.5% . Item 4.1.1
11	Rest time prior to testing	10, 20 , & 30 minutes	Use ≥ 10 minutes	Item 5.7.1: ≥ 10 minutes
12	Sample batching & molding	1 batch 5 or 4 samples vs. single (i.e., 5 batches 5 samples)	Single →consistent results – but not very significant	Small batches better, though more work & time. Item 4.1:
13	Sample thickness	1.0, 1.5, 2.0, & 2.5 inches	Little impact on variability	Item 5.2.1.3

1) Lubrication & 5-10 min wait
2) Consider discarding plates after treads are worn out by over 80%(1.5 mm tread depth)

Click HERE for Detailed OT Sensitivity Evaluation

OT Sample Thickness Variation

Placed 2 inch overlays &/or lift thickness

Best 3 of 5

Avg. OT Cycles

Thickness (Inch)	Waco Type B Limestone	Corpus Type C With RAP + RAS	Atlanta Type D Quartzite + RAP
1.0	-	-	67
1.5	28	9	304
2.0	237	347	1 000+
2.5	1 000+	970	-

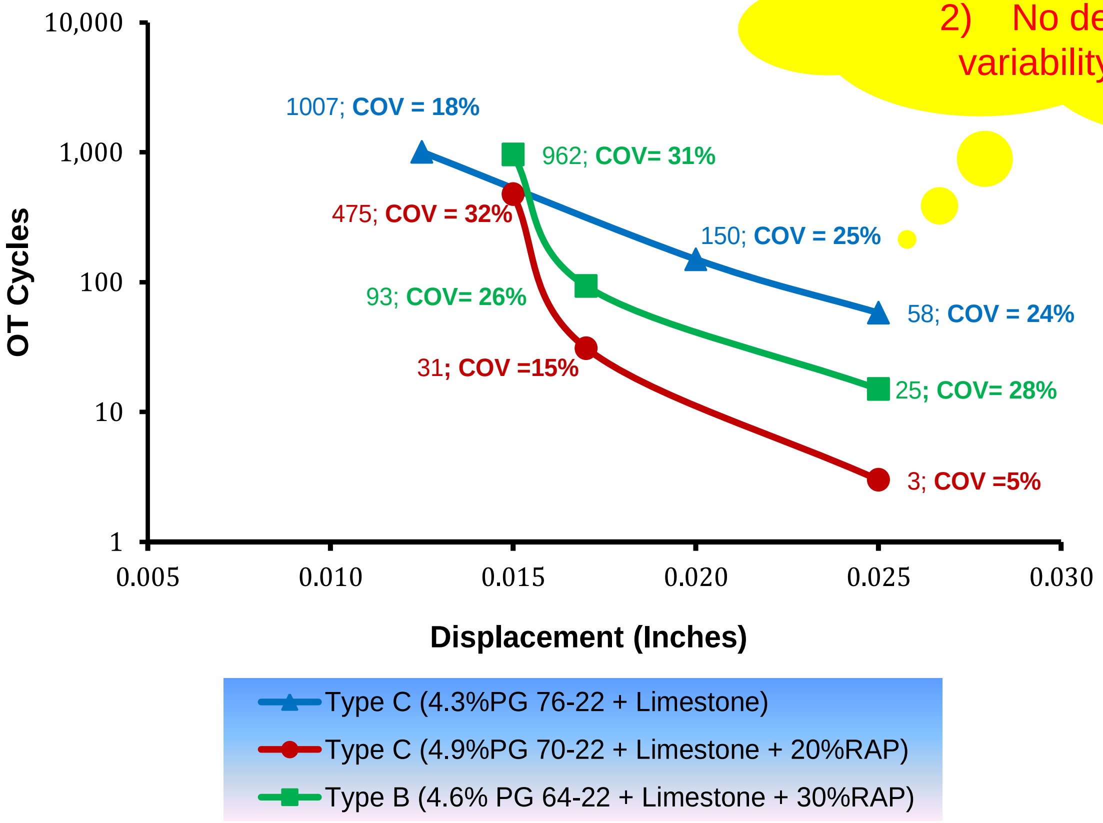
Variability (COV)

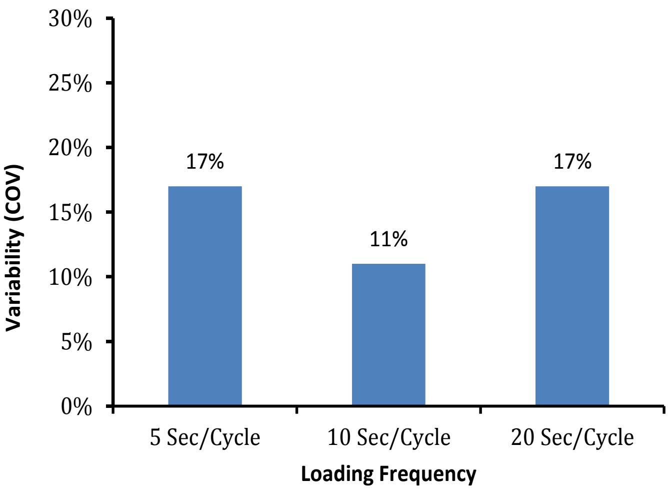
Thickness (Inch)	Waco Type B Limestone	Corpus Type C With RAP + RAS	Atlanta Type D Quartzite + RAP
1.0	-	-	23%
1.5	22%	12%	11%
2.0	19%	18%	-
2.5	-	16%	-

Change in sample thickness significantly impacts OT cycles, but not really on variability!!

OT Load-Frequency Variation

1) Significant impact on OT cycles with decreasing displacement
2) No definite trend on variability in terms of COV





Best 3 of 5

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Effects of Sample Notching

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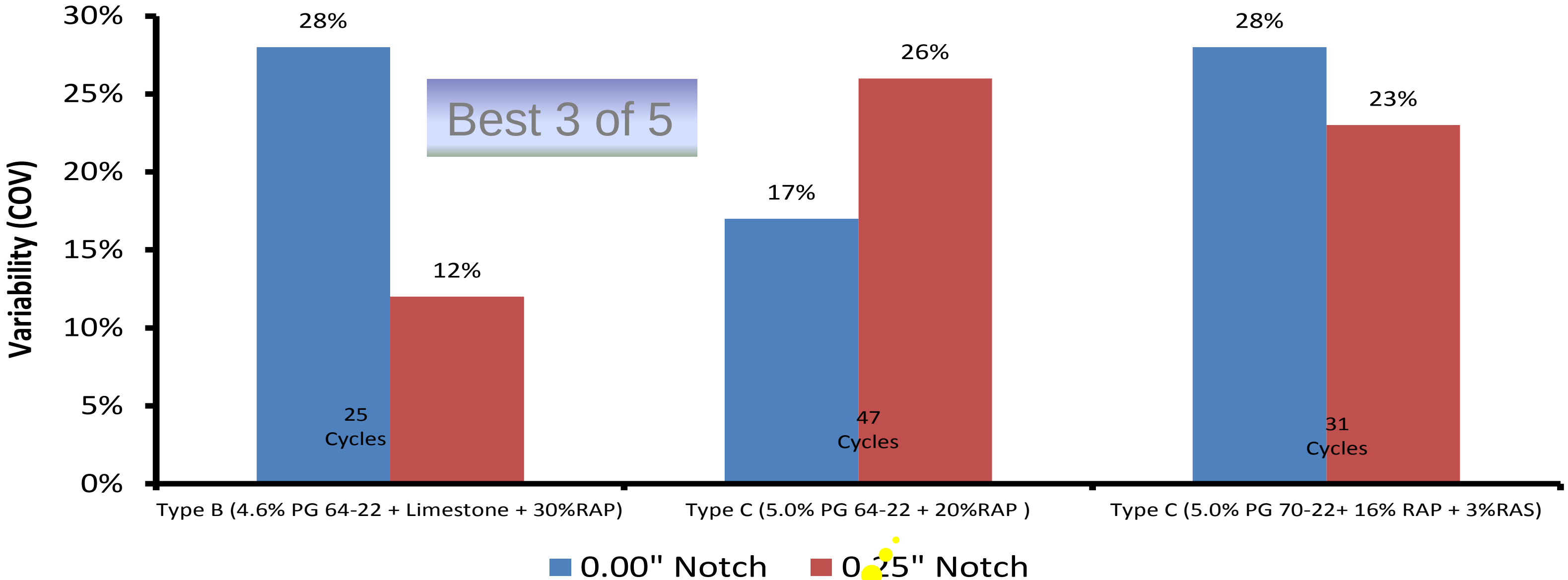
¼″ notch depth by 1/8 ″ width
(~ 45 minutes additional process)

No notch



No definite trend on variability in terms of COV except for the coarse-graded Type B mix; So, maybe worth notching on coarse-graded mixes

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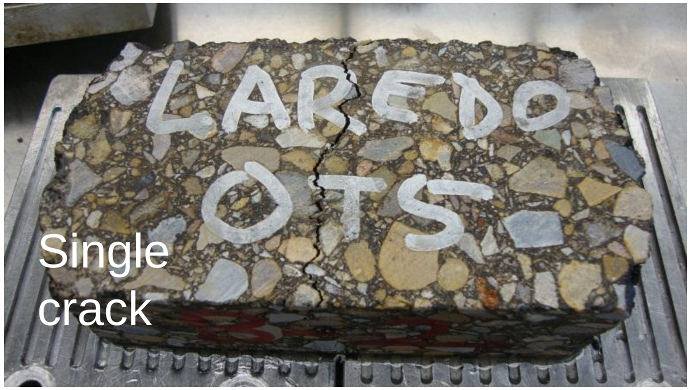
OT Crack Failure Mode



Multiple Cracks
– aggregate size & orientation
- So for coarse-graded mixes, high variability should not be a surprise!!!!

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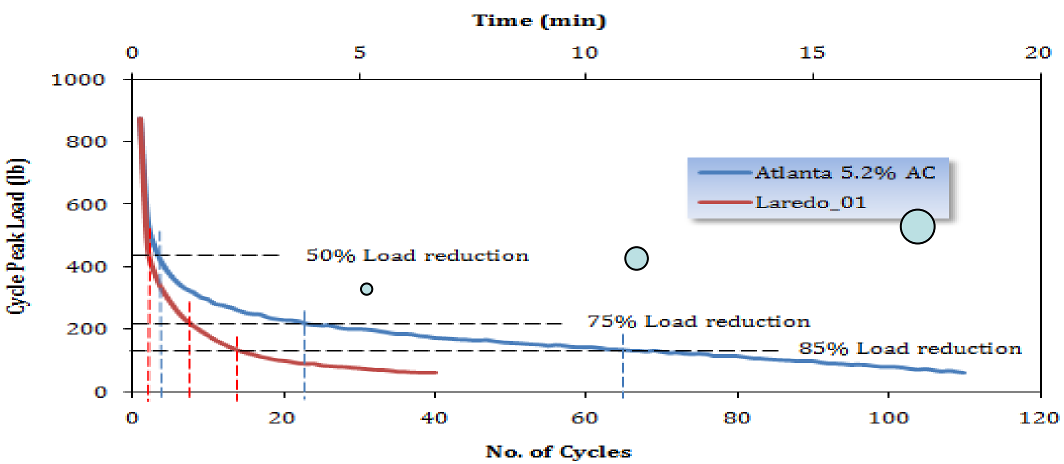
Alternative OT Data Analysis Methods: Items 5.7.2 & 6.0

#	Item	Variable	Key Findings & Recommendations
1	Load reduction criterion	50, 75%, 85%, & 93%	– 50 & 75% → Not viable, sharp drop in load with small & hardly differentiable cycles – 85% gives reasonable COV with interpretable OT cycles → Validation & correlation with field data??
2	Rate of load decrease	Slope change → load-circle curve	– Unsatisfactory results – Problems determining the inflexion point beyond 50% load reduction
3	Pseudo fracture energy (Pseudo-FE)	Area under load-cycle curve	– No improvement in variability with use of Pseudo-FE!
4	OT monotonic testing	σ, ε, FE, & FE Index	– FE Index → promising → see Part B of this PPT



50 & 75% ⇒ sharp drop in load

Click HERE for Detailed Data Analysis

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OT Round-Robin.

LRD Type C = 5% PG 64-22 + Gravel + 1% Lime + 20% RAP						
Sample ID#	**TxDOT Austin**	**TxDOT Childress**	**TxDOT Houston**	**TTI Lubinda**	**TTI Hossain**	**Overall**
OT1	54	41	72	43	46	-
OT2	38	53	73	36	41	-
OT3	52	37	52	32	71	-

Best 3 of 5

Stats & Variability: Average (Avg) & Coefficient of Variation (COV)						
Avg	48	44	66	37	55	
COV (≤30%)	18%	19%	18%	15%	26%	

Considering All 5 OT Replicate Samples						
Avg	60	51	50	43	79	
COV	29%	59%	47%	29%	54%	

Reasonably comparable results obtainable if recommendations are adhered to!!

OT Round-Robin..

Best 3 of 5

Avg OT Cycles

Mix (Target ≥ 3 mixes per lab)	**TxDOT Austin**	**TxDOT Childress**	**TxDOT Houston**	**TTI**	**Overall**
Chico Type D 4.5%	-	119	-	118	
LRD Type C (+ RAP)	48	44	66	46	
WAC Type C (+RAP + RAS)	-	25	37	38	
ATL Type D (+RAP)	389	410	354	304	

Variability (COV)

Mix (Target ≥ 3 mixes per lab)	**TxDOT Austin**	**TxDOT Childress**	**TxDOT Houston**	**TTI**	**Overall**
Chico Type D	-	9%	-	12%	
LRD Type C (+ RAP)	18%	19%	18%	27%	
WAC Type C (+RAP + RAS)	-	34%	10%	30%	
ATL Type D (+RAP)	29%	12%	31%	11%	

Reasonably comparable results obtainable if recommendations are adhered to!!
Generally → Higher variability for RAP, RAS, & Coarse-graded mixes!!

OT Operator Effect

Chico Type D= 5% PG 70-22 + Limestone				
Sample ID#	**TTI - Hossain (Trained)**	**TTI – Unnamed (Untrained)**	**TTI – Lubinda (Self Trained)**	**Overall**
OT1	150	180	250	-
OT2	242	458	186	-
OT3	239	143	196	-

Best 3 of 5

Stats & Variability: Average (Avg) & Coefficient of Variation (COV)				
Avg	210	260	211	
COV (≤30%)	25%	66%	16%	

Considering All 5 OT Replicate Samples				
Avg	175	348	247	
COV	39%	108%	31%	

Initiate Certification Training Program ≥ 2 Techs per Lab!!!

Trained Operator Effect

Type D = 5.0% PG 70-22 + Limestone

Operator	Year	Location	Avg. OT Cycles	COV	Comment
Lubinda	2009 Round Robin	TTI, TxDOT labs, & PaveTex	258	23%	28 replicates; 1 sample cut from 2.5"
Lubinda	2011 (June)	TxDOT-CST	213	17%	Best 3 out of 5; 2 sample cut from 5.0"
Hossain	2011 (June)	TTI	230	27%	Best 3 out of 5; 2 samples cut from 5.0"
Hossain	2011 (June)	TTI	210	25%	Best 3 out of 5; 1 sample cut from 4.5" (New base & plates)
Jason	2012	TTI	197	23%	Best 3 out of 5; 2 samples cut from 5.0″

Comparable results obtainable if Spec is adhered to & Operators are trained!!

Operator & Equipment Effect

Type D = 5.1% PG 64-22 + Quartzite + 20% RAP

	AV (7±1)		OT Cycles	
Operator	**Hossain**	Lubinda	**Hossain**	**Lubinda**
OT equipment & location			**TTI**	**TxDOT - Austin**
Sample# 1	6.8%	7.1%	309	294
Sample# 2	6.1%	6.6%	121	241
Sample# 3	6.4%	6.5%	334	197
Sample# 4	6.3%	6.4%	269	257
Sample# 5	6.6%	6.9%	240	306
Avg (all)	**6.4%**	**6.7%**	**255**	**259**
COV (all)	**4.3%**	**4.4%**	**32.6%**	**17%**
Avg (best 3)	**6.4%**	6.5%	**304**	**286**
COV (best 3)	**2.4%**	1.5%	**11%**	**9%**

Comparably reasonable results obtainable if Spec is adhered to & trained Techs are used!!

Tex-248-F: Key Updates

#	Item	Tex-248-F	Modification	TxDOT Response
1	Sample prep	4.1 & 5.1.1	5″ cut 2 or 2.5″ cut 1	5" tall cut 2
2	Replicates	5.1.1 & 6.2	5 or 4 → pick best 3	4 pick best 3
3	Drying method	5.2.3	Oven @ 104 °F (40 °C); ≥ 12 hrs to constant weight	Oven - Okay
4	Glue + quantity	5.3.3	2 500 psi strength, ≤ 8 hrs curing time; 14.0±2.0 lbs per sample	Okay
5	Sample sitting time from molding day	4.1 & 5.7.2	Test within 5 days; record if tested after 5 days	Test within 5 days
6	New plates + base plate	3.3	Use Vaseline to grease sides of space bar, 5-10 min wait → then pull	Buy & use new throughout

Tex-248-F: Video Demo

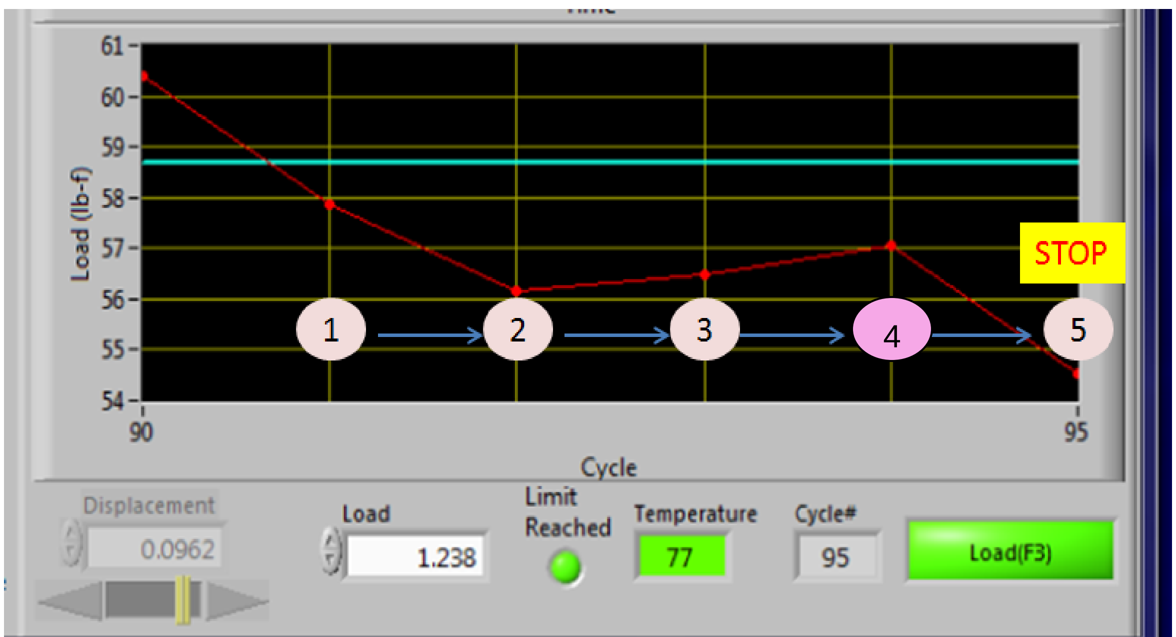
Modified Tex-248-F procedure step-by-step video demo:

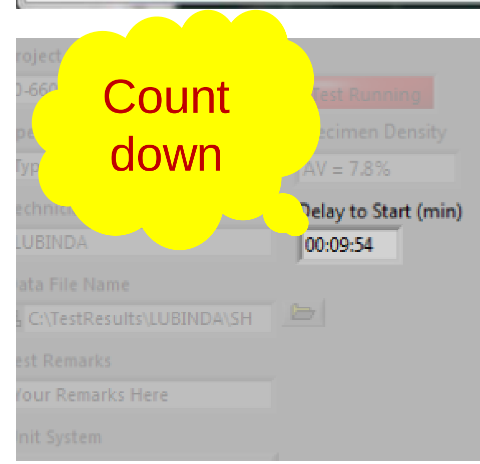
- Sample fabrication
- Sample drying
- Sample gluing & curing
- Sample setup & testing
- Data analysis
- Calibration & maintenance
- Trouble shooting

OT Software Updates

1) Latest Version – 1.9.0 (installed on one TTI OT machine)
2) Start button – disabled when pump is off
3) Delay time – installed
4) Re-programmed to terminate only if **5 Peaks in a Row** are below the threshold

Should be installed on all TTI & TxDOT machines





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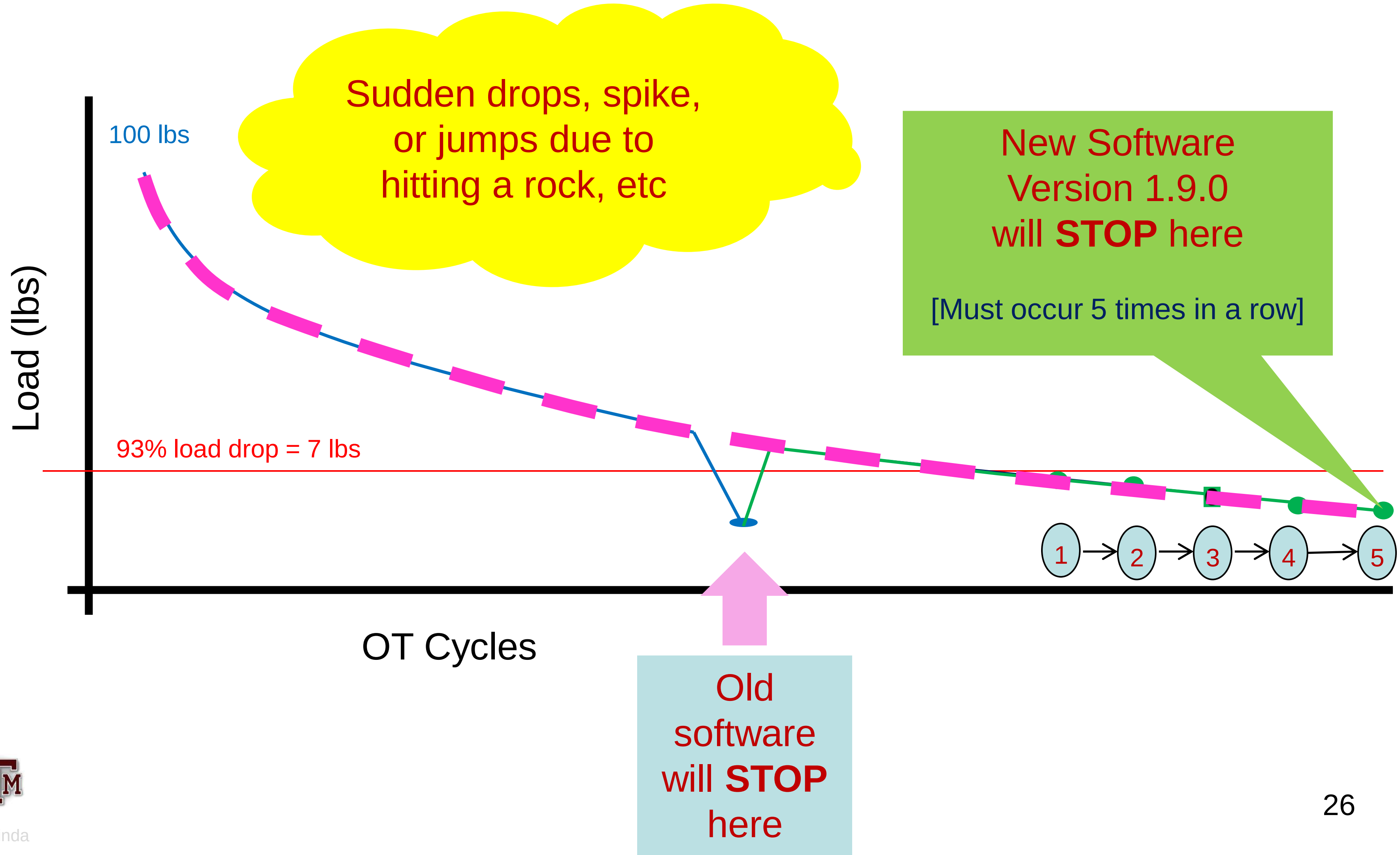
OT Software Comparison



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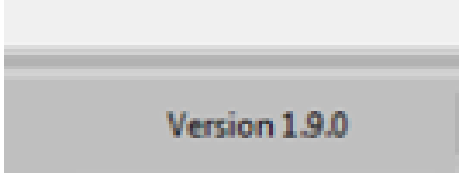
Example Results with New OT Software Version 1.9.0



Mix#1: Type D = 5.5% PG 64-22 + Limestone

Sample1	Sample2	Sample3	Avg	COV	Comment
766	763	778	769	1.03%	Only 3 replicates tested!!

Mix#2: Type C = 4.8% PG 70-22 + 20% RAP

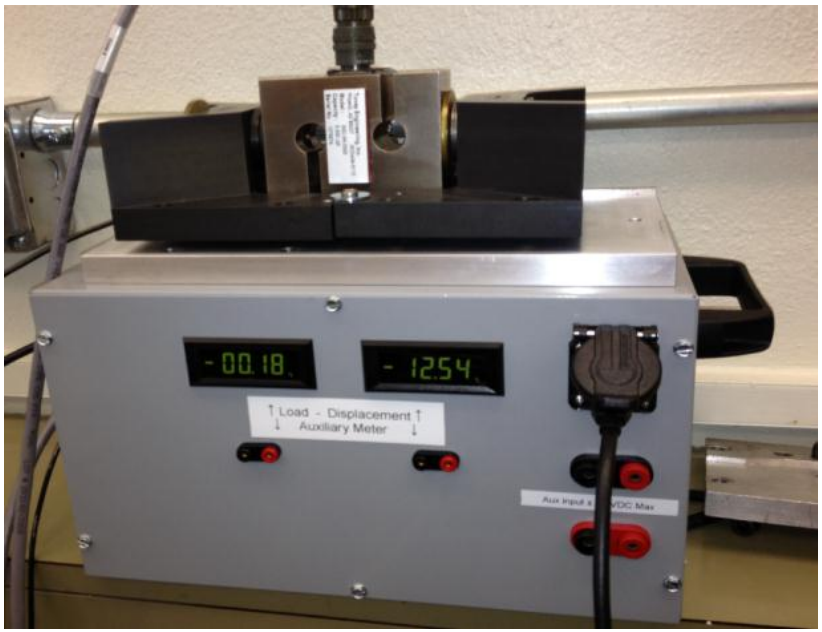
Sample1	Sample2	Sample3	Avg	COV	Comment
8	7	8	8	7.53%	Represents best 3 of 5!!

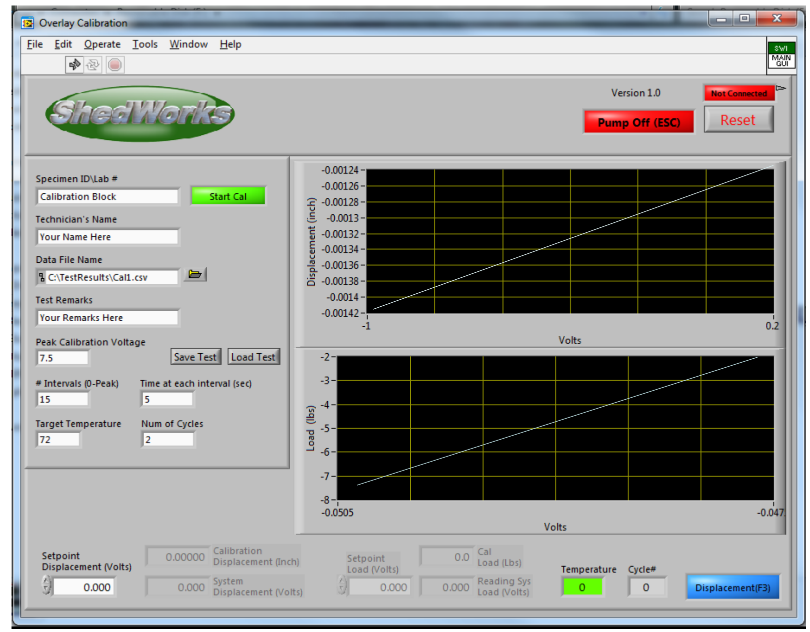
Mix#3: Type B with RAP

Sample1	Sample2	Sample3	Avg	COV	Comment
26	51	40	39	32%	Best 3 of 5

Results look promising so far!

New OT Calibration Block & Software





Block captures & automatically records measurements /data – both load & displacement.

Must be installed on all TTI & TxDOT OT machines

OT Load & Displacement Calibration

1) Calibration manual – draft available

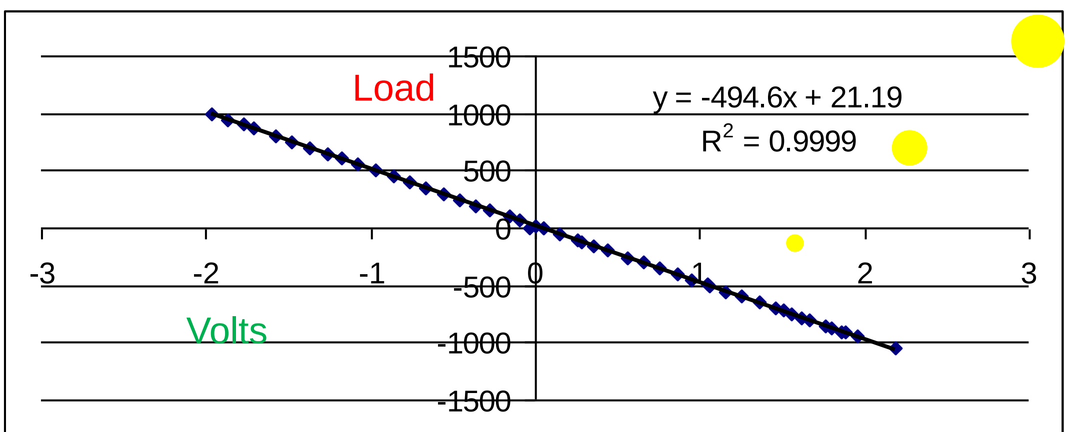
2) Perform calibrations semi-annually???

3) Load tolerance ≤ ±5% difference

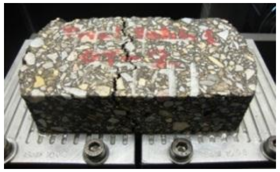
4) Displacement ≤ ±2% difference

5) Load-displ calibration curves = linear

Typical load-voltage curve for well calibrated OT load cell



OT Cal/Tuning Verification – Dummy Trial Testing



8	Actuato	Load Cell	Temperat	Time
9	0.00000	2.00000000	0.0000000	sec
10	[NEW]	0	-0.00909	-0.00909
11	0.0062	0.781075	77	0.0992
12	0.0062	1.989551	77	0.1992
13	0.0062	1.225648	77	
14	0.0062	0.839712	77	
15	0.0062	1.381991	77	
16	0.0062	1.159615	77	
17	0.0062	0.992045	77	0.6992
18	0.0062	1.167257	77	0.7992
19	0.0062	1.362975	77	0.8992
20	0.0062	1.298954	77	0.9992
21	[NEW]	5	0.853242	0.
22	0.0063	1	77	
23	0.0063	8	77	
24	0.0065	1	77	
25	0.0066	87.78095	77	1.16

Load ≤ ±10 lbs

8	Actuator	Load Cell	Temperat	Time
9	0.0000000	0.0000000	0.0000000	sec
10	[NEW]	0	0	0
11	0.011462	43.3545	77	0.0992
	0.011351	-114.957	77	0.1992
	0.012871	54.37211	77	0.2992
	0.012102	-135.66	77	0.3992
	0.01164	-191.406	77	0.4992
	0.01188	-215.238	77	0.5992
17	0.012097	-215.079	77	0.6992
18	0.012358	-208.004	77	0.7992
19	0.012505	-200.577	77	0.8992
20	0.012627	-197.345	77	0.9992
	NEW]	5	0.853242	0.853242
	0.012308	-	77	1.04
	0.013363	1	77	1.08
	0.013202	-	77	1.12
	0.012989	-7.93757	77	1.16

Displ ≤ ±2%

OT Service Maintenance

1) Maintenance manual – draft available

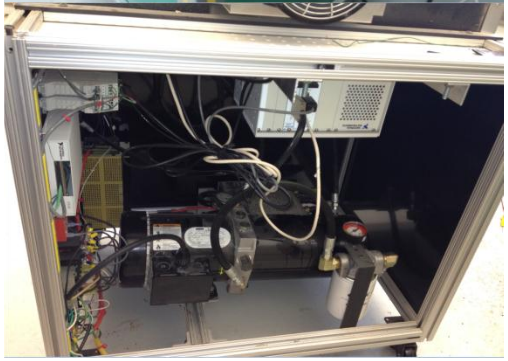
2) Perform maintenance yearly???

3) Check → hydraulic components & oil leaks

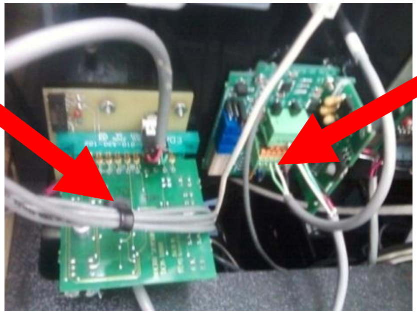
4) Check → mechanical components

5) Check → electrical components

6) Check → dusty, etc



LVDT Signal Conditioner



LOAD CELL Signal Conditioner

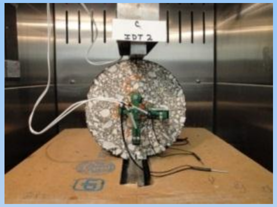
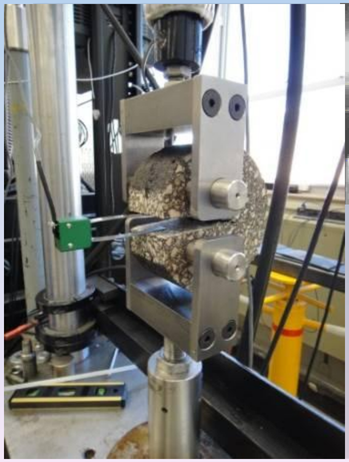
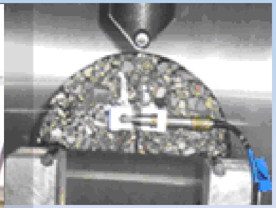
OT Key Findings

1) Implement recommended Tex-248-F modifications
2) Certification requirement for OT operators ≥ two Techs per lab
3) OT calibrations → Check after with Trial Dummy testing ≥3 HMA samples (synthetic samples)

4) Version 1.9.0 → install on all TTI & TxDOT OT machines
5) Video demo & calibration/service manuals should accompany modified Tex-248-F spec
6) Last Round-Robin must be conducted once new software has been installed on all OT machines

Part C: Surrogate Crack Test Methods

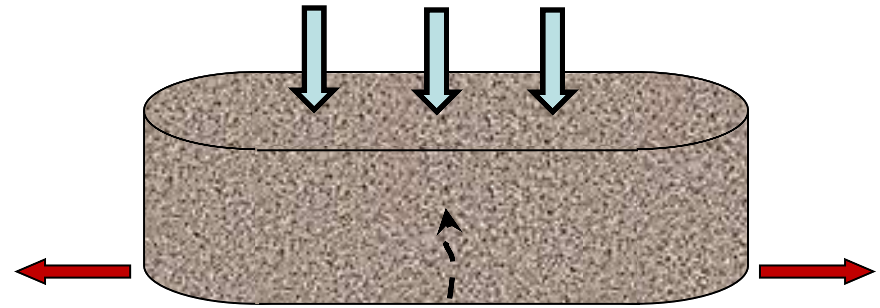
1) The OT monotonic test & FE Index
2) The IDT test – monotonic & repeated loading
3) The SCB test – monotonic & repeated loading
4) The DSCTT test – monotonic loading
5) Response curves, analysis models, & test results

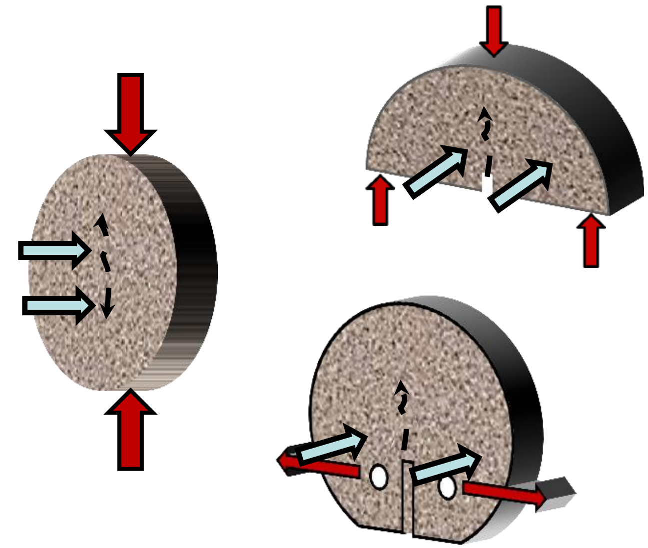
Surrogate Crack Tests

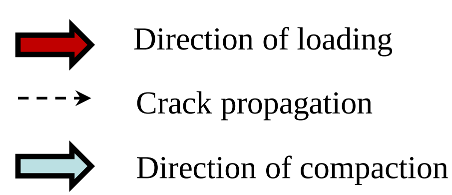
4 Monotonic + 2 Repeated Loading

- **Monotonic Loading OT test**
  - ✓ Overlay Tester (OT ⇒ OT_M)

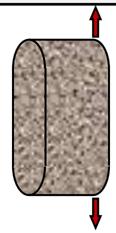
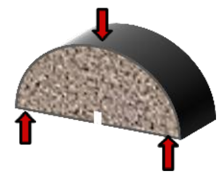
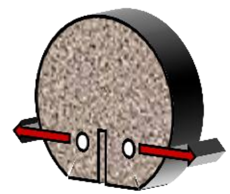
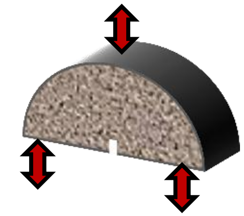


- **3 other Monotonic & 2 Repeated Crack Loading Tests:**
  - ✓ Indirect Tension Test (IDT & R-IDT)
  - ✓ Semicircular Bending Test (SCB & R-SCB)
  - ✓ Disc Shaped Compact Tension Test (DSCTT)

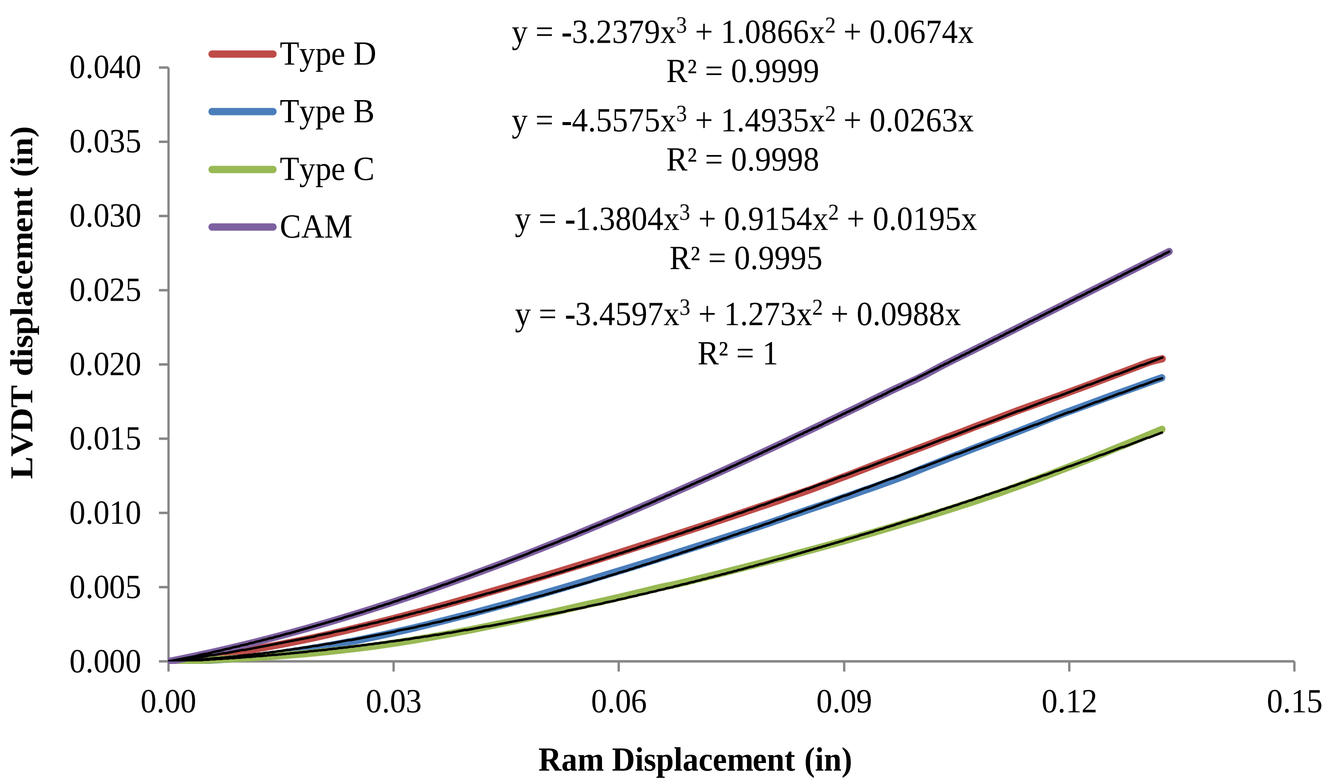


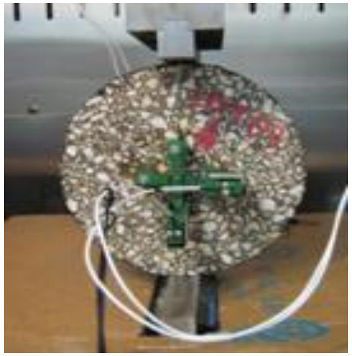


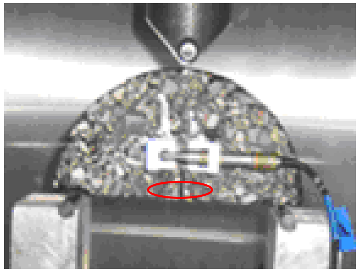
Surrogate Crack Test Setup

	Monotonic Loading				Repeated Loading	
	OT_M	IDT	SCB	DSCTT	R-IDT	R-SCB
Sample						
Sample size	6″ L ×3″ W × 1.5″ T	6″ϕ ×2.5″ T	6″ϕ × 3″ H 2.5″ T	6″ϕ × 5.7″ H 2.5″ T	6″ϕ ×2.5″ T	6″ϕ × 3″ H 2.5″ T
Notching/ Drilling	-	-	Notch = ¼″	Notch =2.5″ Drill= 1″ϕ	-	Notch = ¼″
Gluing/Curing	Yes (≥ 12 hrs)	-	-	-	-	-
Loading mode	Displ.	Displ.	Displ.	Displ.	Load	Load
Load	0.125inch/min	2.0 inch/min	0.05 inch/min	0.04 inch/min	25% IDT peak load (630 psi)	50% SCB peak load (175 lbs)
Sitting load	-	-	-	-	5% of input load	
Rate	-	-	-	-	1 Hz	1 Hz
Temp (°F)	77	77	77	77	77	77
Test stop	When load drops to zero				10,000 cycles	10,000 cycles
Test time	≤ 10 minutes				≤ 180 minutes (3 hrs)	
Output data	P_{max}, σ_t, ε_f, E_t, G_f (FE), & **FE Index**				Cycles, **Cycle Index**	

IDT & SCB Horizontal Displacement if no LVDT is Used







IDT & SCB testing with LVDT's attached to the sample

Comment: A Macro is developed for these four mix types to easily calculate Crack Opening Displacement from the RAM displacements. More mixes will be added to this Macro in future.

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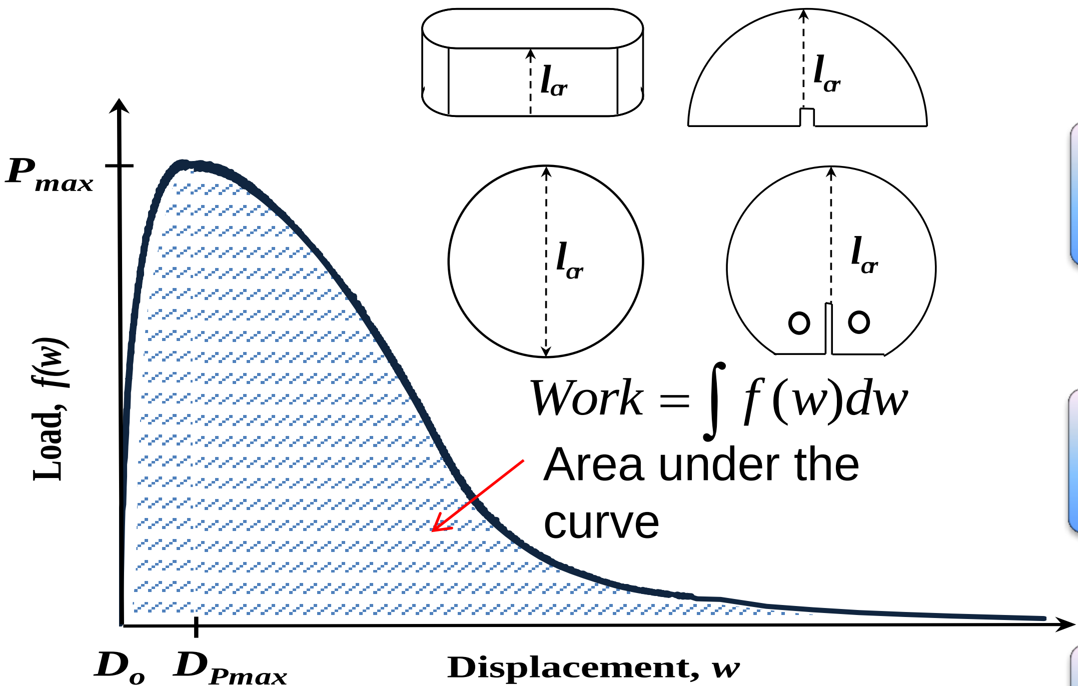
Data Analysis Models – Monotonic Loading Crack Tests



$D_{P\max}$	Displacement @ peak load
D_o	Initial displacement
l_{cr}	Length traversed by the crack

Traditional Fracture Parameters

Fracture Energy (FE)

$$G_f = \frac{Work}{Area\ of\ Cracked\ Section}$$

HMA Tensile Strength

$$\sigma_t = \frac{Peak\ Load}{Cross\ Section\ Area} = \frac{P_{\max}}{A}$$

Strain @ P_{max}

$$\varepsilon_t = \frac{Displacement\ @\ peak\ failure\ load}{Initial\ displacement\ @\ zero\ load}$$

New

FE Index

$$FE\ Index = \frac{FE}{l_{cr}\sigma_t}\varepsilon_f$$

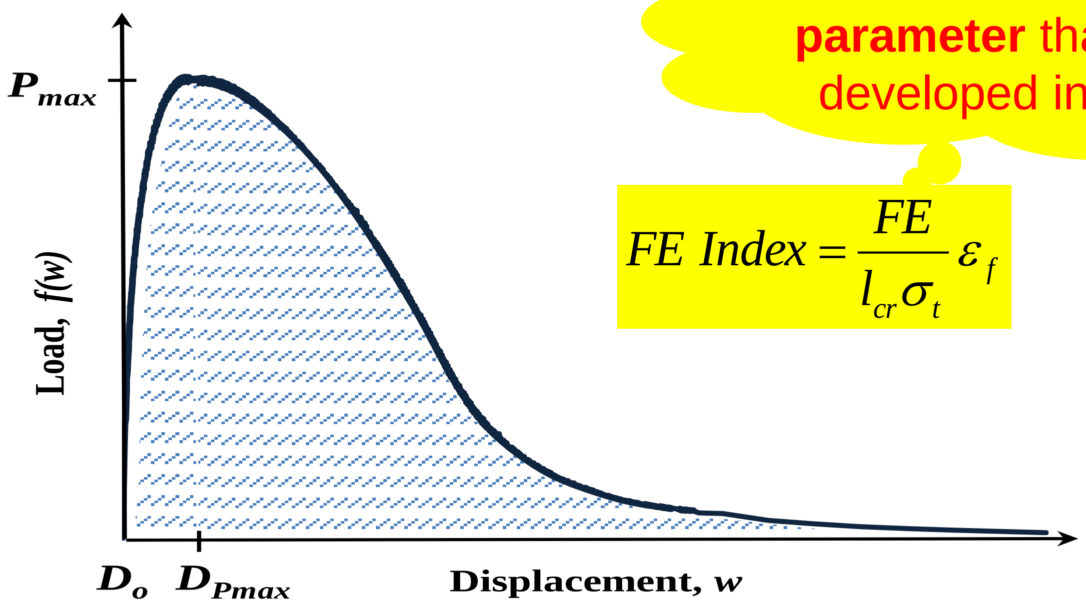
FE Index Concept – Monotonic Loading Crack Tests

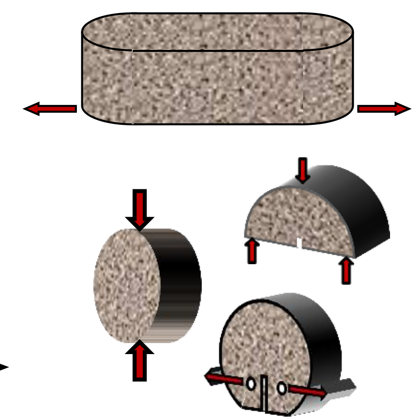
1) FE Index → function of FE, σ, ε, & length traversed by crack

2) FE Index → captures HMA fracture response over entire loading history

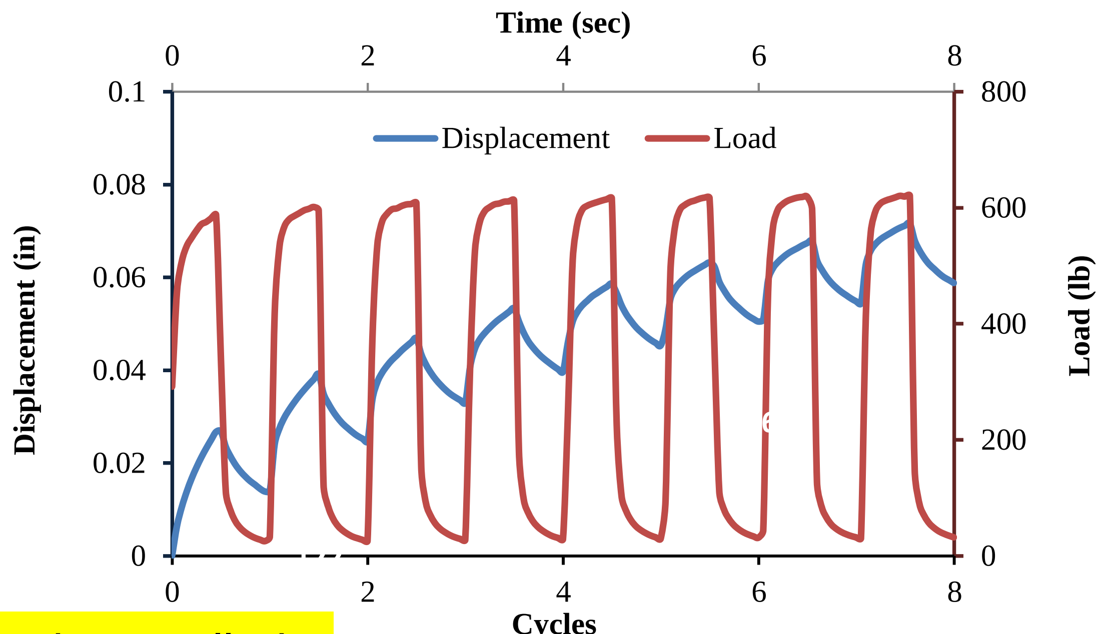
New HMA fracture parameter that has been developed in this study

$$FE\ Index = \frac{FE}{l_{cr}\sigma_t}\varepsilon_f$$





Data Analysis Models –
Repeated Loading Crack Tests.

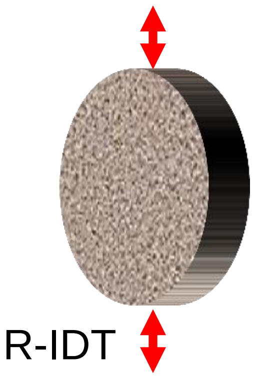


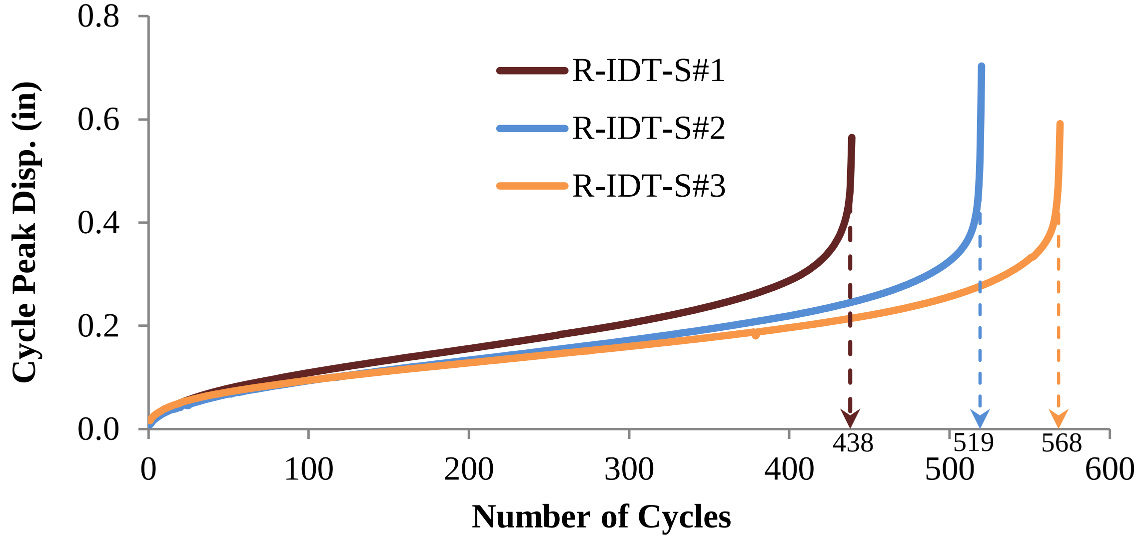
Load-controlled mode

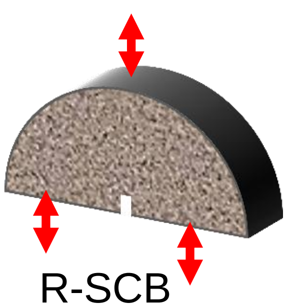
$$R - IDT\ Index = \frac{Input\ Load}{Contact\ Load} \times \frac{1 \times 10^3}{R - IDT\ Cycles}$$

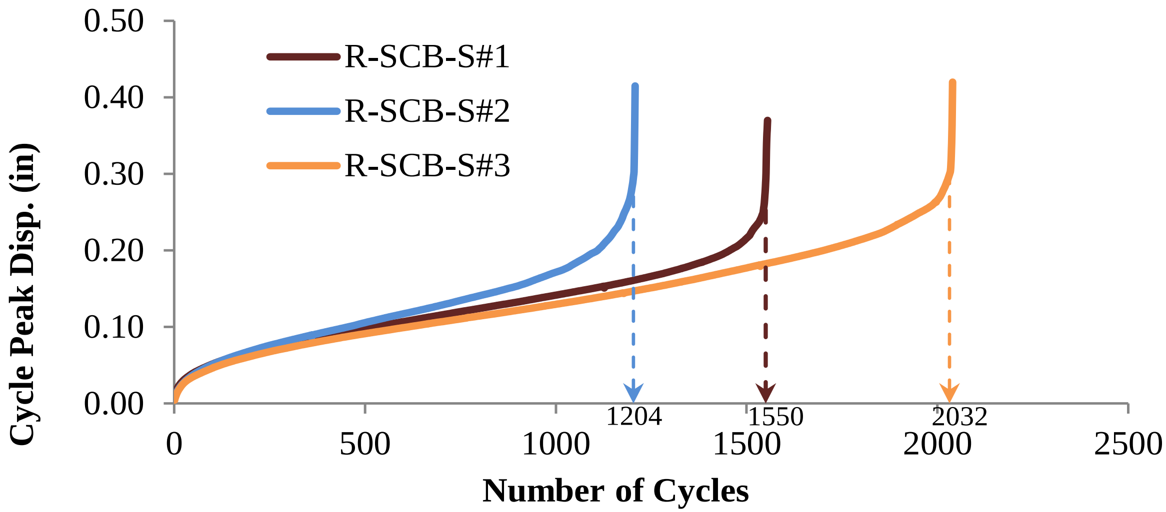
$$R - SCB\ Index = \frac{Input\ Load}{Contact\ Load} \times \frac{1 \times 10^3}{R - SCB\ Cycles}$$

R-IDT & R-SCB Response Curves









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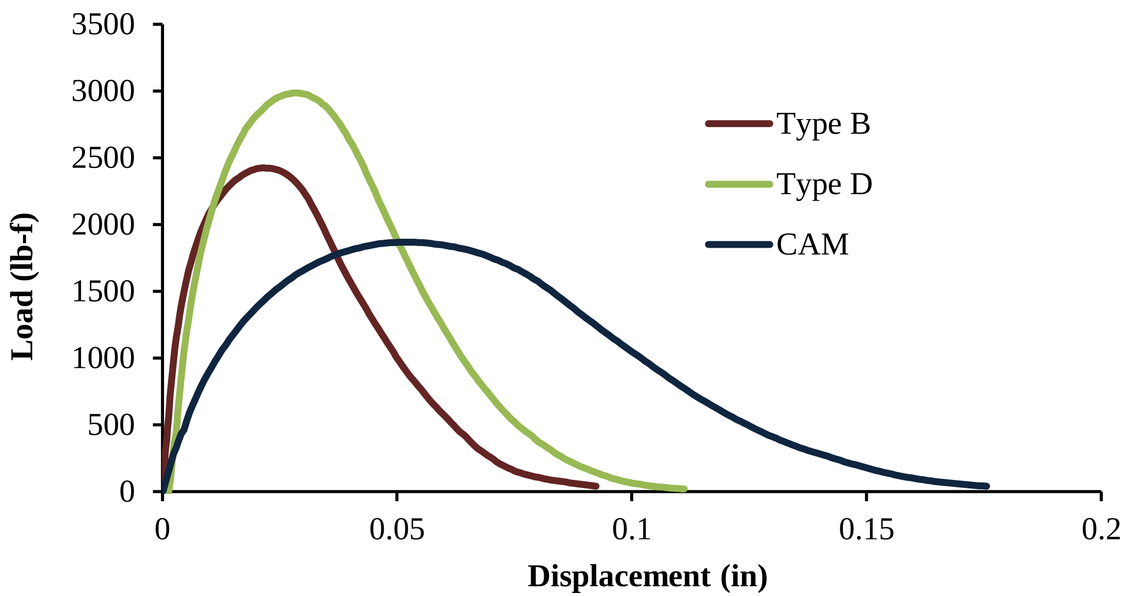
IDT Test Results



IDT sample **before** testing

IDT sample **after** testing

Mix Type	Traditional HMA Fracture Parameters					New
	Fracture Energy		Tensile Str.			
	(J/m^2)	(lb-in/in^2)	(psi)	(MPa)	Strain (mm/mm)	***FE Index***
Type B	136	0.779	103	0.710	0.0149	**1.88**
Type D	193	1.101	127	0.876	0.0190	**2.76**
CAM	226	1.290	79	0.547	0.0340	**9.21**

Average of 3 replicate samples for each mix.
The FE Index shows promising potential

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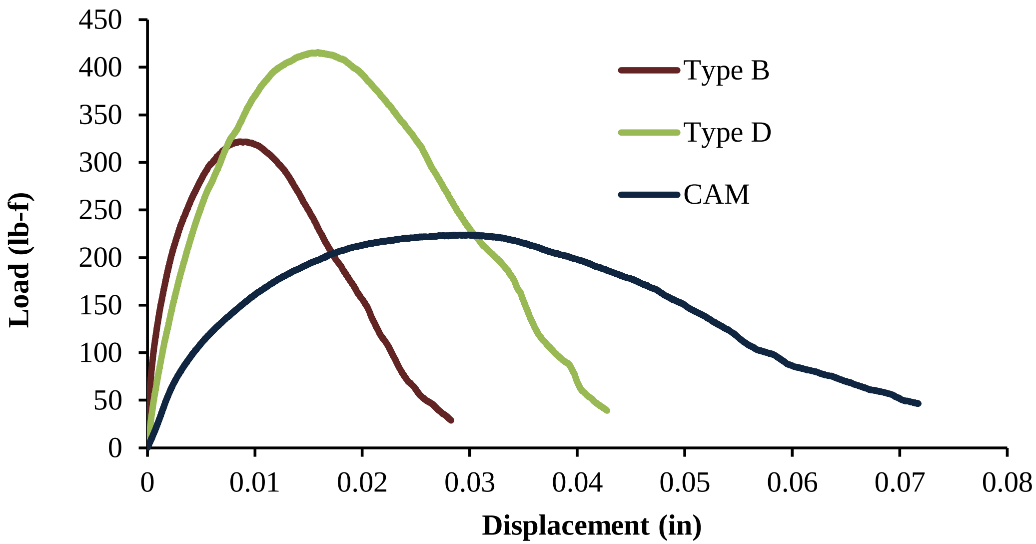
SCB Test Results



	Traditional HMA Fracture Parameters					New
Mix Type	Fracture Energy (J/m^2)	Fracture Energy (lb-in/in^2)	Tensile Str. (psi)	Tensile Str. (MPa)	Strain (mm/mm)	***FE Index***
Type B	145	0.828	203	1.400	0.0062	***0.92***
Type D	285	1.627	265	1.826	0.0108	***2.46***
CAM	280	1.601	147	1.013	0.0188	***7.63***

SCB sample **before** testing

SCB sample **after** testing

Average of 3 replicate samples for each mix.
The FE Index shows promising potential

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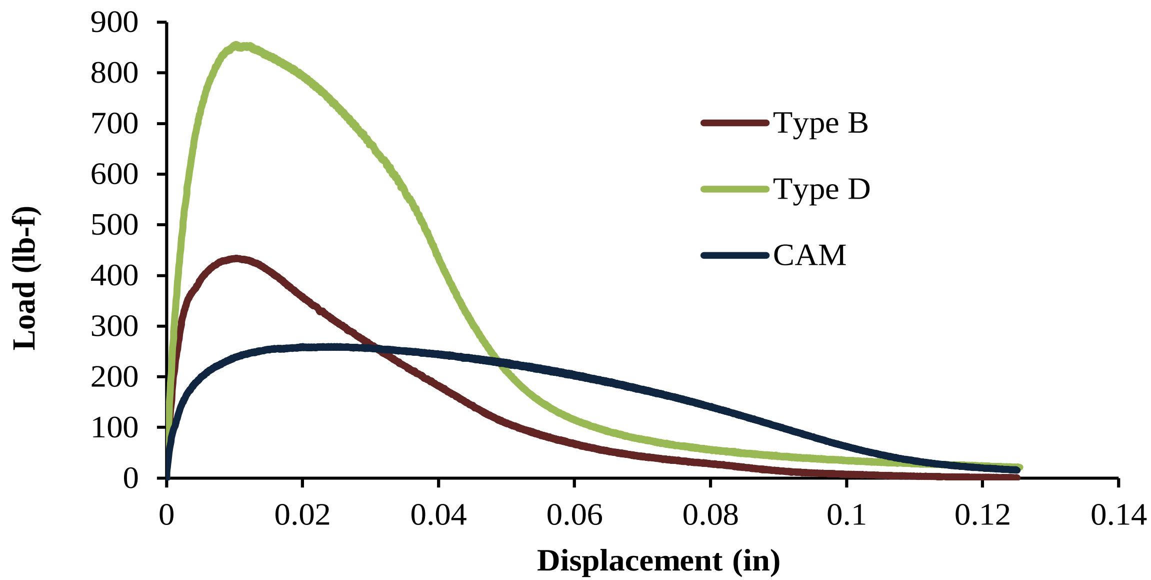
OT_M Test Results



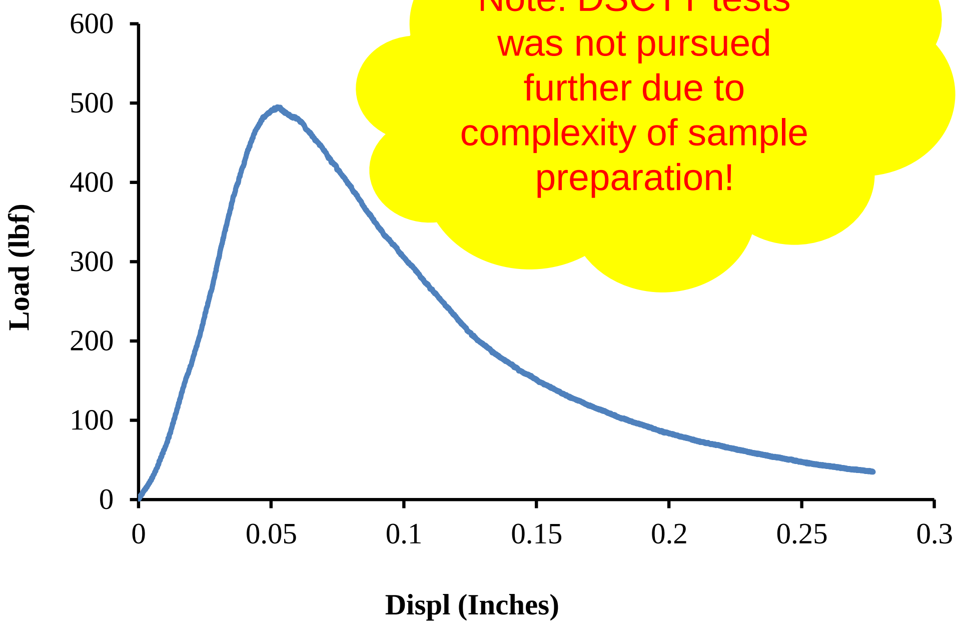
Mix Type	Traditional HMA Fracture Parameters: Fracture Energy (J/m^2)	Fracture Energy (lb-in/in^2)	Tensile Str. (psi)	Tensile Str. (MPa)	Strain (mm/mm)	New: ***FE Index***
Type B	640	3.655	99	0.683	0.1423	**3.68**
Type D	1475	8.423	193	1.331	0.1510	**5.44**
CAM	786	4.488	58	0.400	0.2995	**15.32**

OT_M sample **before** testing

OT_M sample **after** testing

Average of 3 replicate samples for each mix.
The FE Index shows promising potential

DSCTT Test Results



Note: DSCTT tests was not pursued further due to complexity of sample preparation!

	Traditional HMA Fracture Parameters					New
Mix Type	Fracture Energy (J/m^2)	Fracture Energy (lb-in/in^2)	Tensile Str. (psi)	Tensile Str. (MPa)	Strain (mm/mm)	***FE Index***
ATL Type D (5.5%)	1139 (19.2%)	6.50 (19.2%)	96 (7.2%)	0.66 (7.2%)	0.053 (9.2%)	4.22 (21.3%)

Average of 3 replicate samples

Tabulation of All Test Results

Mix Type	FE Index					Cycles/Index			Comment
	Monotonic Loading Tests					Repeated Loading Tests			
	OT_M	IDT	SCB			OT_R	R-IDT	R-SCB	
Type B	3.68	1.88	0.92			28	26.02	3.22	Marginal
Type D	5.44	2.76	2.46			304	41.34	5.49	Good
CAM	15.32	9.21	7.63			1 000+	57.85	8.72	Very Good

Tests show potential to differentiate mixes, with the newly developed Index Concept!

Key Findings

1) Use of FE Index Concept → promising compared to traditional HMA fracture parameters (i.e., Fracture Energy, Strength, or Strain)

2) Use of Cycle Index Concept → promising

3) Monotonic tests → simpler & shorter than dynamic loading tests

4) OT_M, IDT, & R-IDT → promising;
→ should be explored further

5) SCB, R-SCB, & DSCTT tests
→ problematic at room temp
→ weird failure mode @ high AC!!
⇒ Ideal for low temperature testing

Part D: Comparison of Crack Test Methods

1) Potential to differentiate & screen mixes
2) Sensitivity to AC & temp variations
3) Statistical analysis @ 95% reliability
4) Case studies & field correlations
5) Evaluation of crack test methods
6) Crack test practicality & implementation

Repeated Loading Tests

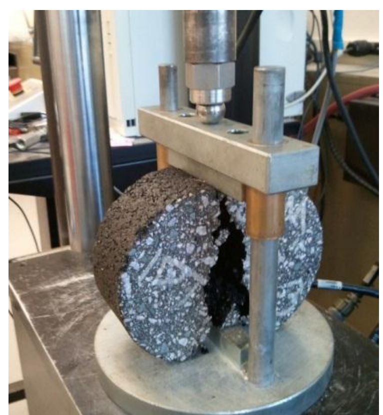
Standard OT-Repeated (OT_R)

Before testing

After testing

R-IDT

Before testing



After testing

R-SCB

Before testing

After testing

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Monotonic Loading Tests

OT_M

Before testing

After testing

IDT

Before testing

After testing

SCB

Before testing

After testing

Potential to Differentiate & Screen Mixes

Mix Type	Monotonic Loading: FE Index			Repeated Loading: Cycles/Index			Comment
	OT_M	IDT	SCB	OT_R	R-IDT	R-SCB	
Type B	3.68	1.88	0.92	28	26.02	3.22	Marginal (M)
Type D	5.44	2.76	2.46	304	41.34	5.49	Good (G)
CAM	15.32	9.21	7.63	1000	57.85	8.72	Very Good (VG)

Discriminatory Ratios (DR)

Mix Type	FE Index			Cycles/Index			Comment
	OT_M	IDT	SCB	OT_R	R-IDT	R-SCB	
CAM/B	4.16	4.90	8.29	**35.71**	2.22	2.71	VG/M
CAM/D	2.82	3.34	3.10	**3.29**	1.40	1.59	VG/G
D/B	1.48	1.47	2.67	**10.86**	1.59	1.70	G/M

OT_R → Best discriminator

Sensitivity to AC & Temperature Variations

R-SCB very problematic @ high AC

AC Variation

Type D (Chico) Asphalt Content	FE Index (Monotonic)					Cycles/Index (Repeated)		
	OT_M	IDT	SCB			OT_R	R-IDT	R-SCB
4.5%	3.40	1.84	1.63			165	54.40	2.78
5.0%	5.28	2.81	1.93			210	59.83	8.01
5.5%	11.51	3.59	2.90			822	104.48	**1.05**

Mix	Parameter	5.2% AC	5.6% AC	6.2% AC
Atlanta Type D: PG 64-22 + Quartzite + 20% RAP	OT_M FE Index (Monotonic)	5.44	6.28	7.13
	OT cycles (Repeated)	269	469	655

Temperature Variation

Mix	Parameter	50 °F	59 °F	77 °F
Laredo Type C: PG 64-22 + Crushed Gravel + 20% RAP + 1% Lime	OT_M FE Index (Monotonic)	0.66	0.70	1.93
	OT cycles (Repeated)	2	3	25

Crack Test Sensitivity – Discriminatory Ratio (DR)

DR - AC Variation

Type D (Chico) Asphalt Content	FE Index (Monotonic)					Cycles/Index (Repeated)		
	IDT	SCB	OT_M			OT_R	R-IDT	R-SCB
5.5%/4.5%	1.95	1.78	**3.39**			**4.98**	**1.92**	0.38
5.5%/5.0%	1.28	1.50	**2.18**			**3.91**	**1.75**	0.13
5.0%/4.5%	1.53	1.18	**1.55**			**1.27**	**1.10**	2.88

Mix	Parameter	6.2% / 5.2%	6.2%/ 5.6%	5.6%/ 5.2%
Atlanta Type D: PG 64-22 + Quartzite + 20% RAP	OT_M FE Index (Monotonic)	1.31	1.14	1.15
	OT cycles (Repeated)	**2.43**	**1.40**	**1.74**

Temperature Variation

Mix	Parameter	77 °F/ 50 °F	77 °F/ 59 °F	59 °F/ 50 °F
Laredo Type C: PG 64-22 + Crushed Gravel + 20% RAP + 1% Lime	OT_M FE Index (Monotonic)	2.92	2.76	1.06
	OT cycles (Repeated)	**12.50**	**8.33**	**1.50**

Statistical Comparisons - COV

Crack Tests & HMA Mixes

Mix Type	FE Index (Monotonic) IDT	SCB	OT_M		Cycles/Index (Repeated) OT_R	R-IDT	R-SCB
Type B	1.88	0.92	3.68		28	26.02	3.22
	11.8%	***24.7%***	***29.0%***		***2.0%***	***65.8%***	***35.9%***
Type D	2.76	2.46	5.44		304	41.34	5.49
	24.4%	***40.9%***	***17.0%***		***11.0%***	***12.9%***	***26.1%***
CAM	9.21	7.63	15.32		1000	57.85	8.72
	10.0%	***38.9%***	***24.0%***		----	***49.7%***	***6.0%***

SCB, R-IDT, & R-SCB → high variability, COV > 30%

Best 3 of 5

Crack Tests & AC Variation

Type D (Chico) AC	FE Index (Monotonic) IDT	SCB	OT_M		Cycles/Index (Repeated) OT_R	R-IDT	R-SCB
4.5%	1.84	1.63	3.40		165	54.40	2.78
	1.2%	***24.0%***	***3.4%***		***6.6%***	***28.4%***	***24.7%***
5.0%	2.81	1.93	5.28		210	59.83	8.01
	4.6%	***33.5%***	***4.2%***		***25.0%***	***6.4%***	***33.9%***
5.5%	3.59	2.90	11.51		822	104.48	1.05
	10.7%	***42.4%***	***10.2%***		***31.3%***	***18.1%***	***43.2%***

* Coefficient of Variation (COV) in **Bold**-*Italic*

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Tukey's HSD Statistical Analysis @ 95% Confidence Level

	Monotonic Loading			Repeated Loading		
Mix Type	FE Index (monotonic)			Repeated Load Tests (Dynamic)		
	IDT	SCB	OT_M	R-IDT Cycles Index	R-SCB Cycles Index	OT Cycles
Type B	A	A	A	A	A	A
Type D (Atlanta)	A	A	A	A	B	B
CAM	B	B	B	A	B	C

OT cycles able to statistically differentiate mixes @ 95% confidence level.

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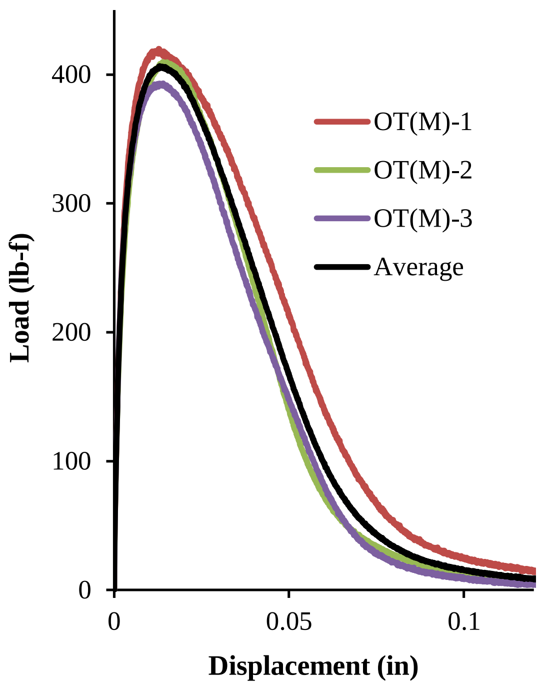
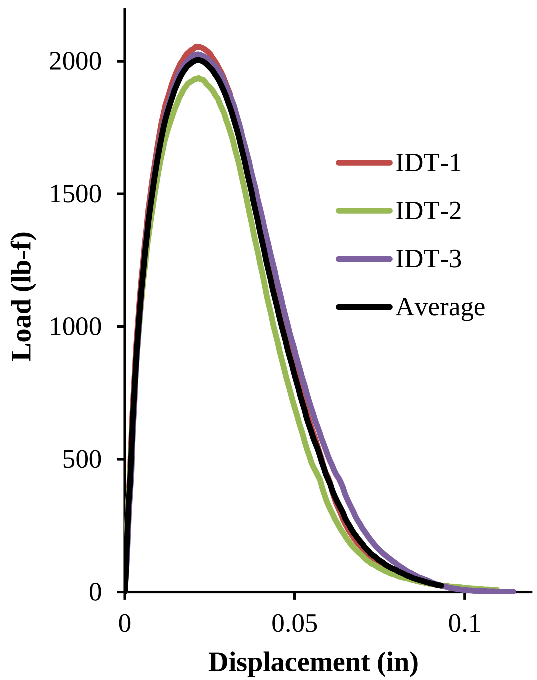
Monotonic Test Repeatability Comparison

OT_M



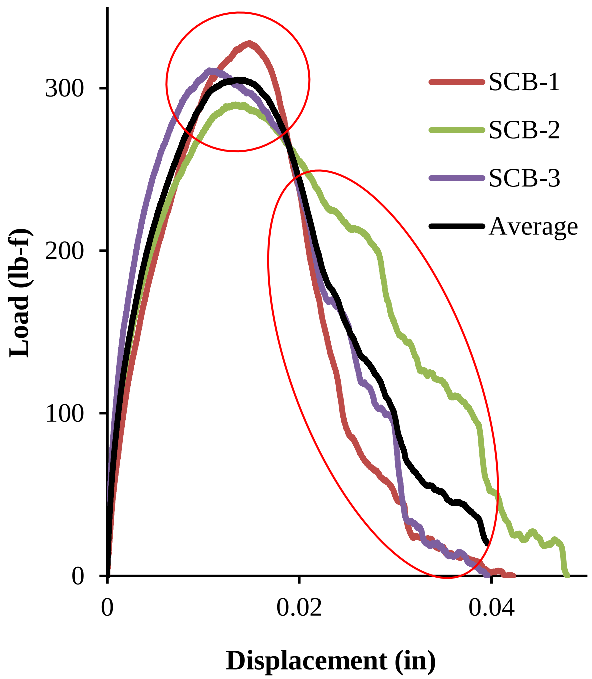
FE Index COV =4.2%

IDT



FE Index COV =1.2%

SCB



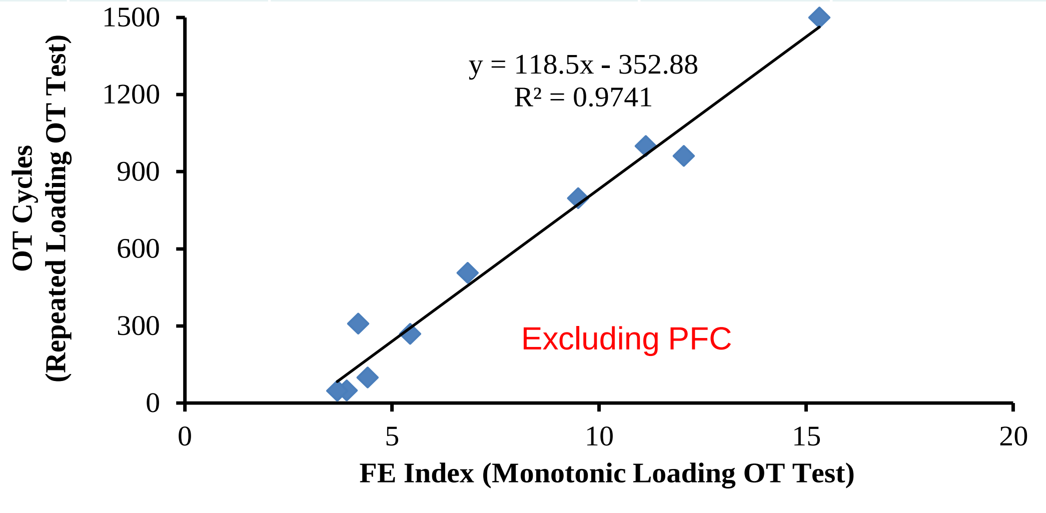
FE Index COV =24%

Chico Type D Mix
(4.5% AC)

SCB → Worst!!; IDT → Best.

OT Comparison: Cycles (Dynamic) vs. FE Index (Monotonic Loading)

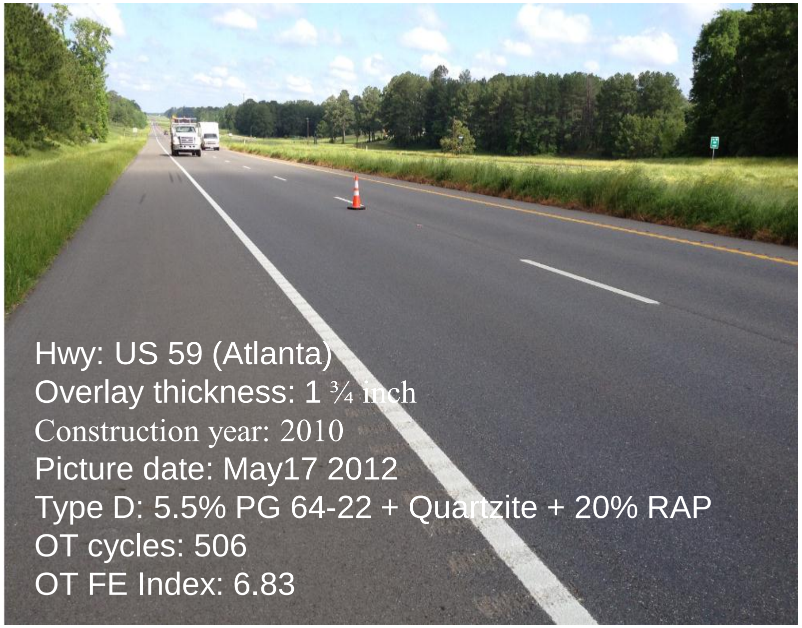
#	Mix Type	Sample Type	Hwy Used	Standard OT Repeated Loading Test	OT Monotonic Loading Test
				Cycles	FE Index
1	CAM1	Plant-mix	SH 121	1 000+	15.32
2	CAM2	Raw materials	FM 258	961	12.05
				1 000+	11.13
				796	9.50
				506	6.83
				903	5.69
				269	5.44
				308	4.19
				126	3.94
				47	3.68
11				9	1.76

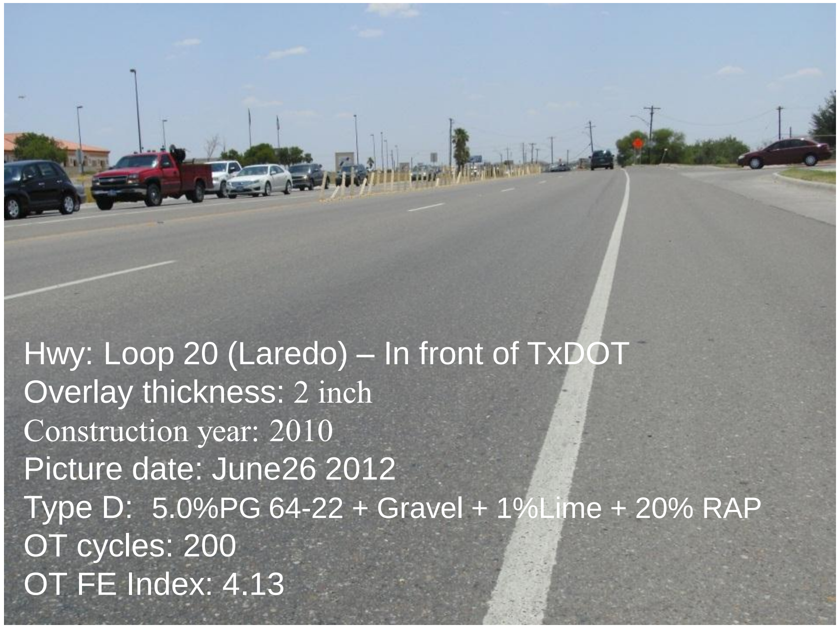


Correlation → Promising
(FE Index ≥ 4.0)

Case Studies & Field Correlations

- TTI mix-design based on OT (& Hamburg)
- Classical examples → Atlanta & Laredo Districts
- Crack performance still satisfactory: 2 yrs of service





Comparison of Test Methods

	Monotonic Loading Crack Tests				Repeated Loading Crack Tests		
	OT_M	IDT	SCB	DSCTT	OT_R	R-IDT	R-SCB
Sample Preparation	Easy	Simplest	Not easy (notching)	Not easy (notch & coring)	Easy	Simplest	Difficult (notching)
Overall Test Simplicity	Very Simple	Very Simple	Simple	Complex	Very Simple	Fair	Fair
Repeatability	Very Repeatable	Very Repeatable	Variable	Test Not Evaluated.	Fair to Variable*	Variable	Variable
Screening ability	Good	Moderate	Moderate		Very Good	Moderate	Marginal
Sensitivity to AC & Temp	Good	Good	Fair		Very Good	Moderate	Poor
Routine applications	Very Good	Very Good	Moderate	NO	Very Good	Fair	NO
Correlation to Field Data	Needs Validation				Yes	Needs Validation	

*If following suggested Tex-248-F modifications

Comparison → Subjective!!!

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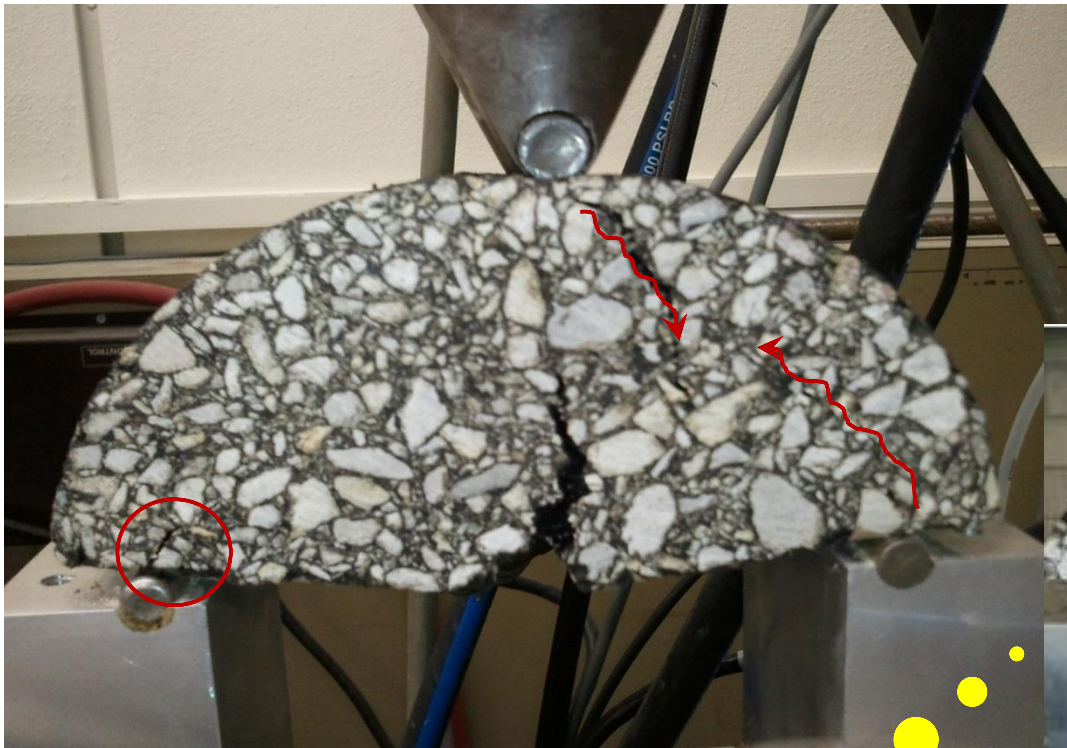
Problems with the SCB Test



Failure problems of SCB samples @ high AC & room temperature

Crack Test Ranking, Practicality, & Implementation

#	Test	Load Mode	Key Advantages	Key Challenges
1	OT_R	Dynamic	− Proven correlation with field data	− Variability minimized with suggested modifications
2	OT_M	Monotonic	− Short & repeatable − Ideal for routine use & production testing − Use existing equip.	− FE Index requires validation with field data
3	IDT	Monotonic	− Short & repeatable − Ideal for routine use & production testing − Use existing equip. − Simplest sample prep	− FE Index requires validation with field data − Loading strips − High AC levels
4	R-IDT	Dynamic		− High variability
5	SCB	Monotonic	− Short test	− Experienced operator − Test setup not easy − High variability
6	R-SCB	Dynamic		
7	DCSTT	Monotonic	− Short test	− Sample prep complex − Test setup impractical

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Key Findings

1) OT cycles → best screener of different mixes → followed by IDT & OT_M

2) Monotonic tests → less variable than dynamic tests

3) OT repeatability & variability → reasonable if adhere to modifications → & also pick best 3 of 5 or of 4.

4) SCB, R-SCB, & R-IDT → problematic & poorest repeatability @ room temperature & higher AC levels → high variability (COV > 30%)

5) SCB, R-SCB, & DSCTT → impractical for daily routine mix-designs at room temperature

6) OT monotonic FE Index → good correlations with OT repeated loading cycles → explore further!!

Part E: Summary

#	Test Method	Loading Mode	Parameter	Spec	Comment
1	OT_R	Dynamic	Cycles	Tex-248-F	Implement suggested modifications + new software updates + Round-robin
2	OT_m	Monotonic	FE Index	Being developed	Field validation should be conducted!!
3	IDT	Monotonic	FE Index		
4	R-IDT??	Dynamic	R-IDT Cycle Index		??????

SCB + R-SCB → impractical = sample prep, high variability, not good at high AC levels & room temperature → maybe good for low AC & low temp level testing

DSCTT → impractical for routine use → sample prep very complex → OK for low AC & low temperature level testing

Part E: Recommendations & Implementation

1) Implement & enforce Tex-248-F modifications
2) Install new software on all OT machines
3) Install & calibrate all OT machines using new calibration kit & software
4) Initiate certification requirement of at least 2 Techs per lab
5) Conduct last Round-robin with new software.
6) Investigate further the FE Index concept (OT_M & IDT) relative to field data & in parallel with OT Tex-248-F testing
7) Continue monitoring performance sections & validate crack tests including developing screening criteria
8) Buy & evaluate one of the new OT machines being made

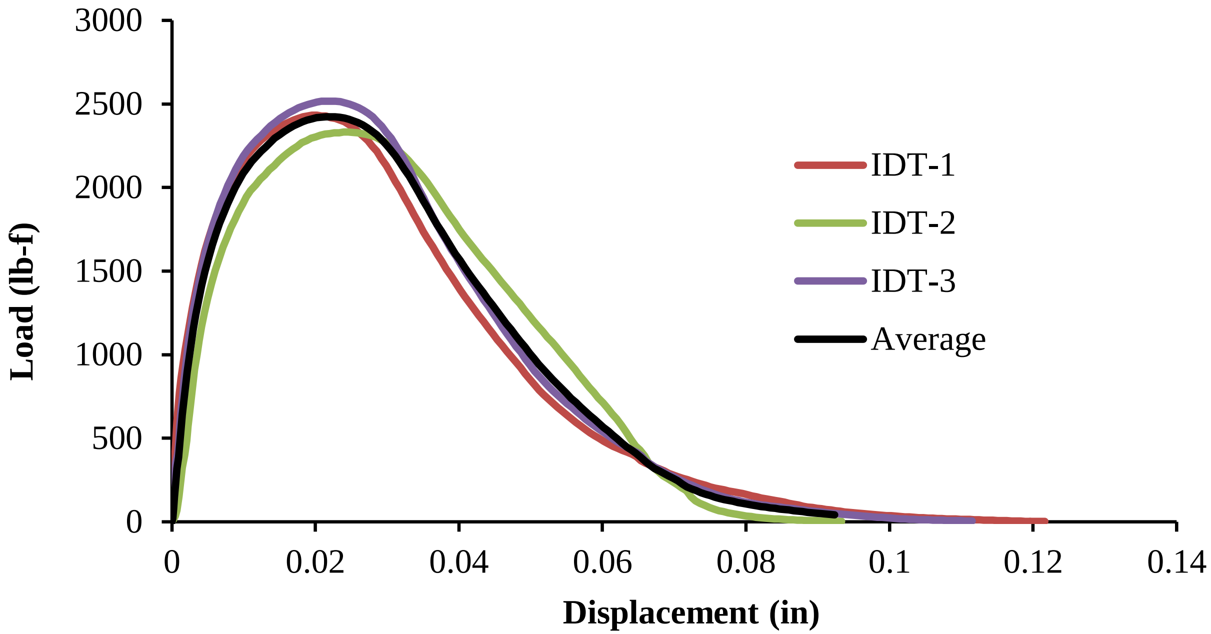
End…Contributions, Comments, & Discussions!!!

Extra Support Data

Monotonic Crack Tests: Load-Displacement Response Curves

IDT Testing:

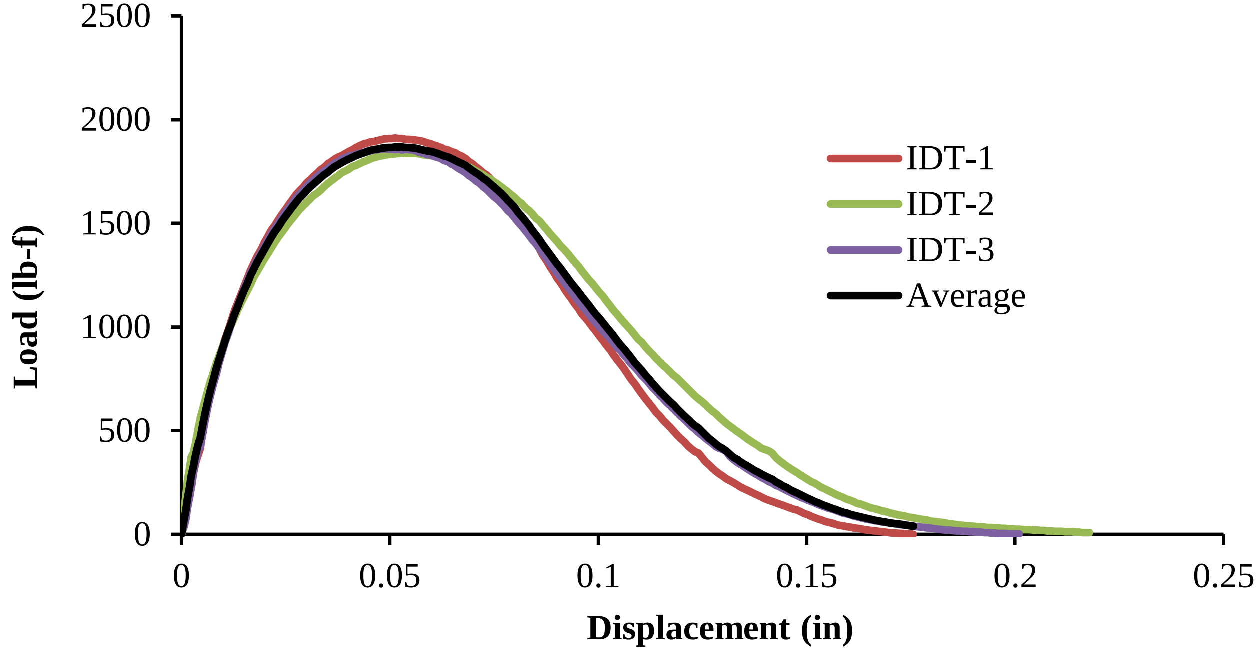
IH-35: Type B Sample Results



Sample#	Fracture Energy (J/m^2)	Fracture Energy ($lb\text{-}in/in^2$)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	FE Index
IDT1	135	0.771	103	0.712	0.0135	**1.6762**
IDT2	134	0.766	99	0.682	0.0164	**2.1158**
IDT3	140	0.799	107	0.736	0.0148	**1.8443**
Average	136	0.779	103	0.710	0.0149	**1.8788**
COV	*2.3%*	*2.3%*	*3.8%*	*3.8%*	*9.9%*	***11.8%***

IDT Testing:

SH 121: CAM Sample Results

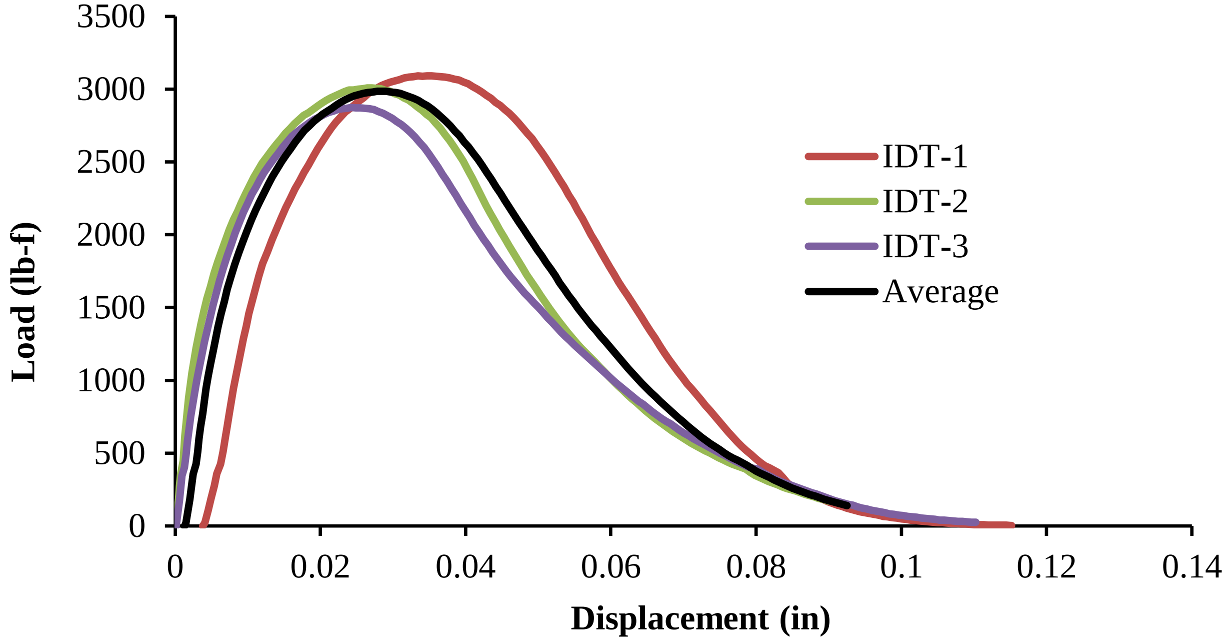


Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	FE Index
IDT1	216	1.235	81	0.559	0.0341	**8.6595**
IDT2	239	1.365	78	0.538	0.0353	**10.2769**
IDT3	222	1.269	79	0.544	0.0325	**8.7048**
Average	226	1.290	79	0.547	0.0340	**9.2138**
COV	*5.2%*	*5.2%*	*2.0%*	*2.0%*	*4.1%*	***10.0%***

Lubinda

IDT Testing:

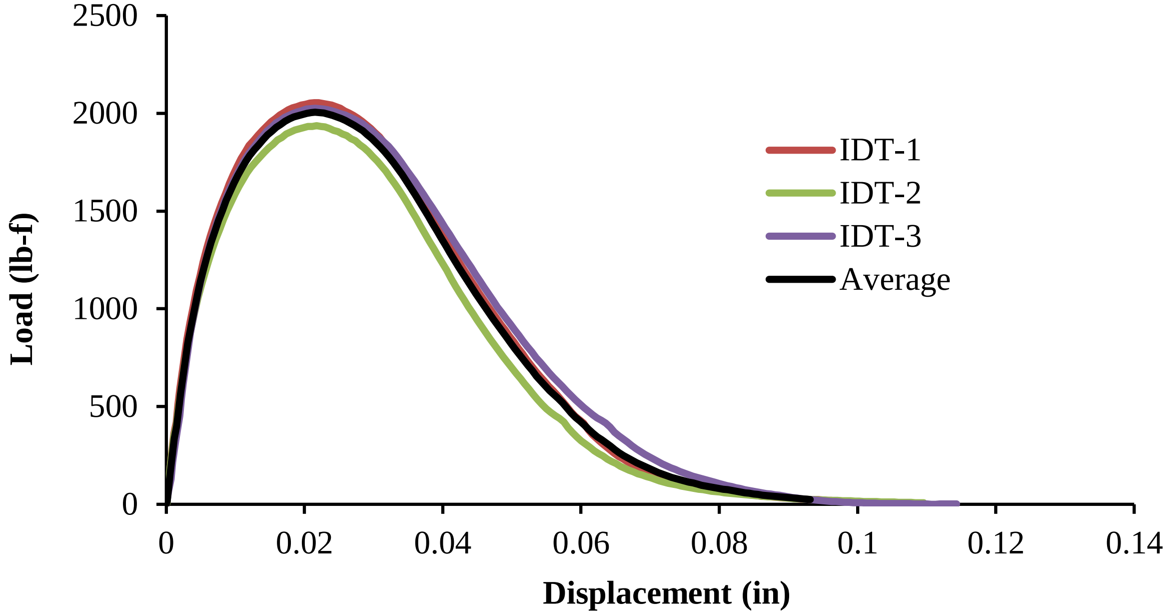
US 59 S: Type D Sample Results



Sample#	Fracture Energy (J/m^2)	Fracture Energy ($lb\text{-}in/in^2$)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	FE Index
IDT1	210	1.199	131	0.905	0.0231	**3.5214**
IDT2	189	1.077	128	0.881	0.0177	**2.4818**
IDT3	180	1.027	122	0.841	0.0161	**2.2634**
Average	193	1.101	127	0.876	0.0190	**2.7555**
COV	*8.1%*	*8.1%*	*3.7%*	*3.7%*	*19.4%*	***24.4%***

IDT Testing:

Chico: Type D (4.5% AC) Sample Results

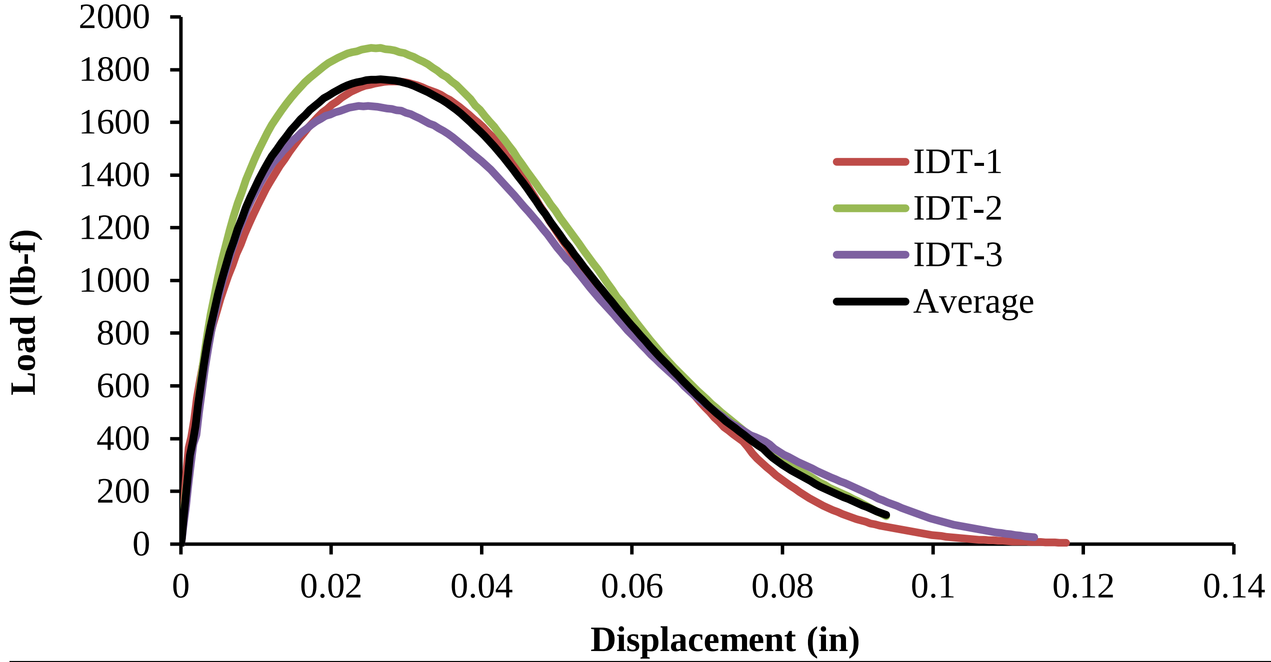


Sample#	Fracture Energy (J/m²)	(lb-in/in²)	Tensile Str. (psi)	(Mpa)	Strain (mm/mm)	**FE Index**
IDT1	113	0.647	87	0.601	0.0147	**1.8214**
IDT2	111	0.637	82	0.567	0.0145	**1.8669**
IDT3	116	0.664	86	0.593	0.0143	**1.8455**
Average	114	0.649	85	0.587	0.0145	**1.8446**
COV	*2.2%*	*2.2%*	*3.1%*	*3.1%*	*1.4%*	***1.2%***

Lubinda

IDT Testing:

Chico: Type D (5.0% AC) Sample Results

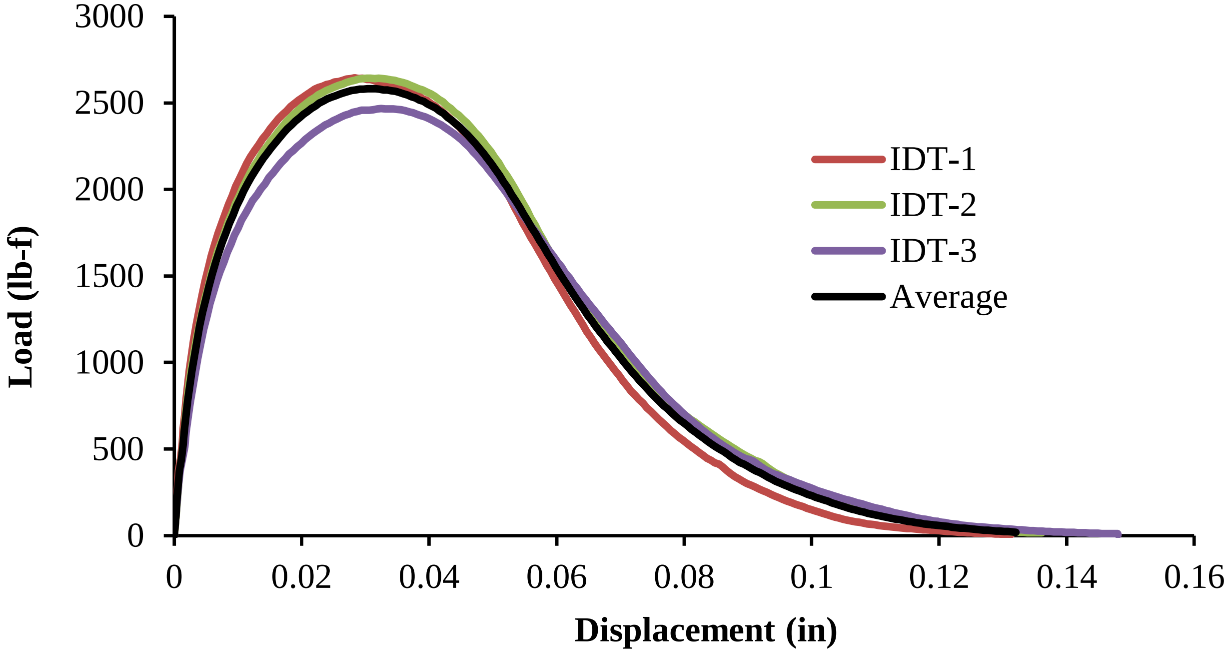


Sample#	Fracture Energy (J/m^2)	Fracture Energy (lb-in/in^2)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
IDT1	120	0.686	75	0.514	0.0193	**2.9564**
IDT2	131	0.746	80	0.551	0.0177	**2.7610**
IDT3	121	0.692	71	0.487	0.0166	**2.7104**
Average	124	0.708	75	0.517	0.0179	**2.8093**
COV	*4.7%*	*4.7%*	*6.2%*	*6.2%*	*7.5%*	***4.6%***

Lubinda

IDT Testing:

Chico: Type D (5.5% AC) Sample Results

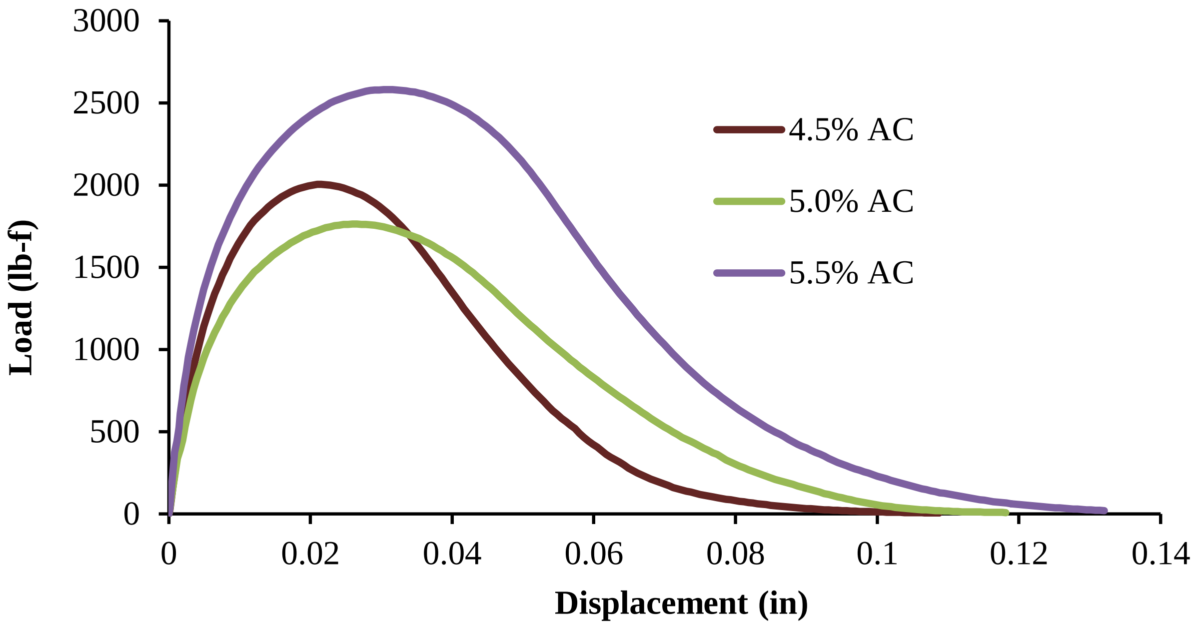


Sample#	Fracture Energy (J/m²)	(lb-in/in²)	Tensile Str. (psi)	(Mpa)	Strain (mm/mm)	**FE Index**
IDT1	199	1.138	112	0.774	0.0189	**3.1873**
IDT2	209	1.193	112	0.773	0.0205	**3.6402**
IDT3	201	1.147	105	0.722	0.0217	**3.9548**
Average	203	1.159	110	0.756	0.0204	**3.5941**
COV	*2.6%*	*2.6%*	*3.9%*	*3.9%*	*6.9%*	***10.7%***

Lubinda

IDT Testing:

Results Summary-AC Variation (Type D)

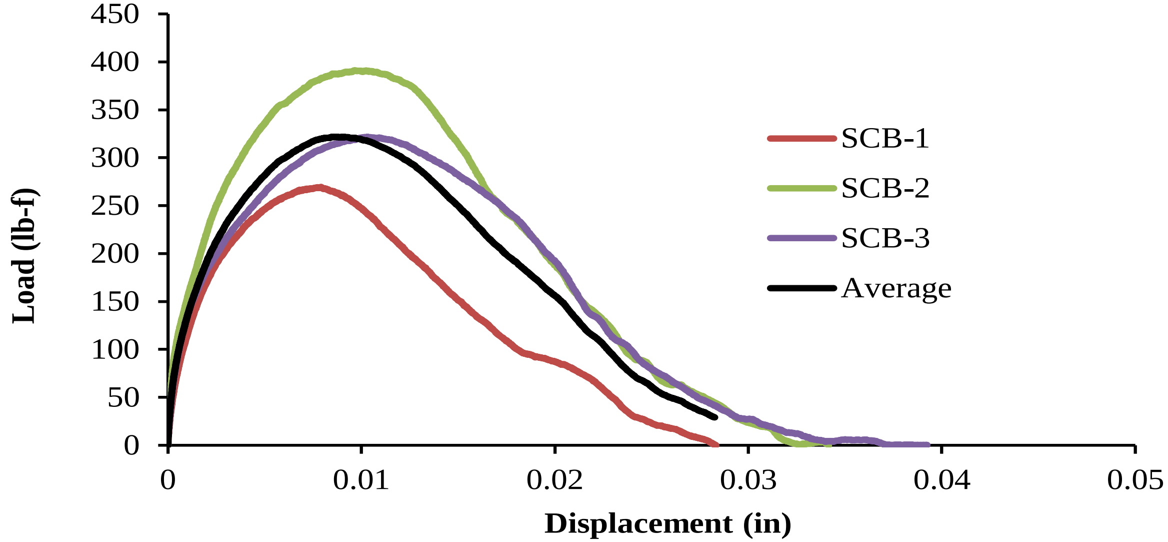


AC	Fracture Energy (J/m²)	(lb-in/in²)	Tensile Str. (psi)	(Mpa)	Strain (mm/mm)	***FE Index***
4.5%	114	0.649	85	0.587	0.0145	**1.84**
5.0%	124	0.708	75	0.517	0.0179	**2.81**
5.5%	203	1.159	110	0.756	0.0204	**3.59**

Lubinda

SCB Testing:

IH-35: Type B Sample Results

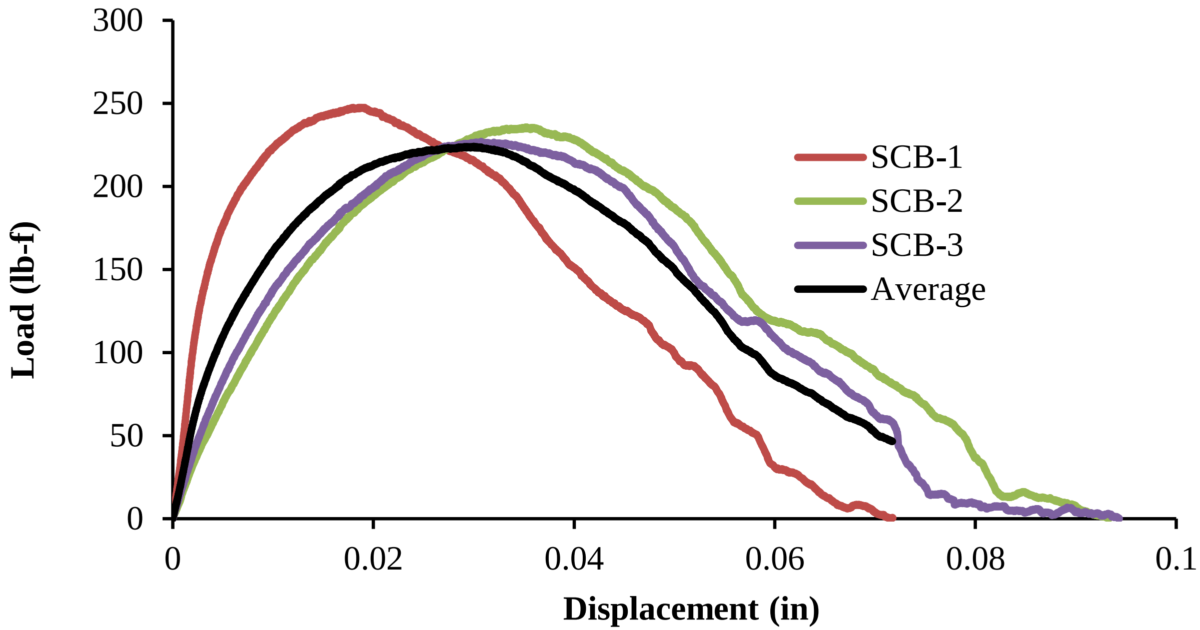


Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
SCB1	102	0.585	167	1.152	0.0053	**0.67**
SCB2	177	1.008	243	1.672232	0.0064	**0.97**
SCB3	156	0.891	200	1.375638	0.0069	**1.12**
Average	145	0.828	203	1.400	0.0062	**0.92**
COV	*26.4%*	*26.4%*	*18.6%*	*18.6%*	*13.3%*	***24.7%***

Lubinda

SCB Testing:

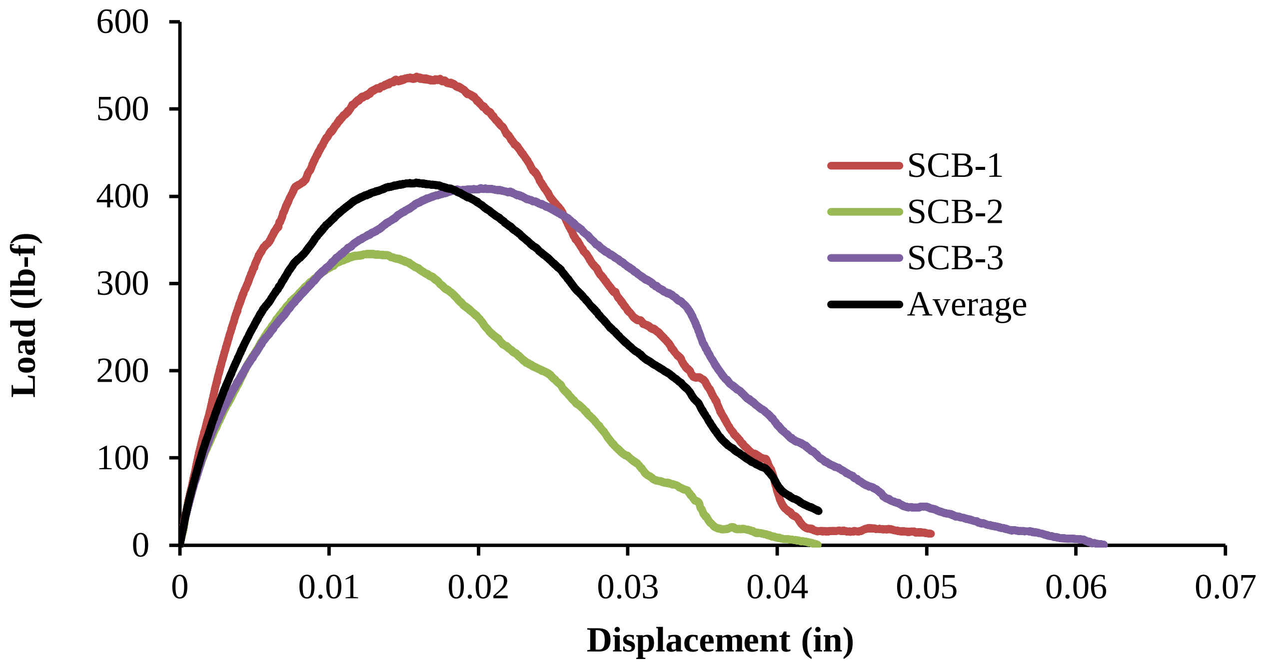
SH 121: CAM Sample Results



Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
SCB1	258	1.475	154	1.059	0.0124	**4.3298**
SCB2	301	1.721	146	1.008	0.0235	**10.0710**
SCB3	281	1.607	141	0.971	0.0205	**8.4945**
Average	280	1.601	147	1.013	0.0188	**7.6318**
COV	*7.7%*	*7.7%*	*4.4%*	*4.4%*	*30.6%*	***38.9%***

SCB Testing:

US 59 S: Type D Sample Results

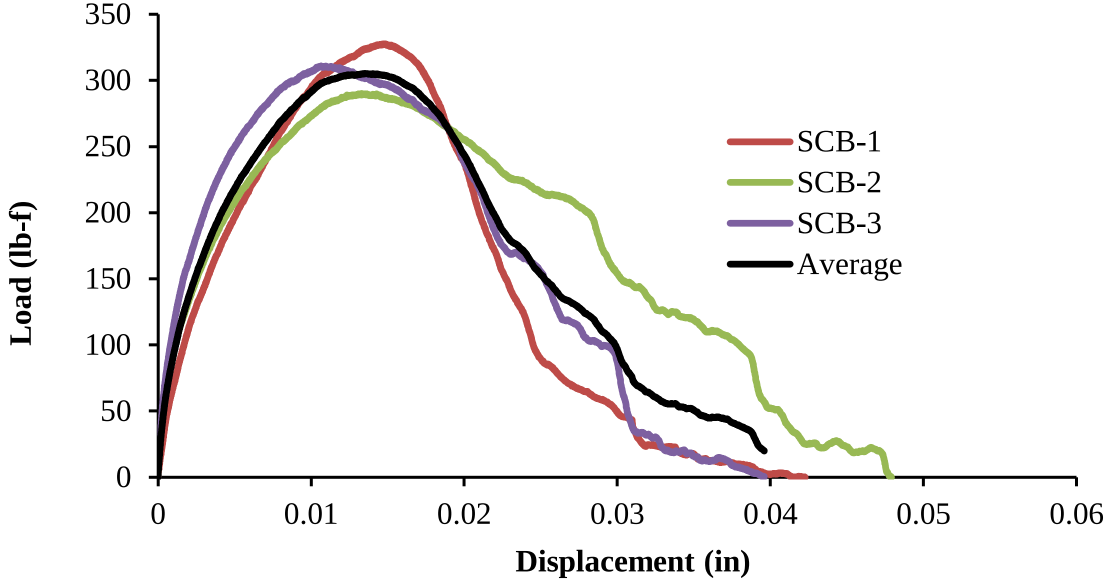


Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	FE Index
SCB1	347	1.983	333	2.298	0.0105	**2.28**
SCB2	186	1.063	207	1.429	0.0083	**1.55**
SCB3	322	1.836	254	1.751	0.0135	**3.54**
Average	285	1.627	265	1.826	0.0108	**2.46**
COV	*30.4%*	*30.4%*	*24.1%*	*24.1%*	*23.9%*	***40.9%***

Texas Transportation Institute

SCB Testing:

Chico: Type D (4.5% AC) Sample Results



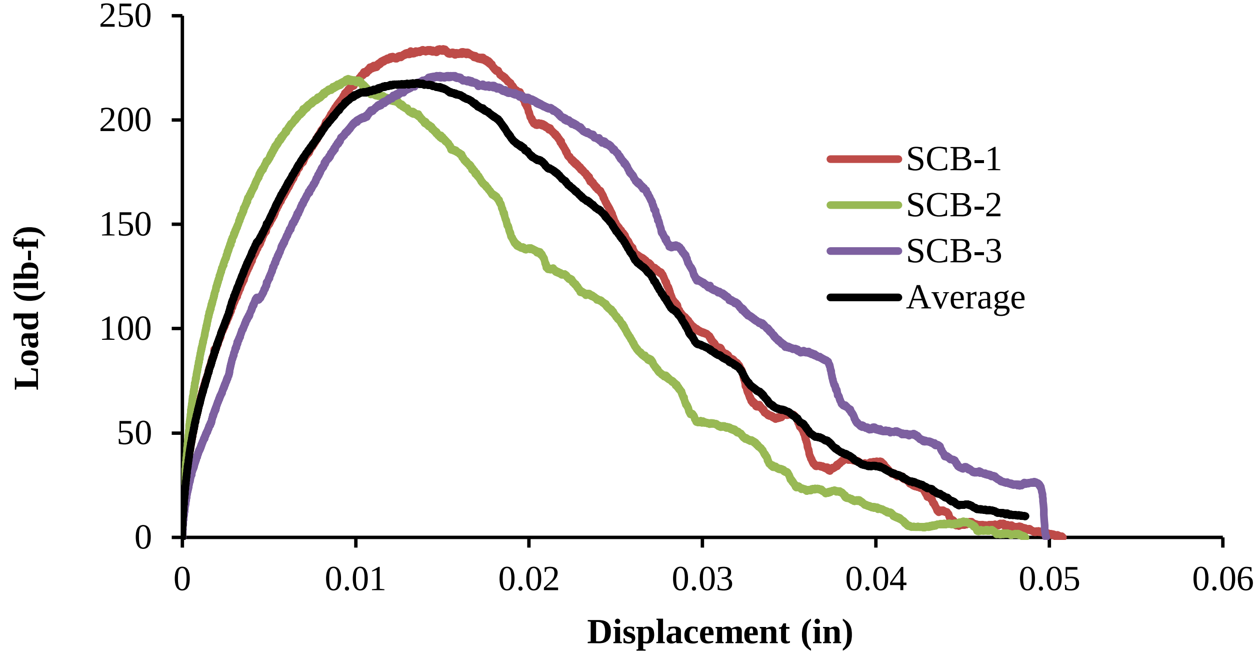
Sample#	Fracture Energy (J/m²)	(lb-in/in²)	Tensile Str. (psi)	(Mpa)	Strain (mm/mm)	FE Index
SCB1	152	0.869	203	1.401	0.0099	**1.5340**
SCB2	201	1.151	180	1.24	0.0089	**2.0626**
SCB3	170	0.973	193	1.329	0.0071	**1.2964**
Average	175	0.997	192	1.324	0.0086	**1.6310**
COV	*14.3%*	*14.3%*	*6.1%*	*6.1%*	*16.5%*	***24.0%***

ATM

Lubinda

SCB Testing:

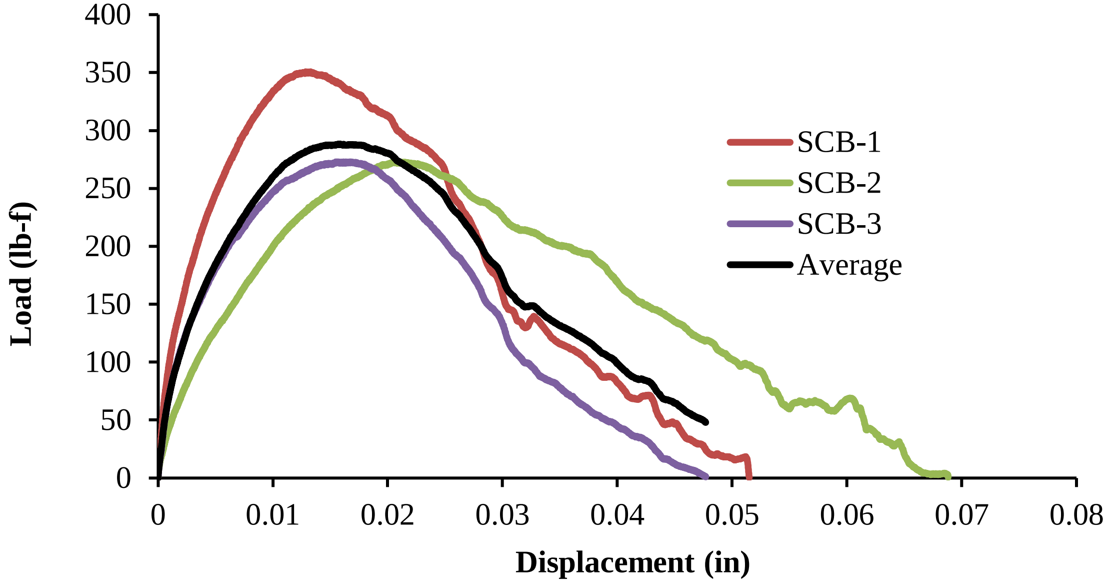
Chico: Type D (5.0% AC) Sample Results



Sample#	Fracture Energy (J/m^2)	Fracture Energy (lb-in/in^2)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
SCB1	146	0.834	145	1.001	0.0100	**2.0897**
SCB2	125	0.715	136	0.94	0.0064	**1.2216**
SCB3	157	0.897	137	0.946	0.0105	**2.4879**
Average	143	0.816	140	0.962	0.0090	**1.9331**
COV	*11.3%*	*11.3%*	*3.5%*	*3.5%*	*24.8%*	***33.5%***

SCB Testing:

Chico: Type D (5.5% AC) Sample Results

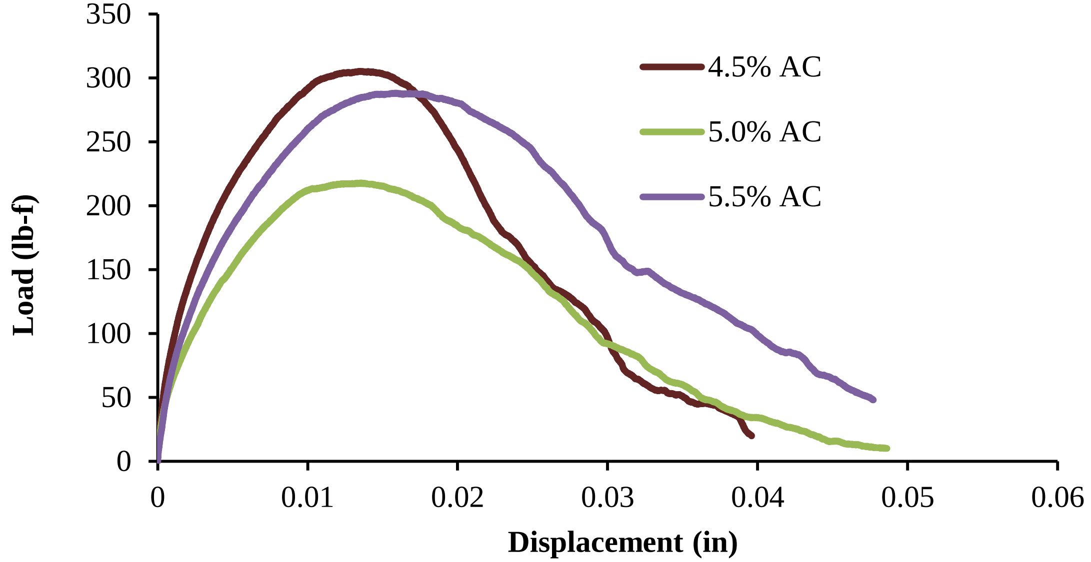


Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
SCB1	241	1.375	217	1.499	0.0085	**1.9625**
SCB2	256	1.460	169	1.167	0.0137	**4.2853**
SCB3	177	1.014	169	1.167	0.0112	**2.4378**
Average	225	1.283	185	1.278	0.0111	**2.8952**
COV	*18.5%*	*18.5%*	*15.0%*	*15.0%*	*23.1%*	***42.4%***

Lubinda

SCB Testing:

Results Summary-AC Variation (Type D)

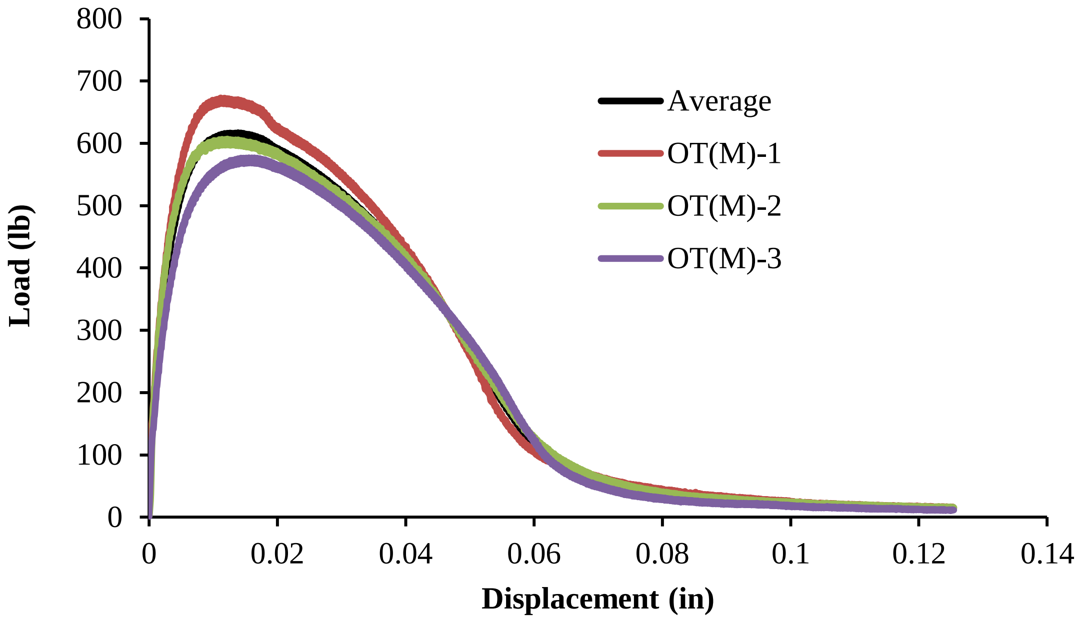


AC	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	***FE Index***
4.5%	175	0.997	192	1.324	0.0086	***1.63***
5.0%	143	0.816	140	0.962	0.0090	***1.93***
5.5%	225	1.283	185	1.278	0.0111	***2.90***

Lubinda

OT_M Testing:

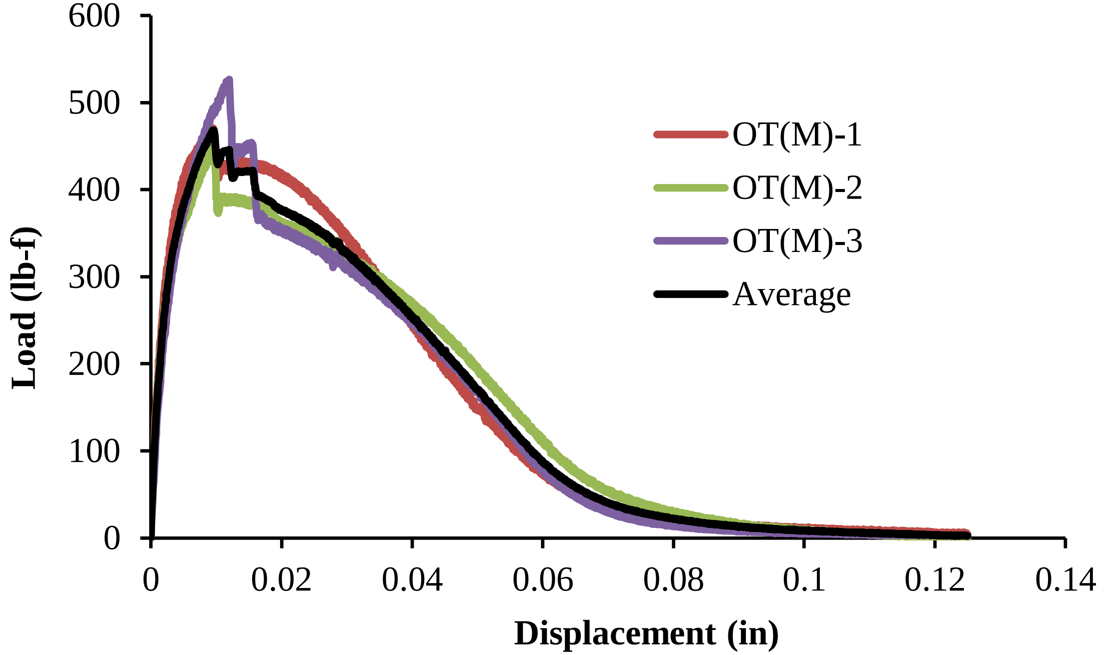
US-59: Type D Sample Results



Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
OT_M1	1275	7.28	183	1.26	0.131	**5.85**
OT_M2	1438	8.21	210	1.45	0.125	**4.38**
OT_M3	1711	9.78	185	1.28	0.198	**6.10**
Average	1475	8.42	193	1.33	0.151	**5.44**
COV	*14.9%*	*14.9%*	*7.9%*	*7.9%*	*27.0%*	***17.0%***

OT_M Testing:

Chico: Type D (4.5% AC) Sample Results

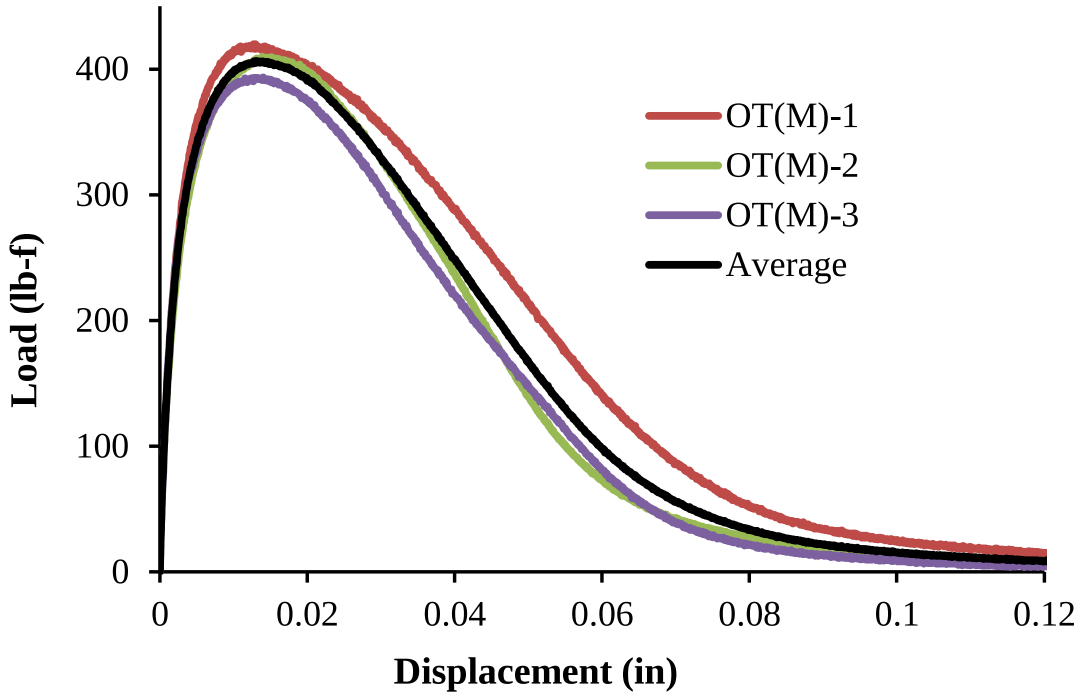


Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
OT_M1	742	4.235	105	0.721	0.1213	**3.2739**
OT_M2	740	4.228	100	0.69	0.1225	**3.4506**
OT_M3	703	4.014	117	0.807	0.1525	**3.4893**
Average	728	4.159	107	0.739	0.1321	**3.4046**
COV	*3.0%*	*3.0%*	*8.2%*	*8.2%*	*13.4%*	***3.4%***

Lubinda

OT_M Testing:

Chico: Type D (5.0% AC) Sample Results

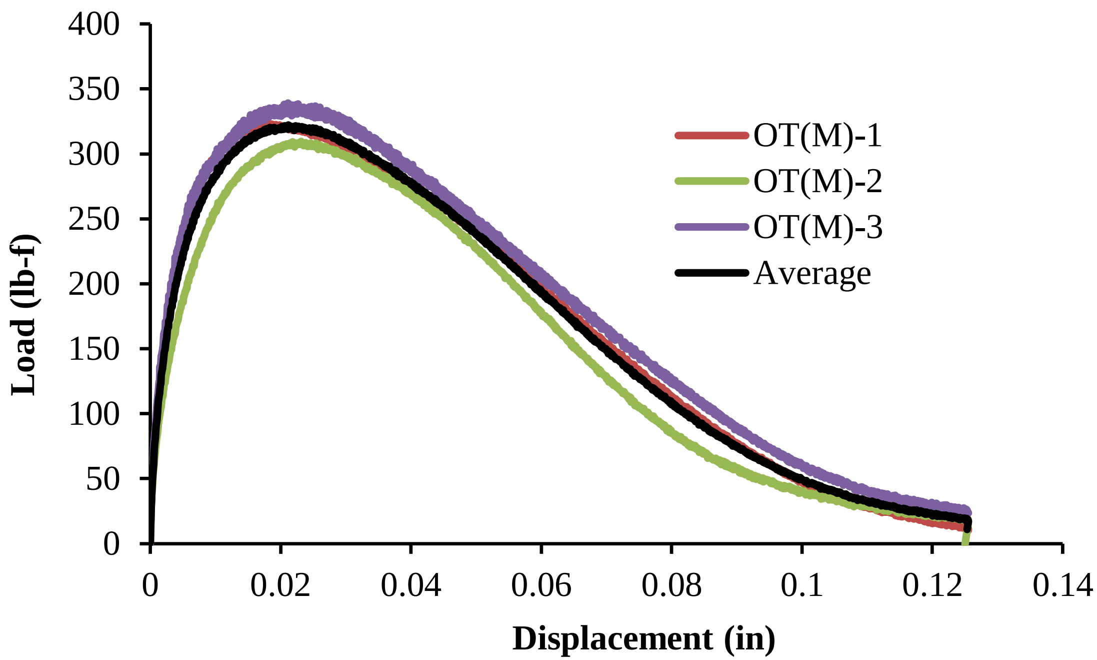


Sample#	Fracture Energy (J/m²)	(lb-in/in²)	Tensile Str. (psi)	(Mpa)	Strain (mm/mm)	**FE Index**
OT_M1	839	4.792	93	0.643	0.1615	**5.5298**
OT_M2	696	3.972	91	0.628	0.1764	**5.1277**
OT_M3	668	3.816	87	0.603	0.1776	**5.1693**
Average	734	4.193	91	0.625	0.1718	**5.2756**
COV	*12.5%*	*12.5%*	*3.3%*	*3.3%*	*5.2%*	***4.2%***

Lubinda

OT_M Testing:

Chico: Type D (5.5% AC) Sample Results

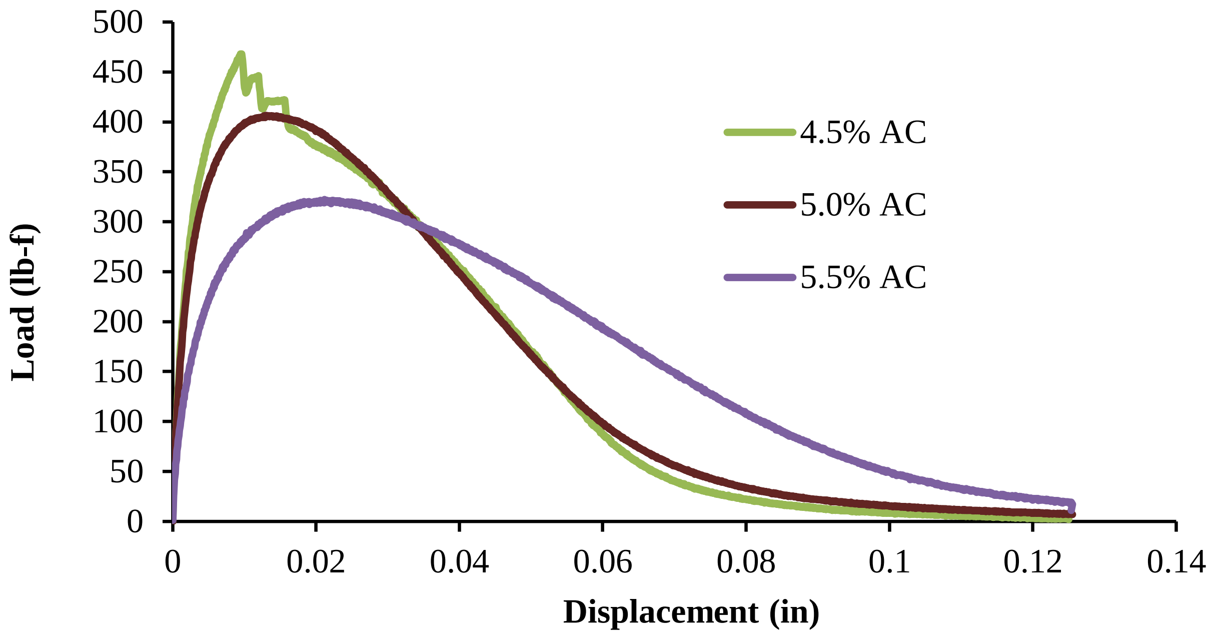


Sample#	Fracture Energy (J/m²)	Fracture Energy (lb-in/in²)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	**FE Index**
OT_M1	834	4.760	72	0.496	0.2304	**10.1659**
OT_M2	758	4.330	69	0.474	0.2935	**12.3180**
OT_M3	887	5.067	75	0.52	0.2686	**12.0359**
Average	826	4.719	72	0.497	0.2642	**11.5066**
COV	*7.8%*	*7.8%*	*4.6%*	*4.6%*	*12.0%*	***10.2%***

Lubinda

OT$_M$ Testing:

Results Summary-AC Variation (Type D)



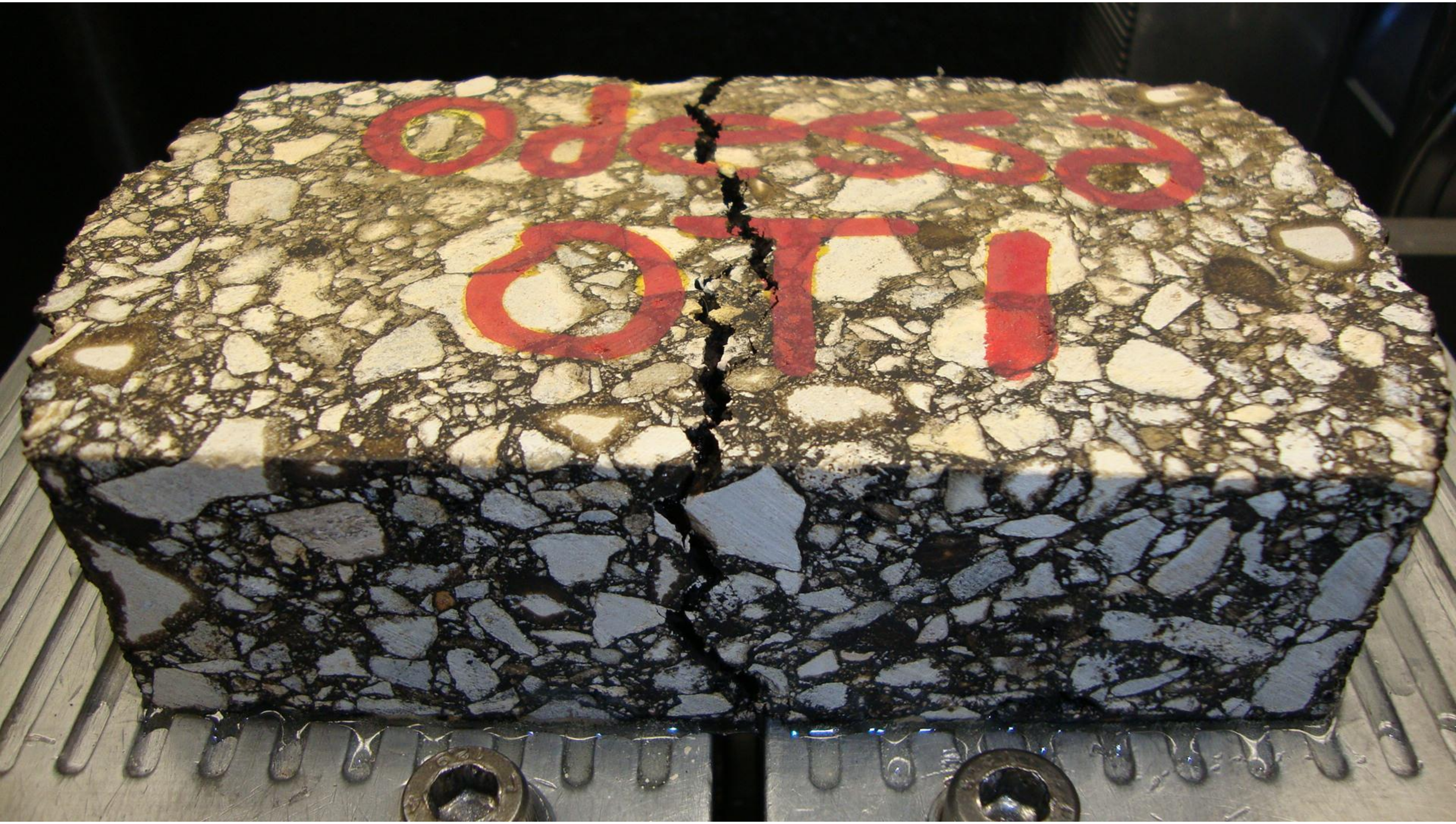
AC	Fracture Energy (J/m^2)	Fracture Energy (lb-in/in^2)	Tensile Str. (psi)	Tensile Str. (Mpa)	Strain (mm/mm)	***FE Index***
4.5%	728	4.159	107	0.739	0.1321	**3.40**
5.0%	734	4.193	91	0.625	0.1718	**5.28**
5.5%	826	4.719	72	0.497	0.2642	**11.51**

Lubinda

Extra Support Data

Single Crack Examples


LAREDO
OTS


Odessa
110


Set# 1004
Set# 1005


BR
TD
RT

Extra Support Data

Multiple Crack Examples


DIP 0.025

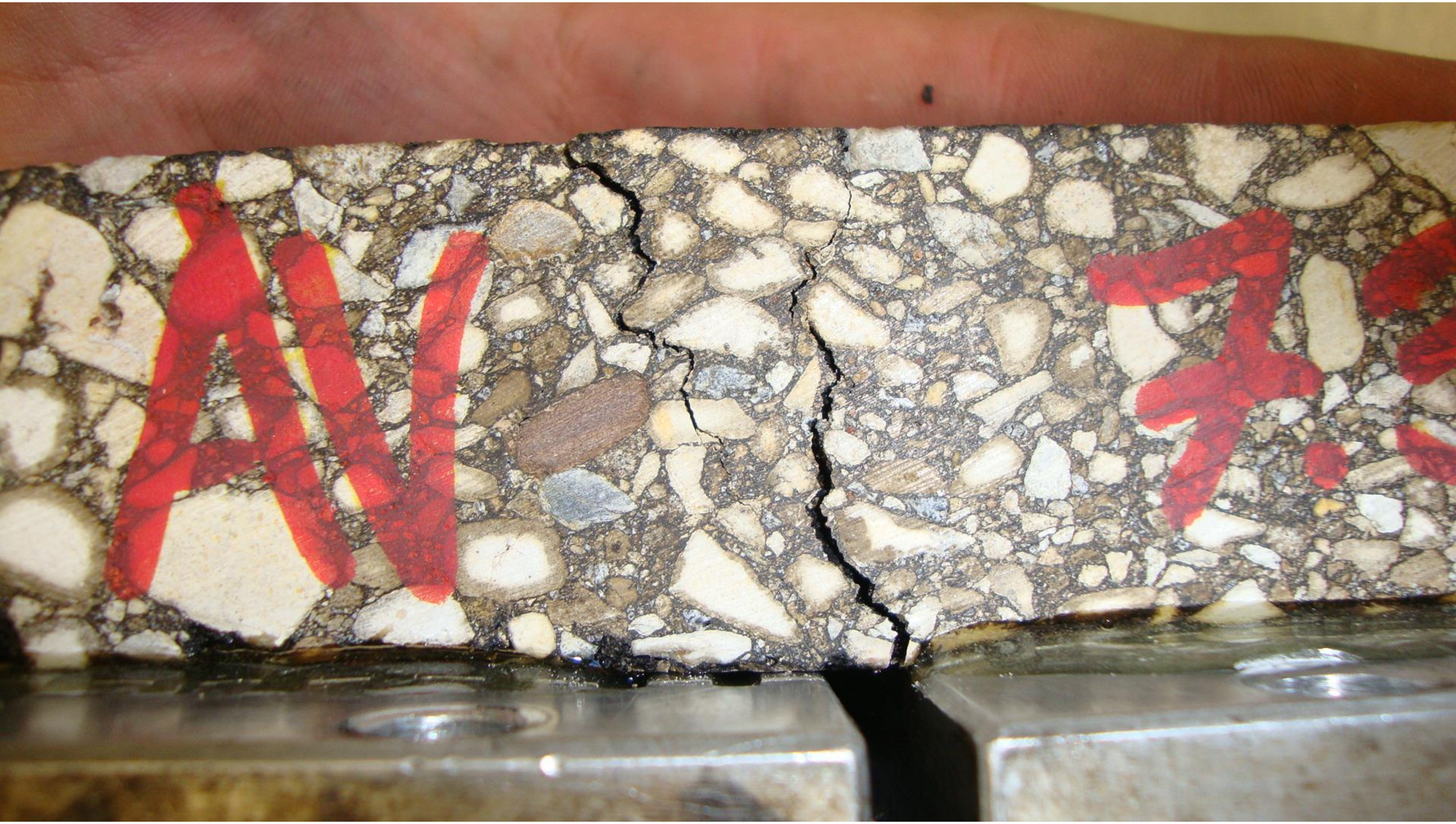

Freq
10s
SH358

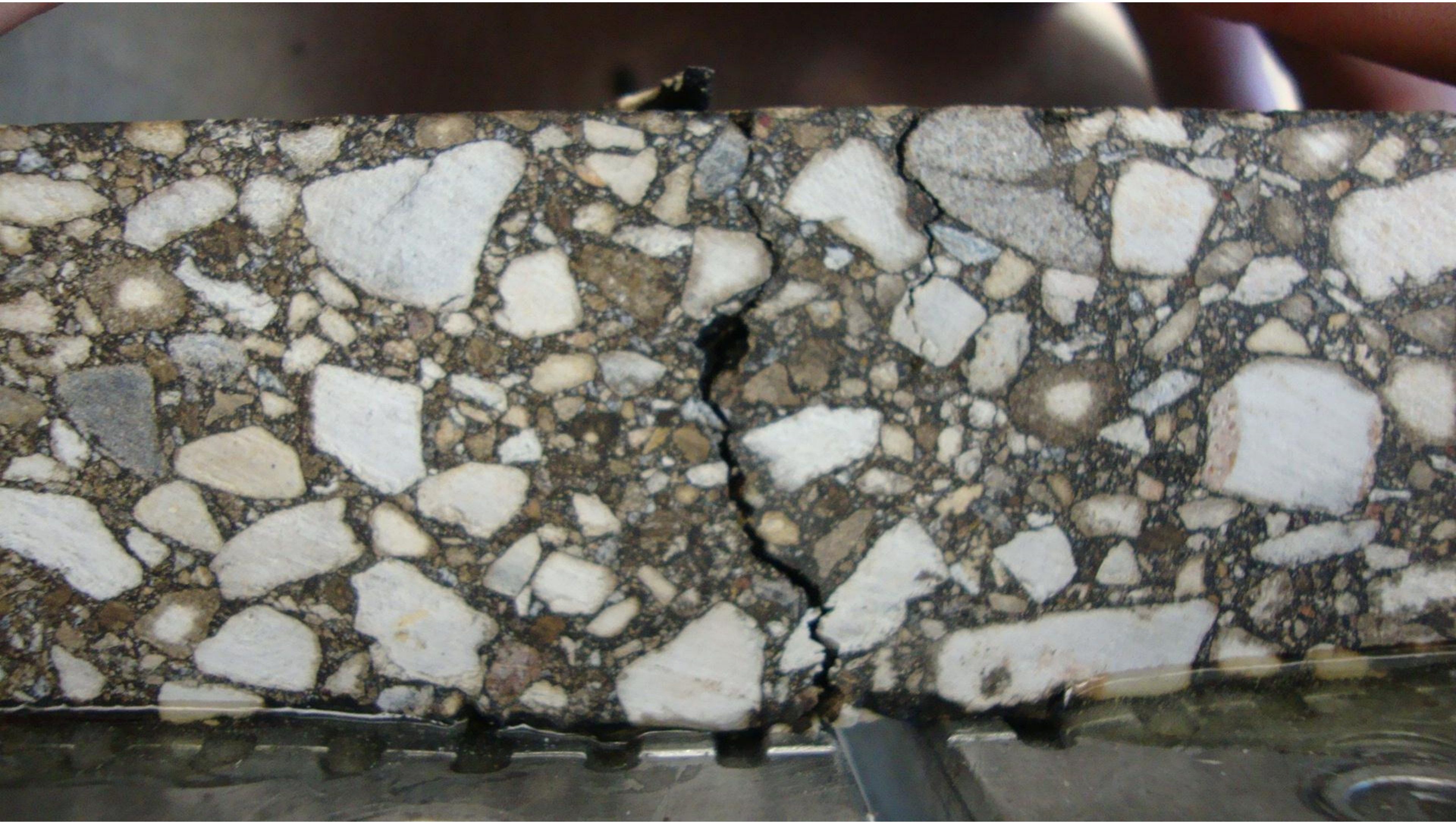

0.025


SH358


Disp
.0125


DiSP 0.015






401
8·1·12
6.8
402
8·1·12
6.5