FHWA Accelerated Load Facility Transportation Pooled Fund Studies

TPF-5(019) Full-Scale Accelerated Performance Testing for Superpave and Structural Validation

SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements

1st Closeout Webinar
August 16-17, 2010
11am – 2pm EST

Day 1:

Agenda

Introductions & Housekeeping

Attendees

- Participants at Turner-Fairbank
- Participants online/over the phone

Agenda

- 3 hours each day (11am-2pm EST)
- Do we want to stop for a 20-30 min. break?

Agenda

- Day 1
  - Introductions & Ground Rules
  - Background and Problem Statement
  - Experimental Design and Construction
  - Test Lane Performance
  - MEPDG Analysis of Construction Uniformity
  - Ranking Approach

  - Discussion and questions

Agenda

- Day 2
  - Ranking of Laboratory Mixture Tests
  - Ranking of Candidate Binder Tests
  - Conclusions and Recommendations

  - Discussion and questions

  - Prospective for ALF 8 experiment: Review of Stakeholder Input; High RAP

Asking Questions

- Please feel free to interrupt for clarification questions
- Hold more detailed questions for discussion periods between sections

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Day 1:

Background

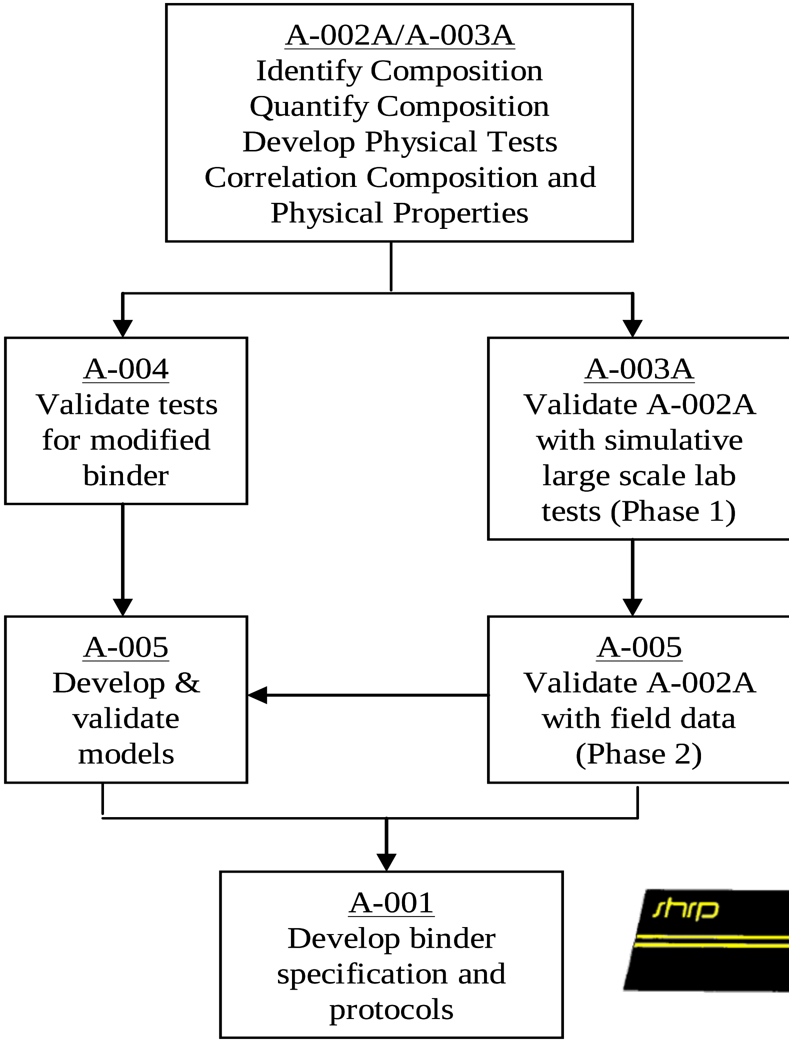
Problem Statement

Background – The SHRP Program

shrp

Objectives

1. Increase the life of pavements,
2. Decrease life cycle costs and maintenance requirements
3. Avoid premature failure



Products (Asphalt)

1. **A performance based binder specification**
2. **An asphalt aggregate mixture design and analysis system**

Background – The SHRP Program

- Rutting

$$\frac{|G^*|}{\sin\delta}$$

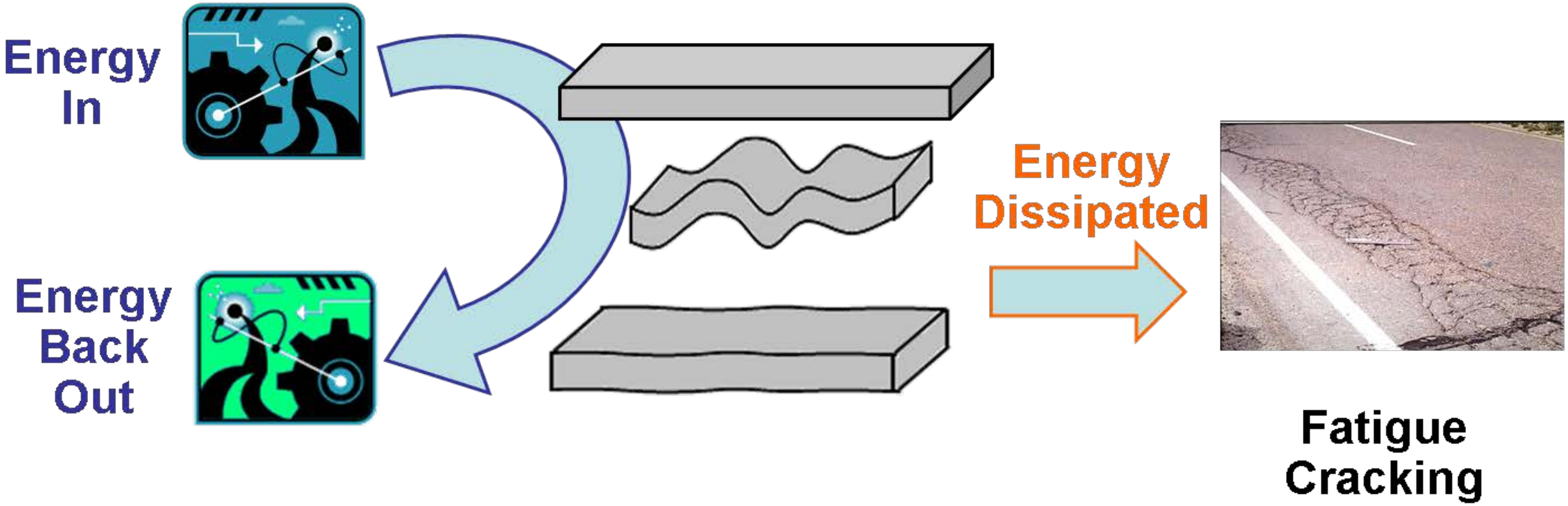
$|G^*|$ ← **Stiffer = less rutting**

$\sin\delta$ ← **More = less rutting**
Elastic

Background – The SHRP Program

- **Fatigue Cracking**

$$|G^*|\sin\delta$$



Then the use of polymer modified binder increased…

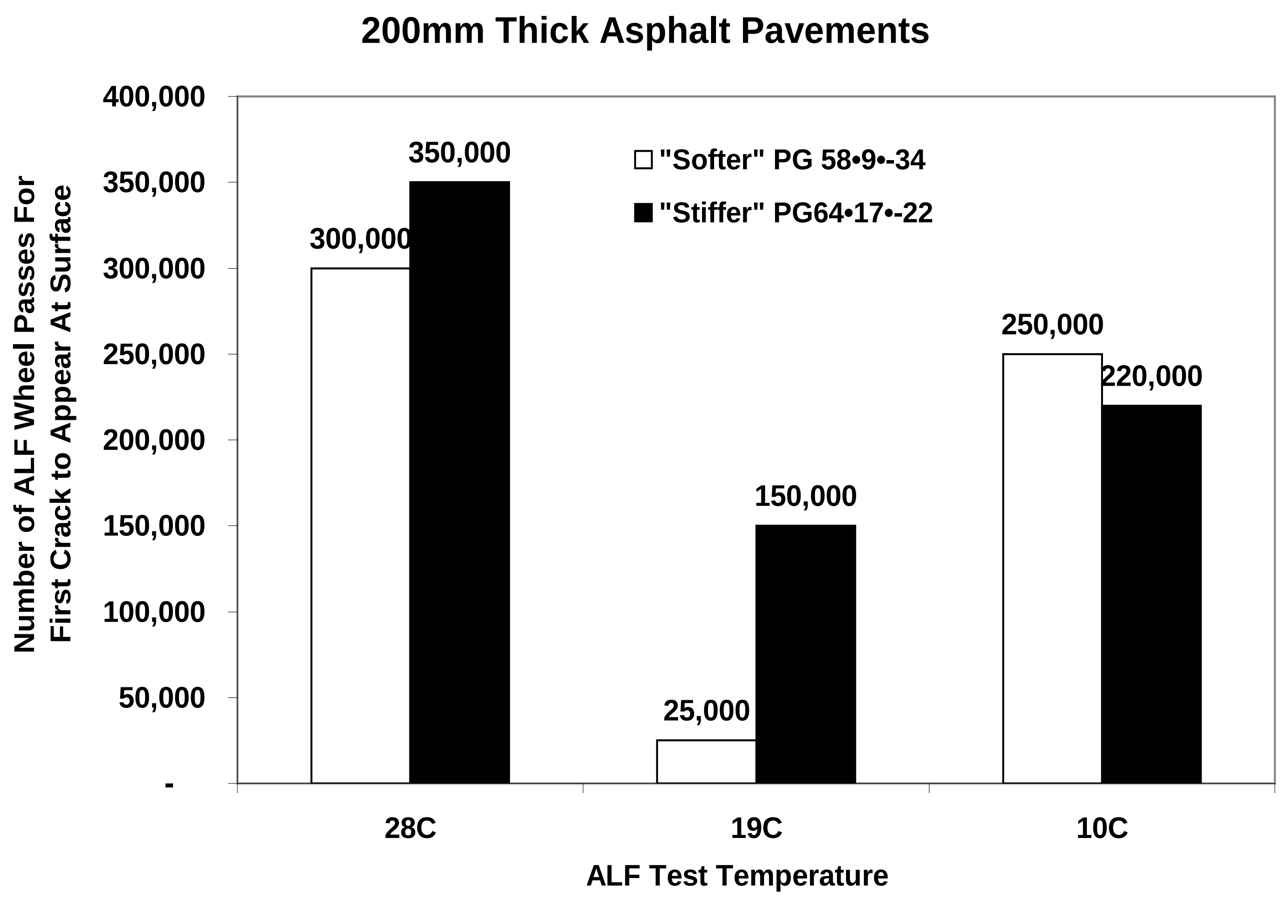
Shortcomings of PG: |G*|sinδ

- **1993 FHWA SHRP Validation – FHWA ALF**

	Thick 200 mm	Thin 100 mm
Soft PG58(9)-34	More Cracks	More Cracks
Stiff PG64(17)-22	Less Cracks (Better Fatigue)	Less Cracks (Better Fatigue)
	✗	✗

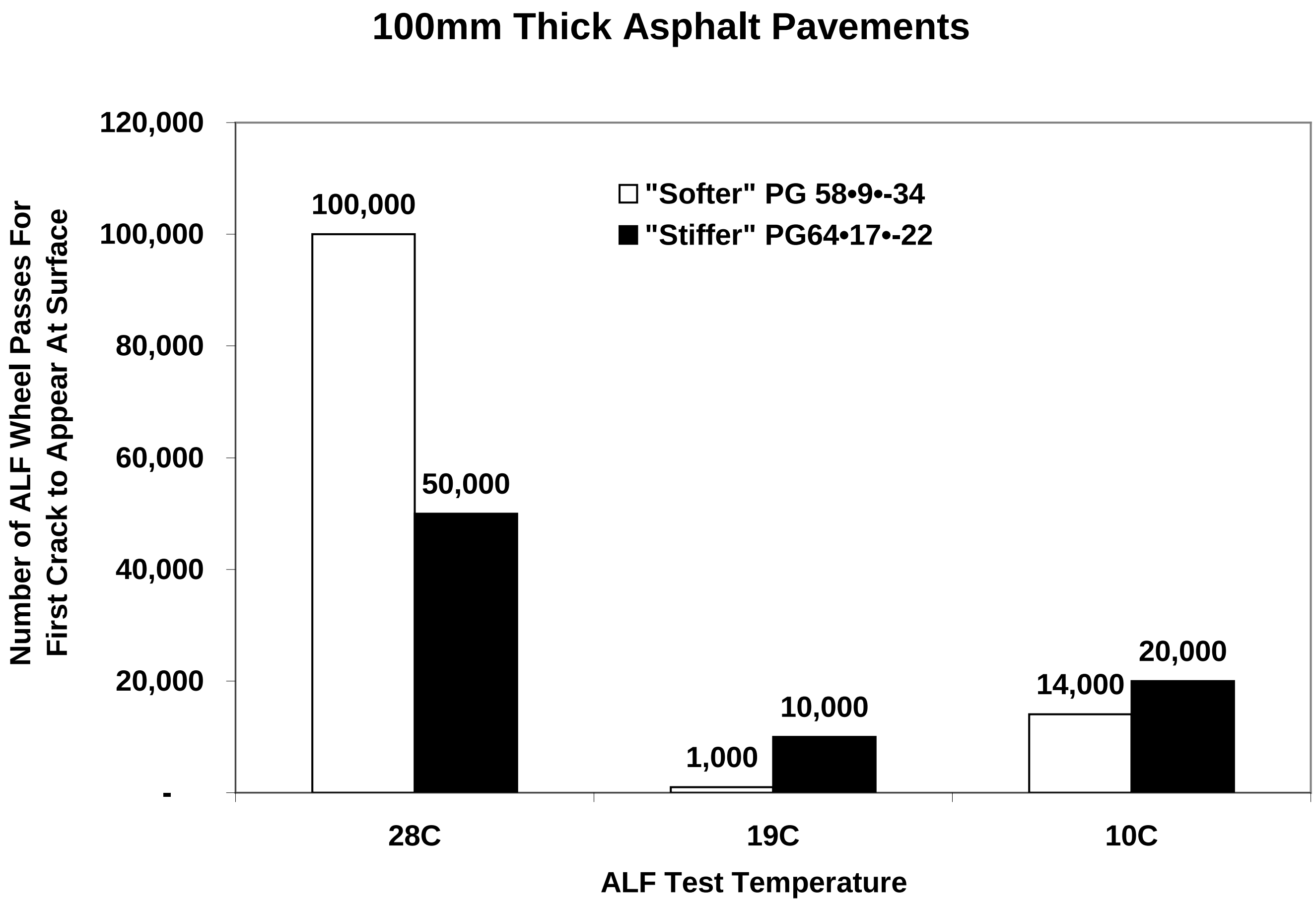
Shortcomings of PG: |G*|sinδ

- **1993 FHWA SHRP Validation – FHWA ALF**



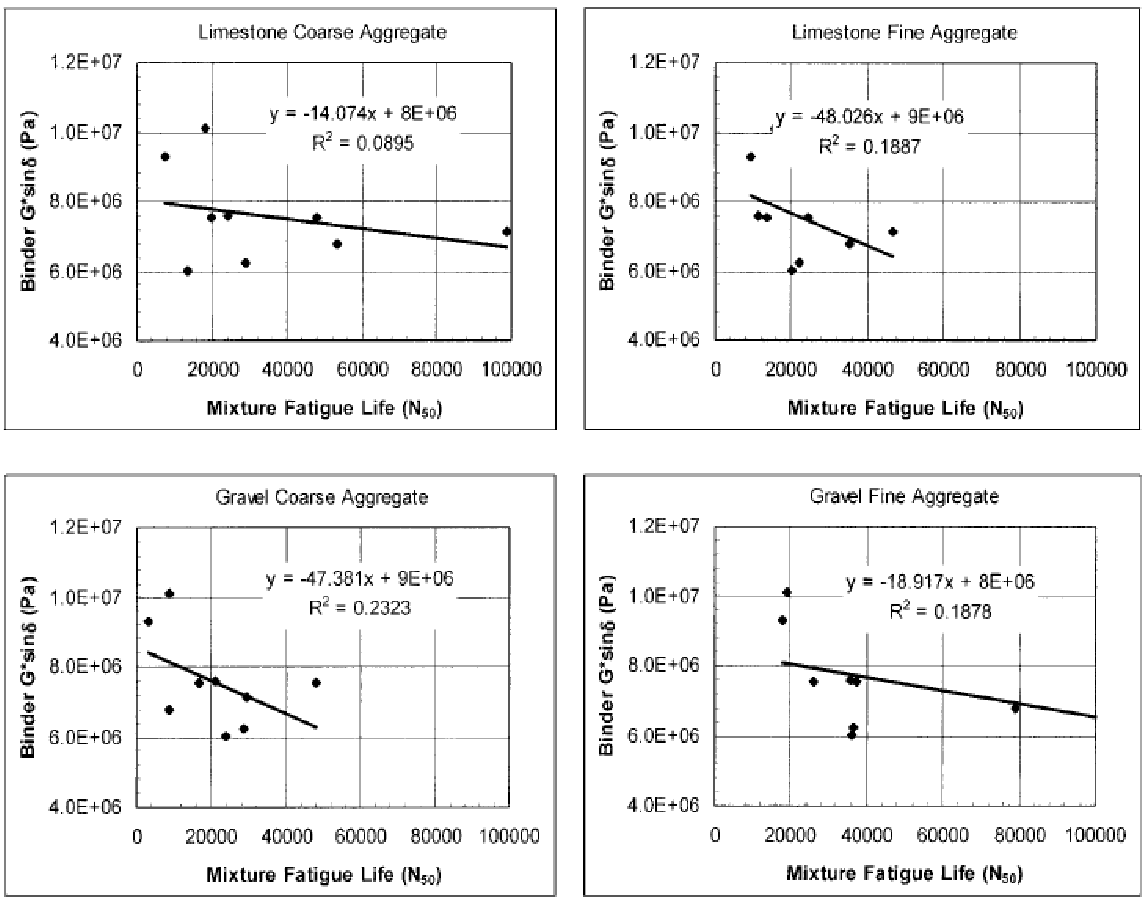
Shortcomings of PG: |G*|sinδ

- **1993 FHWA SHRP Validation – FHWA ALF**



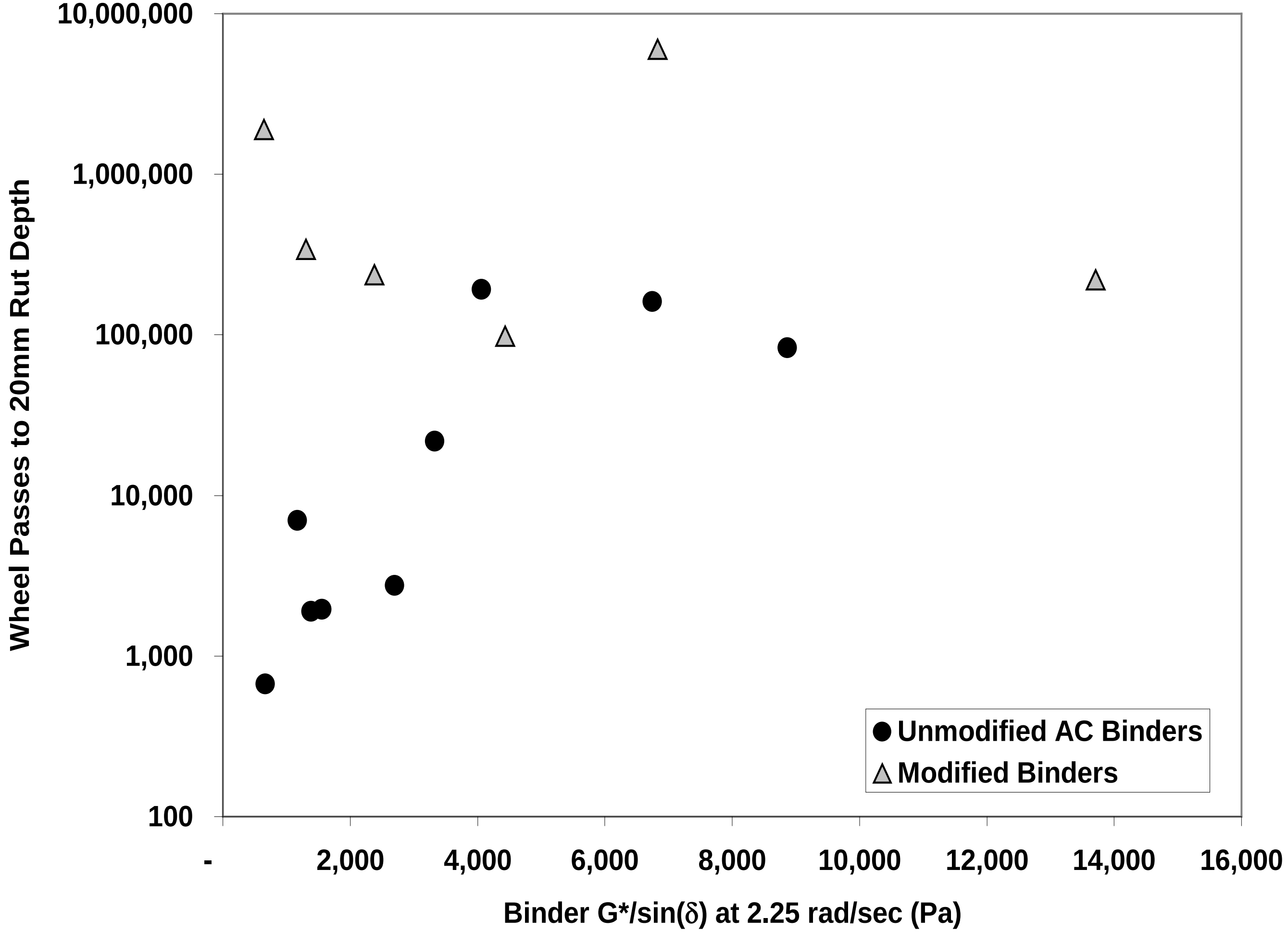
Shortcomings of PG: |G*|sinδ

- **NCHRP 9-10: |G*|sinδ did not correlate with mixture beam fatigue**



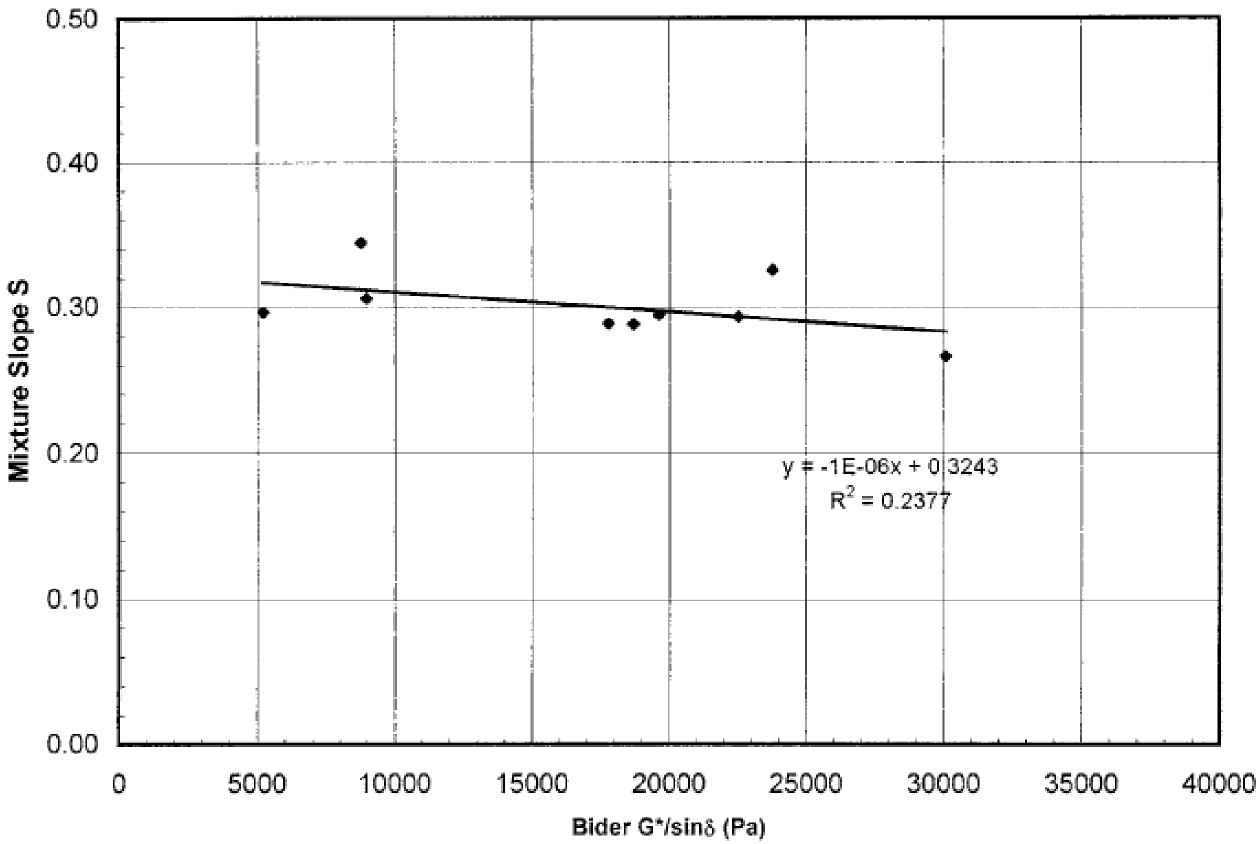
Shortcomings of PG: |G*|/sinδ

- **1993 FHWA SHRP Validation – FHWA ALF**



Shortcomings of PG: |G*|/sinδ

- NCHRP 9-10: |G*|/sinδ did not correlate with permanent shear strains



OBJECTIVES for *Full-Scale Accelerated Performance Testing for Superpave & Structural Validation*

- **Recommendations that provide AASHTO with a binder purchase specification that is "blind" to the type of modification.**

Secondary Objectives

Q & A

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Day 1:

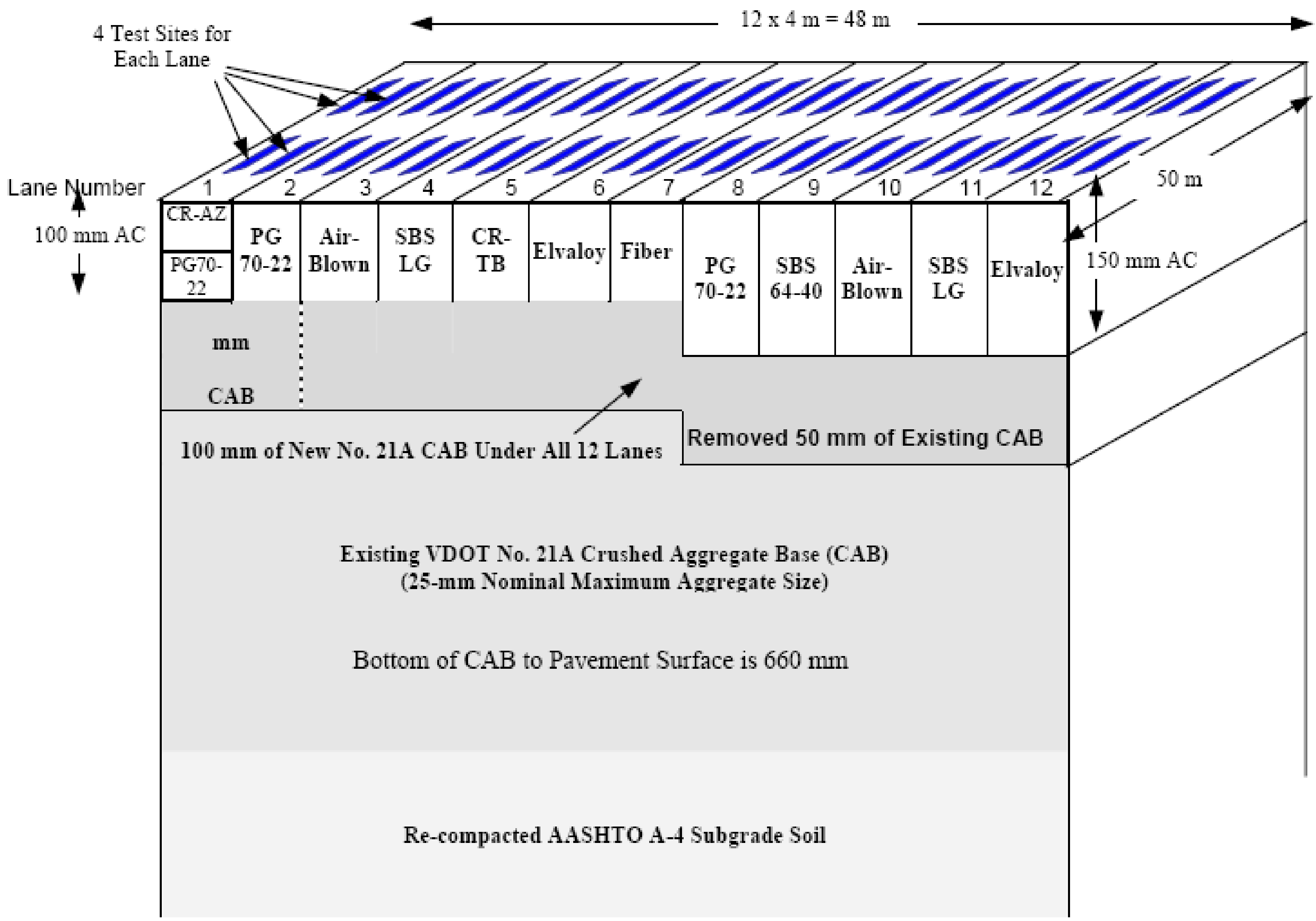
Experimental Design

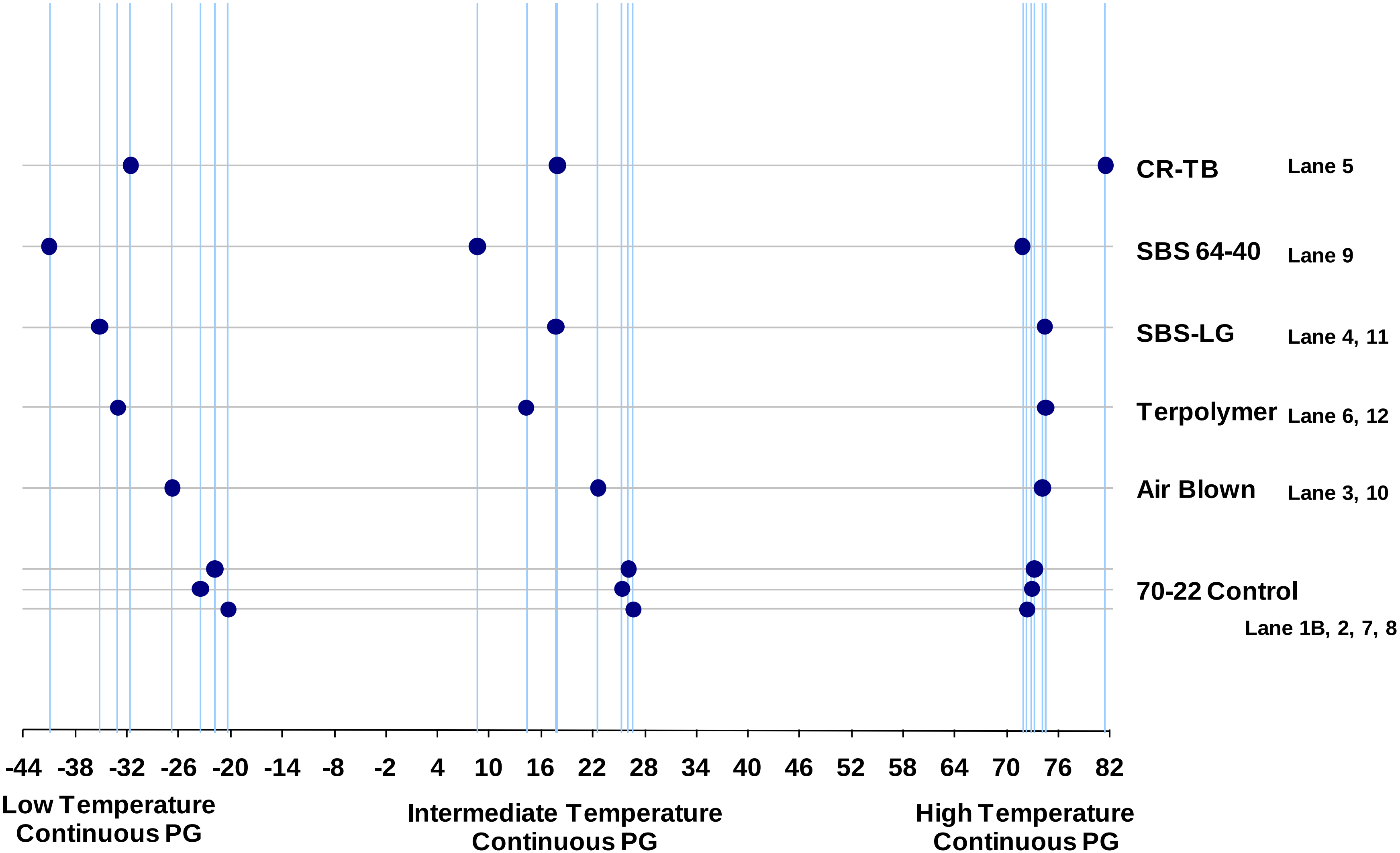
Construction

"90-07" Exploratory Experiment before ALF

1. Unmodified PG 64
2. Unmodified PG 70
3. Air-Blown
4. Ethylene Terpolymer
5. SBS Linear Grafted
6. SBS Linear
7. SBS Radial Grafted
8. Ethylene Vinyl Acetate
9. EVA Grafted
10. Ethylene Styrene Interpolymer
11. Chemically Modified Crumb Rubber Asphalt

- 11 binders
- Identified how the type of base asphalt crude responds to different polymers
- Binder & mixture tests
- Allowed optimization of the PG grades and types of binders targeted for larger quantities needed for ALF construction


12 x 4 m = 48 m
4 Test Sites for Each Lane
Lane Number
1
2
3
4
5
6
7
8
9
10
11
12
50 m
100 mm AC
CR-AZ
PG70-22
PG 70-22
Air-Blown
SBS LG
CR-TB
Elvaloy
Fiber
PG 70-22
SBS 64-40
Air-Blown
SBS LG
Elvaloy
150 mm AC
mm
CAB
100 mm of New No. 21A CAB Under All 12 Lanes
Removed 50 mm of Existing CAB
Existing VDOT No. 21A Crushed Aggregate Base (CAB)
(25-mm Nominal Maximum Aggregate Size)
Bottom of CAB to Pavement Surface is 660 mm
Re-compacted AASHTO A-4 Subgrade Soil


CR-TB
Lane 5
SBS 64-40
Lane 9
SBS-LG
Lane 4, 11
Terpolymer
Lane 6, 12
Air Blown
Lane 3, 10
70-22 Control
Lane 1B, 2, 7, 8
-44
-38
-32
-26
-20
-14
-8
-2
4
10
16
22
28
34
40
46
52
58
64
70
76
82
Low Temperature Continuous PG
Intermediate Temperature Continuous PG
High Temperature Continuous PG

Dense Graded Mix Design - 12.5 mm NMAS Coarse

- N_{Design} = 75
- Binder Content = 5.3%
- Effective Binder = 5.0%
- Binder Volume = 12.5%
- Design Air Voids = 4.5%
- VMA = 17.2%
- VFA = 73.0%
- Dust:Binder = 1.27
- 1% Hydrated Lime (Anti-Strip)

Sieve Size		Gap Graded CR-AZ Mix Design Percent Passing		Dense Graded 12.5mm NMAS Percent Passing	
Standard	[mm]	Target Blend	Limits	Target Blend	Limits
1”	25	100		100	
¾”	19	100		100	
½”	12.5	87		94	
3/8”	9.5	73		85	
No. 4	4.75	33	30 - 36	55	52 - 58
No. 8	2.36	16		35	
No. 16	1.18	11			
No. 30	0.6	8	6 - 10	17	15 - 19
No. 50	0.3	6		12	
No. 100	0.15	5			
No. 200	0.075	3	2.3 - 3.7	6.3	5.6 - 7.0

Arizona "Wet Process" Crumb Rubber Asphalt

- 17% Crumb Rubber, #40 mesh
- Base Binder PG58-22
- PG Estimates
  - High Temperature Grade = 90.1^{o}C
  - Intermediate Temp. Grade = 23.4^{o}C

Fiber (polyester) Reinforced Mix

- 0.2% by weight of aggregate
- Volumetric calculations assumed fiber was part of the aggregate
- Blown into the drum plant

Subgrade

- AASHTO A4
- Decomposed Rock
- CBR = 6.7
- Proctor = 111.9 pcf
- Modified Proctor = 121.6 pcf
- O.M.C. = 14.9% & 11.4%

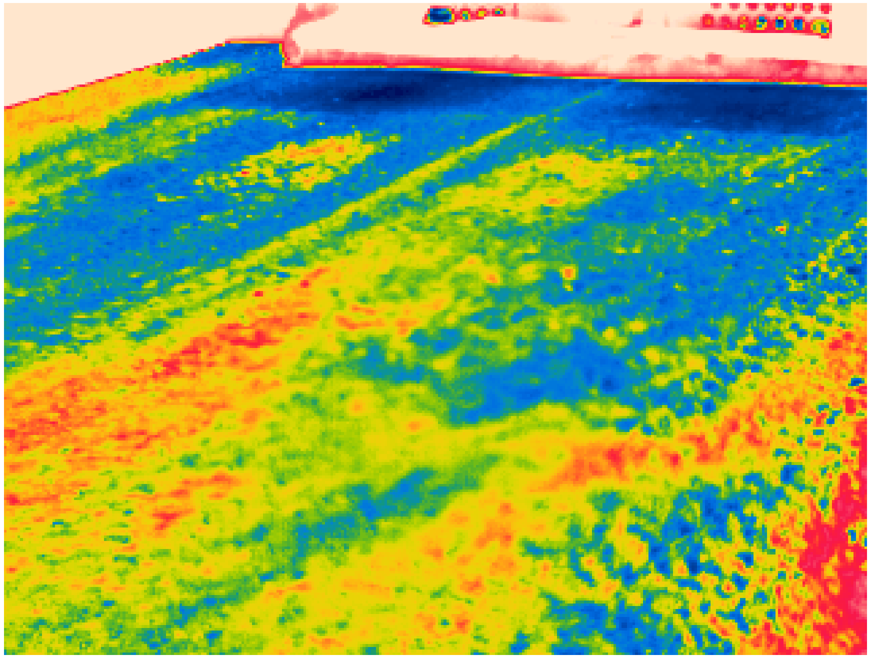
Sieve Size (mm)	Total Percent Passing (%)
25	100
14	97
12.5	94
9.5	92
4.75	87
2	83
0.425	71
0.075	34

Crushed Stone Base

- O.M.C. = 5.3%
- Compacted to 95% of 156 pcf

Sieve Size (mm)	Total Percent Passing (%)
50	100
25	95
9.5	66
2	35
0.425	19
0.075	8

Material Transfer Device and Remixing

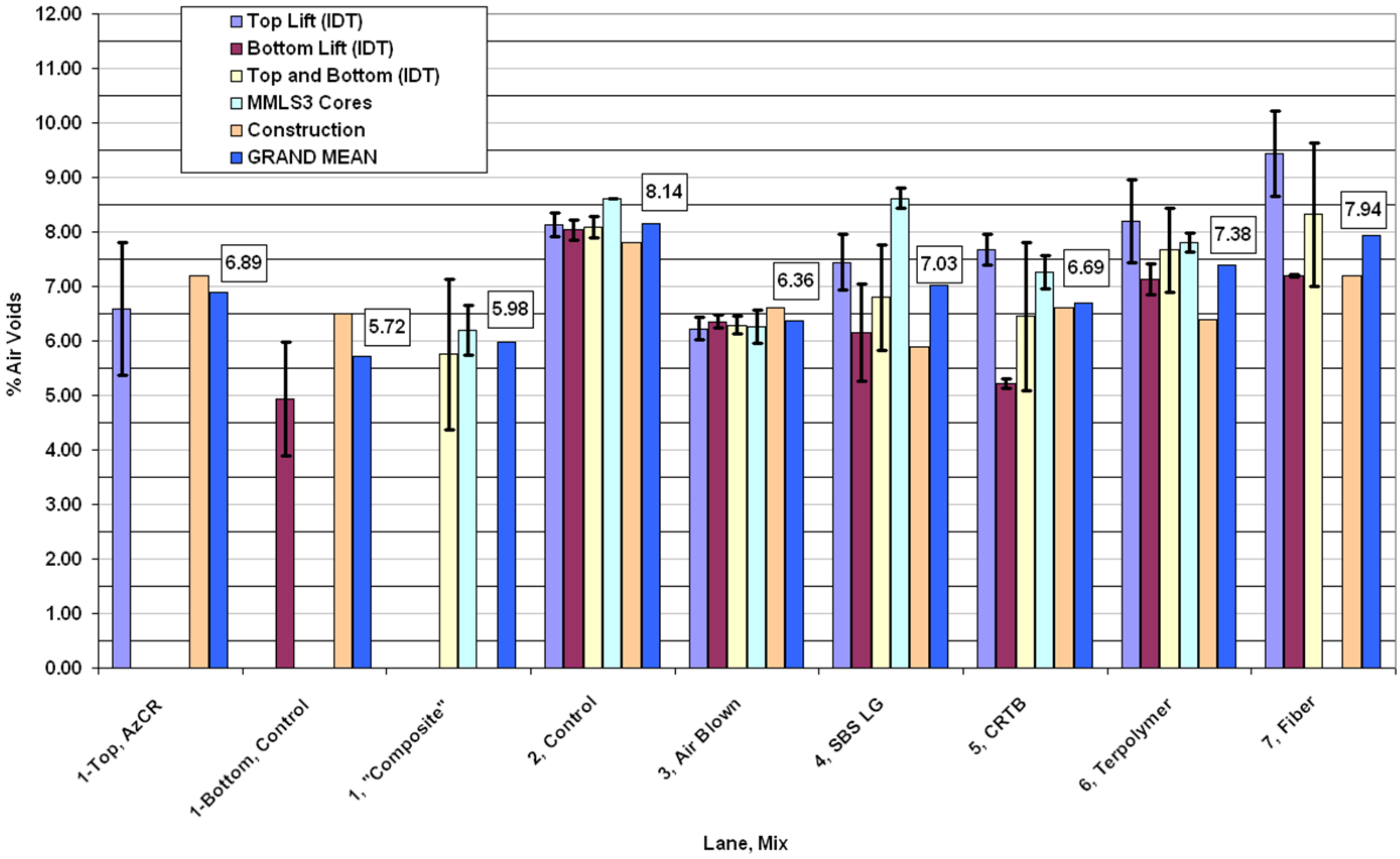


- 148ºC - 150ºC (298 ºF - 302ºF)
- Coolest parts of the loose mat within view is about 118ºC - 120ºC (244 ºF -248 ºF)

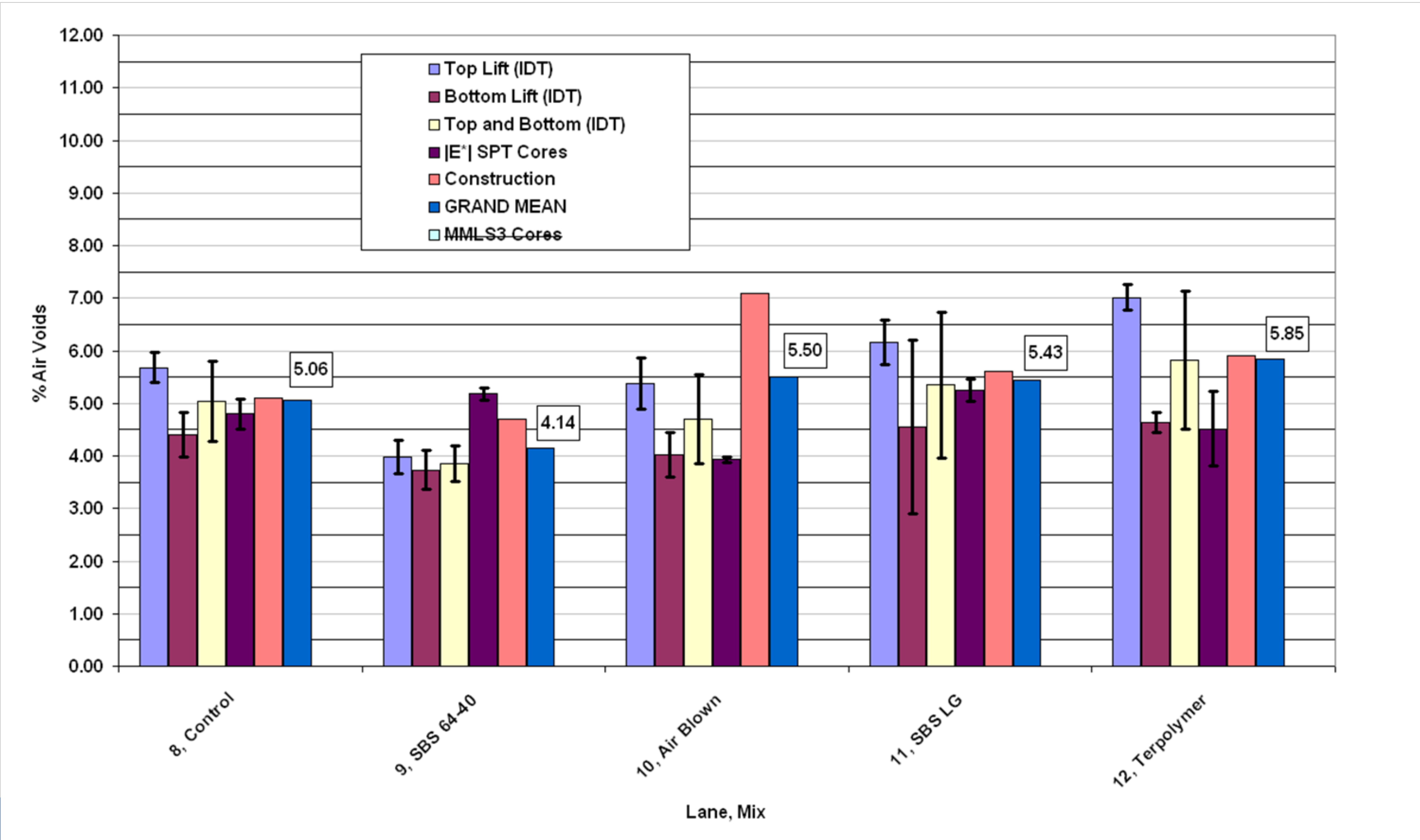
Acceptance Criteria

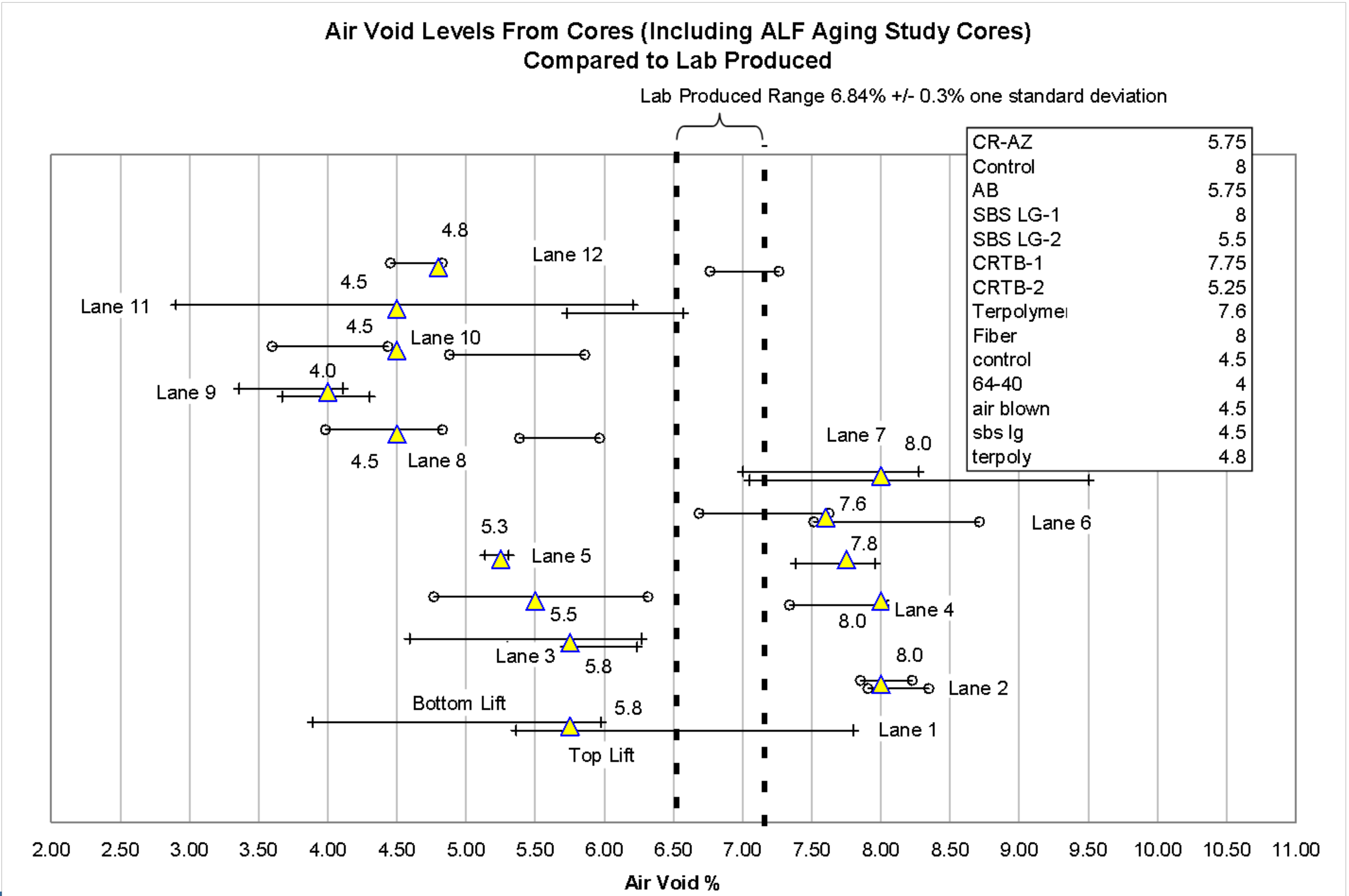
Material Property	Test Method	Number of Tests	Tolerance
Aggregate Gradation	AASHTO T 30	3 per test lane	Target ± 3.0 % for 4.75 mm
			Target ± 2.0 % for 0.600 mm
			Target ± 0.7 % for 0.075 mm
Asphalt Binder Content	AASHTO T 308 Ignition Oven	3 per test lane	Target ±0.2 %
	AASHTO T 287 Nuclear	3 per control strip	No specification
Maximum Specific Gravity	AASHTO T 209	3 per test lane	Target ±0.015
Mixture Volumetrics	AASHTO PP 28	3 per test lane	No specification
In-Place Density	ASTM D 2950 Nuclear Density Gauge	15 per lift per test lane	Target ±1 %
Air Voids Using Cores	AASHTO T 166 ASTM D 3203	6 per test lane	7.0 ±1 %
Thickness Using Cores	Federal Lands Method T 501	6 per test lane	Target ±10 mm

Air Void Content – 100 mm Lanes

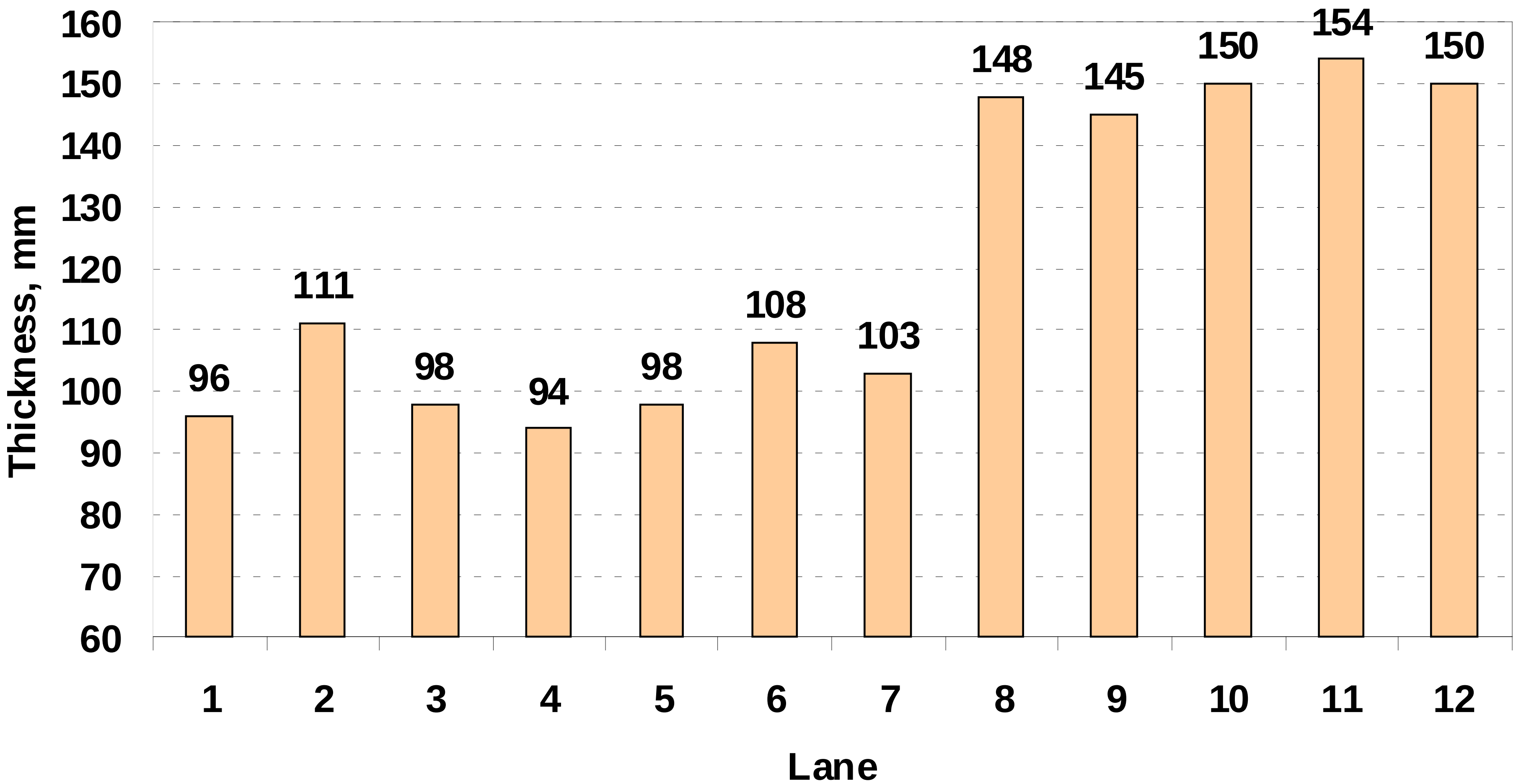


Air Void Content – 150 mm Lanes




Air Void Levels From Cores (Including ALF Aging Study Cores)
Compared to Lab Produced
Lab Produced Range 6.84% +/- 0.3% one standard deviation
CR-AZ 5.75
Control 8
AB 5.75
SBS LG-1 8
SBS LG-2 5.5
CRTB-1 7.75
CRTB-2 5.25
Terpolymer 7.6
Fiber 8
control 4.5
64-40 4
air blown 4.5
sbs lg 4.5
terpoly 4.8
4.8
Lane 12
4.5
Lane 11
4.5
Lane 10
4.0
Lane 9
4.5
Lane 8
Lane 7
8.0
7.6
Lane 6
5.3
Lane 5
7.8
5.5
Lane 4
8.0
Lane 3
5.8
8.0
Lane 2
Bottom Lift
5.8
Lane 1
Top Lift
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.00
6.50
7.00
7.50
8.00
8.50
9.00
9.50
10.00
10.50
11.00
Air Void %

HMA Thickness



Lime Clods

- **Screenings stockpile was wet-marinated before hand**

Lime Content

	Single Test Preliminary Analysis		Detailed Analysis Lime Content %
	Acid Used	Lime Content %	
Lane 1	Hydrochloric	1.10	-
Lane 2	Hydrochloric	0.44	0.42 +/-0.05
Lane 3	Hydrochloric	-	0.50 +/-0.20
Lane 4	Hydrochloric	0.33	-
Lane 5	Hydrochloric	0.41	-
Lane 6	Hydrochloric	0.49	-
Lane 7 – Middle	Acetic	0.12	-
Lane 7 – End	Acetic	0.12	-
Lane 7	Hydrochloric	-	-
Lane 8 – Middle	Acetic	0.15	-
Lane 8 – End	Acetic	0.15	-
Lane 8	Hydrochloric	0.30	-
Lane 9 – Middle	Acetic	0.61	-
Lane 9 – End	Acetic	0.49	-
Lane 9	Hydrochloric	0.52	-
Lane 10 –Middle	Acetic	0.47	-
Lane 10 – End	Acetic	0.49	-
Lane 10	Hydrochloric	0.87	-
Lane 11	Hydrochloric	0.41	-
Lane 12	Hydrochloric	0.54	-

- **Arnold, T.S., Rozario-Ranasinghe, M., Youtcheff, J., "Determination of Lime in Hot-Mix Asphalt," *Transportation Research Record*: Journal of the Transportation Research Board Issue Number 1962 (2006)**

Q & A

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SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements

1st Closeout Webinar

August 16-17, 2010

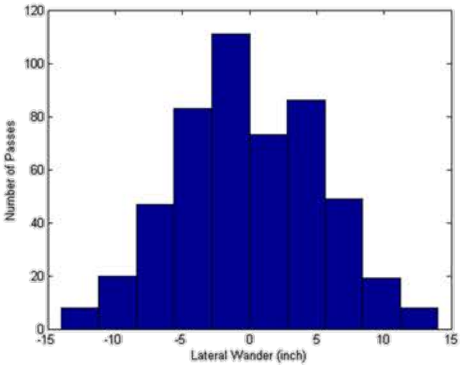
11am – 2pm

Day 1:

ALF Rutting Performance

ALF Fatigue Cracking Performance

Accelerated Loading Conditions



64°C (147°F)

74°C (165°F)

45°C (113°F)

100 psi Inflation

10,000 pounds

No Wander

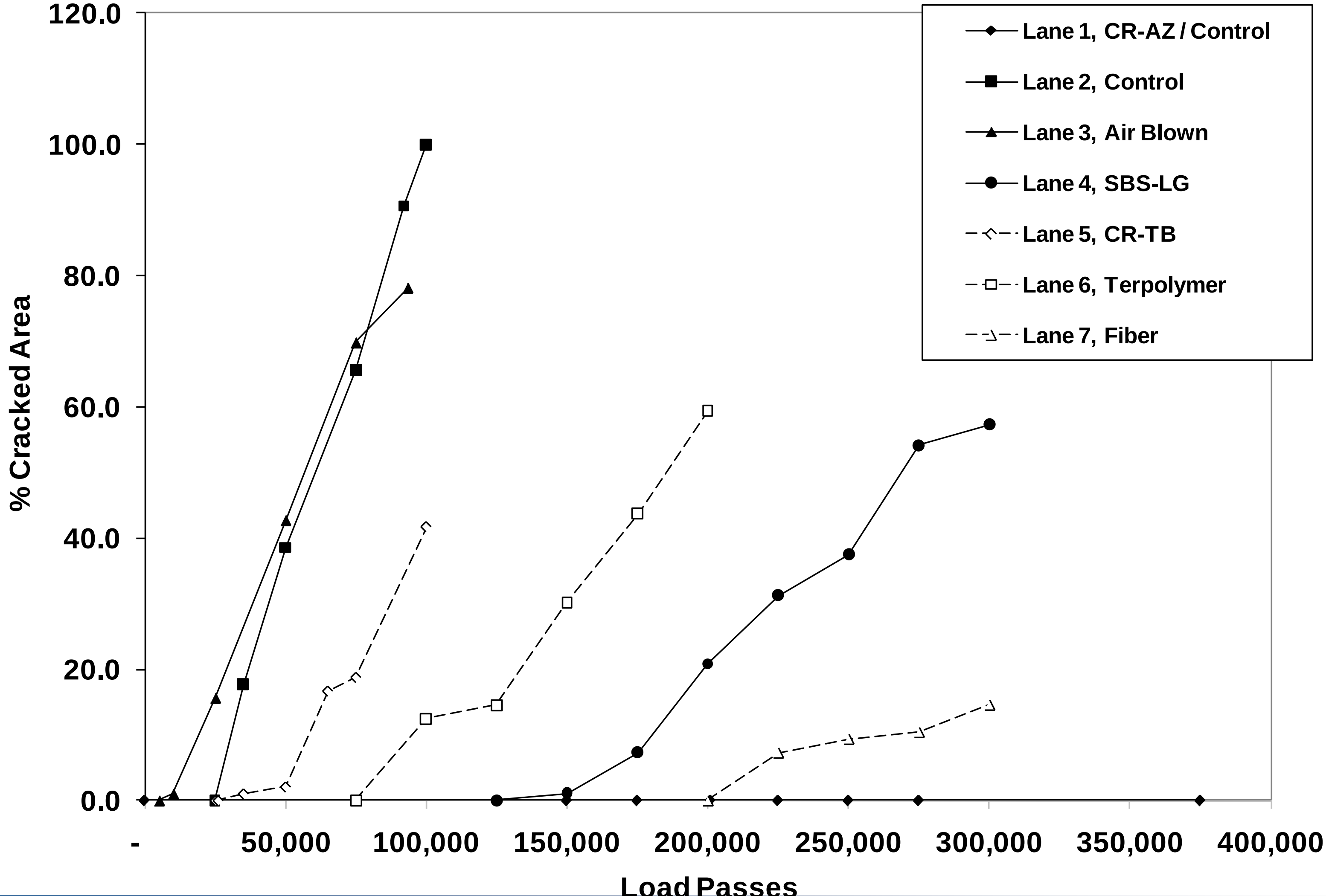
19°C (66°F)

120 psi Inflation

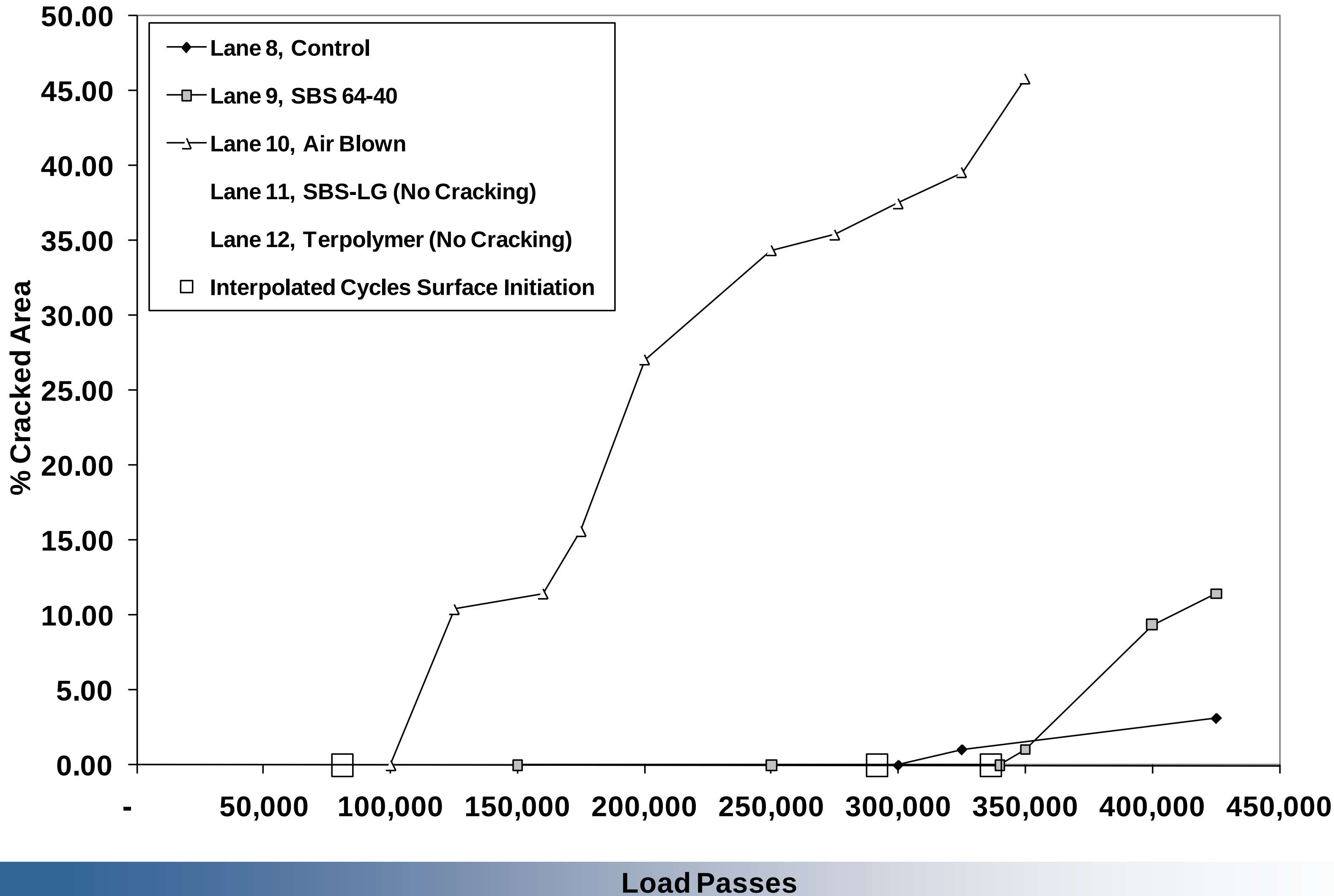
16,000 pounds

Wheel Wander

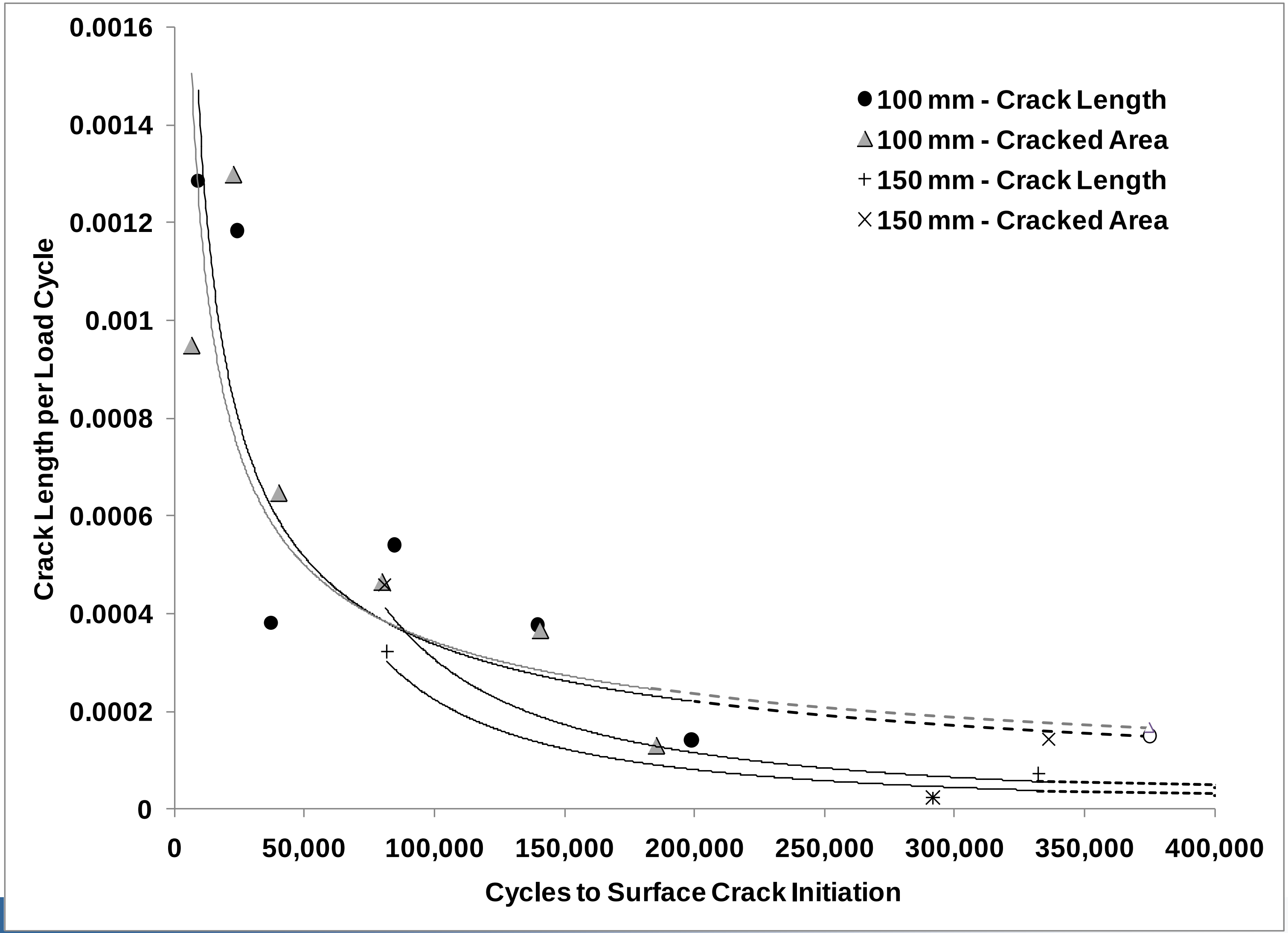
100 mm Fatigue Cracking – 19ºC



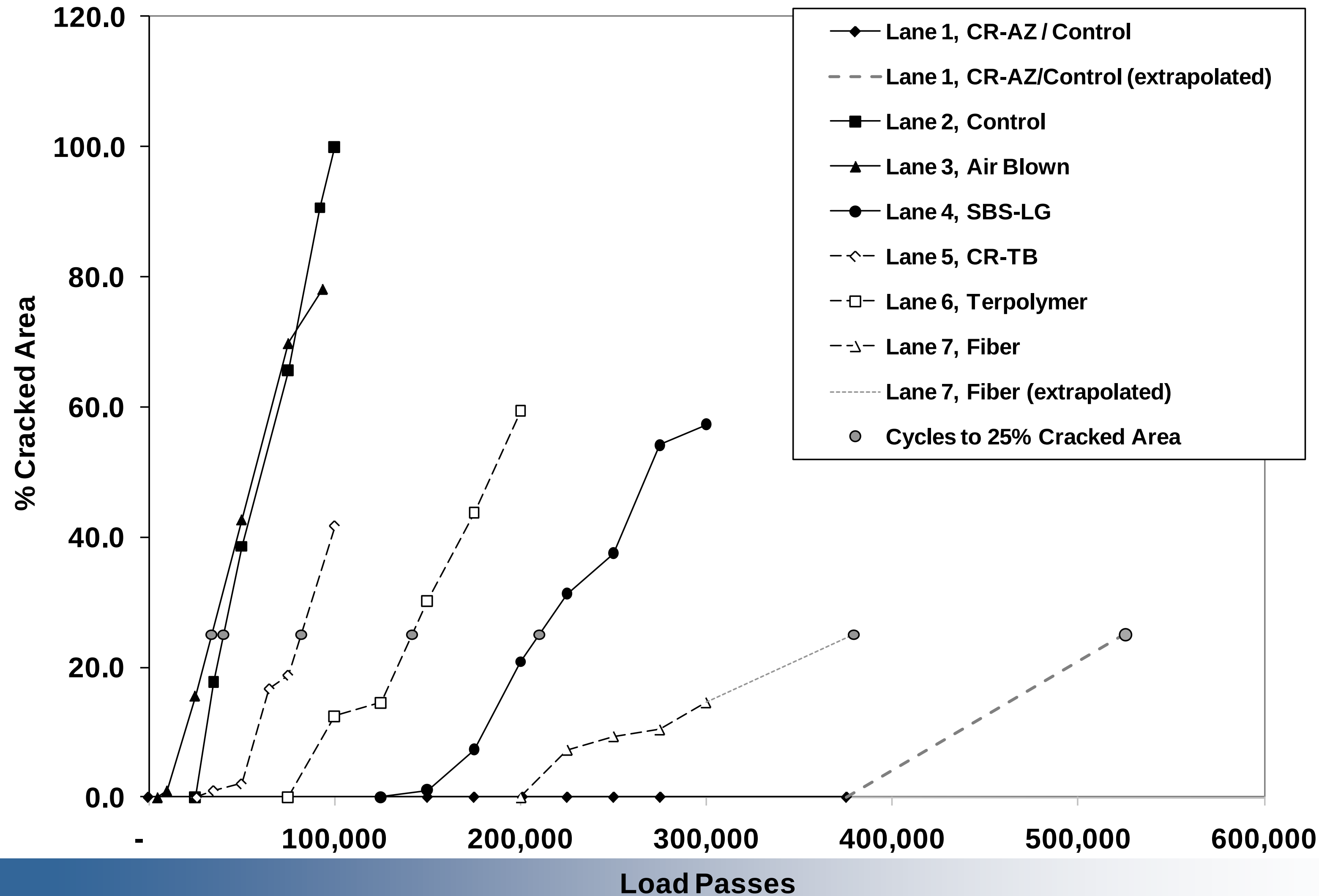
150 mm Fatigue Cracking – 19ºC



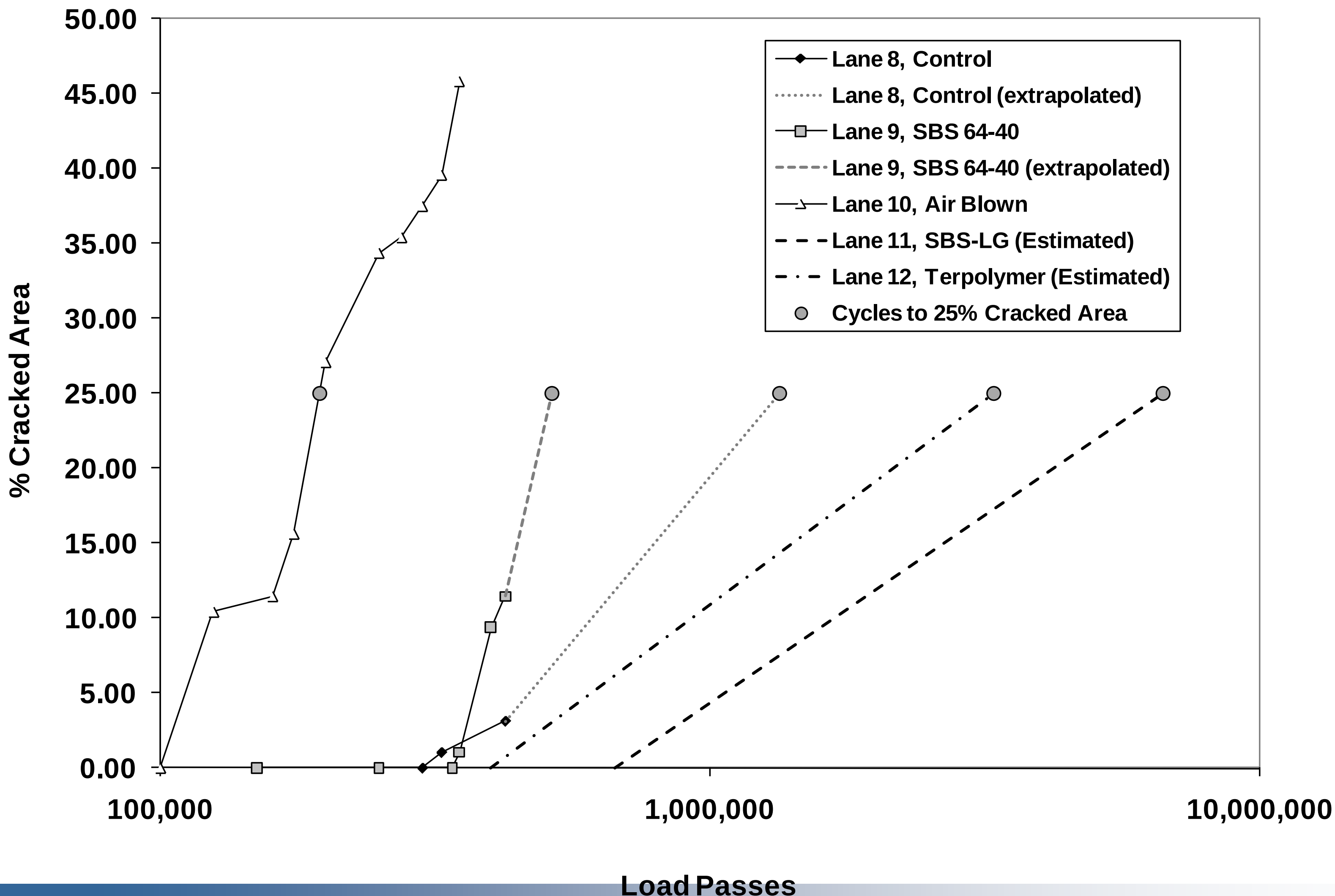
Surface Crack Initiation & Crack Rate



100 mm Fatigue Cracking – 19°C

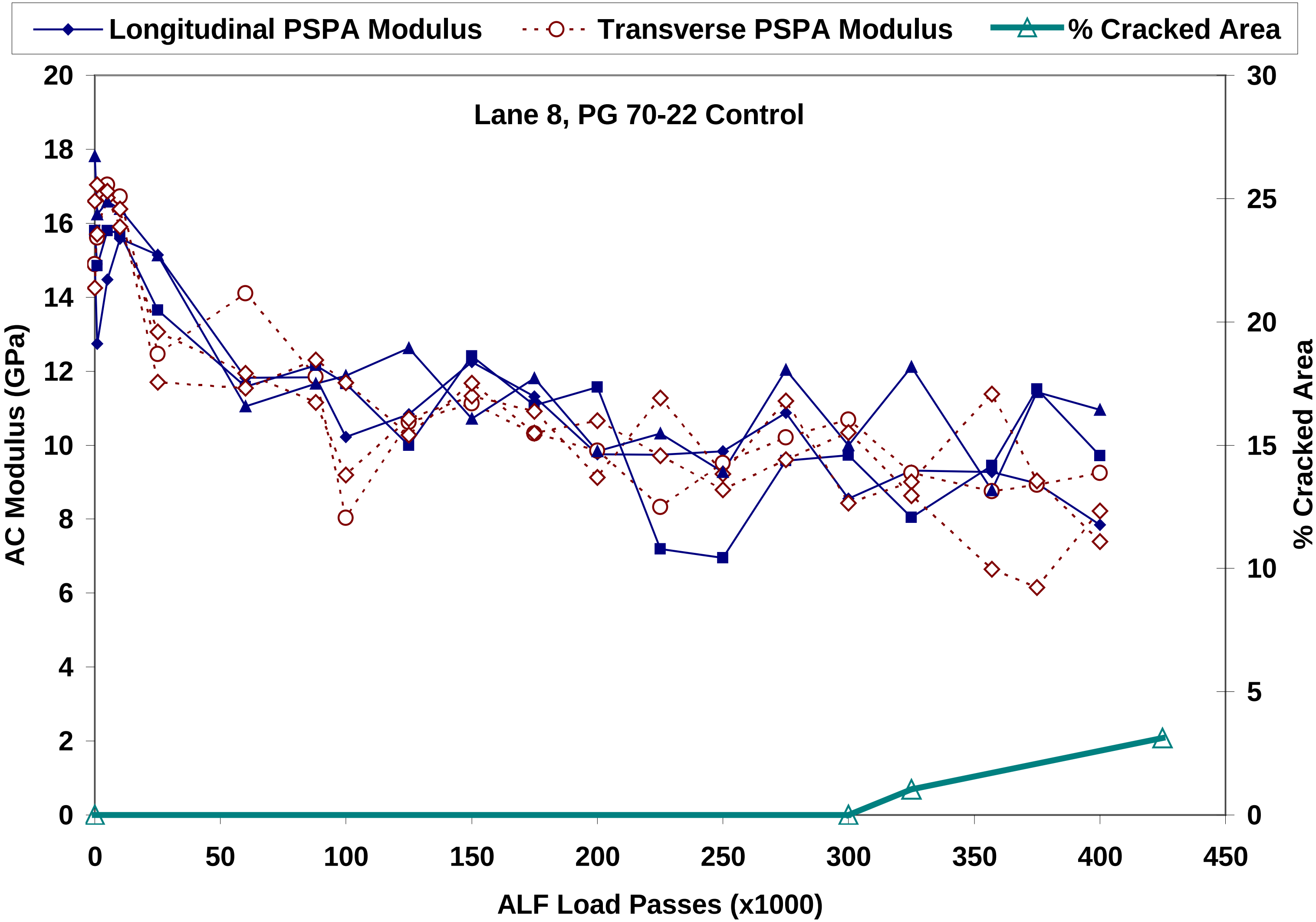


150 mm Fatigue Cracking – 19ºC

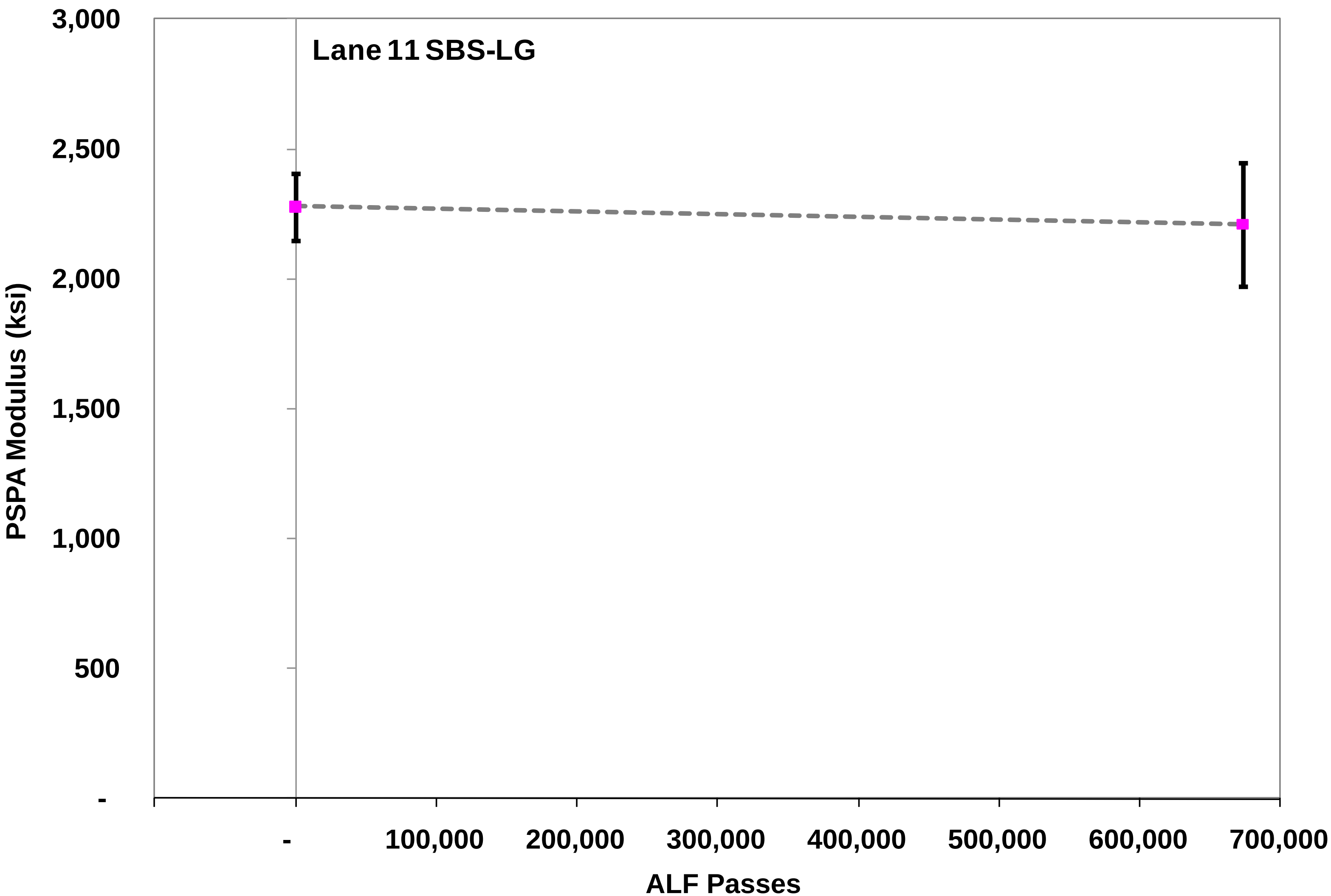


Portable Siesmic Pavement Analyzer PSPA

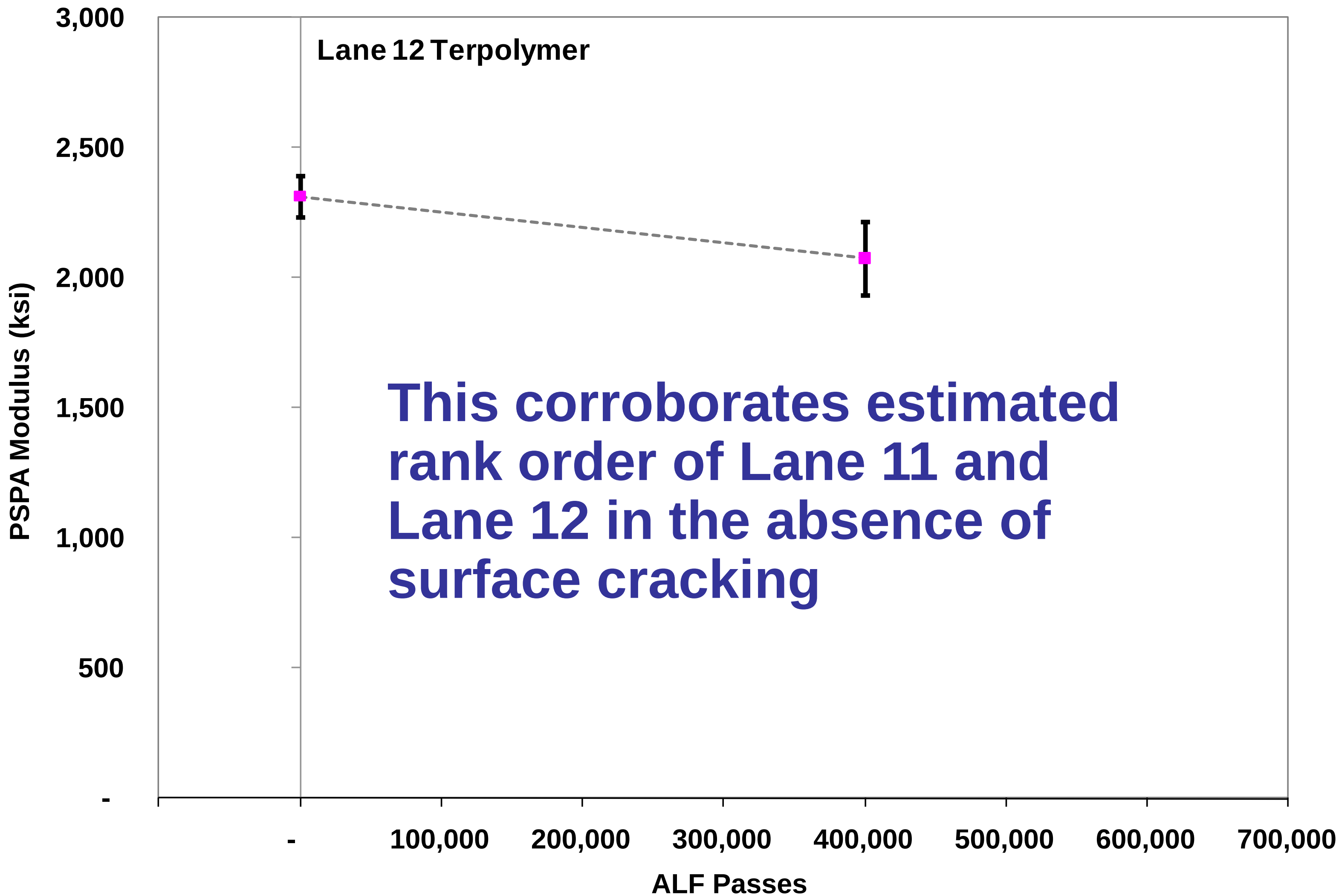
PSPA Modulus Changes with Damage



PSPA Modulus – Lane 12



PSPA Modulus – Lane 11



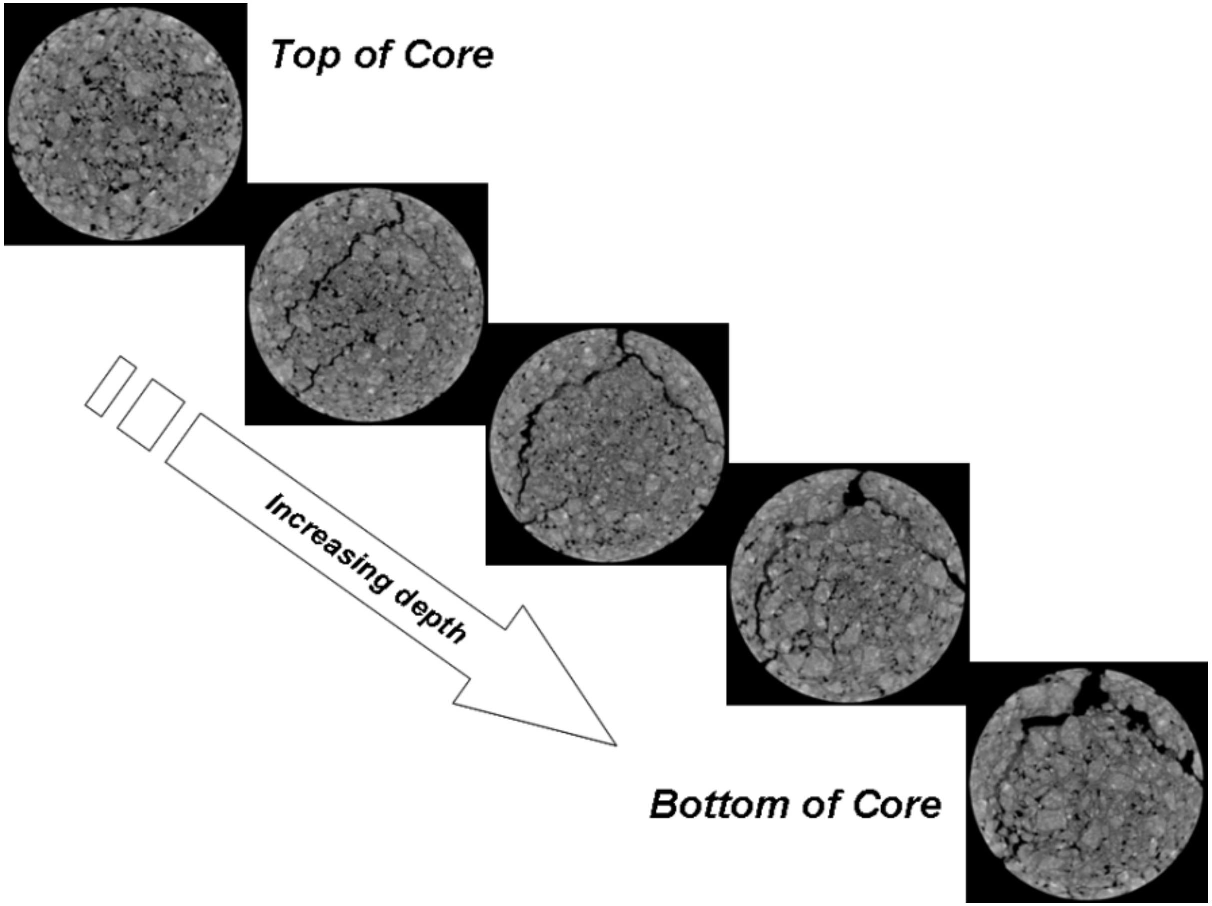
This corroborates estimated rank order of Lane 11 and Lane 12 in the absence of surface cracking

Ranked Fatigue Cracking

		Load Passes to Surface Crack Initiation	Load Passes to 25m Cumulative Crack	Load Passes to 25% Cracked Area
Lane 3	Air Blown	6,648	32,336	33,654
Lane 2	Control	22,728	44,311	40,250
Lane 5	CR-TB	40,178	100,297	81,818
Lane 6	Terpolymer	79,915	139,583	141,667
Lane 4	SBS-LG	140,857	208,349	210,000
Lane 7	Fiber	185,484	375,516	379,032
Lane 1	CR-AZ / Control	>375,000	541,405	525,075

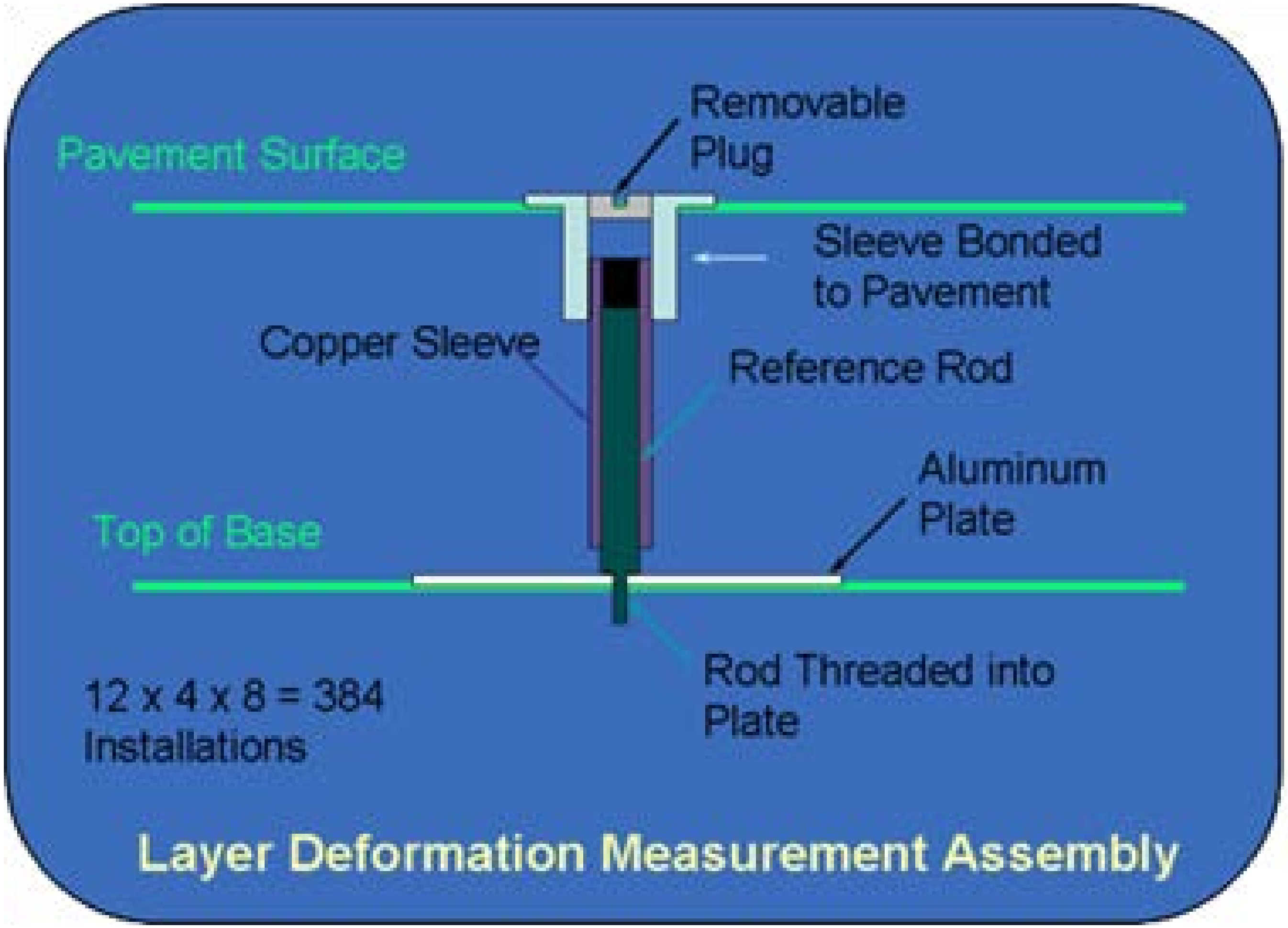
		Load Passes to Surface Crack Initiation	Load Passes to 25m Cumulative Crack	Load Passes to 25% Cracked Area
Lane 10	Air Blown	80,984	197,496	195,455
Lane 8	Control	291,667	1,385,417	1,341,667
Lane 9	SBS 64-40	336,326	675,602	516,091
Lane 12	Terpolymer	>400000	4,704,085	3,285,555
Lane 11	SBS-LG	>673000	9,390,351	6,682,329

Cracking is Bottom-Up

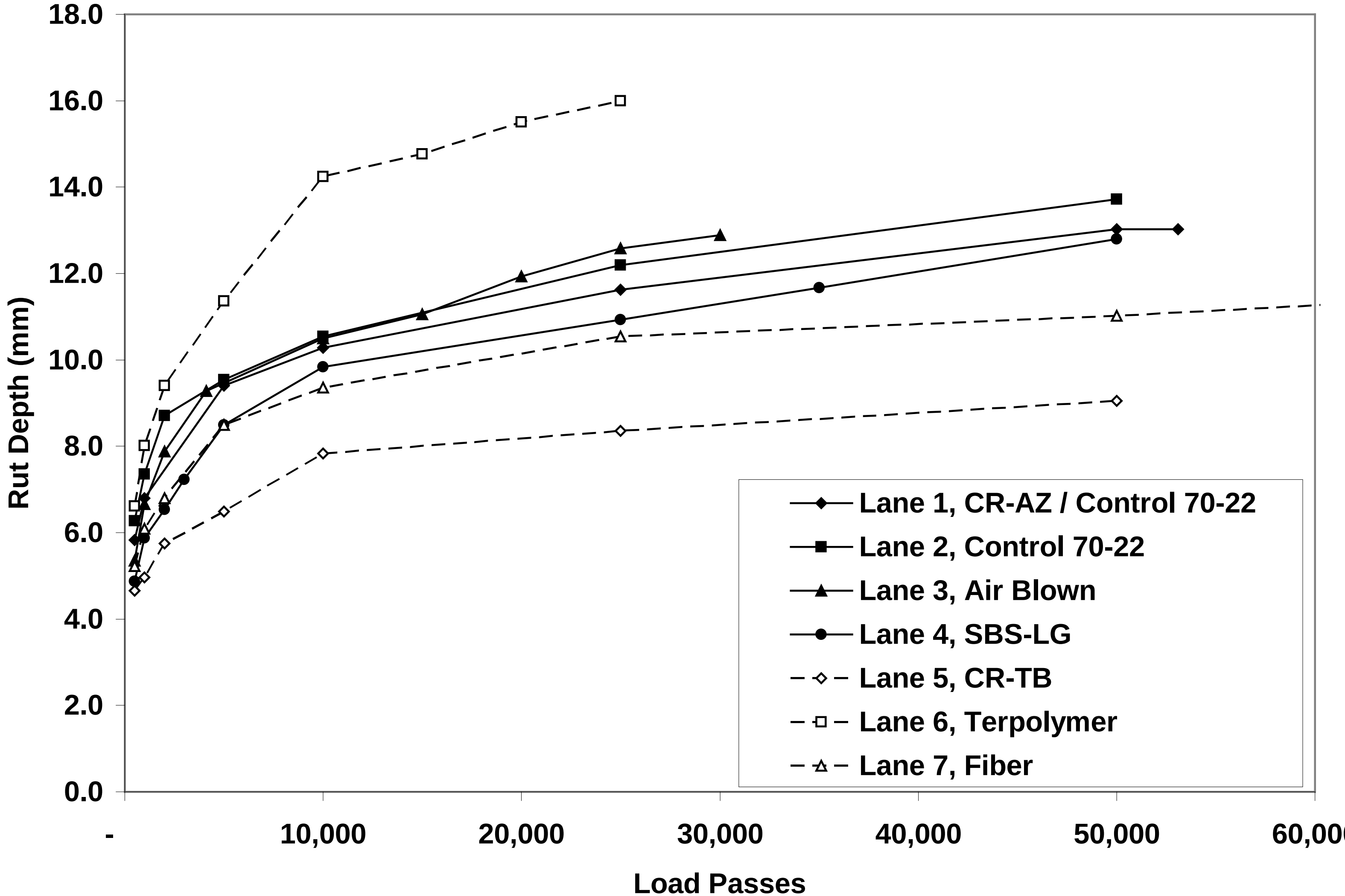


Cracks Arrested in Crumb Rubber Composite Pavement

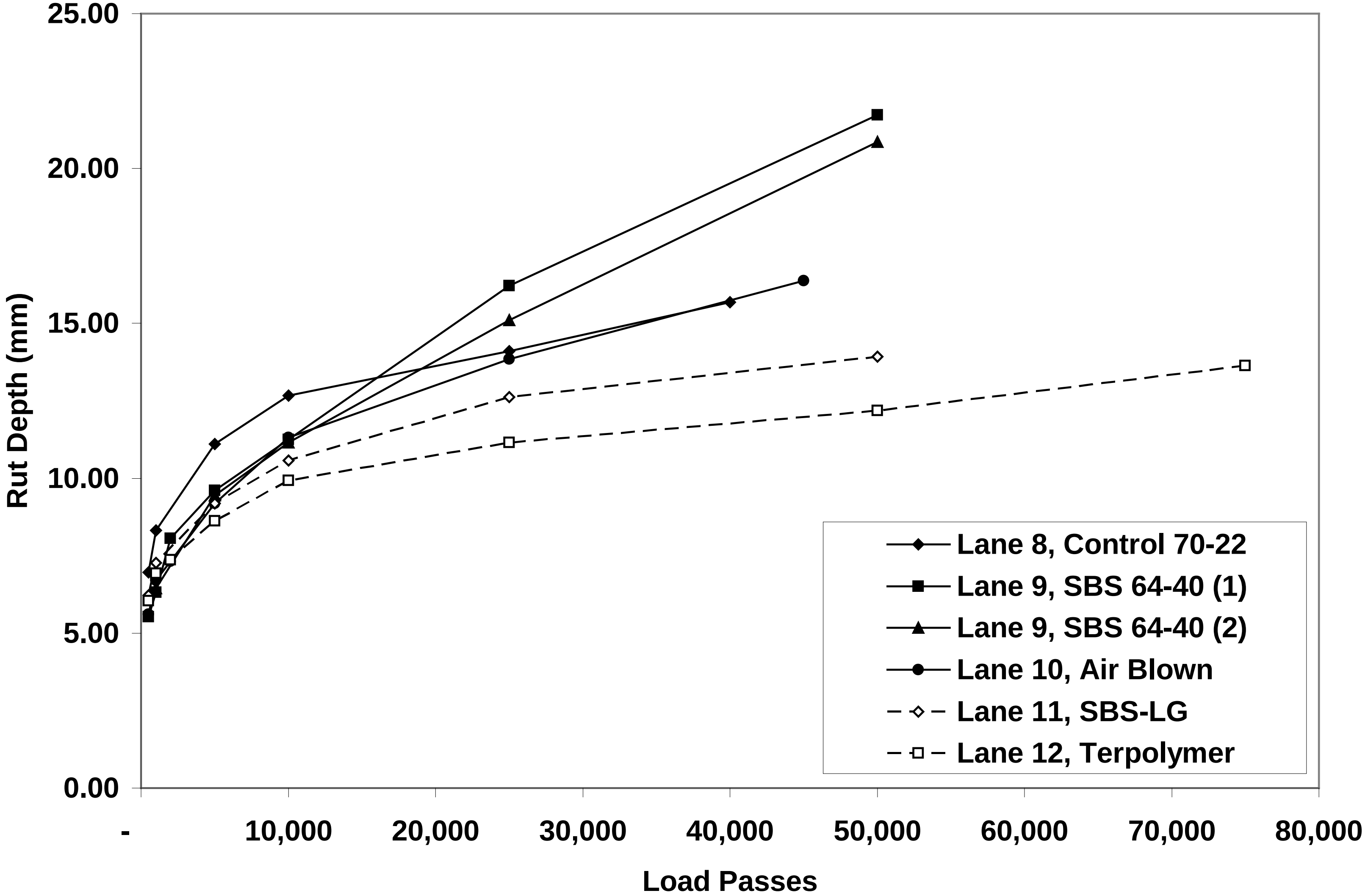
Measuring Rutting in HMA



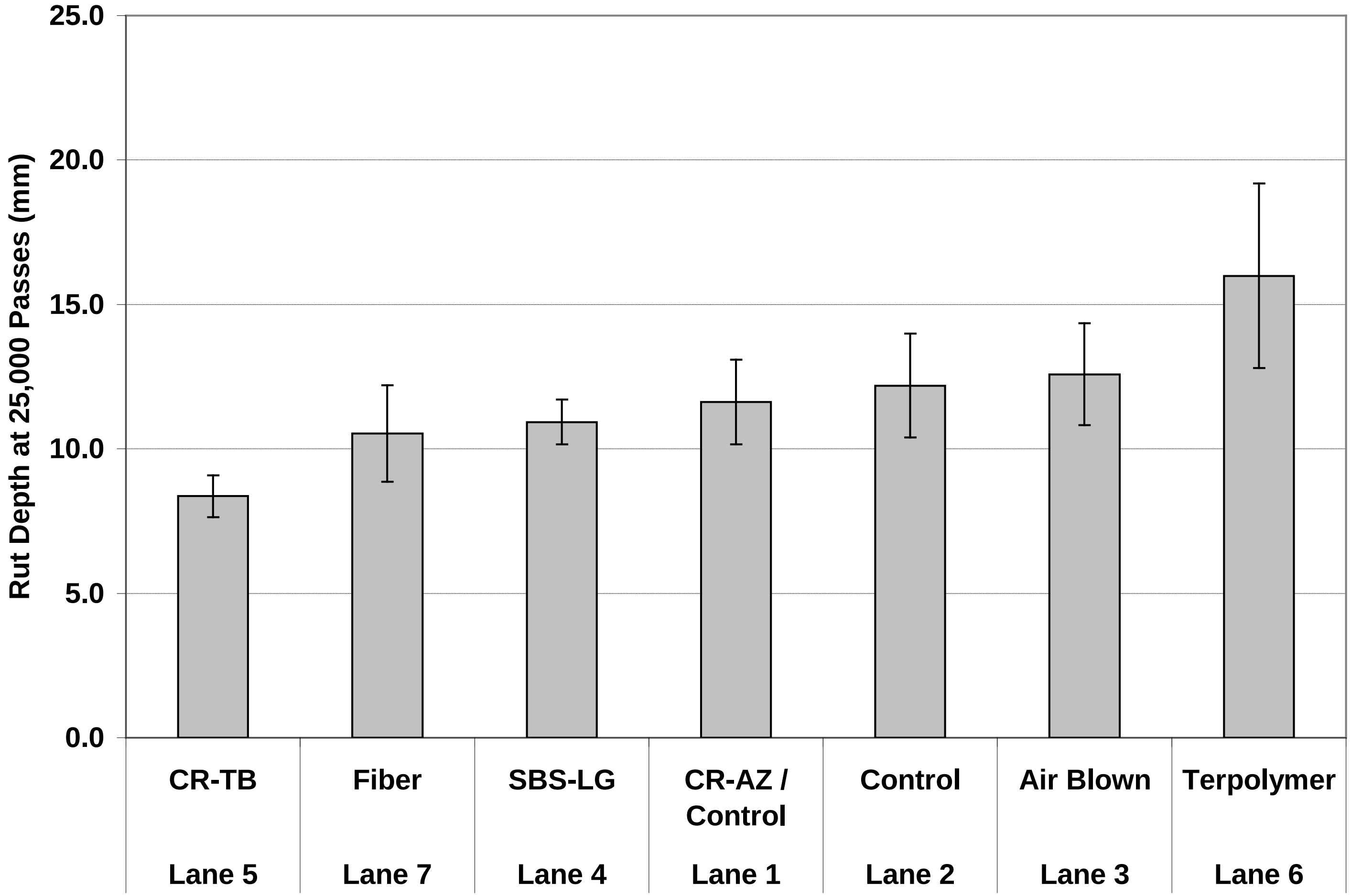
100 mm Rutting – 64°C



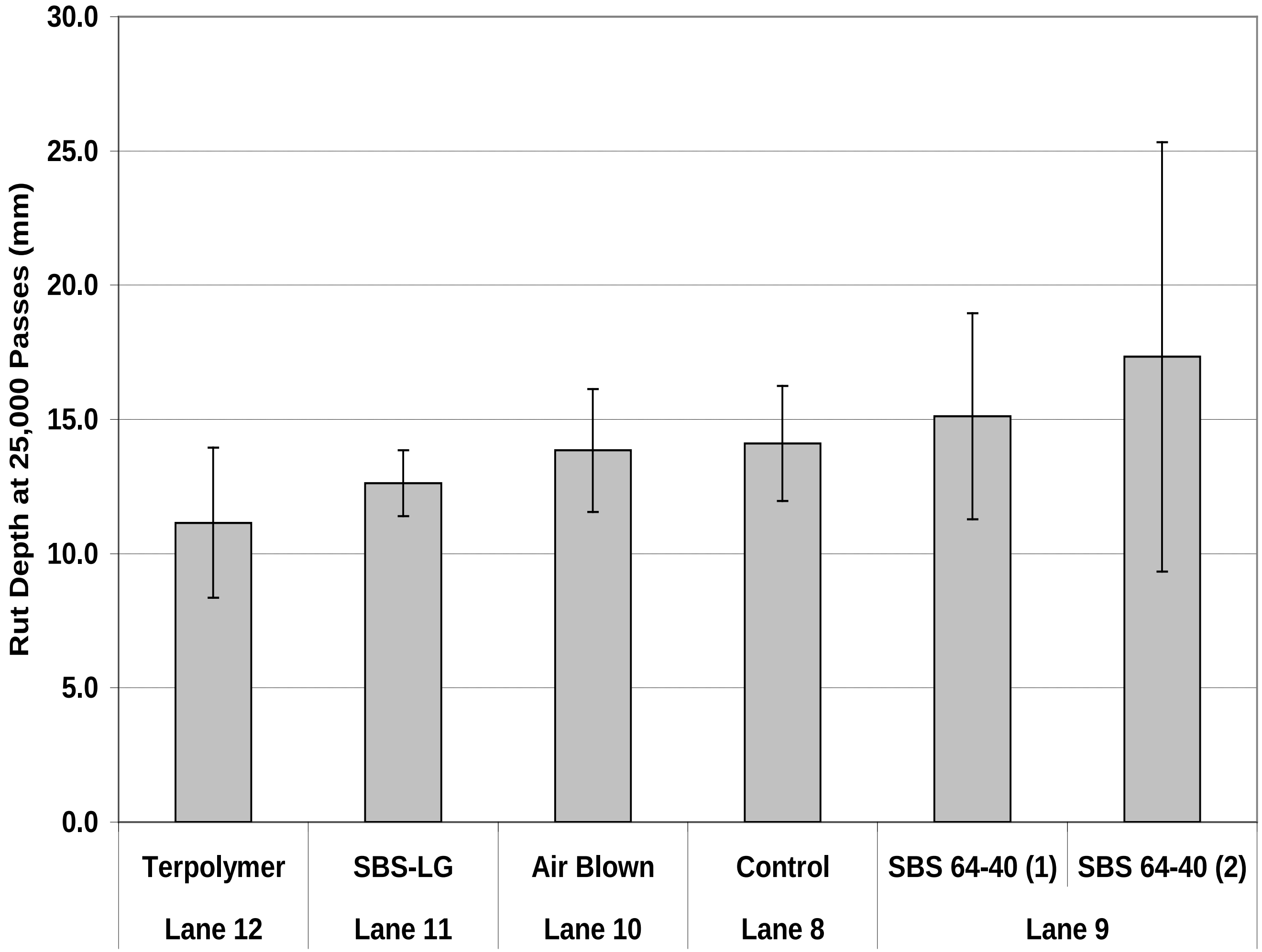
150 mm Rutting – 64ºC



100 mm Rutting – 64°C



150 mm Rutting – 64°C



100 mm Rutting – 64°C

	CR-TB	Fiber	SBS-LG	CR-AZ / Control	Control	Air Blown	Terpolymer
CR-TB	•	=	≠	≠	≠	≠	≠
Fiber		•	=	=	=	=	≠
SBS-LG			•	=	=	=	≠
CR-AZ / Control				•	=	=	≠
Control					•	=	=
Air Blown						•	=
Terpolymer							•

150 mm Rutting – 64ºC

	Terpolymer	SBS-LG	Air Blown	Control	SBS 64-40 (1)	SBS 64-40 (2)
Terpolymer	•	=	=	=	=	≠
SBS-LG		•	=	=	=	=
Air Blown			•	=	=	=
Control				•	=	=
SBS 64-40 (1)					•	=
SBS 64-40 (2)						•

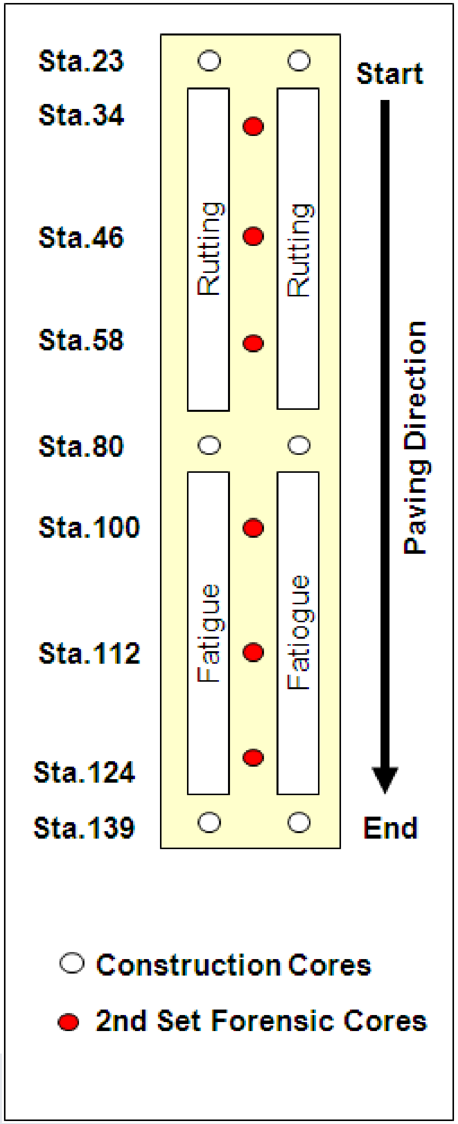
Anomalous Lane 6 Terpolymer Rutting

- Conflicting Performance
  - Worst in 100 mm
  - Best in 150 mm lanes
- Historical experience with this polymer has shown very good performance
- Top performer in all mixture tests from FHWA 90-07 Study
  - Hamburg
  - SST
  - Beam Fatigue

1. Unmodified PG 64
2. Unmodified PG 70
3. Air-Blown
4. Ethylene Terpolymer
5. SBS Linear Grafted
6. SBS Linear
7. SBS Radial Grafted
8. Ethylene Vinyl Acetate
9. EVA Grafted
10. Ethylene Styrene Interpolymer
11. Chemically Modified Crumb Rubber Asphalt

Anomalous Lane 6 Terpolymer Rutting

- Forensic cores taken from Lane 6 (Terpolymer), Lane 12 (Terpolymer) and Lane 2 (Control)
- Binder extraction and recovery showed binder was not the cause
- Air void content on forensic cores slightly higher than original cores
- Water absorption significantly larger in the upper lift of Lane 6
- Aggregate gradation of Lane 6 and Lane 12 was finer and just outside limits
- Higher density in Lane 12 and Lane 6 Bottom overcame the gradation issue



Q & A

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MEPDG Analysis of Construction Uniformity

Did Construction Influence Ranking?

- Unbound Base Layer Construction Influence?
  - As-Built ←→ As-Built + Average Unbound Layer
- HMA Construction Influence?
  - As-Built + Average Unbound Layer ←→ As-Designed

- As-Built
  - In-Place Thickness
  - In-Place Density
  - *In-Place |E*|
  - Each Lane / Site FWD Back-Calculated

- As-Designed
  - Exact Thickness
  - Uniform Density
  - SGC Fabricated |E*|
  - FWD Averaged Base & Subgrade across

FWD Back Calculation

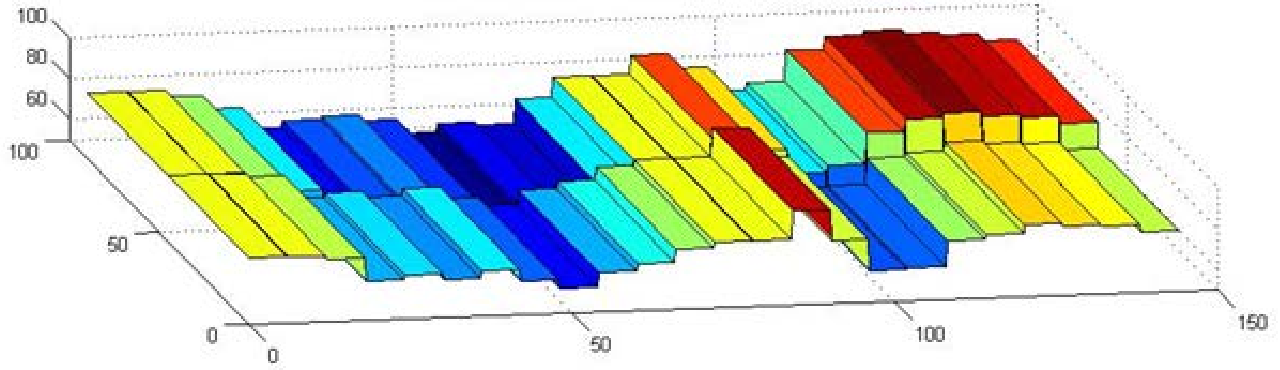
- FWD on top of crushed stone base before placing HMA
  - Root Mean Square error was high; between 8% and 25%
  - Crushed stone base was between 16 ksi and 11 ksi on two locations having the extremes in composite modulus
  - Subgrade modulus was between 9.5 ksi and 7.2 ksi on two locations having the extremes in composite modulus

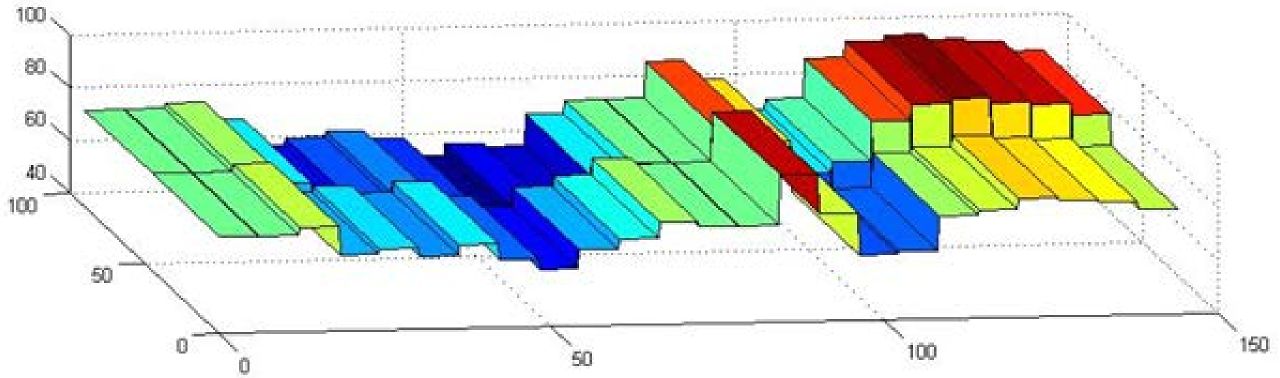
FWD Back Calculation

- FWD after placing HMA
  - Two programs used: MODCOMP & EVERCALC
  - Depth to bedrock easily detected
  - IDT resilient modulus from HMA cores used as seed modulus
  - The EVERCALC average crushed stone base and subgrade modulus was 11.8 ksi and 11.2 ksi respectively; with RMSE 3.5% to 0.8%
  - The MODCOMP average crushed stone base and subgrade modulus was 9.5 ksi and 11.4 ksi respectively; with RMSE mostly around 4%

FWD Back Calculation

- **FWD after placing HMA – graphical representation of base and subgrade variation**

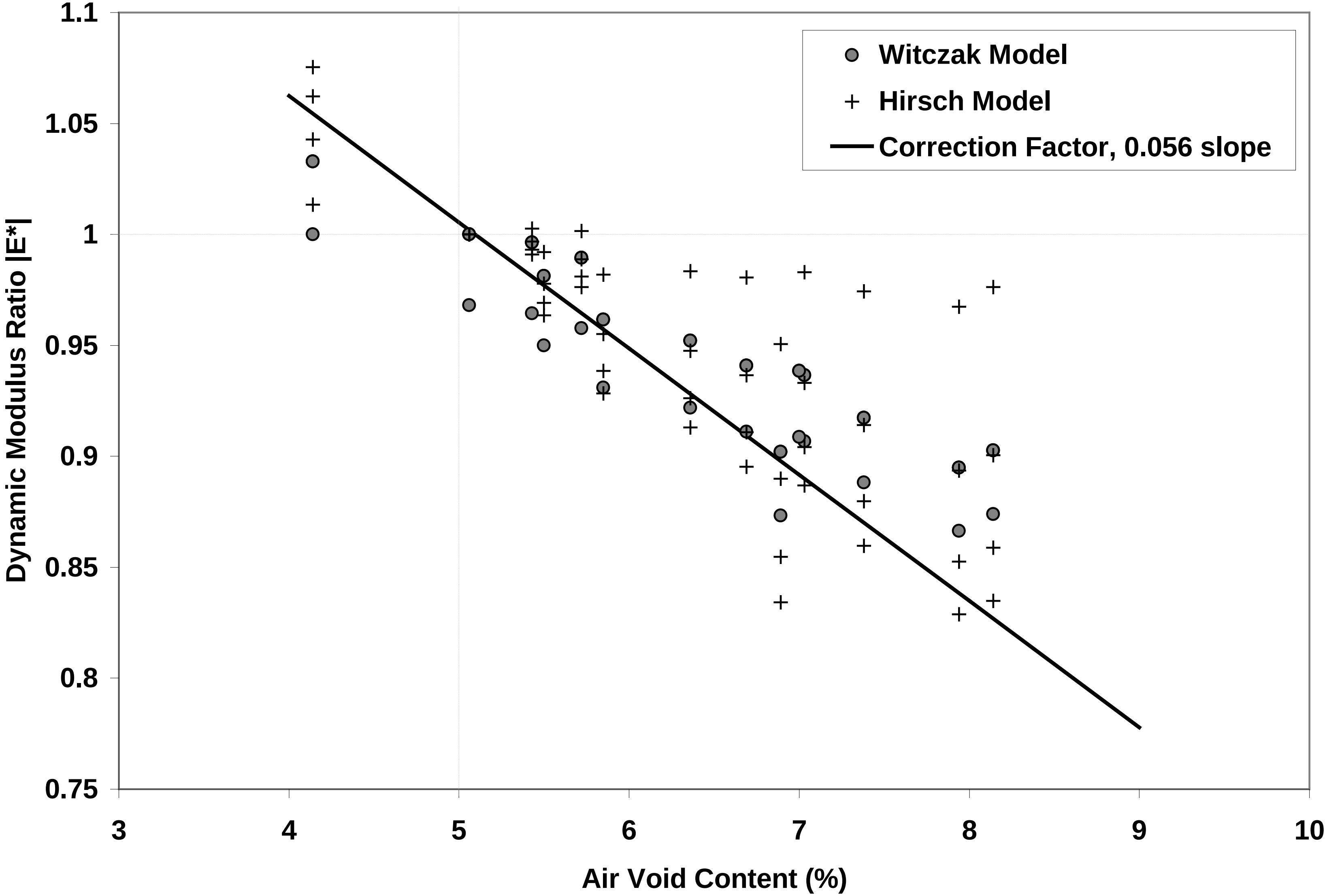




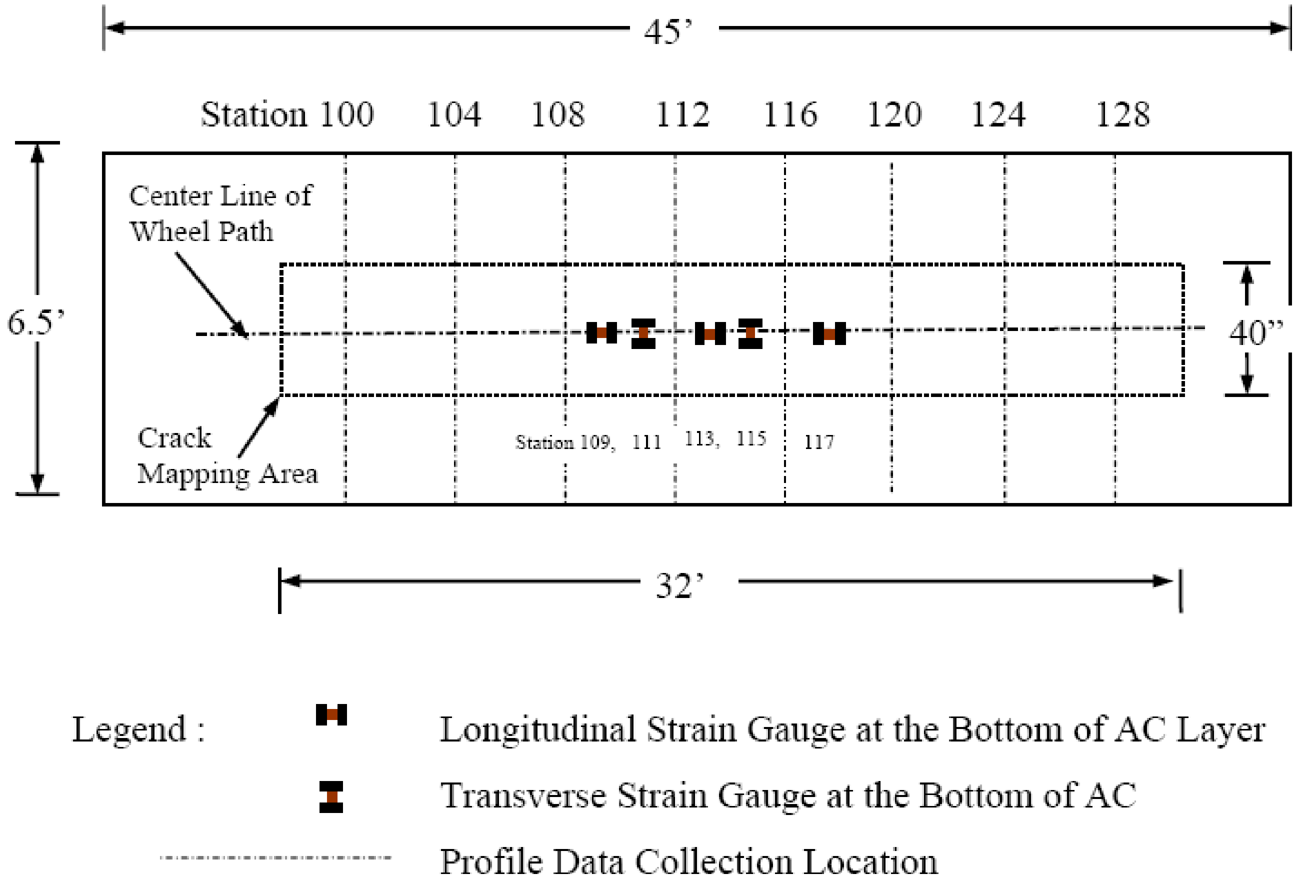
HMA |E*| Dynamic Modulus

- Cores, plant produced mixtures and laboratory produced mixtures were tested
- Where possible (i.e. 150 mm Lanes), field cores were tested for HMA and directly input to the MEPDG
- When cores were not available (i.e. 100 mm lanes), core modulus or plant produced modulus was adjusted based on the air void content of that particular lane

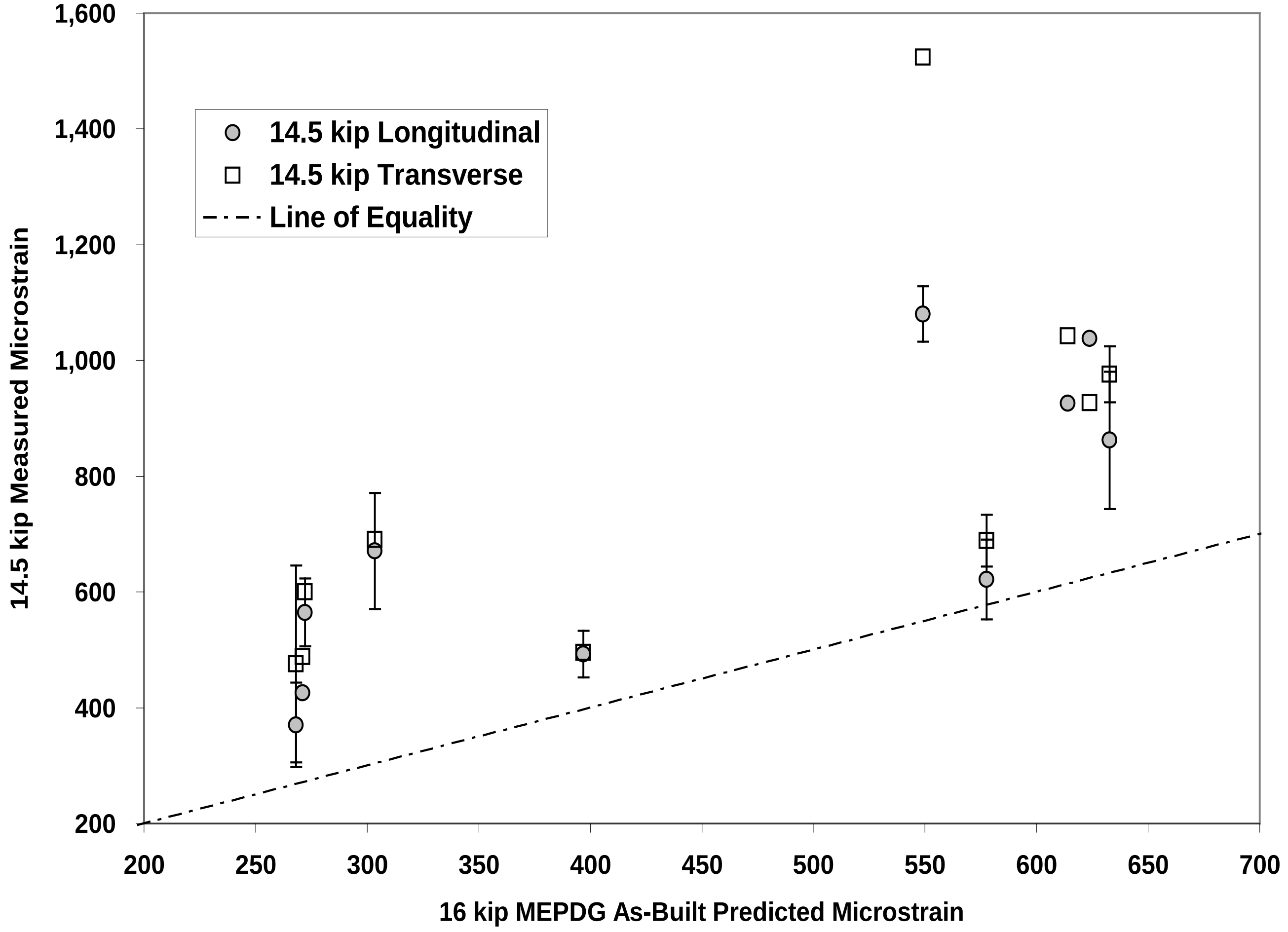
Adjustment of |E*| for Density



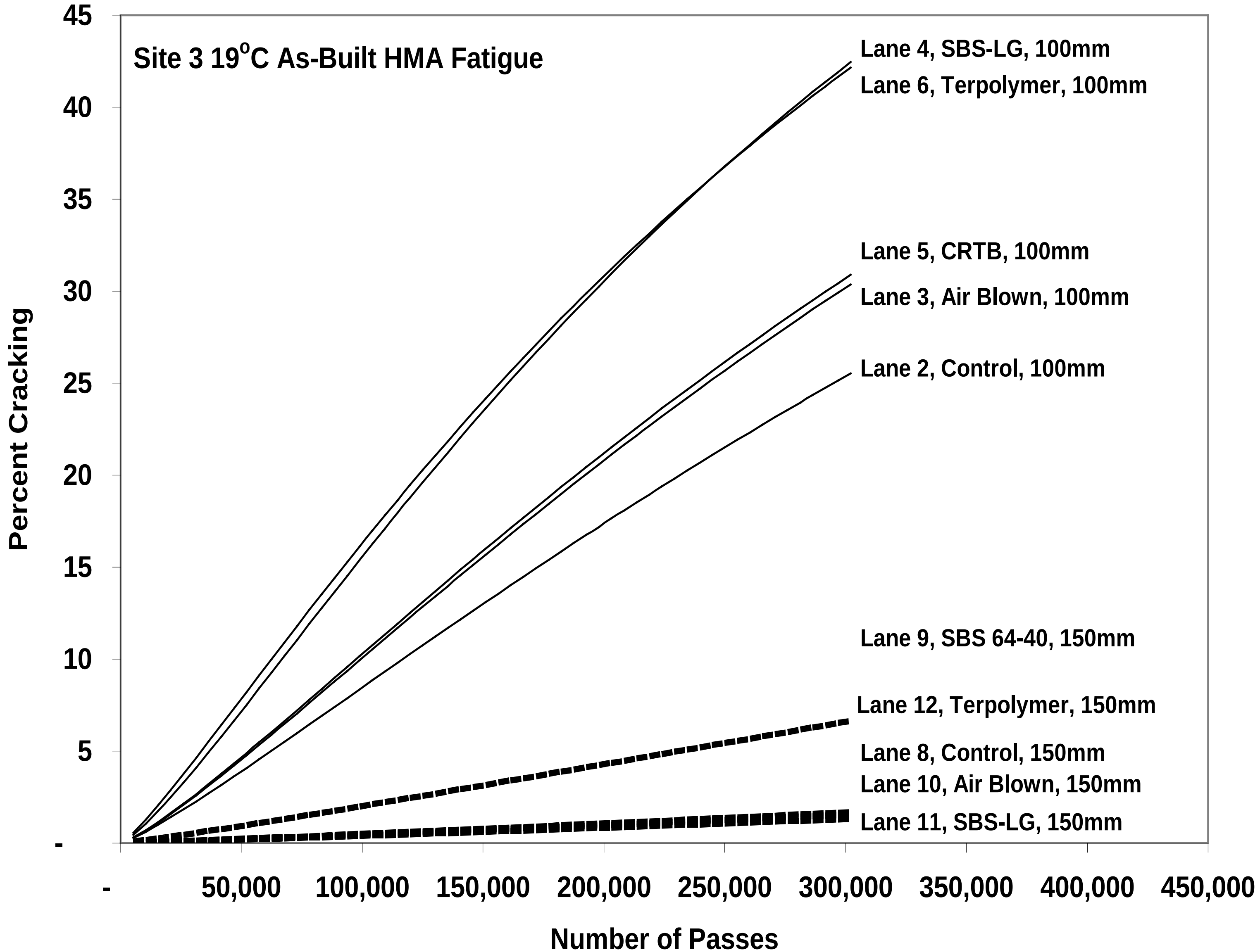
Embedded HMA strain gauges were used to assess the MEPDG elastic moduli input



Strain was under predicted, but a consistent rank order with measured strains was predicted

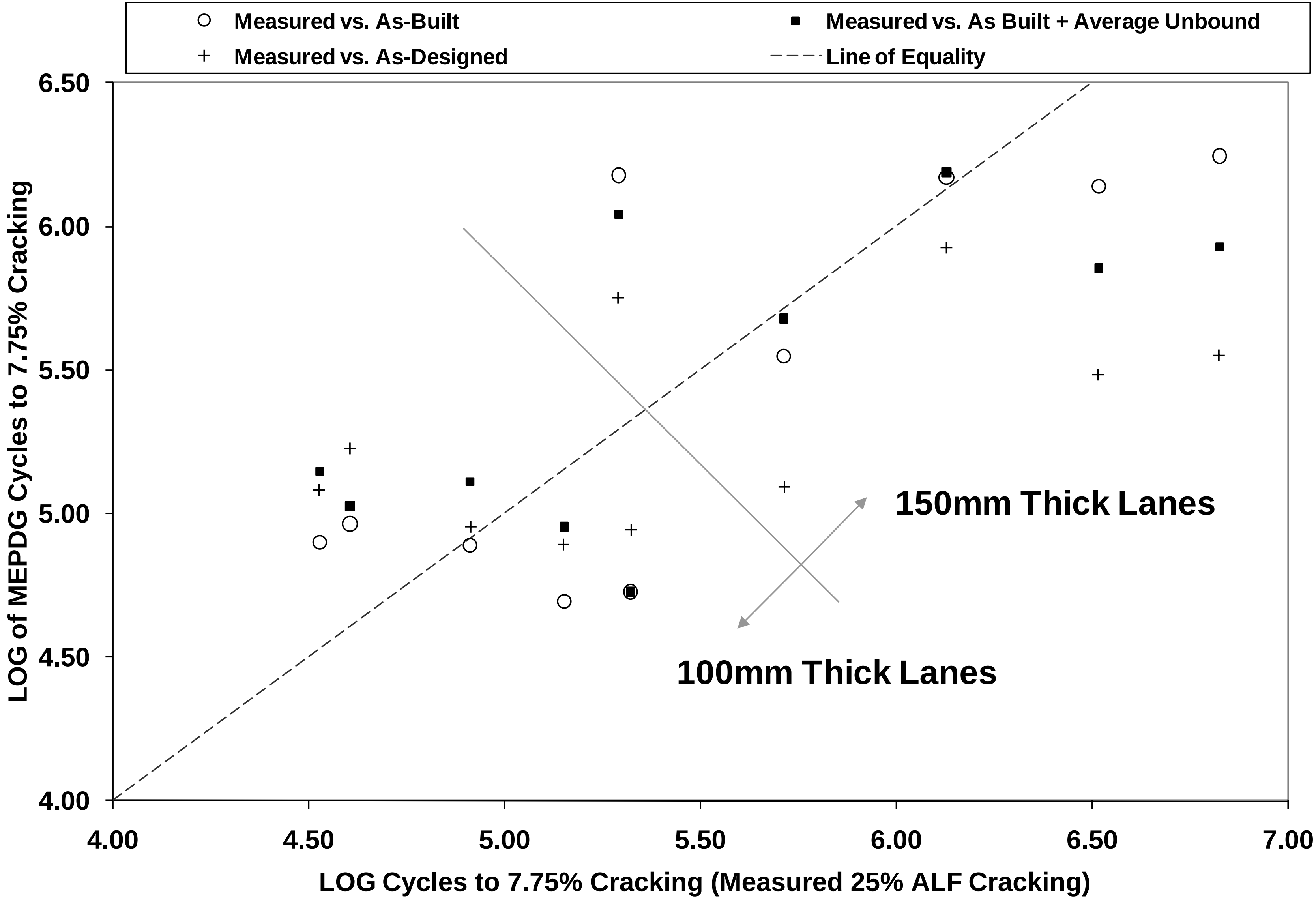


			As-Built		As-Built with Average Unbound Layer Modulus		As-Designed	
			MEPDG Stand-Alone Rut Depth (in.)	Ranking	MEPDG Stand-Alone Rut Depth (in.)	Ranking	MEPDG Stand-Alone Rut Depth (in.)	Ranking
Lane 5	CR-TB	100 mm	1.87	1	1.84	1	2.50	5
Lane 10	Air Blown	150 mm	2.06	2	2.06	2	1.40	1
Lane 3	Air Blown	100 mm	2.60	3	2.70	3	1.67	2
Lane 8	Control	150 mm	3.43	4	3.47	4	2.00	3
Lane 11	SBS-LG	150 mm	3.80	5	3.60	5	3.40	6
Lane 2	Control	100 mm	3.96	6	3.88	6	2.20	4
Lane 4	SBS-LG	100 mm	4.20	7	4.26	7	3.60	7
Lane 12	Terpolymer	150 mm	5.00	8	4.80	8	4.40	8
Lane 9	SBS 64-40	150 mm	5.50	9	5.65	9	6.08	10
Lane 6	Terpolymer	100 mm	5.70	10	5.86	10	4.60	9



Site 3 19°C As-Built HMA Fatigue
Percent Cracking
Number of Passes
45
40
35
30
25
20
15
10
5
-
-
50,000
100,000
150,000
200,000
250,000
300,000
350,000
400,000
450,000
Lane 4, SBS-LG, 100mm
Lane 6, Terpolymer, 100mm
Lane 5, CRTB, 100mm
Lane 3, Air Blown, 100mm
Lane 2, Control, 100mm
Lane 9, SBS 64-40, 150mm
Lane 12, Terpolymer, 150mm
Lane 8, Control, 150mm
Lane 10, Air Blown, 150mm
Lane 11, SBS-LG, 150mm

			As-Built		As-Built with Average Unbound Layer Modulus		As-Designed	
			MEPDG Stand-Alone Cracking (%)	Ranking	MEPDG Stand-Alone Cracking (%)	Ranking	MEPDG Stand-Alone Cracking (%)	Ranking
Lane 11	SBS-LG	150 mm	1.30	1	2.74	3	6.57	3
Lane 10	Air Blown	150 mm	1.53	2	2.11	2	4.20	2
Lane 8	Control	150 mm	1.56	3	1.50	1	2.76	1
Lane 12	Terpolymer	150 mm	1.68	4	3.25	4	7.70	4
Lane 9	SBS 64-40	150 mm	6.64	5	4.90	5	18.60	6
Lane 2	Control	100 mm	25.50	6	22.50	8	14.50	5
Lane 3	Air Blown	100 mm	30.40	7	17.70	6	20.50	7
Lane 5	CR-TB	100 mm	30.90	8	19.30	7	27.20	8
Lane 6	Terpolymer	100 mm	42.20	9	26.30	9	30.40	10
Lane 4	SBS-LG	100 mm	42.50	10	31.50	10	27.60	9


Measured vs. As-Built
Measured vs. As-Designed
Measured vs. As Built + Average Unbound
Line of Equality
6.50
6.00
5.50
5.00
4.50
4.00
LOG of MEPDG Cycles to 7.75% Cracking
4.00
4.50
5.00
5.50
6.00
6.50
7.00
LOG Cycles to 7.75% Cracking (Measured 25% ALF Cracking)
150mm Thick Lanes
100mm Thick Lanes

Assessment of Uniformity

- *With the exception of Lane 6 Terpolymer*, **the mild variation in layer thickness, density and base/subgrade stiffness did not appear to cause any concerns the rank order of the rutting and fatigue cracking should be adjusted**
  - **This is important because the strengths and weakness of different binder parameters will be judged by the rank order**

Assessment of Uniformity

- **The MEPDG, could not capture the fatigue cracking and rutting rank order and magnitude of the polymer modified binders**
  - This is NOT a criticism of the MEPDG
  - ALF included polymer modified binder by design; LTPP for MEPDG calibration could not
  - Using a single global calibration for rutting and cracking distress along with small strain |E*| tests that do not mobilize the mixture to larger strains where polymer modification is better revealed

Q & A

FHWA Accelerated Load Facility Transportation Pooled Fund Studies

TPF-5(019) Full-Scale Accelerated Performance Testing for Superpave and Structural Validation

SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements

1st Closeout Webinar

August 16-17, 2010

11am – 2pm

Day 1:

Approach to Rank Candidate Binder Tests

12 Lanes for Performance Comparison
Binder vs. Full Scale

Seven 100mm Sections

7

Lane 1 Composite CR-AZ/Control -1

= 6

Lane 7 Fibers -1

= 5

Five 150mm Sections

5

All Lanes Rutted

5

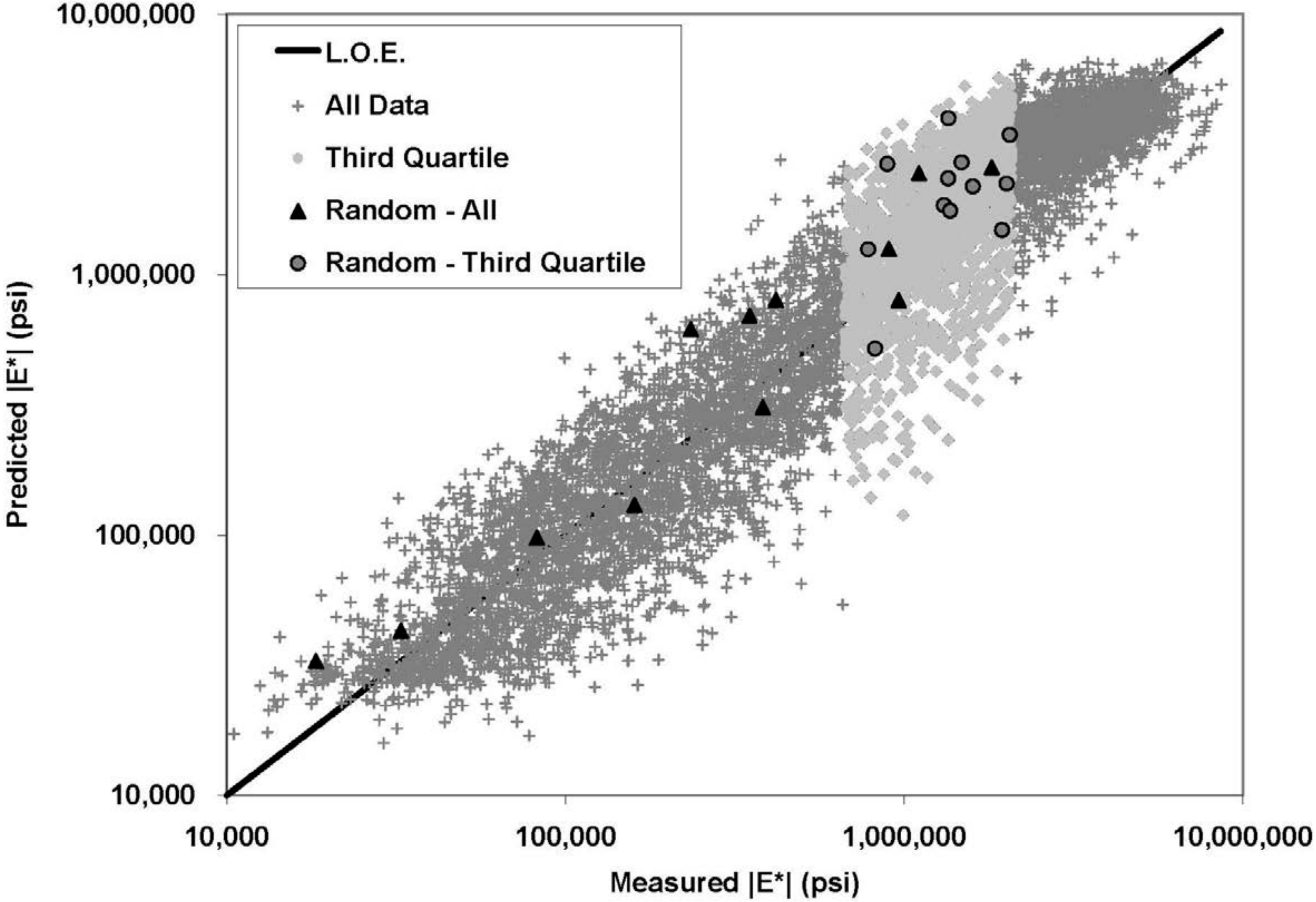
Two Lanes Did Not Crack -2

= 3

Statistical and Numerical Challenges

- The number of data points available is small
- Considering usual scatter encountered in pavement performance scenarios, more robust techniques other than the familiar R^2 were necessary
- This research is essentially trying to detect the presence of an underlying relationship with sparse data points

Consider a Relationship Familiar to Most Pavement Engineers

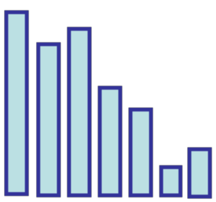


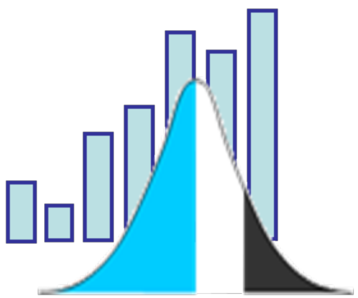
Kendall's Tau

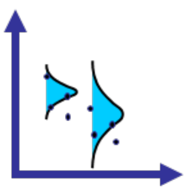
- A measure of association
- Quantifies the quality of two data sets ranked against each other
- Distribution-Free parameter
- Well suited for smaller number of data points
- Allows a statistical significance of the score to be computed as well
- Ranges between -1 to +1
  - +1 Perfect Agreement
  - 0 No relationship between two sets of data
  - -1 Perfect Disagreement

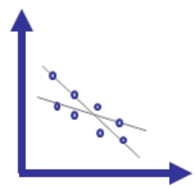
Composite Score

-1→1		0→1		0→1		-1→1
|Kendall's Tau τ|	+	Kendall's Tau Significance	+	Significance of Regression (1-p)	+	|Correlation Coefficient R|









$$CS = \frac{(1-p_{REG})_{ALF} + (1-p_{REG})_{Mix} + \left|\tau_{K,ALF}\right| + \left|\tau_{K,Mix}\right| + (1-p_{\tau-K})_{ALF} + (1-p_{\tau-K})_{Mix} + \left|R_{ALF}\right| + \left|R_{Mix}\right|}{8}$$

Q & A

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Day 2

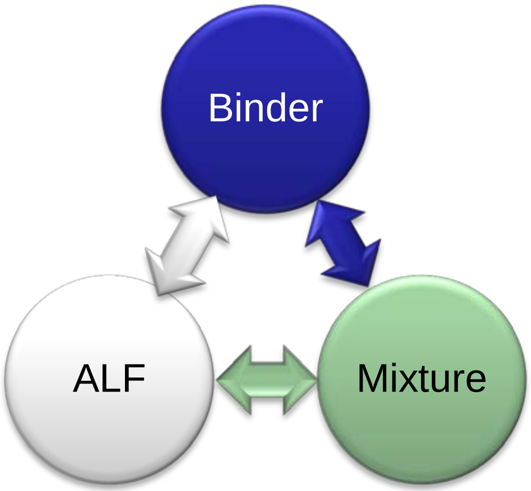
Ranking of Laboratory Mixture Tests

Role of Mixture Tests

- **Mixture performance accompanies comparisons between binder properties and full scale ALF performance.**

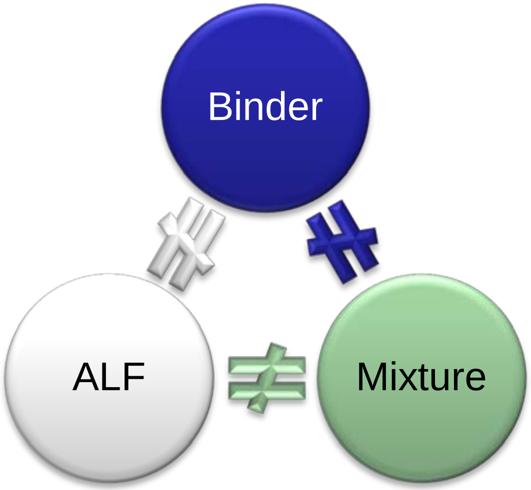
- **Just like ALF - How well do candidate binder parameters reflect performance?**

Role of Mixture Tests



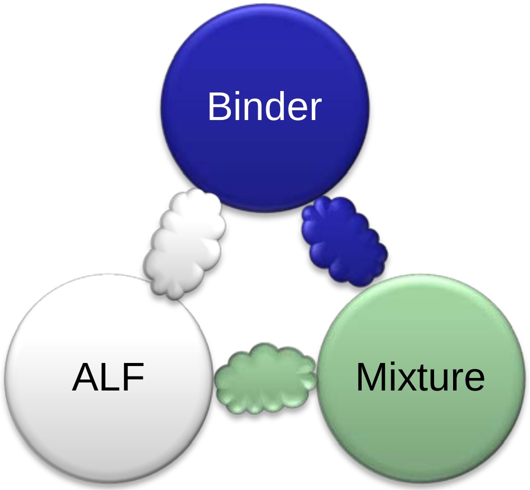
- **Do we have very strong agreement between all three?**

Role of Mixture Tests



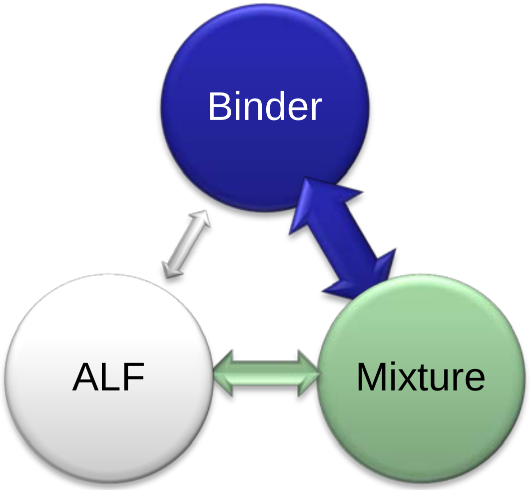
- **Do we have no agreement between all three?**

Role of Mixture Tests



- **Do we have very weak agreement between all three?**

Role of Mixture Tests



- **Do we have mixed levels of agreement between all three? The likely case**

Role of Mixture Tests

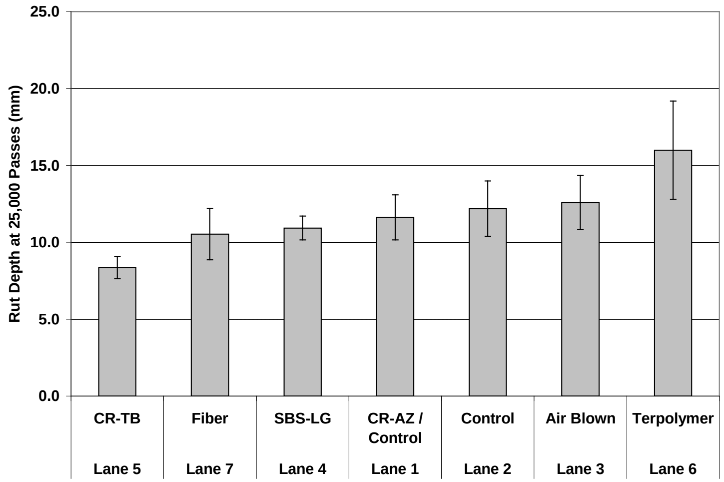
- 'Levels the playing field' by specifically emphasizing the binders' effects in only a laboratory setting (no factors such as layer thickness and base stiffness)

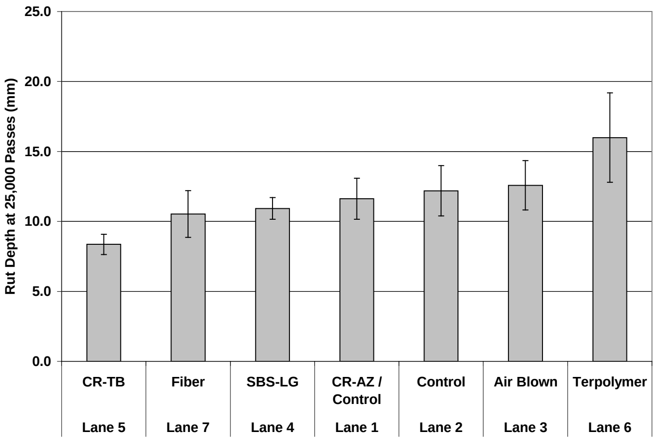
Role of Mixture Tests

- **Lab-produced mixtures assess binder contributions more directly especially when the air void content of the mixtures is a common fixed value.**
- **Cores provide a more direct evaluation of particular tests when compared to the ALF.**

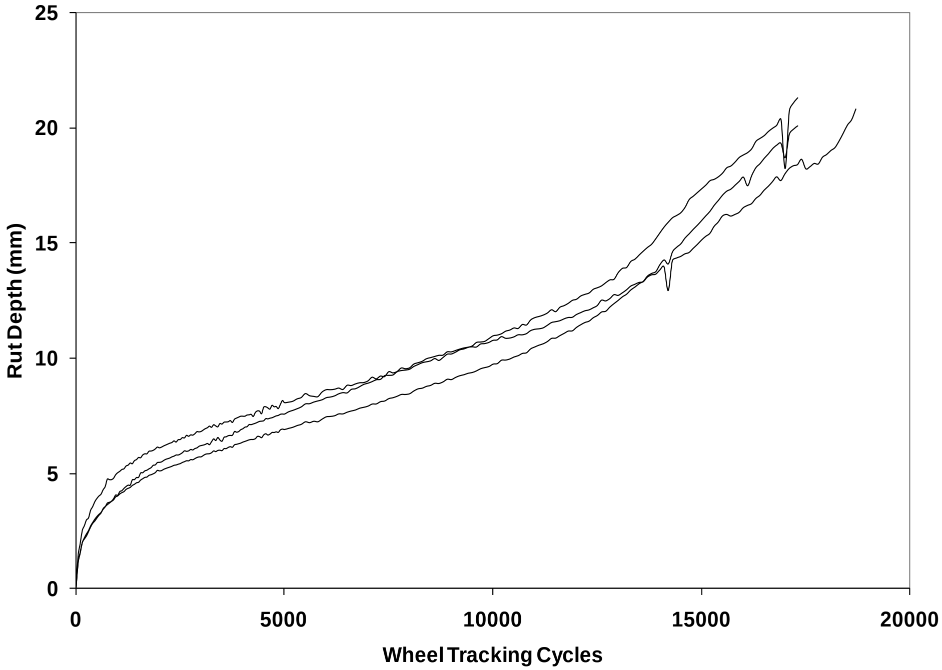
Mixture Tests for Rutting and Permanent Deformation

If a laboratory mixture test correctly reflects ALF rutting, then it will produce curves with small differences in means in which the variability reduces those differences





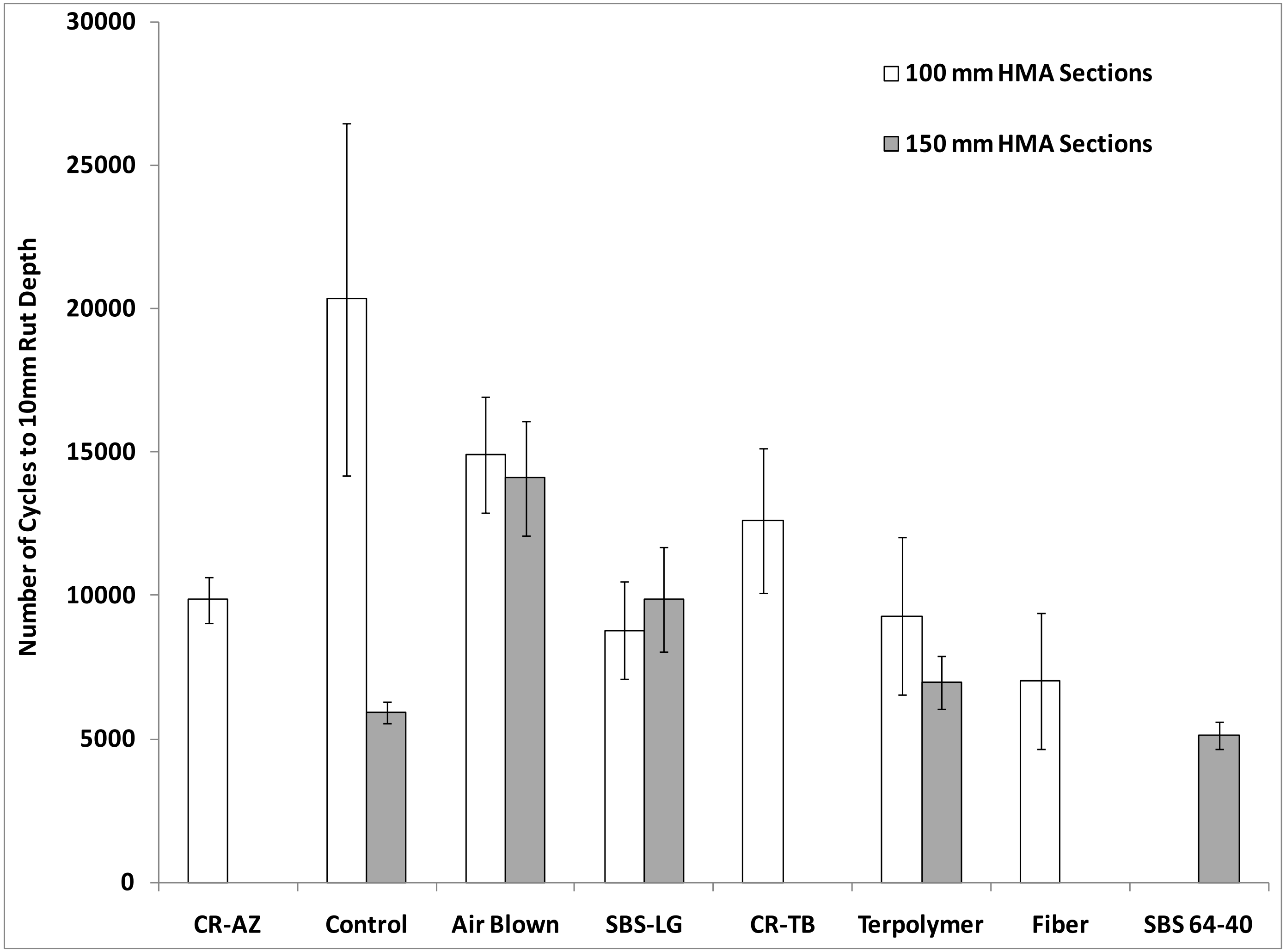
Hamburg Wheel Tracking



64^{o}C, Plant-Produced Lab-Compacted Mixtures

Hamburg Wheel Tracking

Better



Worse

Hamburg Wheel Tracking

- Unmodified binders better
- Mix from both thickness similar except Control binder (reconstructed)

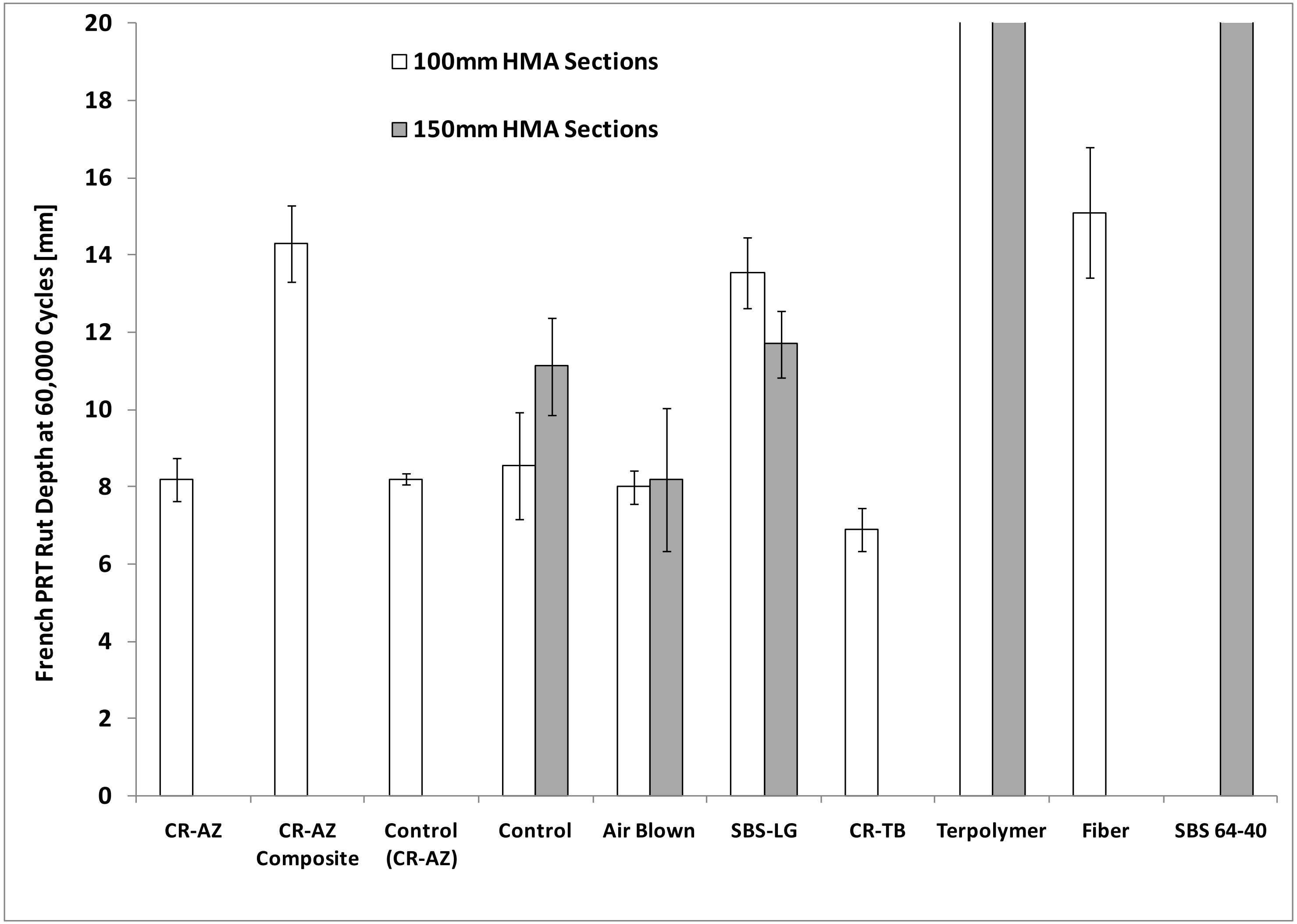
French Pavement Rut Tester

74ºC, Plant-Produced Lab-Compacted Mixtures

French Pavement Rut Tester

Worse

Better



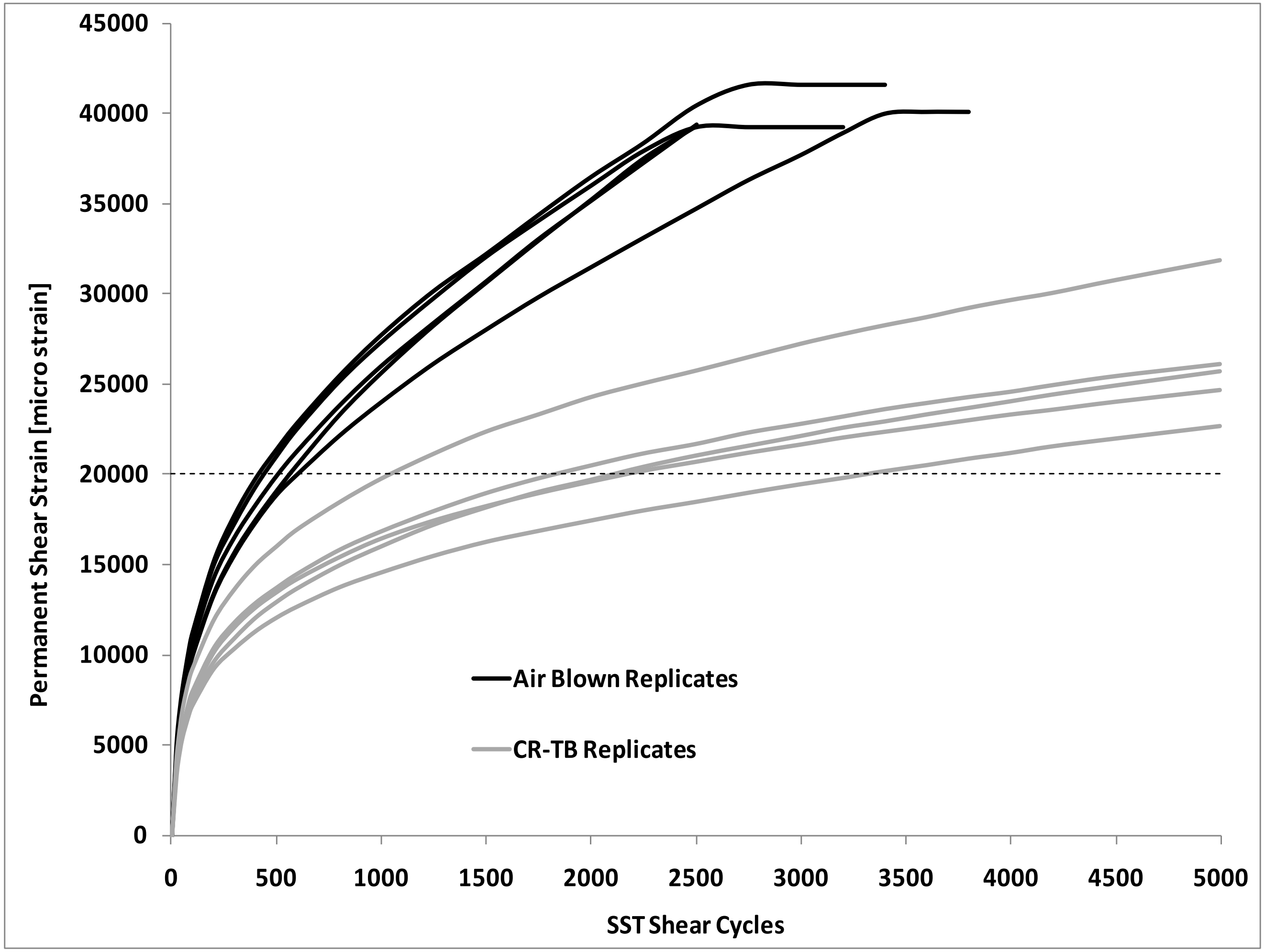
French Pavement Rut Tester

- Soft modified binders performed poorly
- Control mix from two lanes now similar
- Testing composite slab introduced air pockets and performed poorly while materials tested separately did well

Superpave Shear Tester

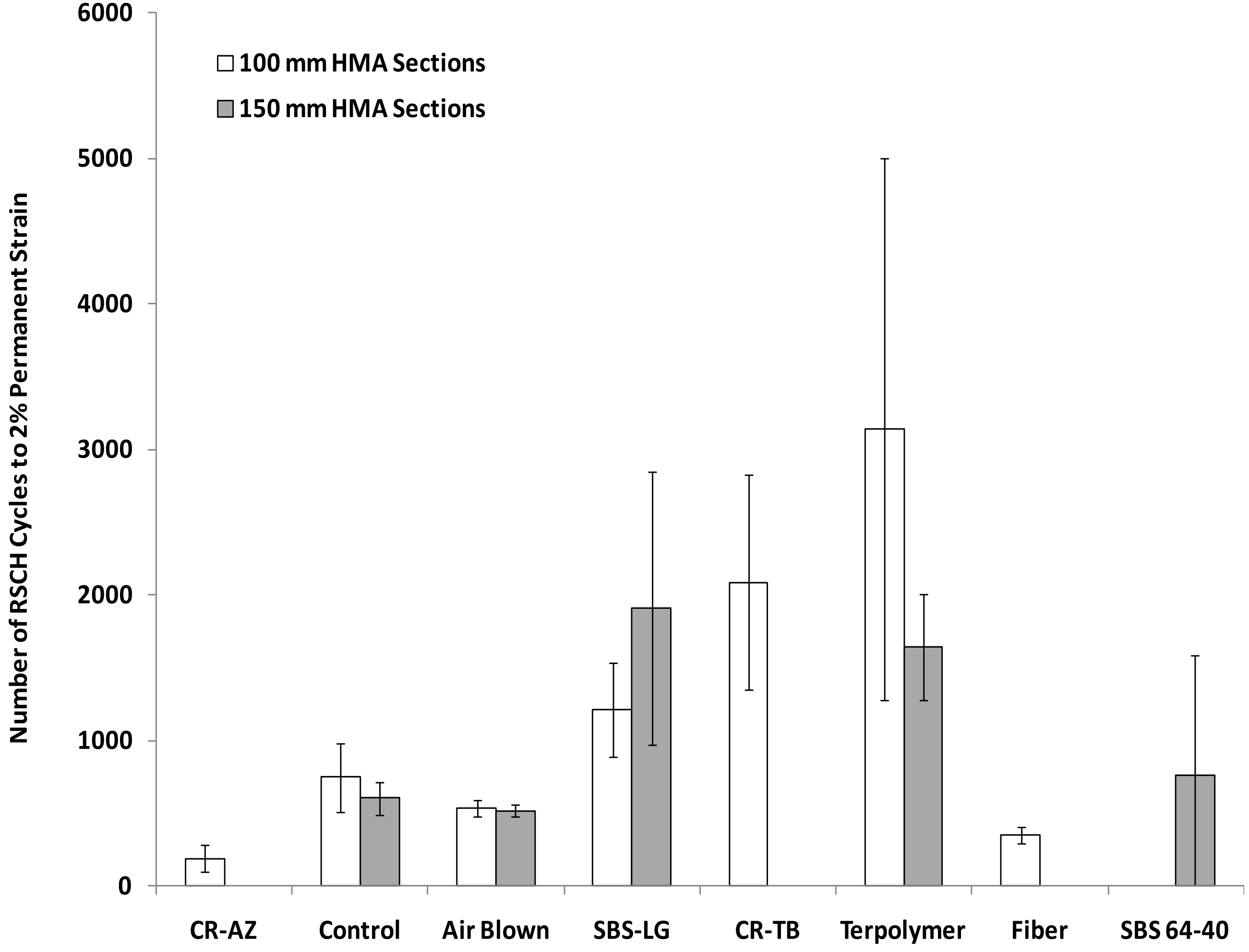
- 74ºC, Plant-Produced Lab-Compacted Mixtures
- 64ºC, Cores from 150mm Lanes (4/5)

Superpave Shear Tester



Superpave Shear Tester

Better



Worse

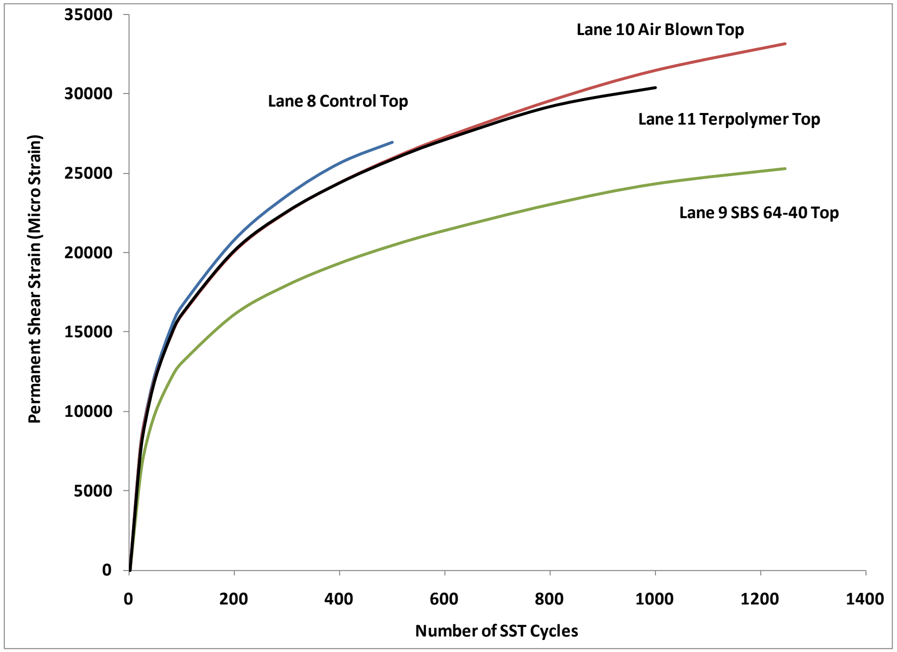
Superpave Shear Tester

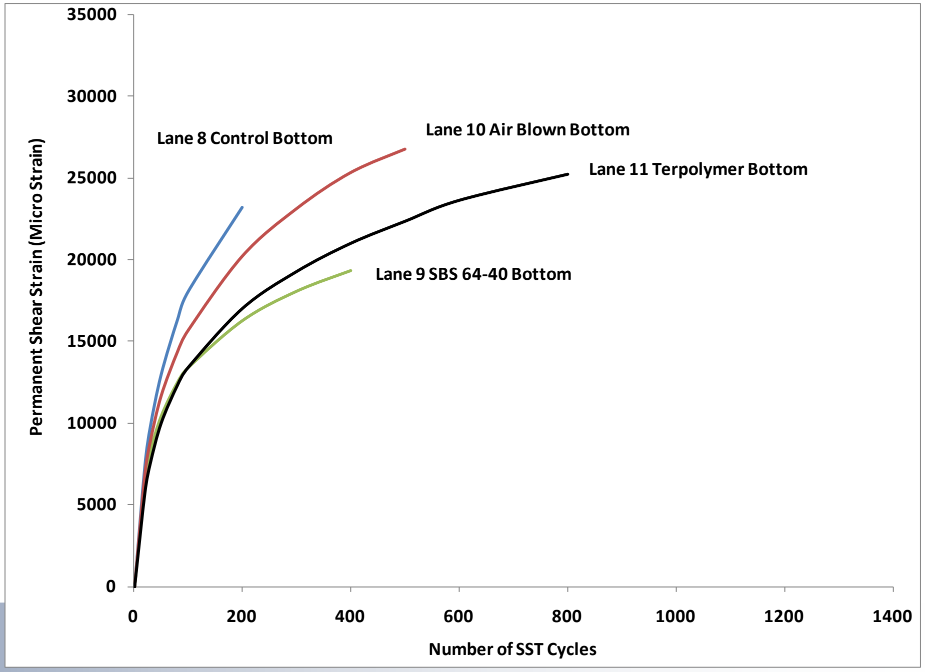
- No tertiary flow observed in Repeated Shear at Constant Height
- Large variability
- Terpolymer mix from two lanes now showing differences
- Modified binders better than unmodified but CR-AZ mix very poor

Superpave Shear Tester

Cores

Top & Bottom Lifts

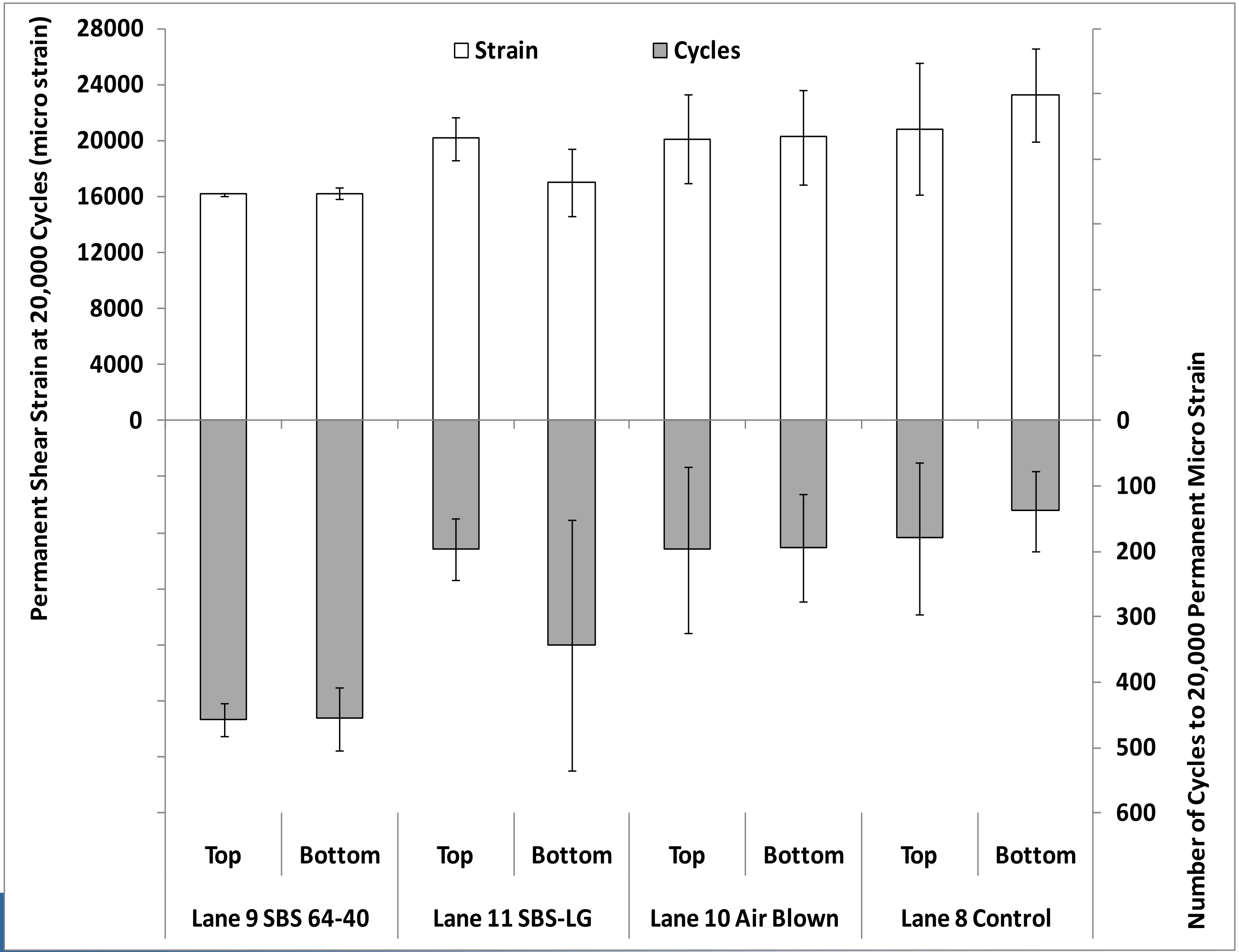




Superpave Shear Tester

Worse

Better



Worse

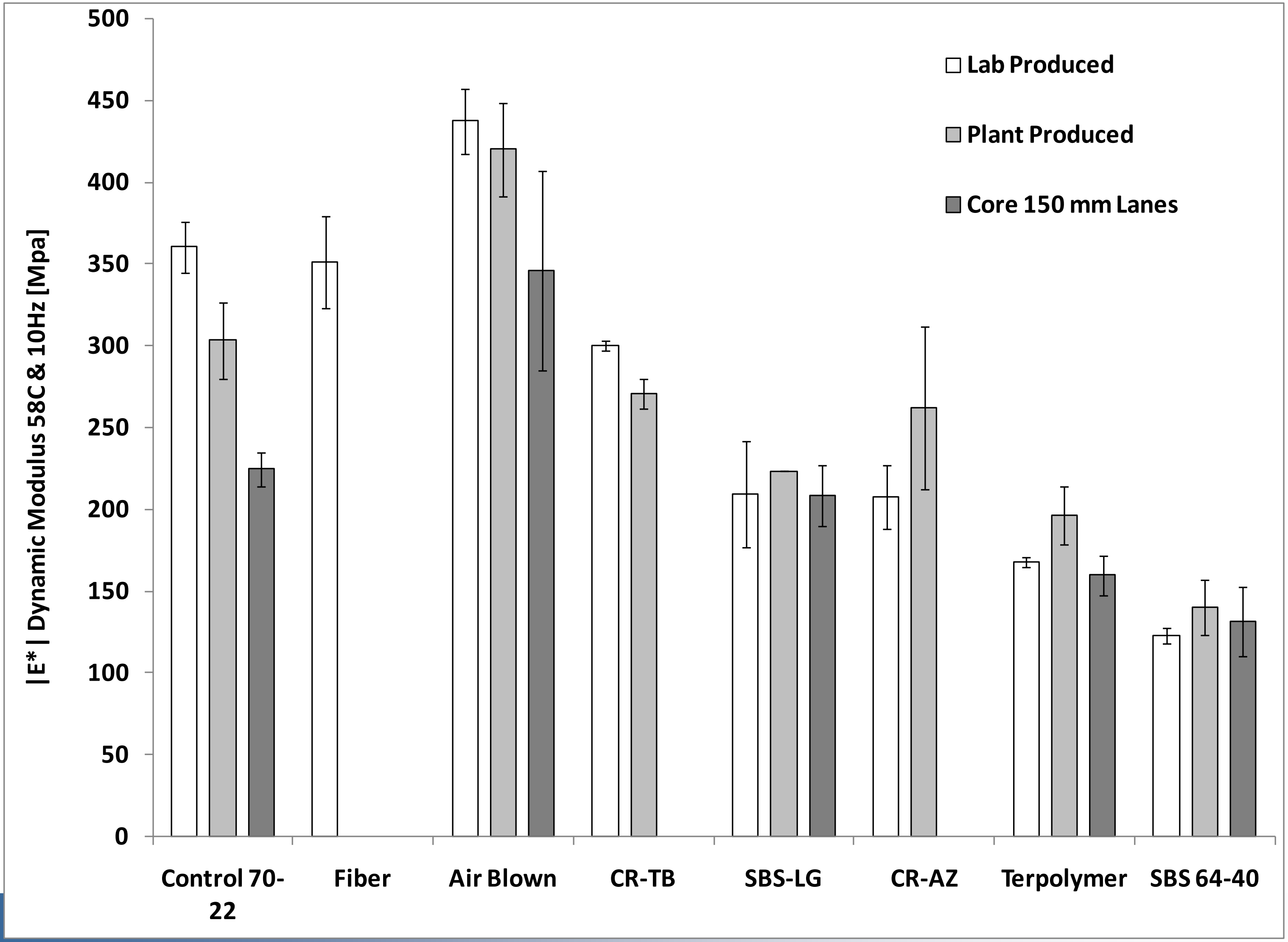
Better

Superpave Shear Tester

- Cooler temperature reduced variability
- Top and bottom lift very similar
- Little effect of binder type, like rutting

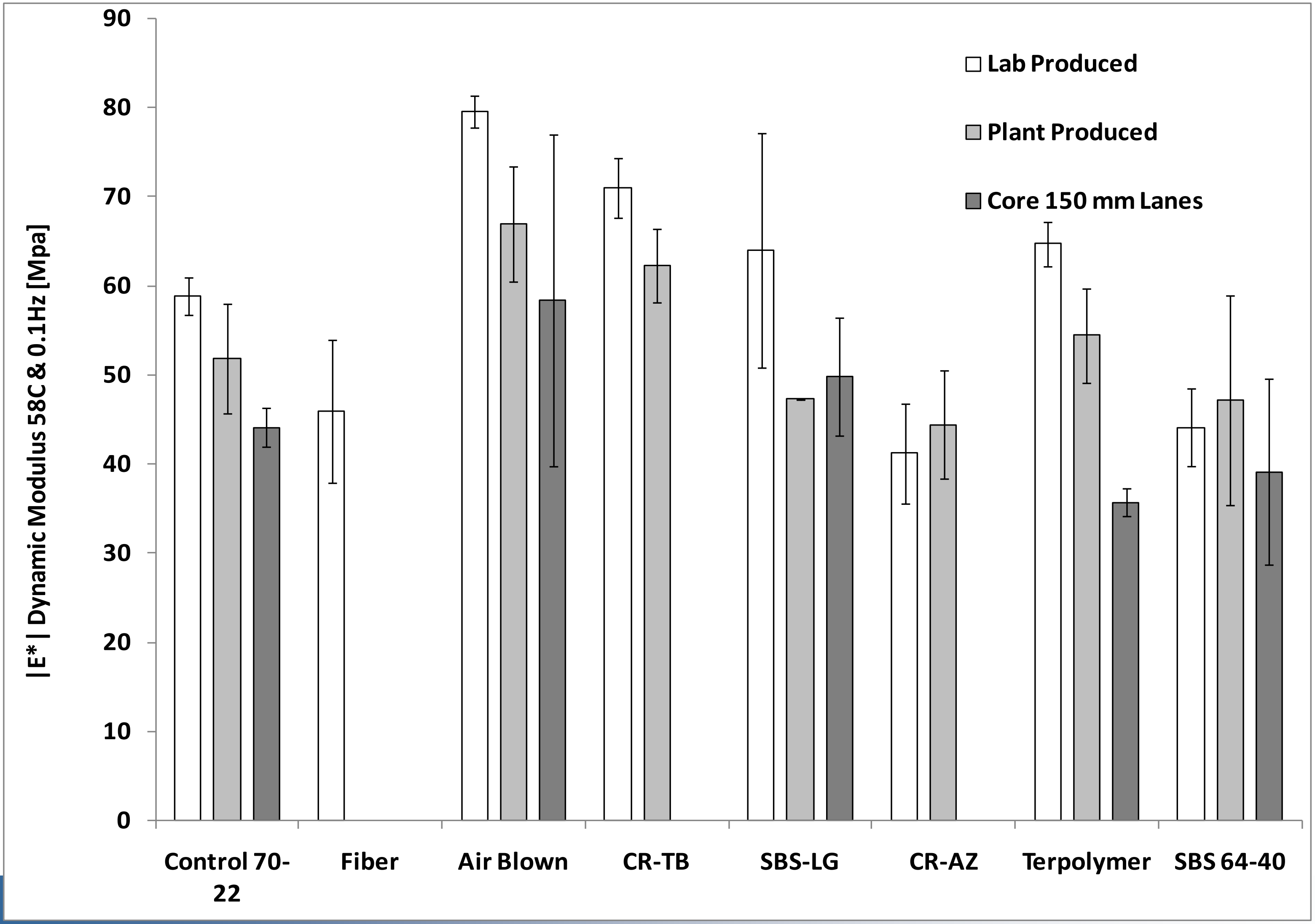
Dynamic Modulus |E*| and Phase Angle δ

|E*|
10Hz



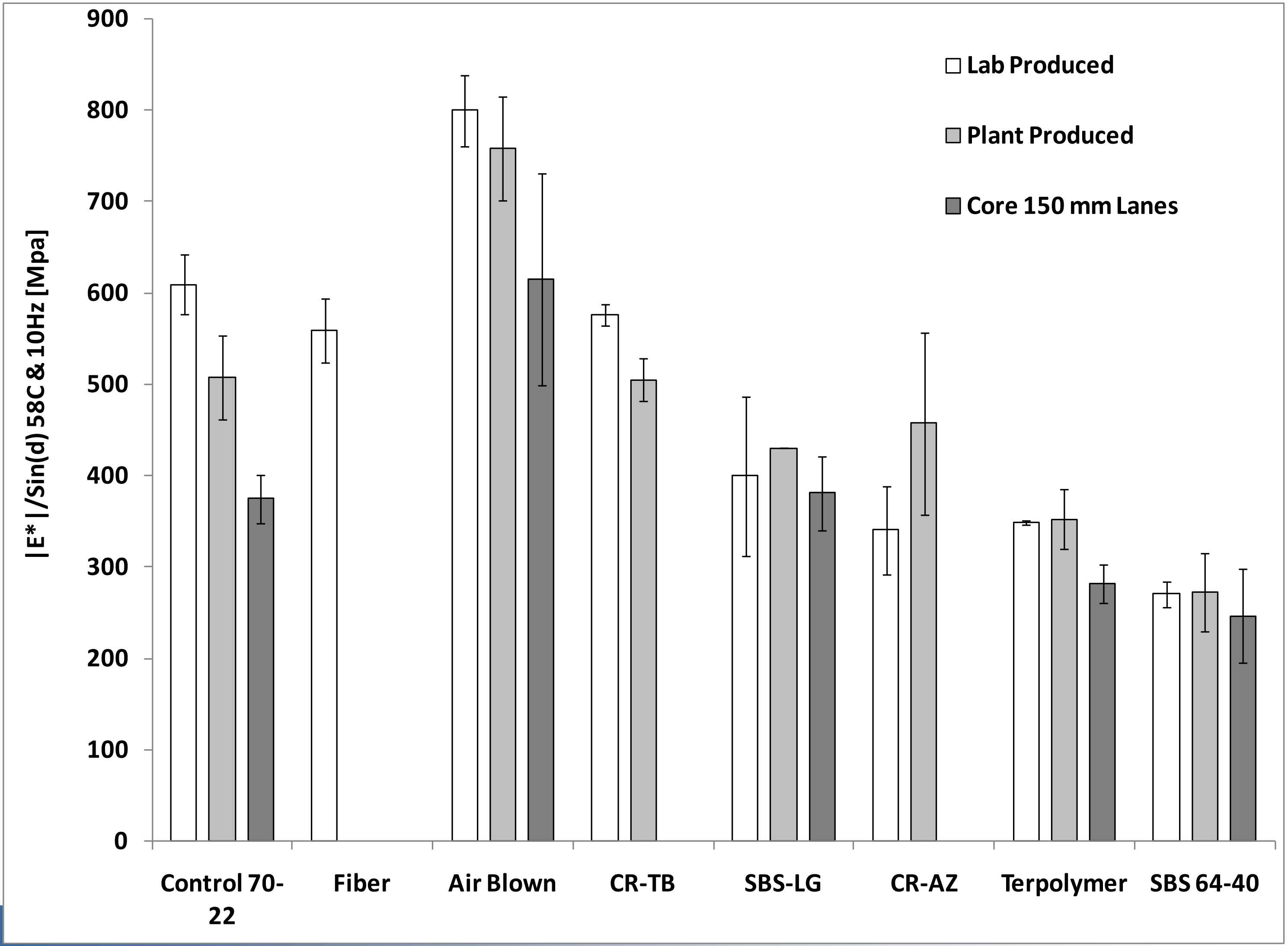
Dynamic Modulus |E*| and Phase Angle δ

|E*|
0.1Hz



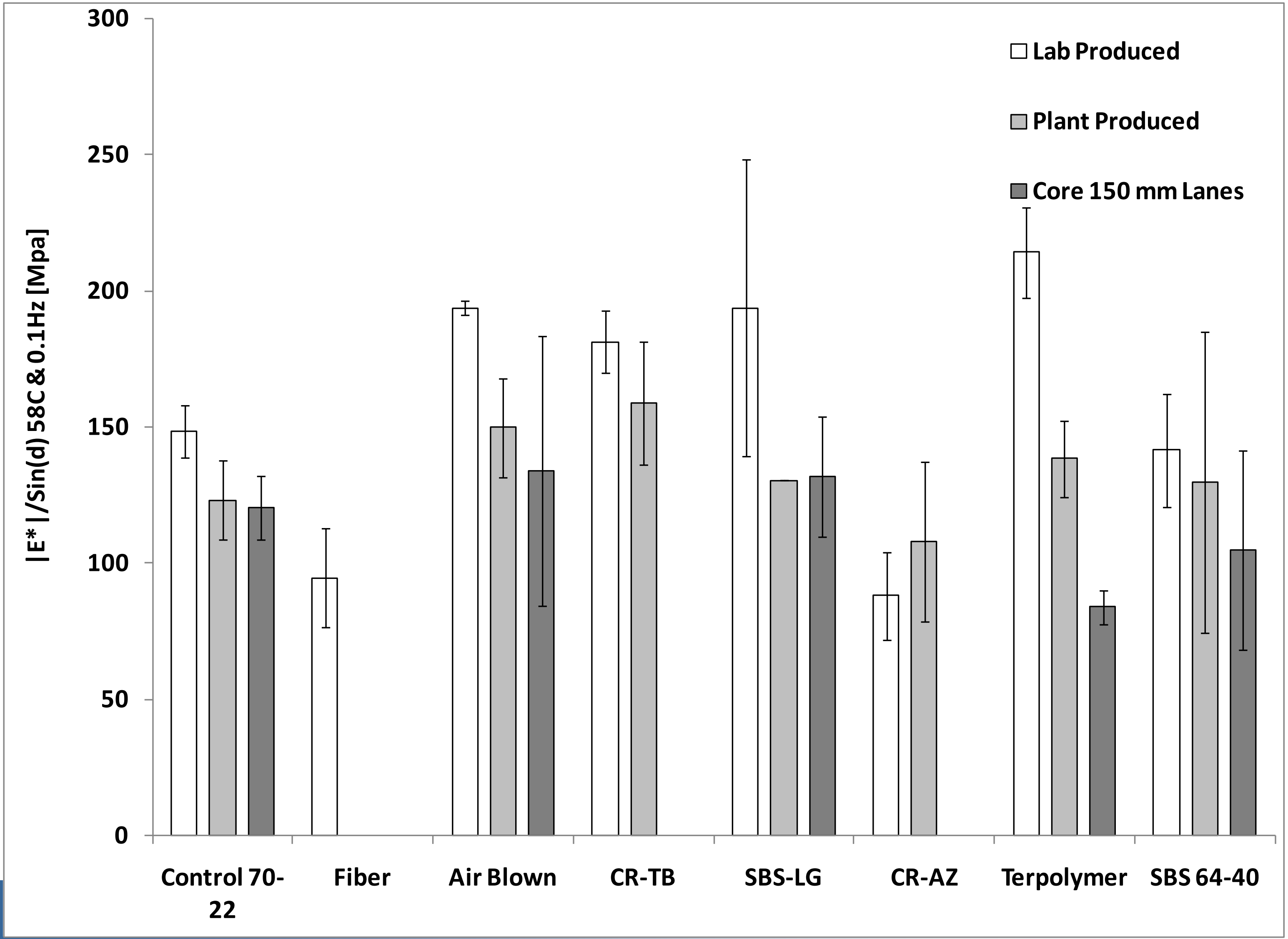
Dynamic Modulus |E*| and Phase Angle δ

|E*|/sinδ 10Hz



Dynamic Modulus |E*| and Phase Angle δ

|E*|/sinδ 0.1Hz



Dynamic Modulus |E*| and Phase Angle δ

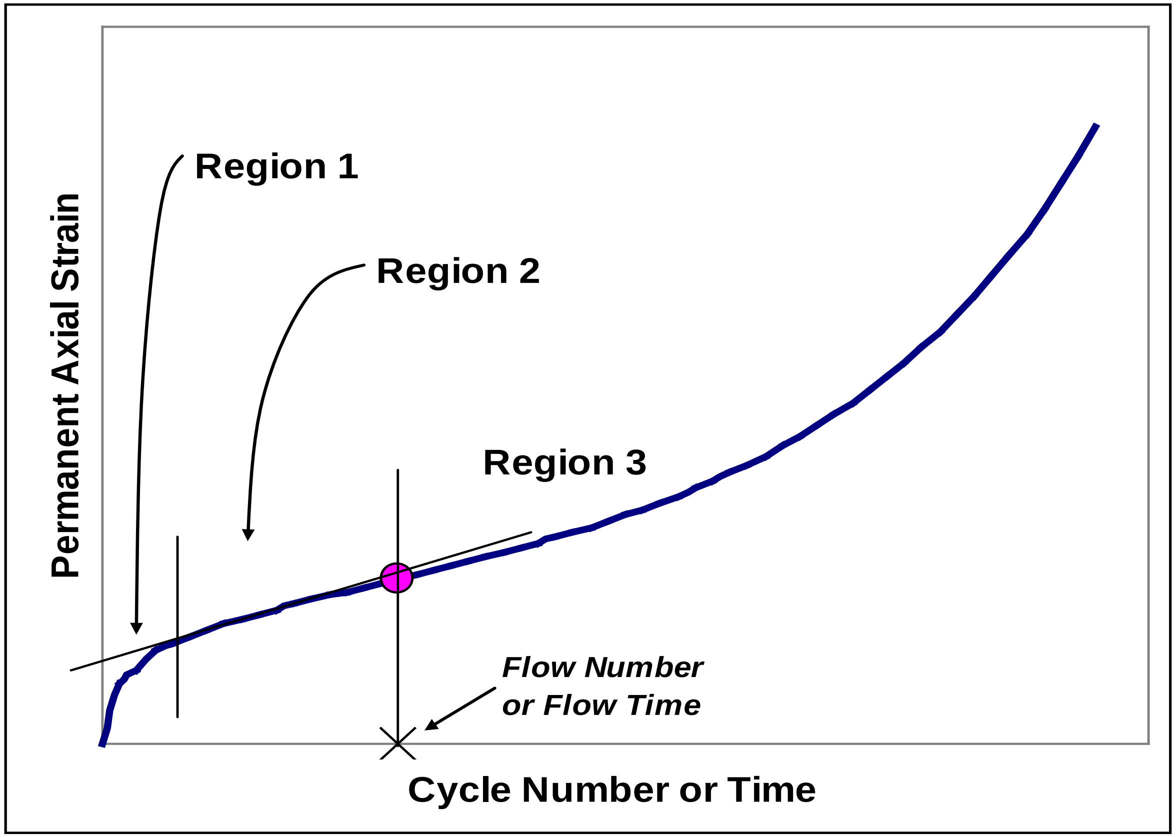
- **Stiffness trends consistent**
  1. **Lab Produced**
  2. **Plant Produced**

     } Less dense, ~7%
  3. **Cores** More dense, ~5%

- **Mixes more similar at lower frequencies**
- **Unmodified binders slightly stiffer**
- **Phase angle term did not change ranking at 10Hz but decreased differences at 0.1 Hz**

Flow Number

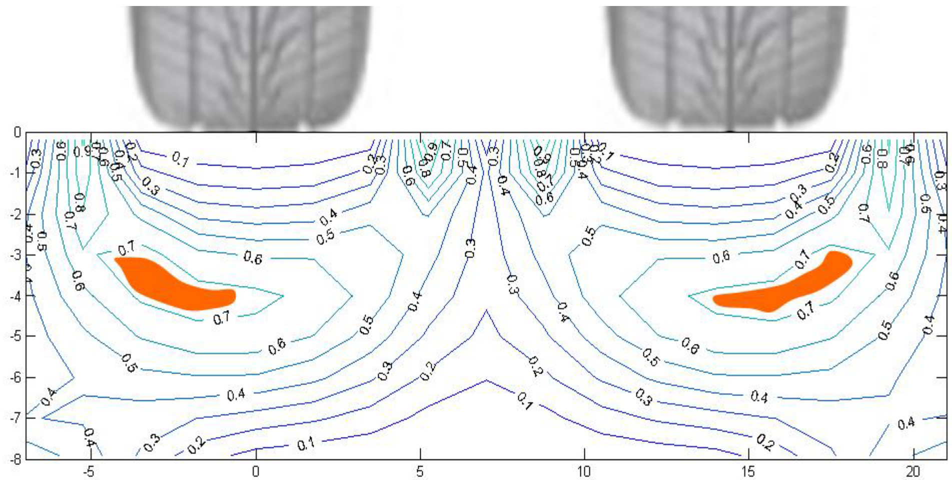
(triaxial repeated load permanent deformation)



64^{o}C, Lab-Produced Lab-Compacted Mixtures

Flow Number

(triaxial repeated load permanent deformation)



$\sigma_{confining}$ ~ 10 psi

$\sigma_{deviator}$ ~ 70 psi

Gibson N., Kutay M. E., Keramat D. and Youtcheff J. "Multiaxial Strain Response of Asphalt Concrete Measure during Flow Number Simple Performance Test," Asphalt Paving Technology, Journal of the Association of Asphalt Paving Technologists, Vol. 78, pp.25-66.

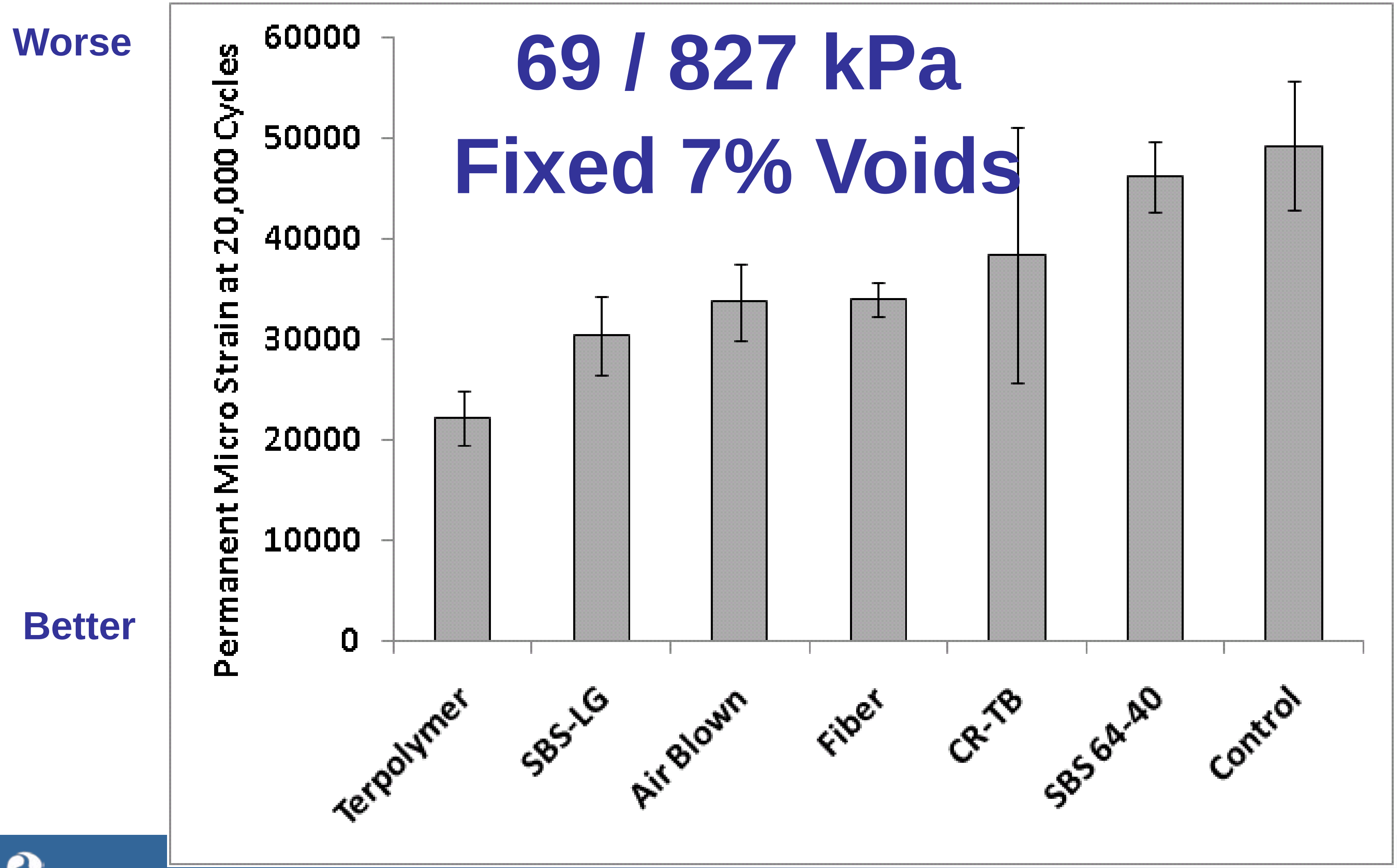
Flow Number

(triaxial repeated load permanent deformation)

Binder Type	Corresponding Test Lane	Air Void Content	Triaxial Stress	
			Confining Pressure	Deviator Stress
Control Control + Fiber Air Blown CR-TB SBS-LG SBS 64-40 Terpolymer	General	7.00%	69 kPa (10 psi)	523 kPa (76 psi)
Control	100mm Lane 2	8.00%	69 kPa (10 psi)	827 kPa (120 psi)
Air Blown	100mm Lane 3	5.75%		
SBS-LG	100mm Lane 4	8.00% & 5.50%		
CR-TB	100mm Lane 5	7.75% & 5.25%		
Terpolymer	100mm Lane 6	7.60%		
Control + Fiber	100mm Lane 7	8.00%		
Control	150mm Lane 8	5.00%	6.9 kPa (1 psi) & 69 kPa (10 psi)	207 kPa (30 psi) & 827 kPa (120 psi)
SBS 64-40	150mm Lane 9	4.14%		
Air Blown	150mm Lane 10	5.50%		
SBS-LG	150mm Lane 11	5.43%		
Terpolymer	150mm Lane 12	5.85%		

Flow Number

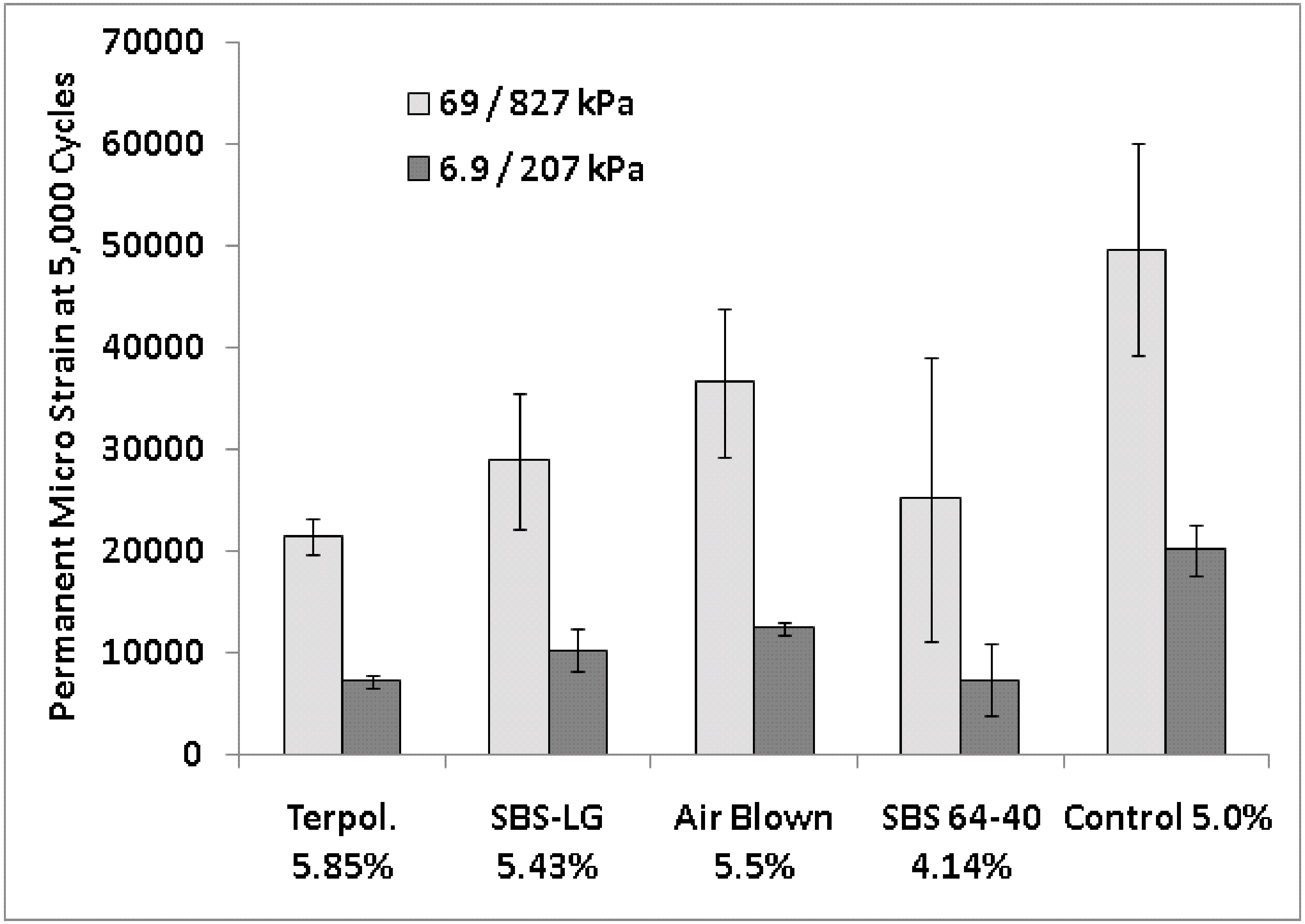
(triaxial repeated load permanent deformation)



Flow Number

(triaxial repeated load permanent deformation)

Worse



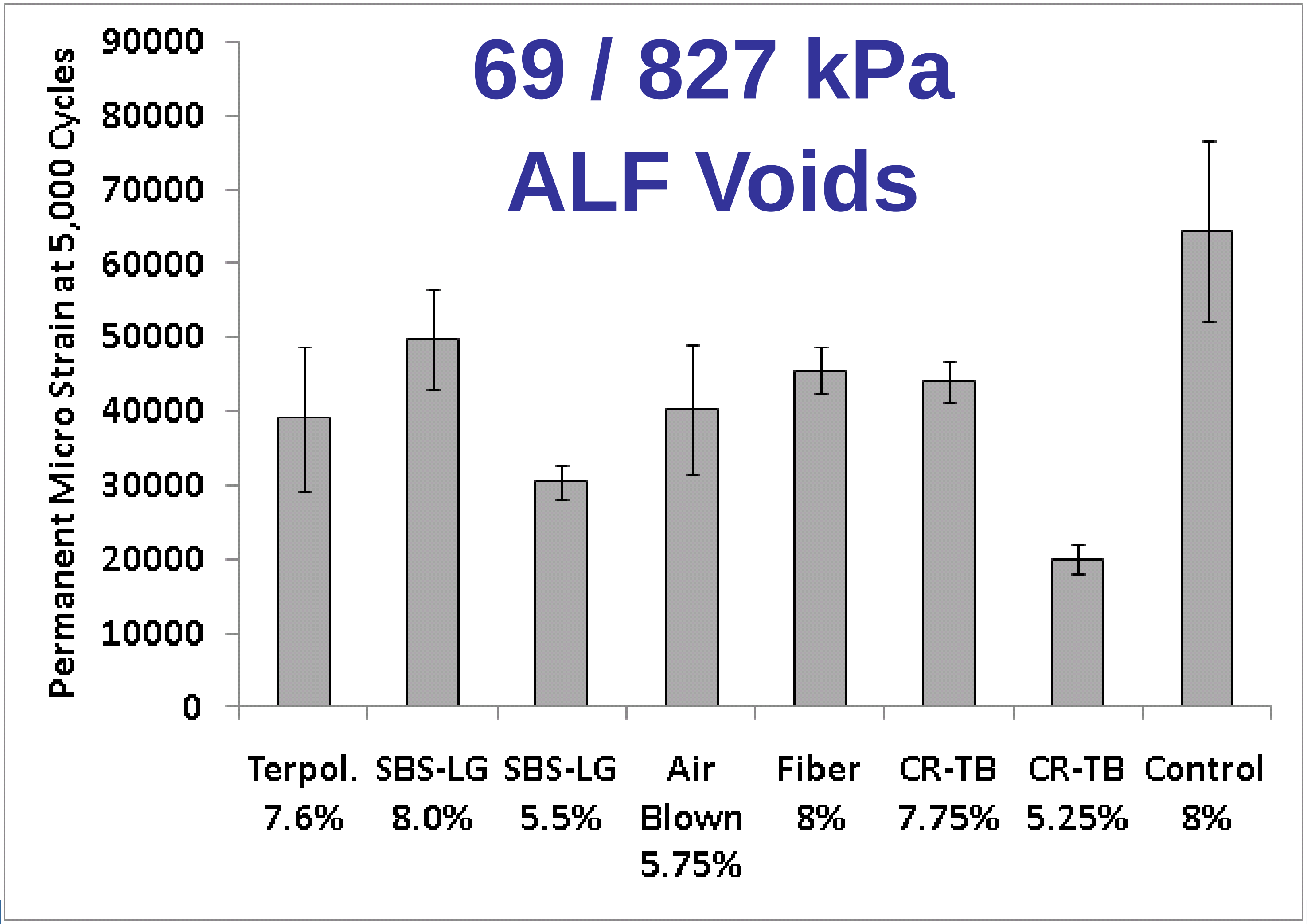
Better

Flow Number

(triaxial repeated load permanent deformation)

Worse

Better



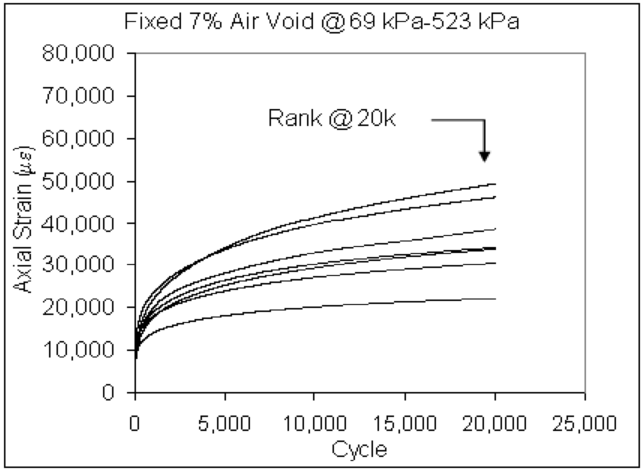
Flow Number

(triaxial repeated load permanent deformation)

- **Less confined tests can rank mixtures the same as confined tests**
- **Soft SBS 64-40 mix sensitive to air void content and stress**
- **Less variability but variability relative to means shows same qualitative trends as full scale rutting**

Predicted Rutting using ε_p from Flow Number

$$\frac{\varepsilon_p}{\varepsilon_r} = k_z 10^{k_1} T^{k_2} N^{k_3} \qquad \left[\frac{\varepsilon_p}{\varepsilon_r}\right]_{LabTest} = \left[\frac{\varepsilon_p}{\varepsilon_r}\right]_{MEPDG}$$



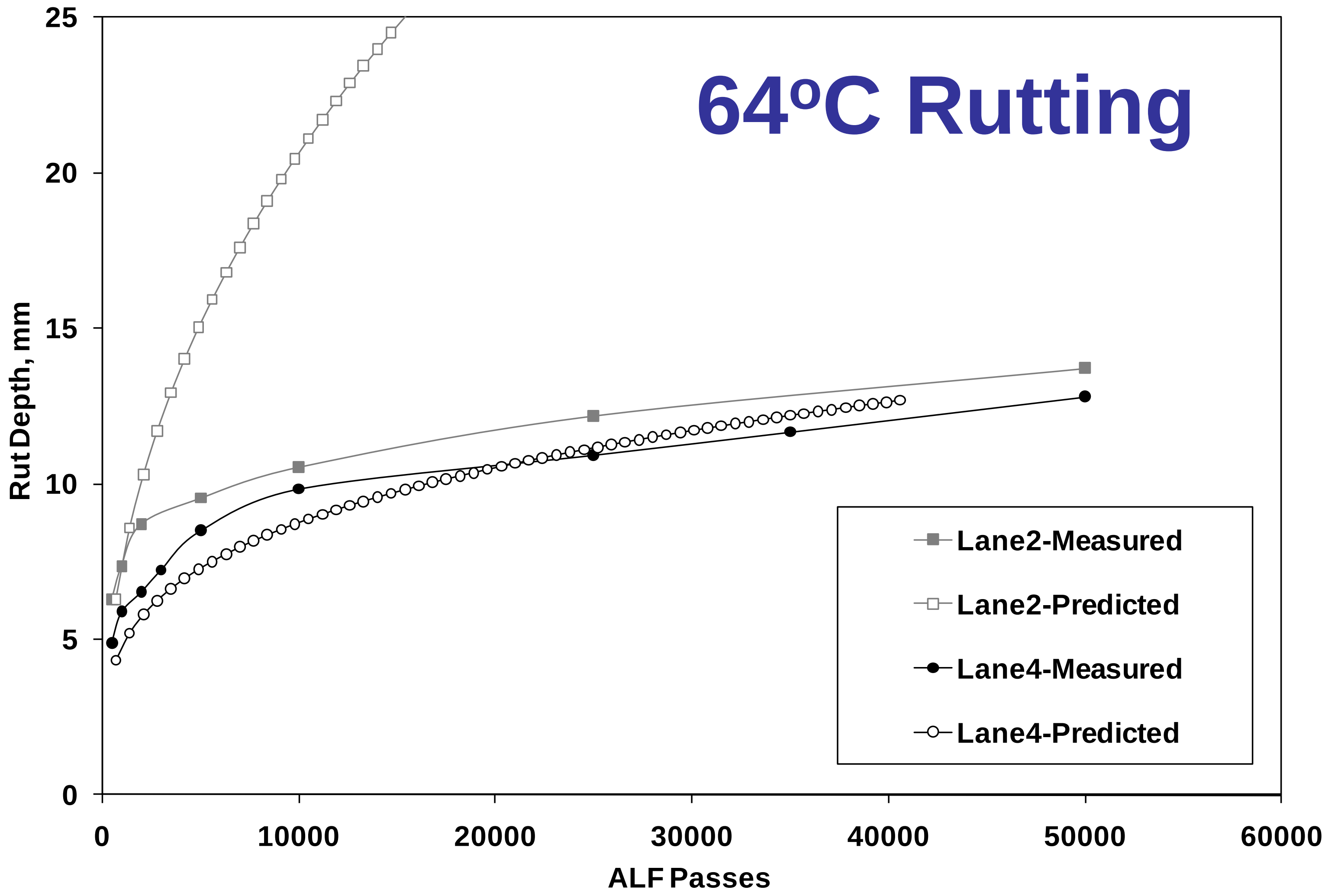
$$\left[\frac{aN^b}{\varepsilon_r}\right]_{LabTest} = k_z 10^{k_1} T^{k_2} N^{k_3}$$

Details of derivation spared here but objective of analysis was to find k_1 and k_3

Predicted Rutting using ε_p from Flow Number

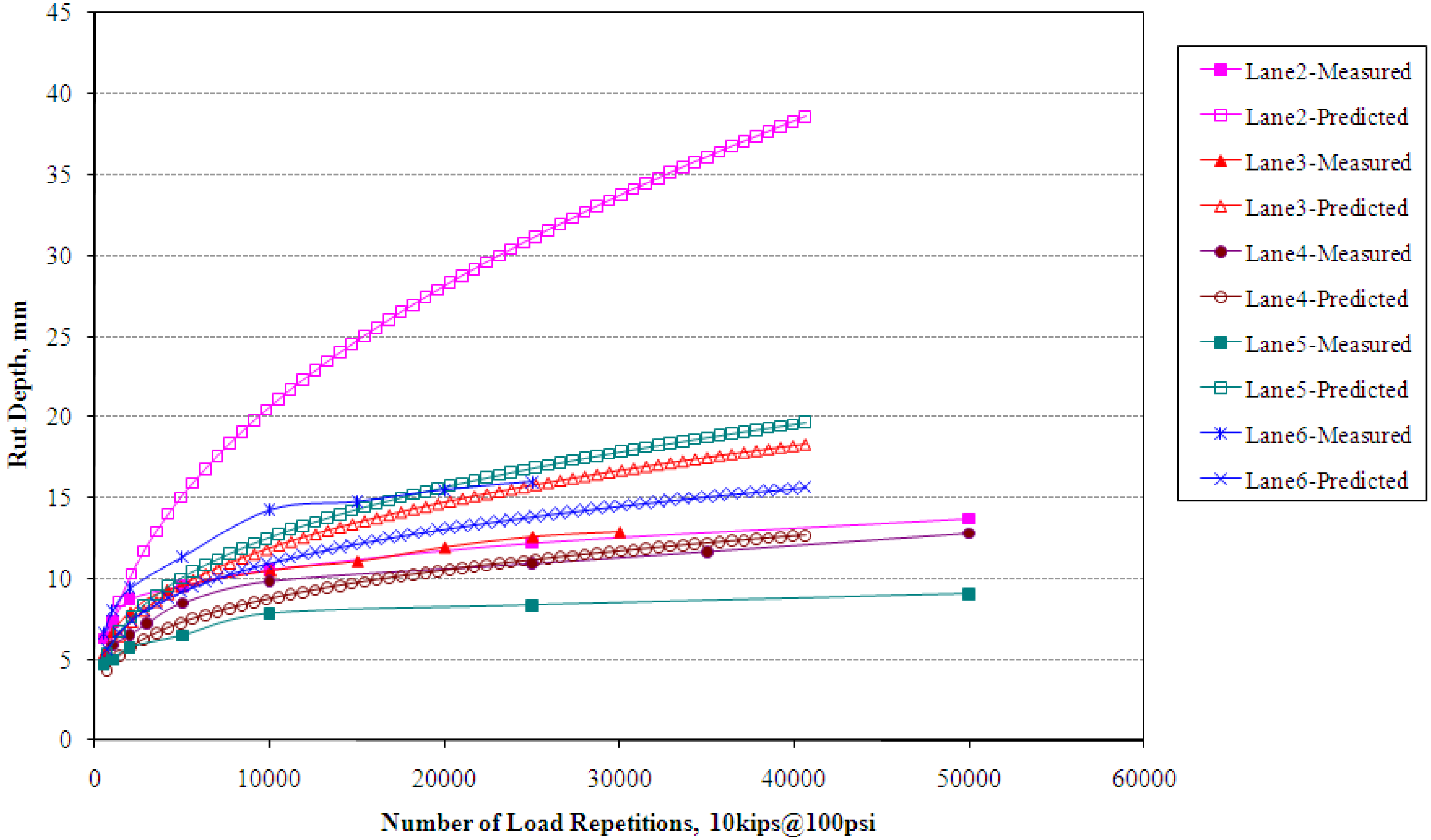
Mix	k_1	k_2	k_3	k_1	k_2	k_3
Lane 2	-3.620	1.5606	0.4465	-	-	-
Lane 3	-3.130	1.5606	0.3093	-	-	-
Lane 4	-3.293	1.5606	0.2651	-	-	-
Lane 5	-3.001	1.5606	0.3196	-	-	-
Lane 6	-3.279	1.5606	0.2530	-	-	-
Lane 8	-3.366	1.5606	0.3580	-3.508	1.5606	0.385
Lane 9	-3.362	1.5606	0.2582	-3.383	1.5606	0.225
Lane 10	-3.140	1.5606	0.3226	-3.4917	1.5606	0.398
Lane 11	-3.148	1.5606	0.2262	-3.247	1.5606	0.219
Lane 12	-3.176	1.5606	0.1853	-3.138	1.5606	0.145
MEPDG Global Calibration Values: k_1 = -3.354 , k_2 = 1.506, k_3 = 0.479						

Predicted Rutting using ε_p from Flow Number

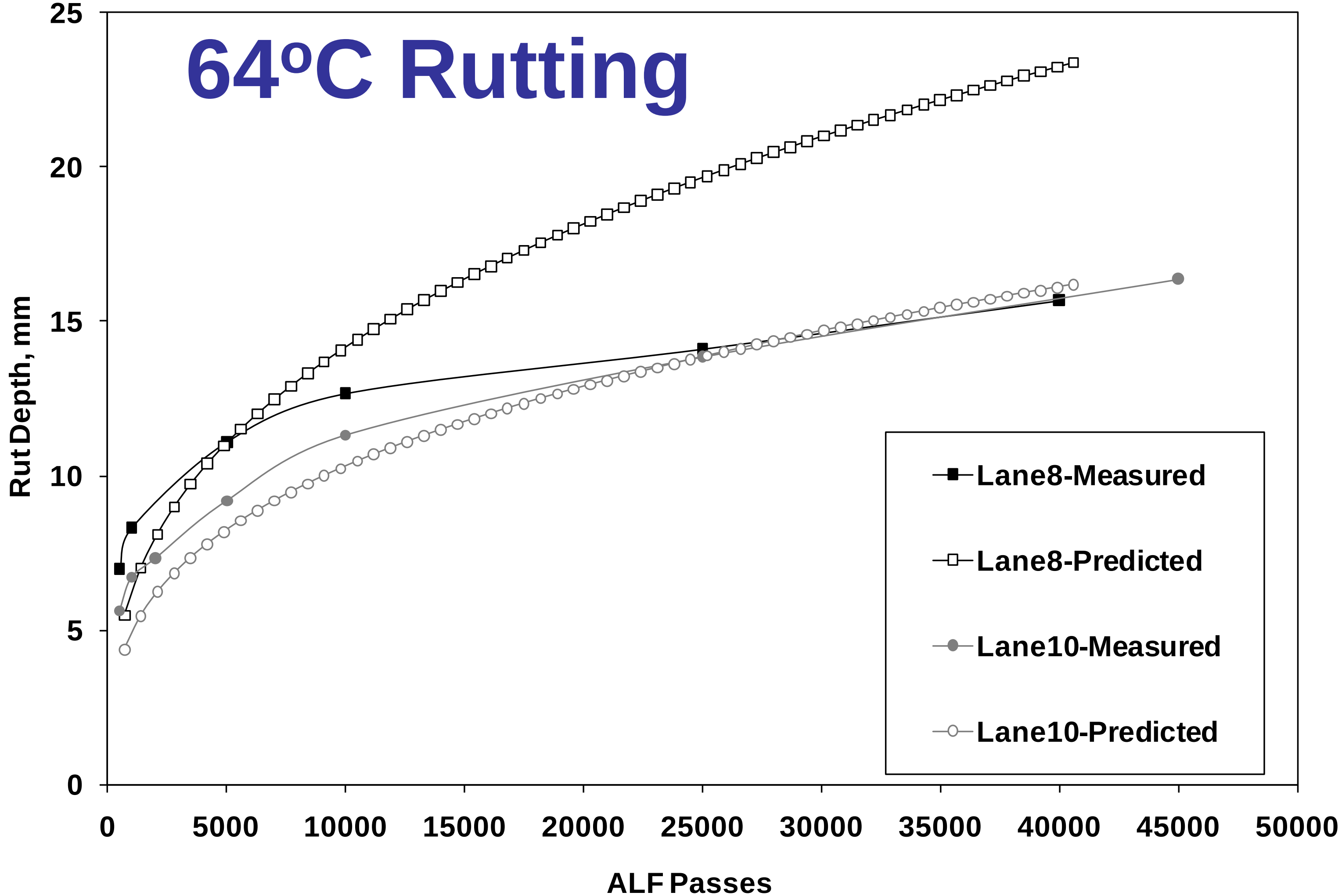


Predicted Rutting using ε_p from Flow Number

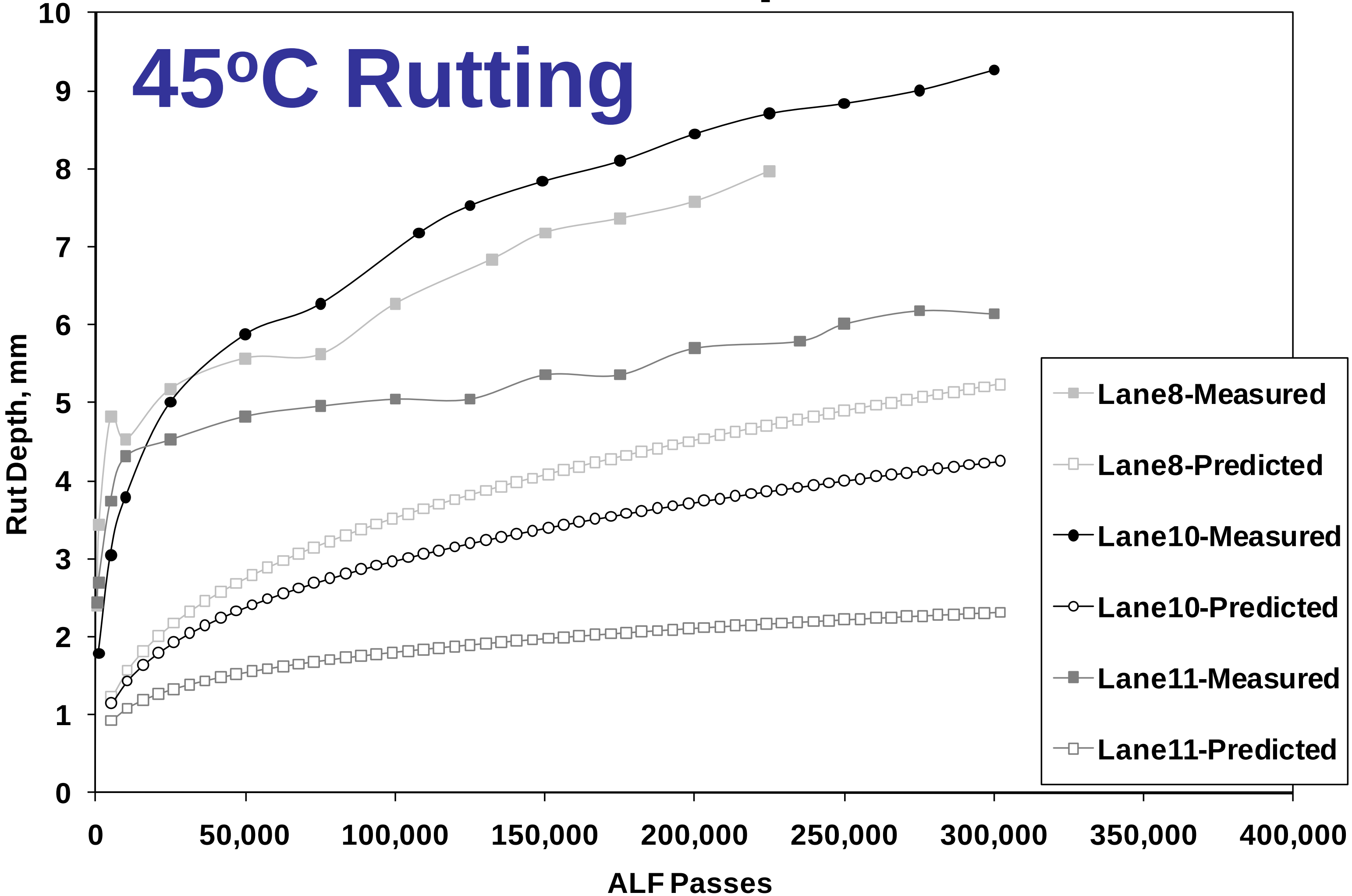
64ºC Rutting



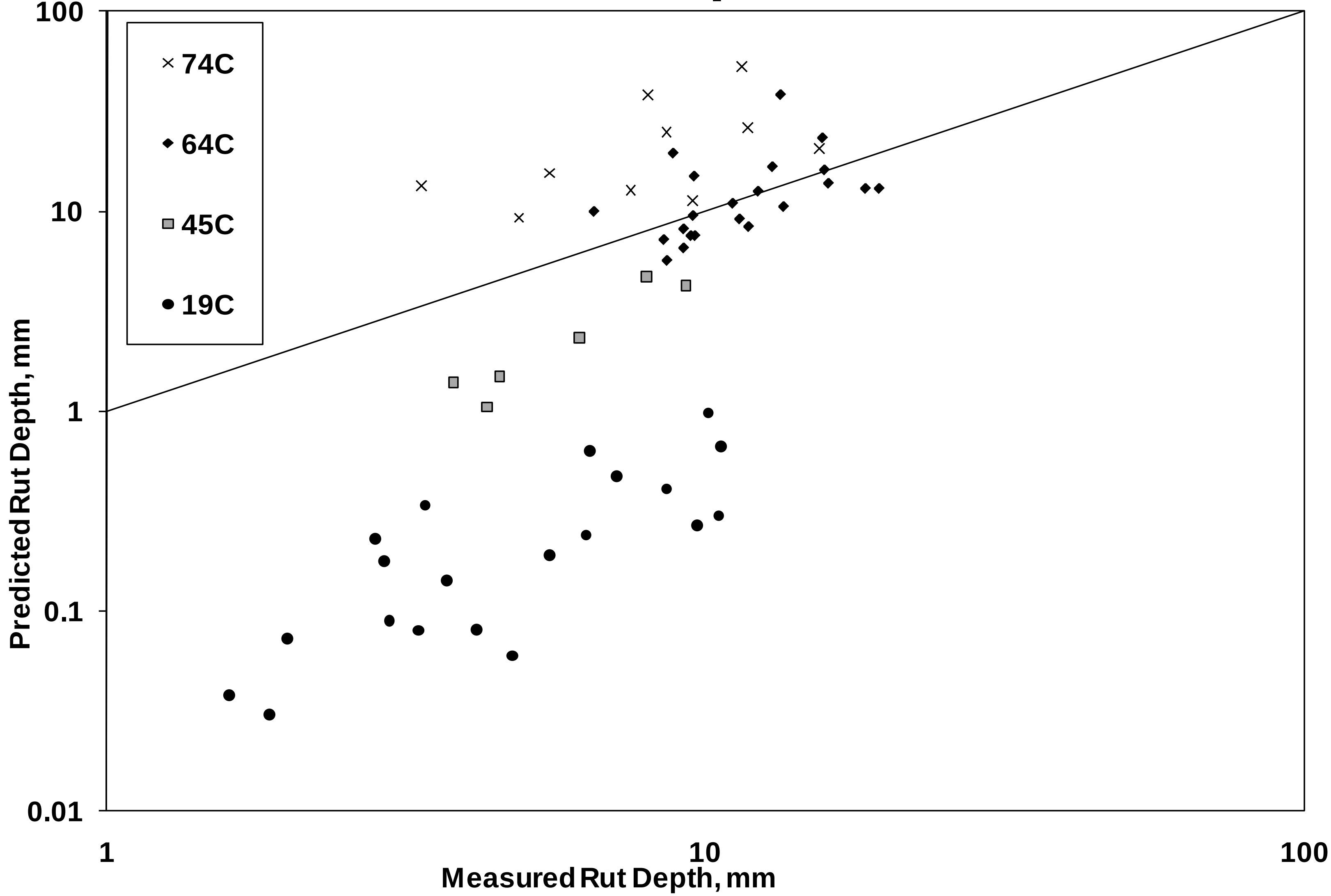
Predicted Rutting using ε_p from Flow Number



Predicted Rutting using ε_p from Flow Number



Predicted Rutting using ε_p from Flow Number



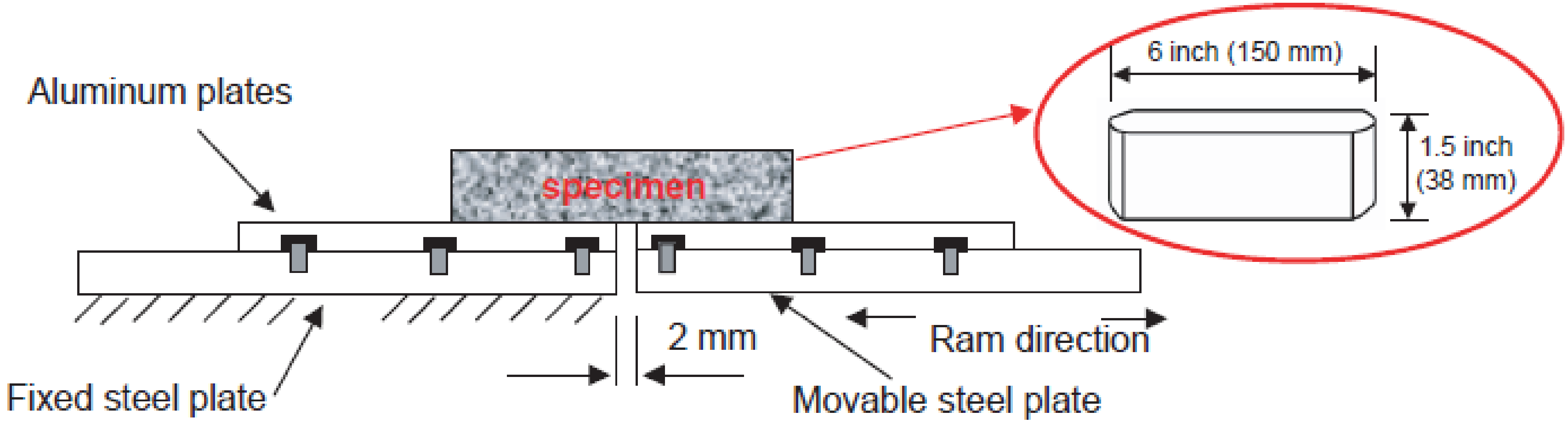
Predicted Rutting using ε_p from Flow Number

- Although not identical to methods that will come from NCHRP 9-30A, very similar.
- Magnitude of predicted rutting drastically improved
- Ranking not captured, but measured variability (error bars) brackets predictions
- Under and over-prediction at temperatures cooler and warmer than 64C indicate there is value in running tests at multiple temperatures to capture temperature effects.

Mixture Tests for Fatigue and Cracking

TTI Overlay Tester

- Cores from 100 mm lanes shared w/ TTI staff

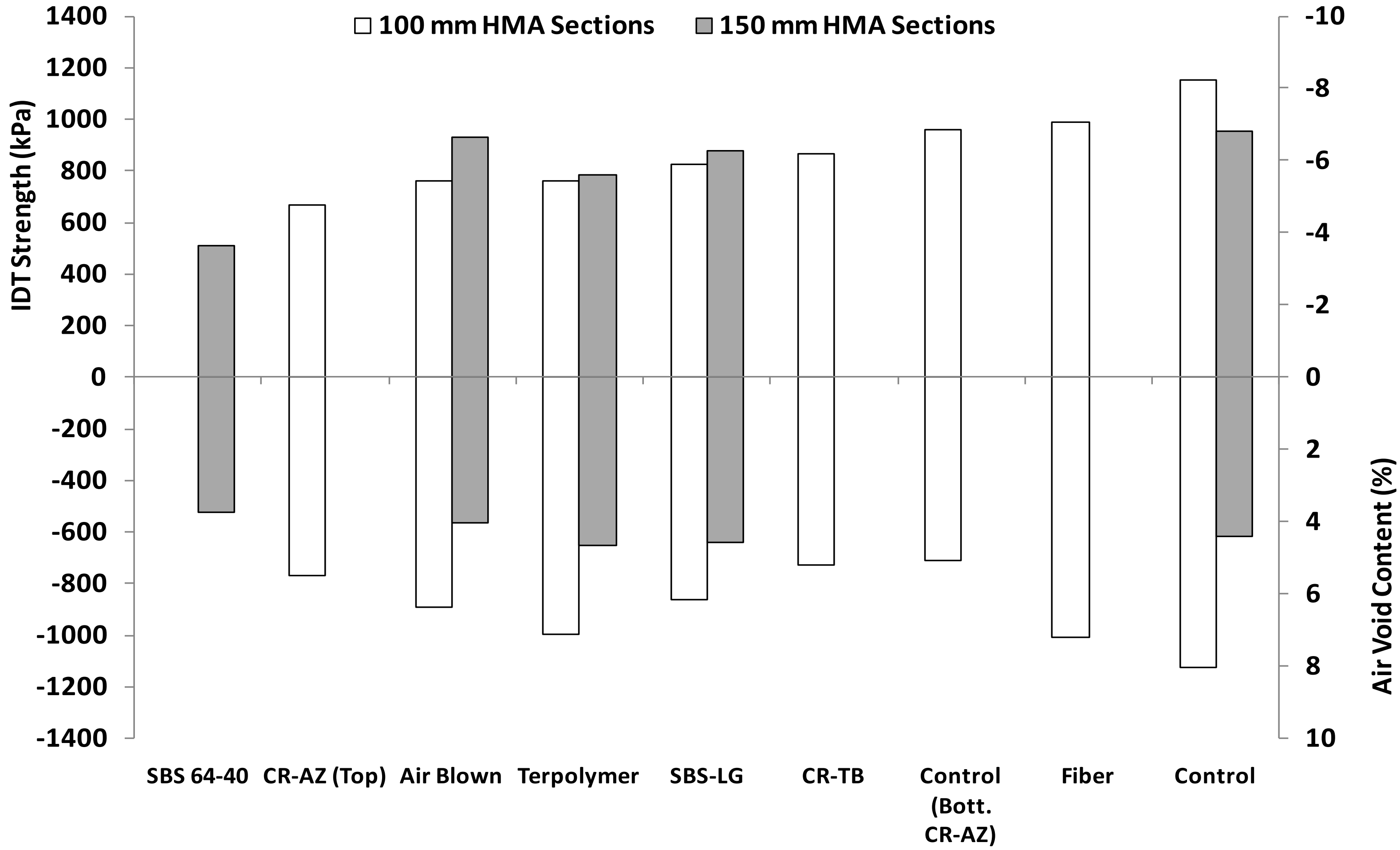


TTI Overlay Tester

	Number of Cycles to Full Fracture in TTI Overlay Tester
Lane 2 Control	60
Lane 3 Air Blown	80
Lane 4 SBS-LG	1,890
Lane 5 CR-TB	890
Lane 6 Terpolymer	1,120
Lane 7 Fiber	110

- **Very good agreement with ALF cracking**
- **This and other mix testing approaches were unable to capture fatigue resistance of fiber modified mix**

Indirect Tensile Strength IDT

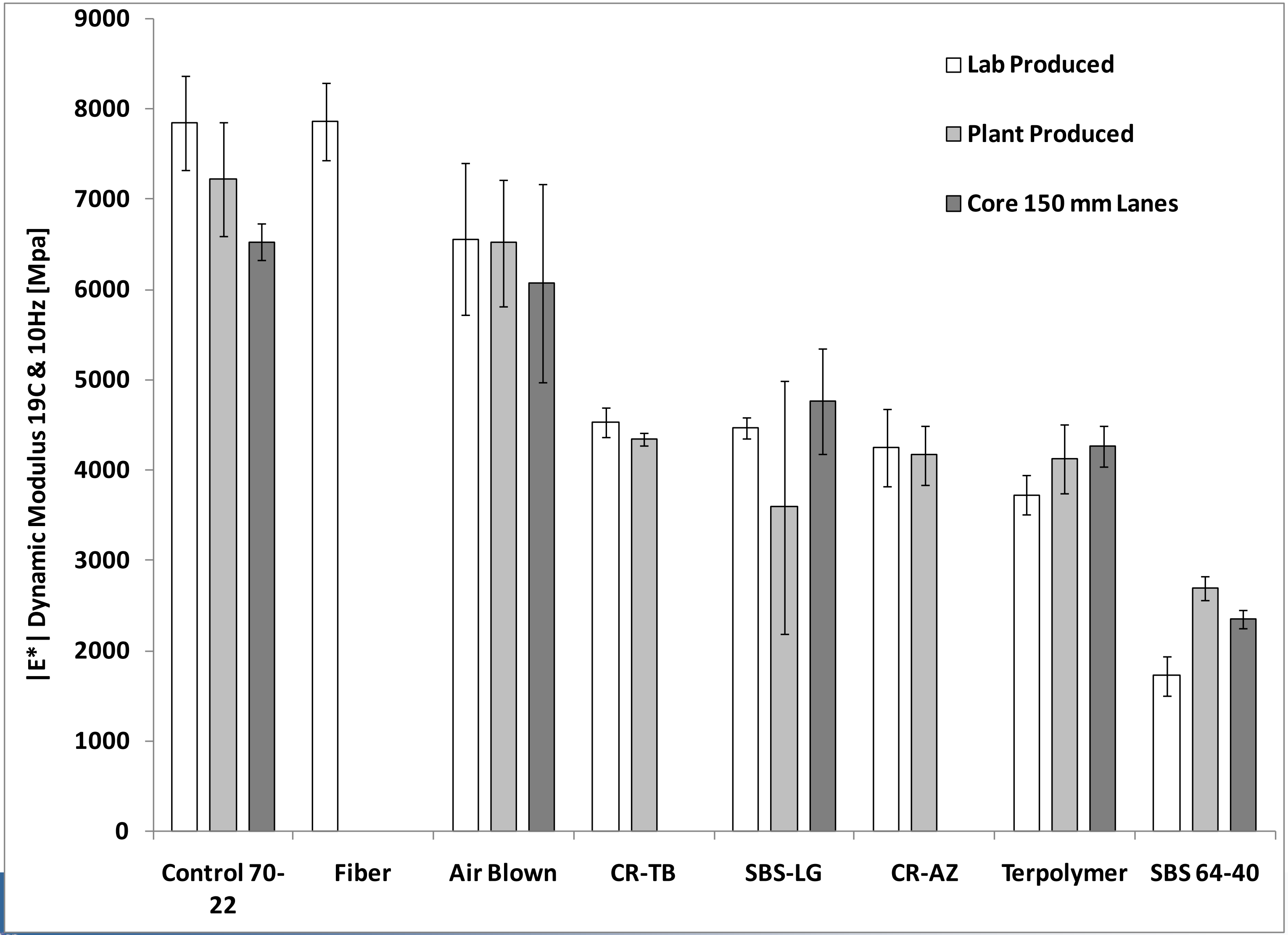


Indirect Tensile Strength IDT

- The repeatability is attractive but the variation in stiffness is not as large as what is observed in fatigue resistance of the mixtures
- Some difference in strength between same mix from different test lanes not attributable to density

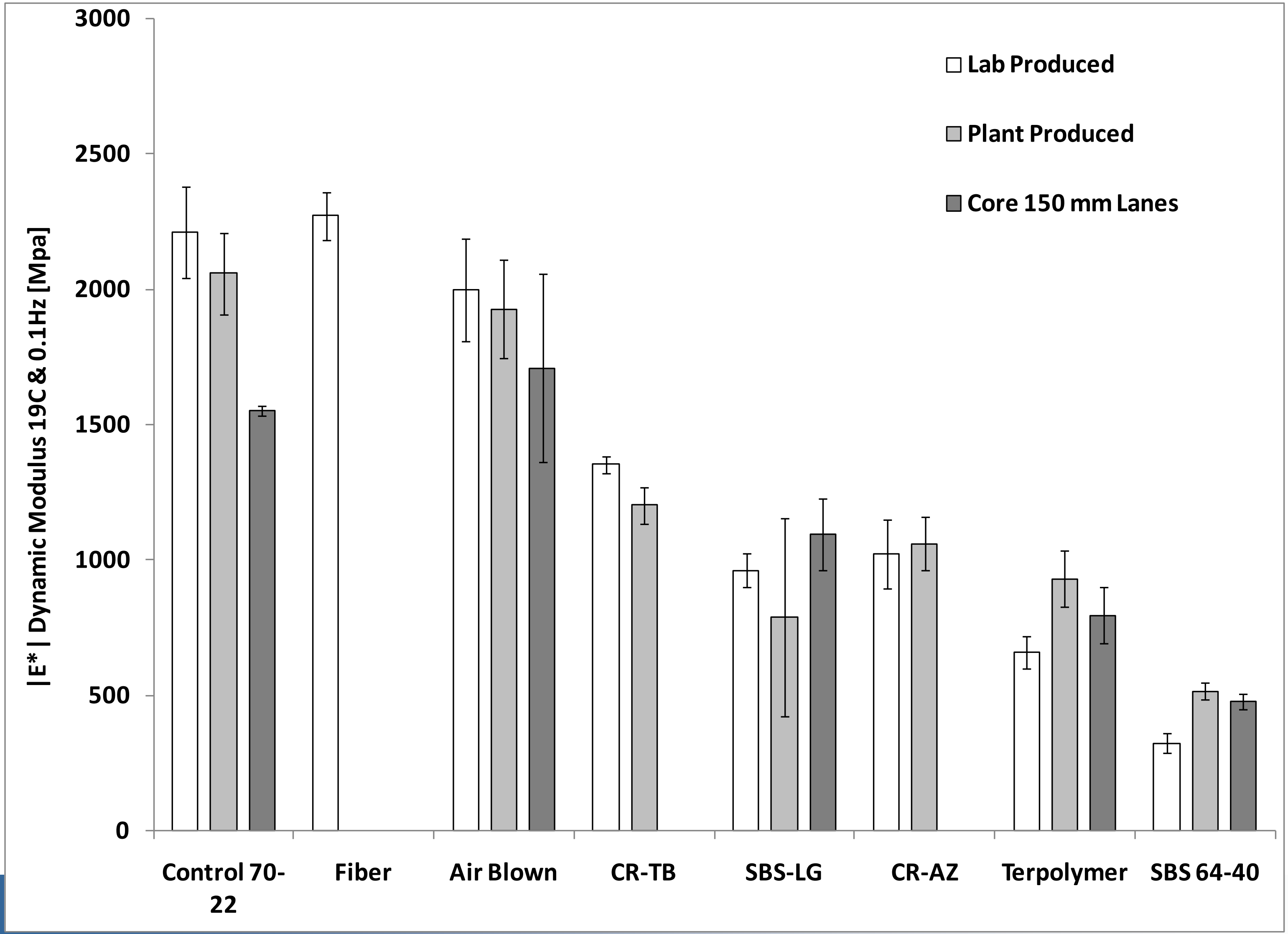
Dynamic Modulus |E*| and Phase Angle δ

|E*|
10Hz



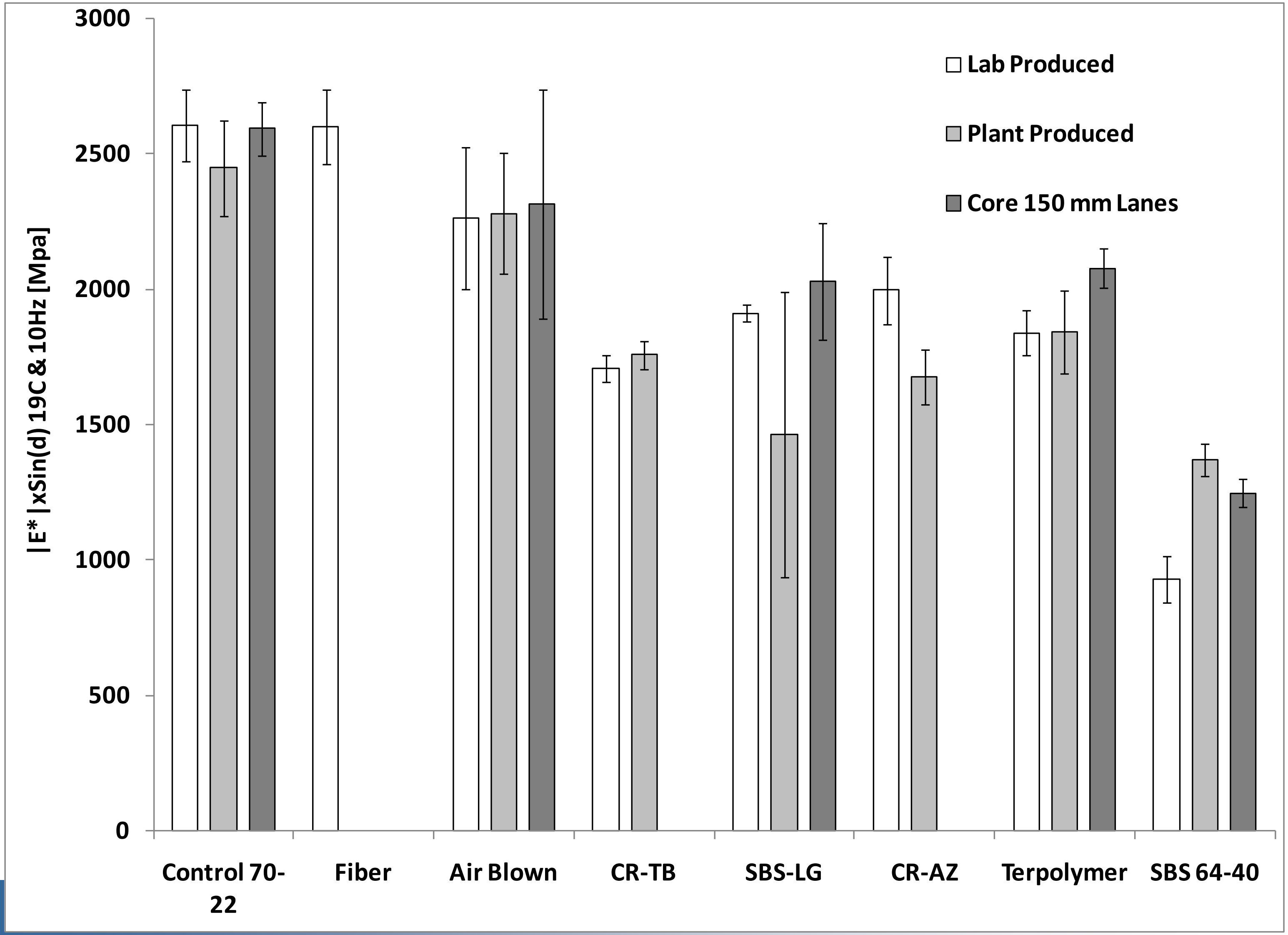
Dynamic Modulus |E*| and Phase Angle δ

|E*|
0.1Hz



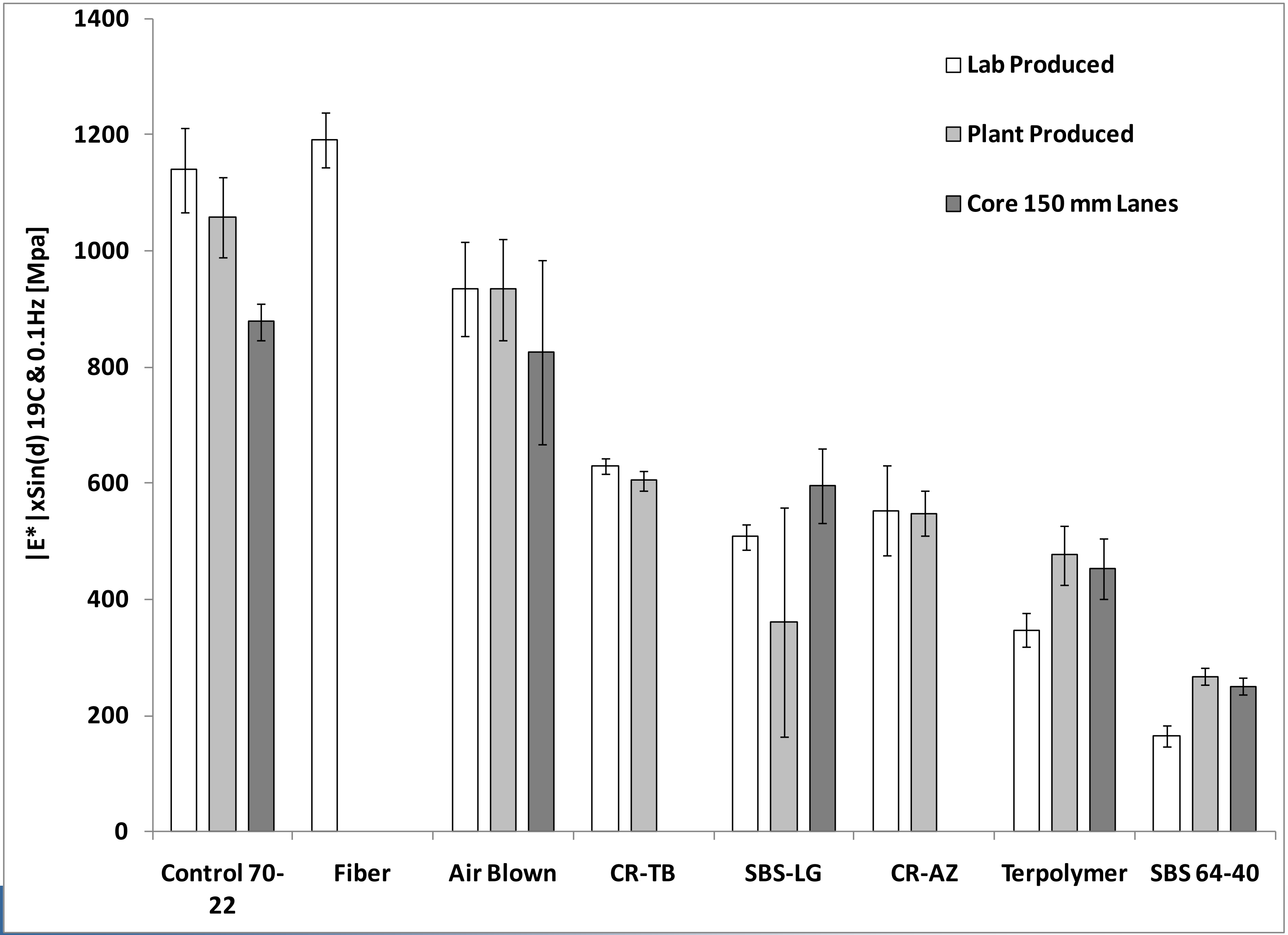
Dynamic Modulus |E*| and Phase Angle δ

|E*|sinδ 10Hz



Dynamic Modulus |E*| and Phase Angle δ

|E*|sinδ
0.1Hz



Dynamic Modulus |E*| and Phase Angle δ

- Less consistent trends with cores than at high temperatures. Cores more dense and sometimes stiffer or softer than counterparts
- Minor effect on ranking from the sinδ term
- Stiffness trends similar with frequency
- Unmodified binders stiffer
- Modified binders softer

Axial Cyclic Fatigue

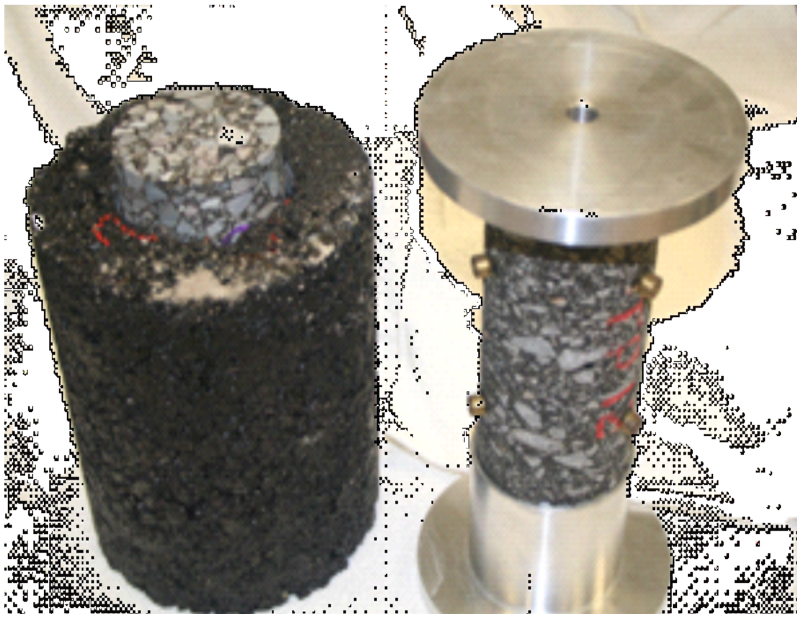
- Alternative to classical flexural beam fatigue
- Specimens can be made in Superpave gyratory compactor
- Stress control or strain control
- Yields same type of behavior as beam fatigue; modulus reduction and dissipated energy

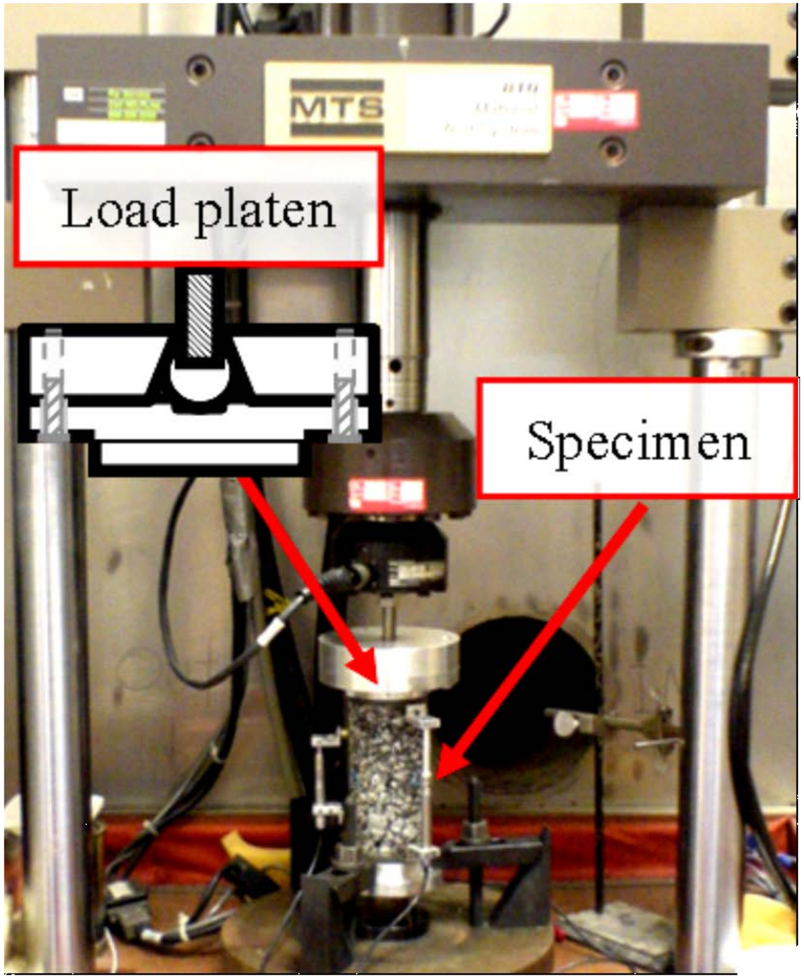
Axial Cyclic Fatigue

- Well developed from past research with continued development and implementation

1. Kim, R., Guddati, M.N., Underwood, B.S., Yun, T.Y., Subramanian, V., and Savadatti, S., "Development of a Multiaxial VEPCD-FEP++: Final Report," Report Number: FHWA-HRT-08-073, Federal Highway Administration, Washington, D.C., 2009.
2. Digital Media CRP-CD-46: Ancillary Reports from Major Area 12 (Tasks F and G) and Major Area 14 (Theses and Dissertations) from Witczak, M.W., NCHRP Report 547: Simple Performance Tests: Summary of Recommended Methods and Database, Transportation Research Board, National Research Council, Washington, D.C., 2005.
3. Lee, H.J., and Y.R. Kim, "Viscoelastic Constitutive Model for Asphalt Concrete Under Cyclic Loading," Journal of Engineering Mechanics, ASCE, Vol. 124, No. 1, 1998, pp.32-40.
4. Lee, H.J., and Y.R. Kim, "Viscoelastic Continuum Damage Model for Asphalt Concrete with Healing," Journal of Engineering Mechanics, ASCE, Vol. 124, No. 11, 1998, pp. 1224-1232.
5. Christensen, D. and Bonaquist, R., "Practical Application of Continuum Damage Theory to Fatigue Phenomena in Asphalt Concrete Mixtures," Journal of the Association of Asphalt Paving Technologists, Vol. 74, 2005, pp. 963-1002
6. Kutay, M.E., N.H.Gibson, and J. Youtcheff, "Conventional and Viscoelastic Continuum Damage (VECD) Based Fatigue Analysis of Polymer Modified Asphalt Pavements," Journal of the Association of the Asphalt Paving Technologists, vol. 77, 2008, pp. 395-434.
7. Christensen, D. and Bonaquist, R., "Analysis of HMA Fatigue Data Using the Concepts of Reduced Loading Cycles and Endurance Limit," Journal of the Association of Asphalt Paving Technologists, Vol. 78, 2008, pp. 377-416.
8. Kutay, M.E., N.H. Gibson, R. Dongre and J. Youtcheff. Use of Small Samples to Predict Fatigue Lives of Field Cores-Newly Developed Formulation Based on Viscoelastic Continuum Damage Theory. Transportation Research Record 2127, 2009, pp.90-97.
9. Hou, T., B. S. Underwood, Y. Richard Kim Fatigue Performance Prediction of North Carolina Mixtures Using the Simplified Viscoelastic Continuum Damage Model," Journal of the Association of Asphalt Paving Technologists, Vol. 80, 2010 (in press).

Axial Cyclic Fatigue



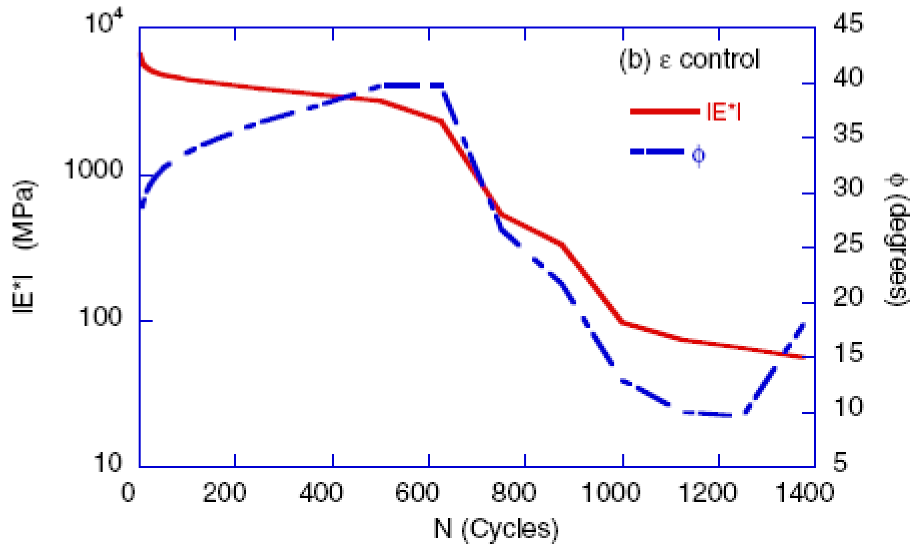


Axial Cyclic Fatigue

Then…

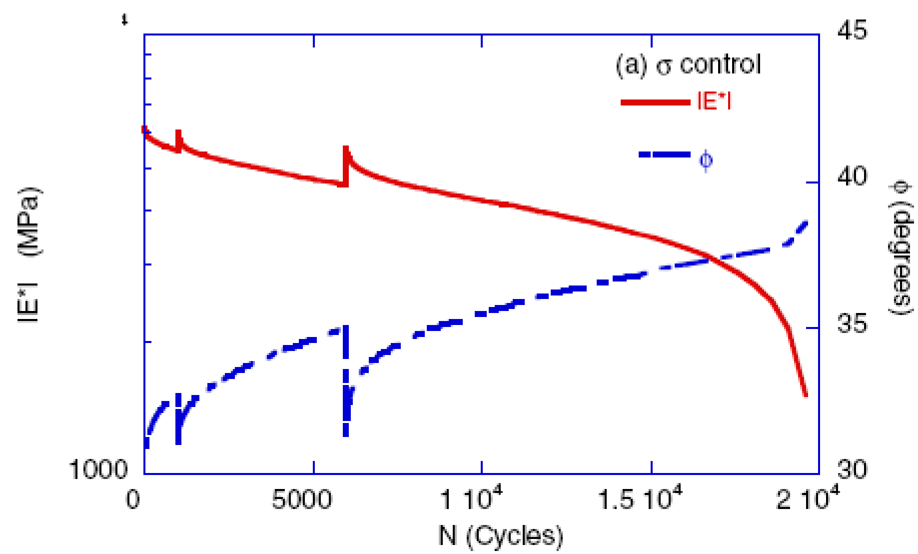
…Now

Axial Cyclic Fatigue



actuator strain control

stress control



Axial Cyclic Fatigue

Mixture	Energy Ratio		Dissipated Energy Ratio		Hysteresis Loop Distortion		50% Modulus Reduction		
	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	ε-control VECD
SBS 64-40	900	n/a	883	n/a	833	n/a	370	33,100	5,071,587
Terpolymer	3,893	128,250	4,659	133,450	5,243	127,800	2,660	88,500	1,333,521
CR-TB	5,560	31,434	6,659	31,068	6,933	31,601	2,510	6,168	59,655
SBS LG	4,893	14,500	5,942	13,567	8,393	13,367	4,333	1,875	167,880
Air Blown	18,093	3,050	17,926	2,675	23,093	2,833	15,760	2,150	11,855
Fiber	50,593	1,063	60,093	1,000	63,926	1,000	44,426	1,000	25,119
Control	25,093	750	28,260	688	31,426	563	24,593	438	12,589

- **Evaluated healing in stress control with rest periods; polymer modified asphalt heals measurably more than unmodified asphalt**
- **Opposite ranking found when stress control or actuator strain control**

Axial Cyclic Fatigue

Mixture	Energy Ratio		Dissipated Energy Ratio		Hysteresis Loop Distortion		50% Modulus Reduction		
	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	ε-control VECD
SBS 64-40	900	n/a	883	n/a	833	n/a	370	33,100	5,071,587
Terpolymer	3,893	128,250	4,659	133,450	5,243	127,800	2,660	88,500	1,333,521
CR-TB	5,560	31,434	6,659	31,068	6,933	31,601	2,510	6,168	59,655
SBS LG	4,893	14,500	5,942	13,567	8,393	13,367	4,333	1,875	167,880
Air Blown	18,093	3,050	17,926	2,675	23,093	2,833	15,760	2,150	11,855
Fiber	50,593	1,063	60,093	1,000	63,926	1,000	44,426	1,000	25,119
Control	25,093	750	28,260	688	31,426	563	24,593	438	12,589

- **On-specimen strains increase during actuator strain control test; neither stress control nor strain control**
- **Viscoelastic continuum damage (VECD) methodologies used to correct for truly strain controlled conditions (validated in research)**

Axial Cyclic Fatigue

Mixture	Energy Ratio		Dissipated Energy Ratio		Hysteresis Loop Distortion		50% Modulus Reduction		
	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	σ-control	ε_{ACT} control	ε-control VECD
SBS 64-40	900	n/a	883	n/a	833	n/a	370	33,100	5,071,587
Terpolymer	3,893	128,250	4,659	133,450	5,243	127,800	2,660	88,500	1,333,521
CR-TB	5,560	31,434	6,659	31,068	6,933	31,601	2,510	6,168	59,655
SBS LG	4,893	14,500	5,942	13,567	8,393	13,367	4,333	1,875	167,880
Air Blown	18,093	3,050	17,926	2,675	23,093	2,833	15,760	2,150	11,855
Fiber	50,593	1,063	60,093	1,000	63,926	1,000	44,426	1,000	25,119
Control	25,093	750	28,260	688	31,426	563	24,593	438	12,589

- **Modified asphalts perform the best in strain control and ranking improves when corrected for strain control conditions**

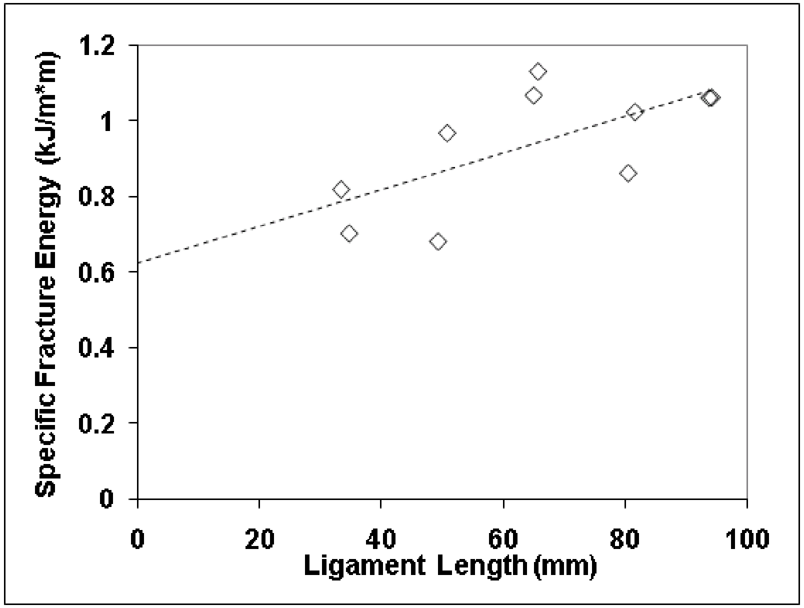
- **Fiber mix challenges this test as well**

DENT Testing

- Double Edge Notched Tension
- Same technique used to characterize binder
- Different notches and ligament lengths
- Calculates a Critical Crack Tip Opening Displacement

DENT Testing

- Mixes with modified binders tend to have larger CTOD and unmodified smaller
- Many replicates needed for multiple ligament lengths
- Repeatability can be challenging



Mixture Performance Test Strengths and Weaknesses

$$CS_{Mix-Lab} = \frac{\left(1 - p_{Regression}\right) + |\tau_{Kendall}| + (1 - p_{Kendall}) + |R|}{4}$$

Strengths of Rutting Tests

Comparison: 100 mm HMA Rutting (WITH Lane 6 Terpolymer)

Laboratory Test	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Expected Trend Direction	Correct Trend Direction	Composite Score
French Pavement Rutting Tester	88%	0.14	55%	0.60	Prop	Yes	0.54
69/827 kPa Flow Number ALF Voids (higher density SBS-LG & CR-TB)	56%	0.20	64%	0.40	Prop	Yes	0.45
|E*| 10 Hz Lab Produced	46%	-0.05	50%	-0.28	Inv	Yes	0.32
|E*|/sinδ 10 Hz Lab Produced	40%	-0.05	50%	-0.24	Inv	Yes	0.30
|E*|/sinδ 0.1 Hz Plant Produced	33%	-0.07	50%	-0.23	Inv	Yes	0.28
|E*|/sinδ 10 Hz Plant Produced	31%	0.07	50%	-0.21	Inv	Yes	0.27
|E*| 0.1 Hz Plant Produced	13%	0.20	64%	-0.09	Inv	Yes	0.27
|E*| 10 Hz Plant Produced	22%	0.07	50%	-0.15	Inv	Yes	0.23
|E*| 0.1 Hz Lab Produced	16%	0.14	61%	0.09	Inv	No	0.25
Hamburg Wheel Tracker	5%	0.24	72%	0.03	Inv	No	0.26
69/827 kPa Flow Number ALF Voids (lower density SBS-LG & CR-TB)	28%	-0.20	64%	-0.19	Prop	No	0.33
74°C SST Rep. Shear Const. Height Plant Produced	60%	0.05	50%	0.38	Inv	No	0.38
|E*|/sinδ 0.1 Hz Lab Produced	56%	0.33	81%	0.35	Inv	No	0.51
69/523 kPa Flow Number Fixed Voids	67%	-0.47	86%	-0.49	Prop	No	0.62

Strengths of Rutting Tests

Comparison: 100 mm HMA Rutting (WITHOUT Lane 6 Terpolymer)

Laboratory Test	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Expected Trend Direction	Correct Trend Direction	Composite Score
74°C SST Rep. Shear Const. Height Plant Produced	92%	-0.33	77%	-0.76	Inv	Yes	0.70
69/827 kPa Flow Number ALF Voids (higher density SBS-LG & CR-TB)	83%	0.40	76%	0.72	Prop	Yes	0.68
|E*|/sinδ 0.1 Hz Plant Produced	60%	-0.20	59%	-0.50	Inv	Yes	0.47
69/827 kPa Flow Number ALF Voids (lower density SBS-LG & CR-TB)	38%	0.20	59%	0.30	Prop	Yes	0.37
|E*| 0.1 Hz Plant Produced	16%	0.20	59%	-0.12	Inv	Yes	0.27
|E*|/sinδ 0.1 Hz Lab Produced	10%	0.07	50%	-0.07	Inv	Yes	0.19
|E*| 0.1 Hz Lab Produced	4%	0.07	50%	-0.02	Inv	Yes	0.16
French Pavement Rutting Tester	11%	-0.14	72%	-0.07	Prop	No	0.26
69/523 kPa Flow Number Fixed Voids	21%	-0.20	59%	0.17	Prop	No	0.29
|E*|/sinδ 10 Hz Lab Produced	34%	0.20	64%	0.23	Inv	No	0.35
|E*| 10 Hz Lab Produced	46%	0.33	77%	0.32	Inv	No	0.47
Hamburg Wheel Tracker	57%	0.47	86%	0.40	Inv	No	0.57
|E*|/sinδ 10 Hz Plant Produced	52%	0.60	88%	0.42	Inv	No	0.61
|E*| 10 Hz Plant Produced	63%	0.60	88%	0.52	Inv	No	0.66

Strengths of Rutting Tests

Comparison: 150 mm HMA Rutting

Laboratory Test	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Expected Trend Direction	Correct Trend Direction	Composite Score
|E*|/sinδ 0.1 Hz Lab Produced	96%	-1.00	99%	-0.89	Inv	Yes	0.96
69/523 kPa Flow Number Fixed Voids	94%	0.80	96%	0.86	Prop	Yes	0.89
|E*| 0.1 Hz Lab Produced	67%	-0.60	88%	-0.55	Inv	Yes	0.68
74°C SST Rep. Shear Const. Height Plant Produced	81%	-0.20	59%	-0.70	Inv	Yes	0.58
|E*| 10 Hz Lab Produced	56%	-0.20	59%	-0.46	Inv	Yes	0.45
69/827 kPa Flow Number ALF Voids	32%	0.40	76%	0.25	Prop	Yes	0.43
|E*|/sinδ 0.1 Hz Plant Produced	30%	-0.40	76%	-0.24	Inv	Yes	0.42
Hamburg Wheel Tracker	30%	-0.40	76%	-0.24	Inv	Yes	0.42
|E*| 0.1 Hz Plant Produced	20%	-0.40	76%	-0.16	Inv	Yes	0.38
6.9/210 kPa Flow Number ALF Voids	18%	0.40	76%	0.14	Prop	Yes	0.37
|E*|/sinδ 10 Hz Core	7%	-0.20	59%	-0.05	Inv	Yes	0.23
|E*| 10 Hz Plant Produced	10%	0.00	41%	-0.08	Inv	Yes	0.15
|E*|/sinδ 10 Hz Plant Produced	9%	0.00	41%	-0.07	Inv	Yes	0.14
|E*| 10 Hz Core	8%	0.00	41%	-0.07	Inv	Yes	0.14
|E*|/sinδ 10 Hz Lab Produced	1%	0.00	41%	0.00	Inv	Yes	0.10
|E*| 0.1 Core	8%	0.00	41%	0.06	Inv	No	0.14
French Pavement Rut Tester	1%	-0.20	59%	0.01	Prop	No	0.20
64°C SST Rep. Shear Const. Height Bottom Core - Strain at 20k Cycles	22%	0.00	38%	-0.22	Prop	No	0.21
|E*|/sinδ 0.1 Hz Core	33%	0.00	41%	0.26	Inv	No	0.25
64°C SST Rep. Shear Const. Height Bottom Core - Cycles to 2% Strain	46%	0.00	38%	0.46	Inv	No	0.33
64°C SST Rep. Shear Const. Height Top Core - Strain at 20k Cycles	85%	-0.33	63%	-0.85	Prop	No	0.66
64°C SST Rep. Shear Const. Height Top Core - Cycles to 2% Strain	88%	0.33	63%	0.88	Inv	No	0.68

Strengths of Rutting Tests

- Scores illustrate numerical and statistical challenges
- SST and Flow Number consistently toward the top with higher scores depending on conditions
- Wheel tracking was not a strong indicator
- Dynamic modulus was interspersed

Strengths of Fatigue Cracking Tests

Comparison: 100 mm HMA

Laboratory Test	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Expected Trend Direction	Correct Trend Direction	Composite Score
TTI Overlay Tester	100%	0.80	96%	0.99	Prop	Yes	0.94
Critical Tip Opening Displacement	95%	0.80	96%	0.87	Prop	Yes	0.89
|E*|sinδ 10 Hz Plant Produced	78%	-0.60	93%	-0.59	Inv	Yes	0.73
|E*|sinδ 0.1Hz Plant Produced	70%	-0.60	93%	-0.51	Inv	Yes	0.68
Axial Fatigue – Strain Control 50% Modulus Red + VECD	46%	0.80	96%	0.37	Prop	Yes	0.65
Essential Work of Fracture	54%	0.40	76%	0.44	Prop	Yes	0.53
Axial Fatigue – Strain Control Energy Ratio	45%	0.40	76%	0.36	Prop	Yes	0.49
Axial Fatigue – Strain Control Hysteresis Loop Quality	44%	0.40	76%	0.35	Prop	Yes	0.49
Axial Fatigue – Strain Control Dissipated Energy Ratio	44%	0.40	76%	0.35	Prop	Yes	0.49
Axial Fatigue – Strain Control 50% Modulus Red	34%	0.20	59%	0.27	Prop	Yes	0.35
|E*|sinδ 0.1 Hz Lab Produced	21%	-0.14	61%	-0.13	Inv	Yes	0.27
|E*|sinδ 10 Hz Lab Produced	1%	0.05	50%	0.00	Inv	No	0.14
Indirect Tensile Strength	68%	-0.14	73%	-0.41	Prop	No	0.49
Axial Fatigue – Stress Control 50% Modulus Red	85%	-0.20	59%	-0.74	Prop	No	0.60
Axial Fatigue – Stress Control Hysteresis Loop Quality	87%	-0.40	76%	-0.77	Prop	No	0.70
Axial Fatigue – Stress Control Dissipated Energy Ratio	87%	-0.60	88%	-0.77	Prop	No	0.78
Axial Fatigue – Stress Control Energy Ratio	90%	-0.60	88%	-0.81	Prop	No	0.80

Strengths of Fatigue Cracking Tests

Comparison: 150 mm HMA

Laboratory Test	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Expected Trend Direction	Correct Trend Direction	Composite Score
Critical Tip Opening Displacement	94%	1.00	96%	0.94	Prop	Yes	0.96
Essential Work of Fracture	67%	0.67	83%	0.67	Prop	Yes	0.71
Axial Fatigue – Strain Control 50% Modulus Red + VECD (SBS 64-40 Removed)	24%	0.67	83%	0.24	Prop	Yes	0.49
|E*|sinδ 0.1Hz Plant Produced	60%	-0.20	59%	-0.49	Inv	Yes	0.47
|E*|sinδ 10 Hz Plant Produced	59%	-0.20	59%	-0.49	Inv	Yes	0.47
Axial Fatigue – Strain Control Energy Ratio	22%	0.33	63%	0.22	Prop	Yes	0.35
Axial Fatigue – Strain Control Hyst. Loop Qual.	21%	0.33	63%	0.21	Prop	Yes	0.35
Axial Fatigue – Strain Control DER	21%	0.33	63%	0.21	Prop	Yes	0.35
Indirect Tensile Strength	23%	0.00	41%	0.18	Prop	Yes	0.20
Axial Fatigue – Strain Control - 50% Modulus Red (SBS 64-40 Removed)	13%	0.00	38%	0.13	Prop	Yes	0.16
Axial Fatigue – Strain Control- 50% Modulus Red	10%	0.00	41%	0.08	Prop	Yes	0.15
E*|sinδ 10 Hz Cores	3%	-0.20	59%	0.02	Inv	No (Somewhat)	0.21
E*|sinδ 0.1 Hz Cores	17%	0.00	41%	-0.14	Inv	No (Mostly)	0.18
E*|sinδ 0.1 Hz Lab Produced	37%	0.00	41%	-0.29	Inv	No (Mostly)	0.27
Axial Fatigue – Stress Control Hyst. Loop Qual.	46%	0.00	41%	-0.37	Prop	No (Mostly)	0.31
Axial Fatigue – Stress Control DER	48%	0.00	41%	-0.39	Prop	No (Mostly)	0.32
Axial Fatigue – Stress Control- 50% Modulus Red	51%	0.00	41%	-0.41	Prop	No (Mostly)	0.33
Axial Fatigue – Stress Control Energy Ratio	53%	0.00	41%	-0.43	Prop	No (Mostly)	0.34
Axial Fatigue – Strain Control 50% Modulus Red + VECD	39%	0.20	59%	-0.31	Prop	No (Mostly)	0.37
E*|sinδ 10 Hz Lab Produced	1%	0.00	41%	0.01	Inv	No	0.10

Strengths of Fatigue Cracking Tests

- TTI Overlay tester strong indicator with 100mm thick HMA
- Mix CTOD consistently stronger
- Dynamic modulus strengths interspersed
- Axial Fatigue
  - Stress control yields incorrect trend directions
  - Strain control axial fatigue ranking improves when the test is corrected for true strain control conditions

Q & A

FHWA Accelerated Load Facility Transportation Pooled Fund Studies

TPF-5(019) Full-Scale Accelerated Performance Testing for Superpave and Structural Validation

SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements

1st Closeout Webinar

August 16-17, 2010

11am – 2pm

Day 2

Ranking of Binder Tests

Overview of Binder Parameters Explored

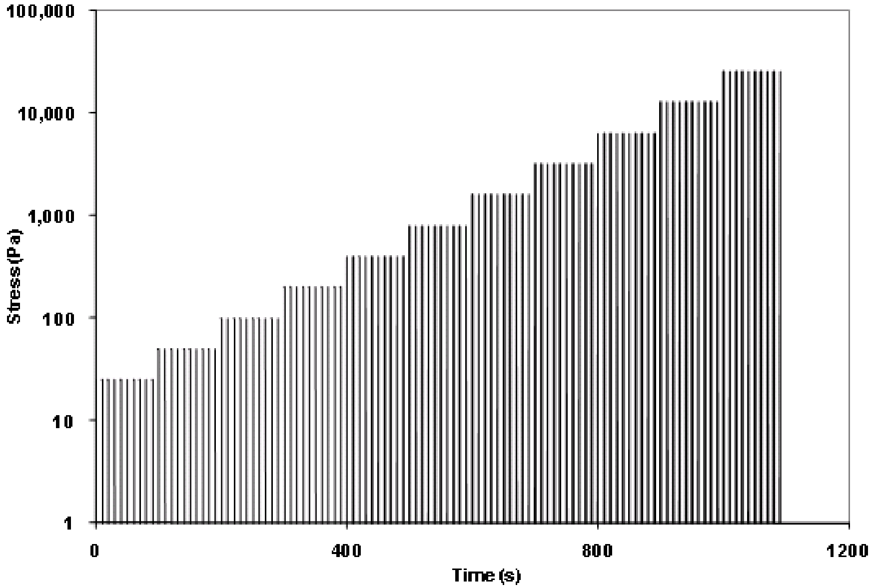
- **Rutting**
  1. Low Shear Viscosity
  2. Zero Shear Viscosity
  3. Oscillatory-based Non-recovered Stiffness
  4. MSCR Non-recovered Compliance
  5. $|G^*|/\sin\delta$ @ 0.25 rad/sec
  6. Material Volumetric Flow Rate
  7. $|G^*|/\sin\delta$ @ 10 rad/sec

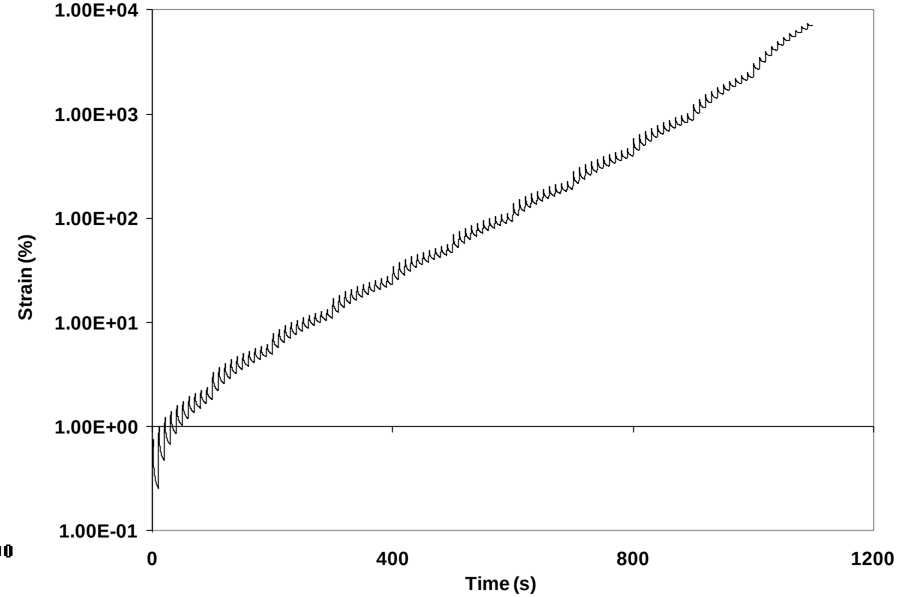
- **Fatigue Cracking**
  1. $|G^*|\sin\delta$
  2. DTT Failure Strain
  3. BBR m-value
  4. Time Sweep N_F
  5. Stress Sweep N_F
  6. Large Strain Time Sweep Surrogate
  7. Essential Work of Fracture
  8. Critical Tip Opening Displacement
  9. Binder Yield Energy

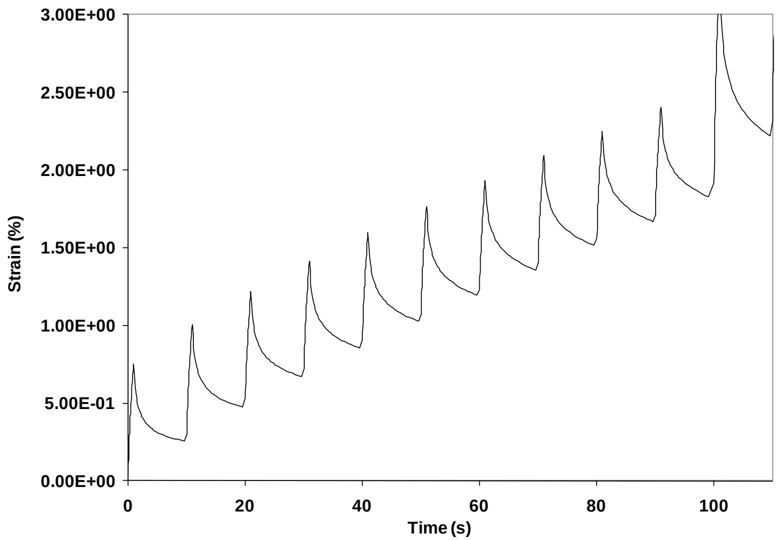
Rutting - Superpave

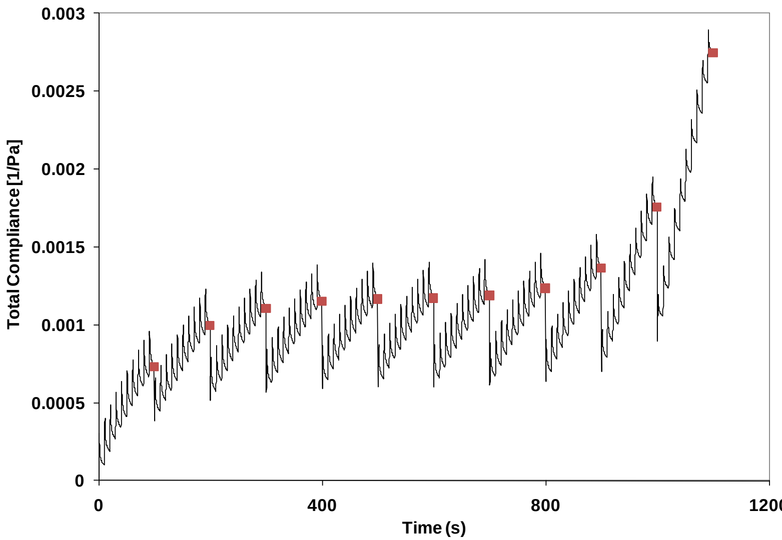
Binder	$\|G^*\|/\sin\delta$ value [Pa] 64°C, 10 rads/sec	Temp [^{o}C] @ $\|G^*\|/\sin\delta$ = 2.2 kPa 10 rads/sec	$\|G^*\|/\sin\delta$ value [Pa] 64°C, 0.25 rads/sec	Temp [^{o}C] @ $\|G^*\|/\sin\delta$ = 50 Pa 0.25 rads/sec
CR-TB	12,846	82.2	952	89.8
Air Blown	10,851	76.9	412	79.2
Control 70-22	6,903	73.6	233	75.5
SBS-LG	6,321	74.7	367	80.8
Terpolymer	5,359	74.6	388	85.6
SBS 64-40	5,192	73.9	454	84.6

Rutting - MSCR









Rutting - MSCR

Binder	Nonrecovered compliance [1/MPa]		
	50 kPa	400 kPa	3200 kPa
SBS 64-40	0.93	1.07	1.17
CR-TB	1.12	1.20	1.40
SBS-LG	1.65	1.76	2.33
Terpolymer	2.99	3.40	3.98
Air Blown	4.99	5.73	6.38
Control	9.47	11.30	12.33

Rutting – Oscillatory Nonrecovered Stiffness

$$\%\gamma_{unr} = \frac{100\sigma_0}{|G^*|}\left(1 - \frac{1}{\tan\delta\sin\delta}\right)$$

Theoretical derivation

More mechanistic than phenomenological |G*|/sinδ

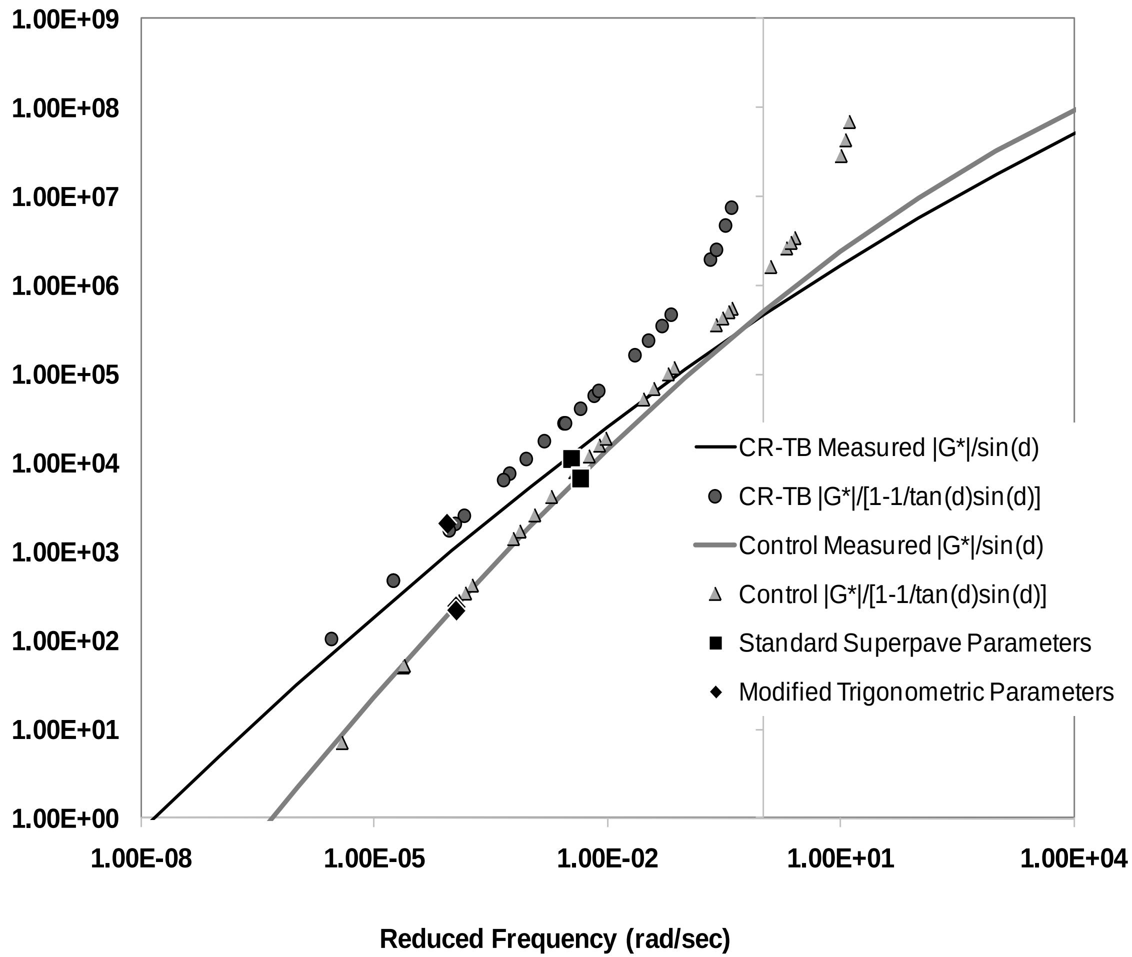
$$\frac{|G^*|}{\left(1 - \frac{1}{\tan\delta\sin\delta}\right)}$$

Rutting – Oscillatory Nonrecovered Stiffness

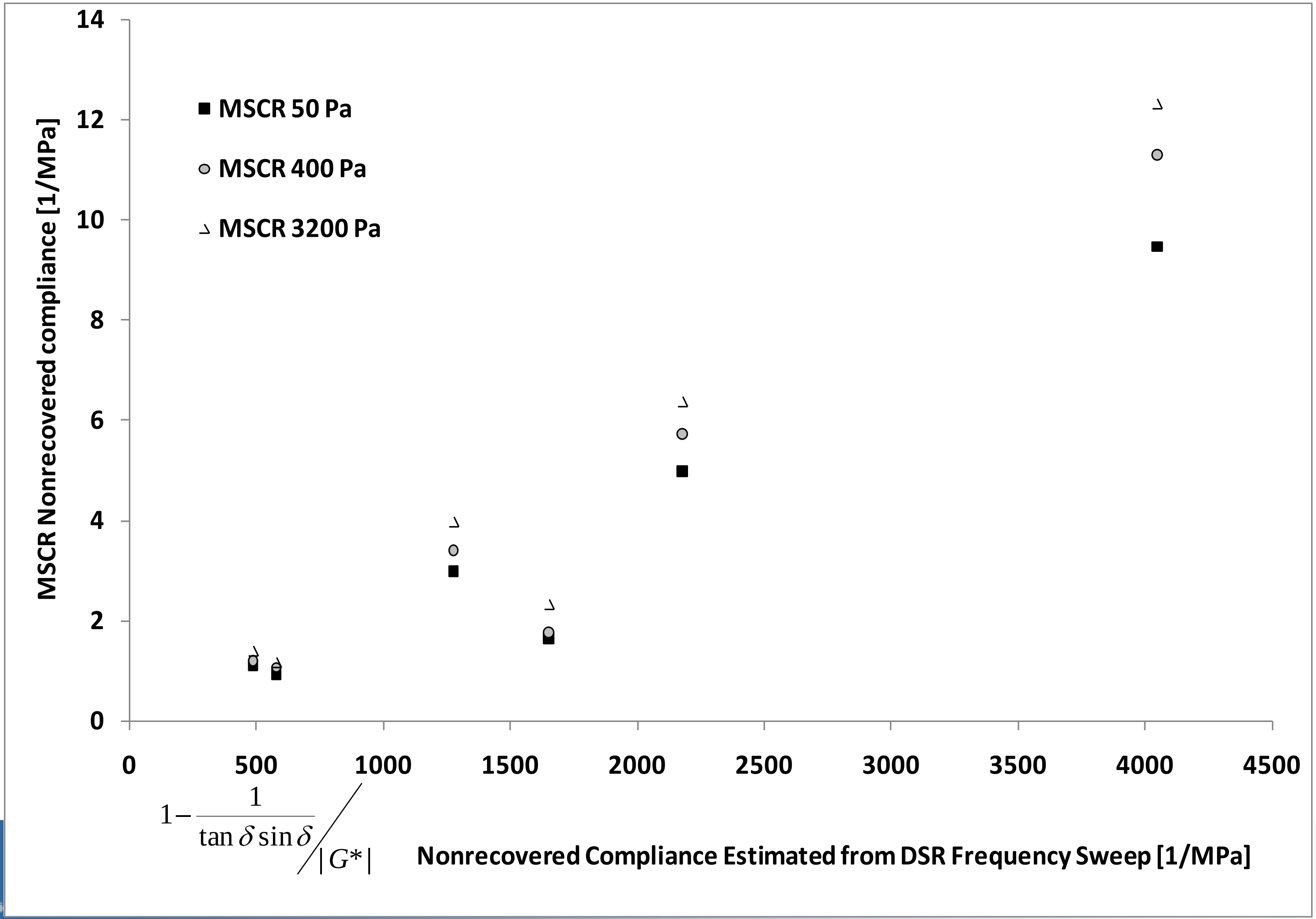
$$\frac{|G^*|}{\sin\delta}$$

and

$$\frac{|G^*|}{1-\frac{1}{\tan\delta\sin\delta}}$$



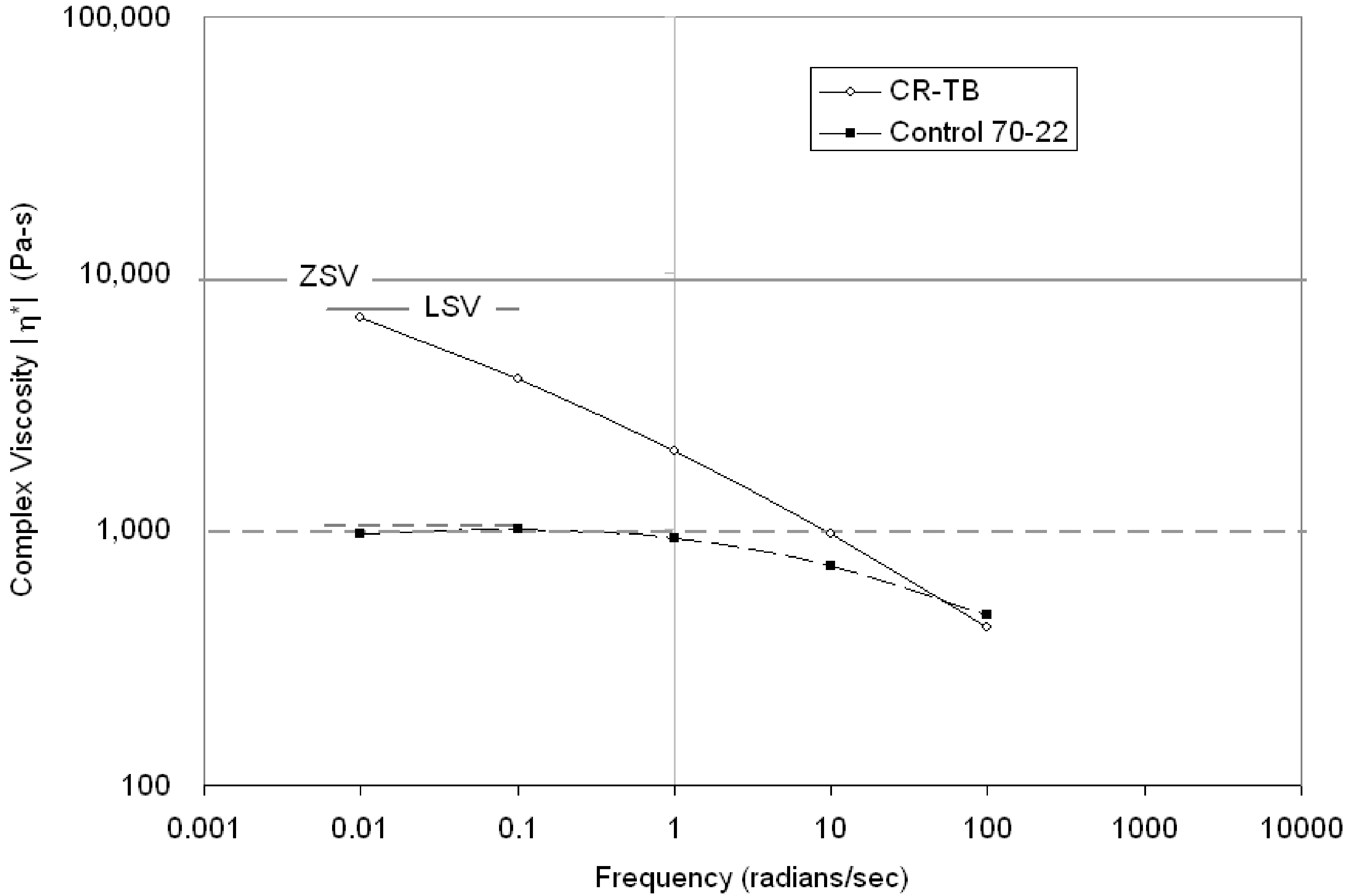
Rutting – Oscillatory Nonrecovered Stiffness



Rutting – Oscillatory Nonrecovered Stiffness

Binder	$\lvert G^*\rvert/(1-(1/\tan\delta\sin\delta))$ @ 64°C, 0.25 rads/s, RTFOT [Pa]	$T_E / (1 - (1/\tan\delta\sin\delta))$ [°C]
CR-TB	2,053	89.0
SBS 64-40	1,729	83.8
Terpolymer	783	86.8
SBS-LG	605	81.2
Air Blown	459	79.4
Control	247	75.6

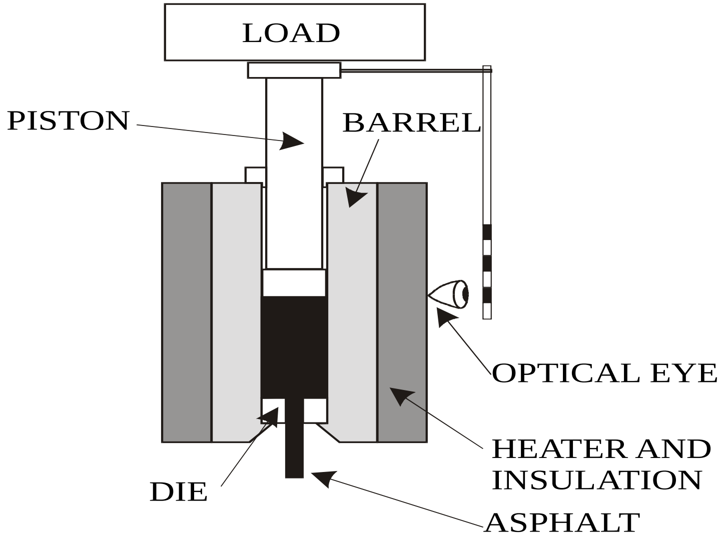
Zero and Low Shear Viscosity



Zero and Low Shear Viscosity

Binder	ZSV [Pa-s]	LSV [Pa-s]
CR-TB	9302	7183
SBS 64-40	7791	7660
SBS-LG	4814	3364
Terpolymer	2974	2470
Air Blown	1981	2455
Control	978	1034

Rutting - Material Volumetric Flow Rate



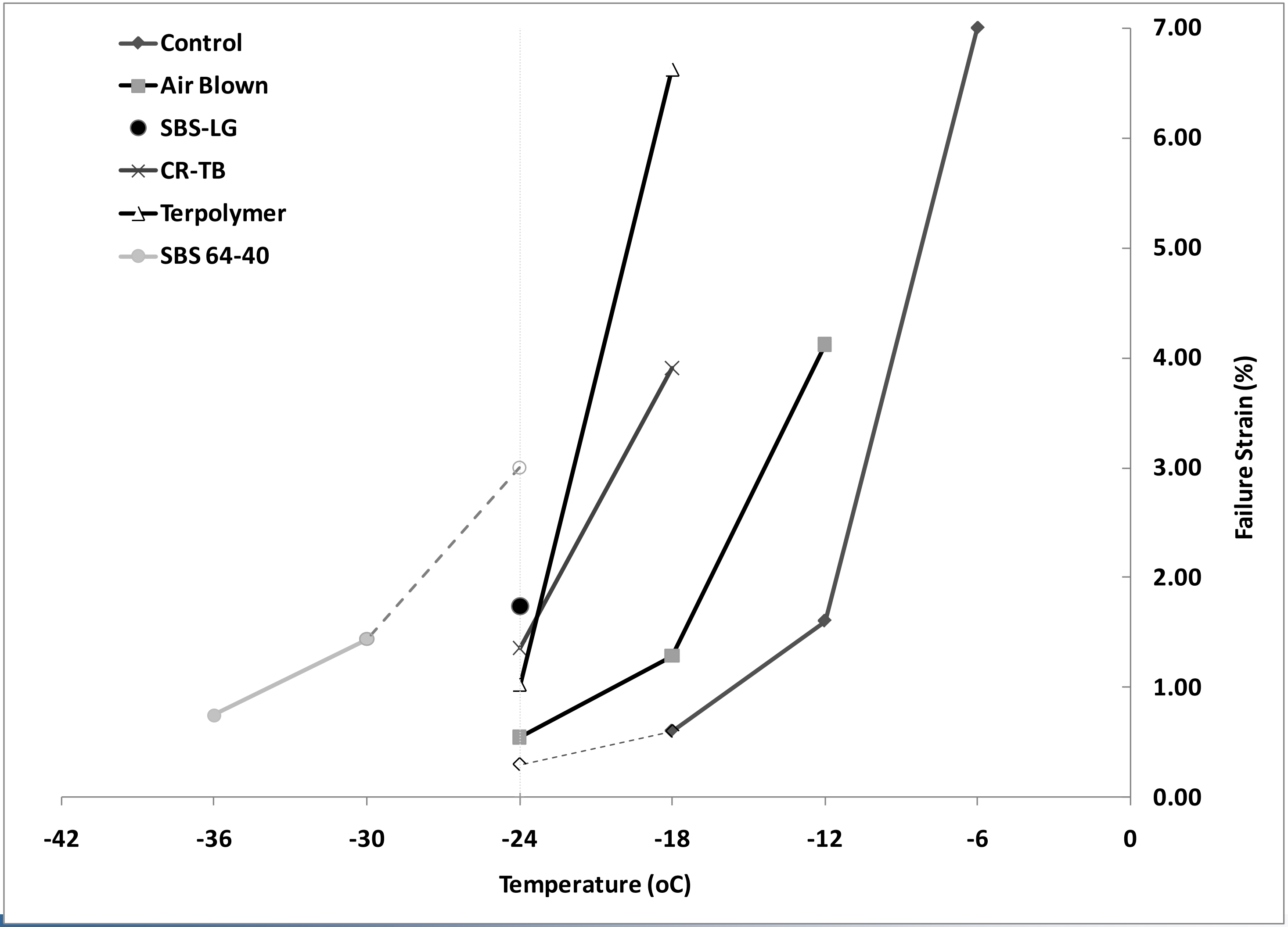
- Adopted from polymer industry
- Developed as a rapid verification for PG grade (high temp only)

Binder	MVR [cc/10min] @ 64°C, 1.225 kg	Temperature [^{o}C] @ 50cc/10min, 1.225 kg
SBS-LG	4.0	77.2
CR-TB	4.4	80.6
Terpolymer	6.1	81.2
Control	11.7	73.5
Air Blown	14.6	74.8
SBS 64-40	19.1	77.0

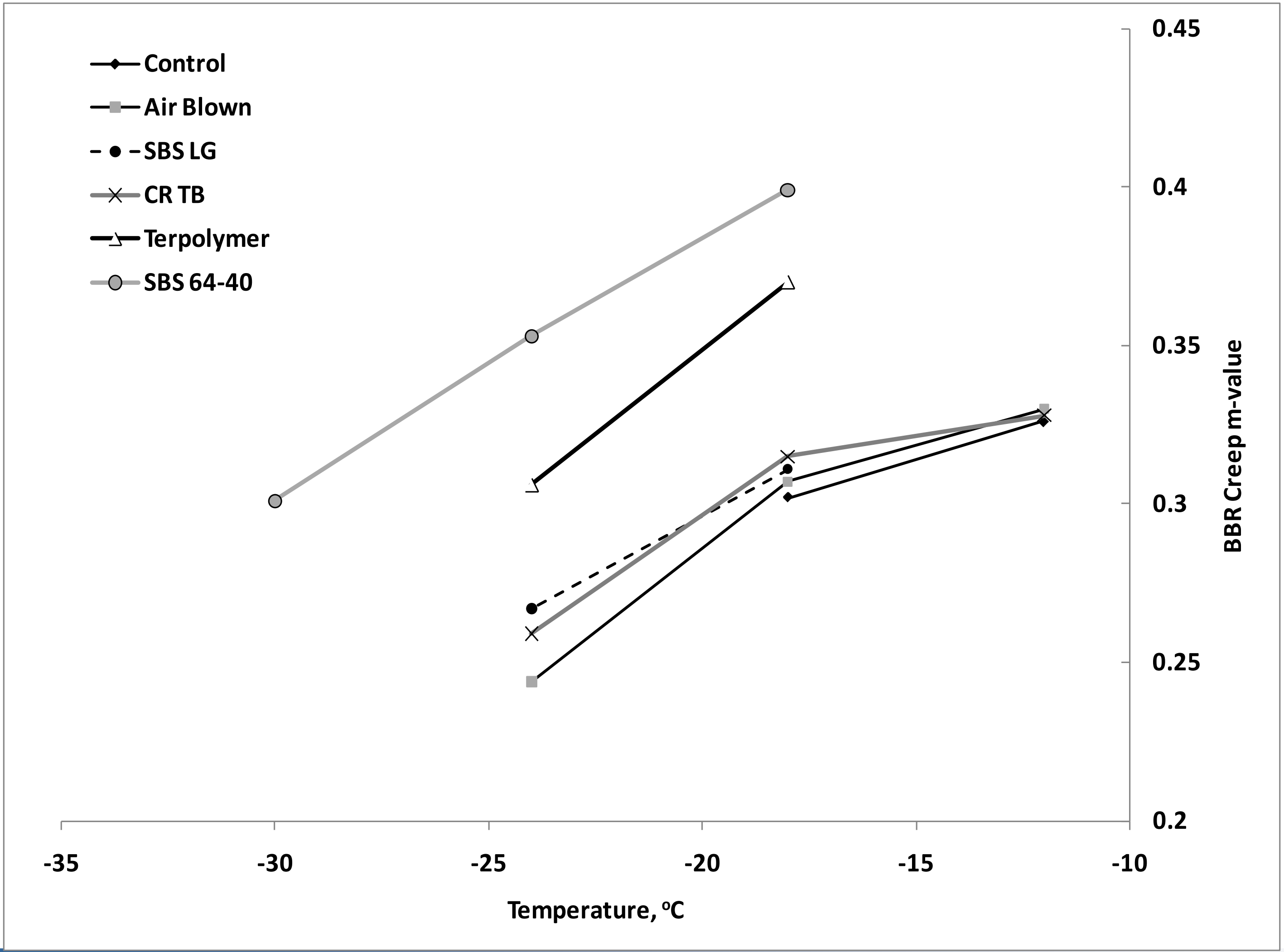
Fatigue - Superpave

Binder	|G*|sinδ value [Pa] 19°C, 10 rads/s, 0.4% strain, PAV	Temp [°C] @ |G*|sinδ = 5 MPa 10 rads/s, 0.4% strain, PAV
Control 70-22	12,100,000	26.0
CR-AZ	-	23.4* *estimated
Air Blown	6,810,000	22.6
SBS-LG	4,060,000	18.1
CR-TB	4,210,000	17.9
Terpolymer	2,610,000	14.3
SBS 64-40	1,761,800	8.6

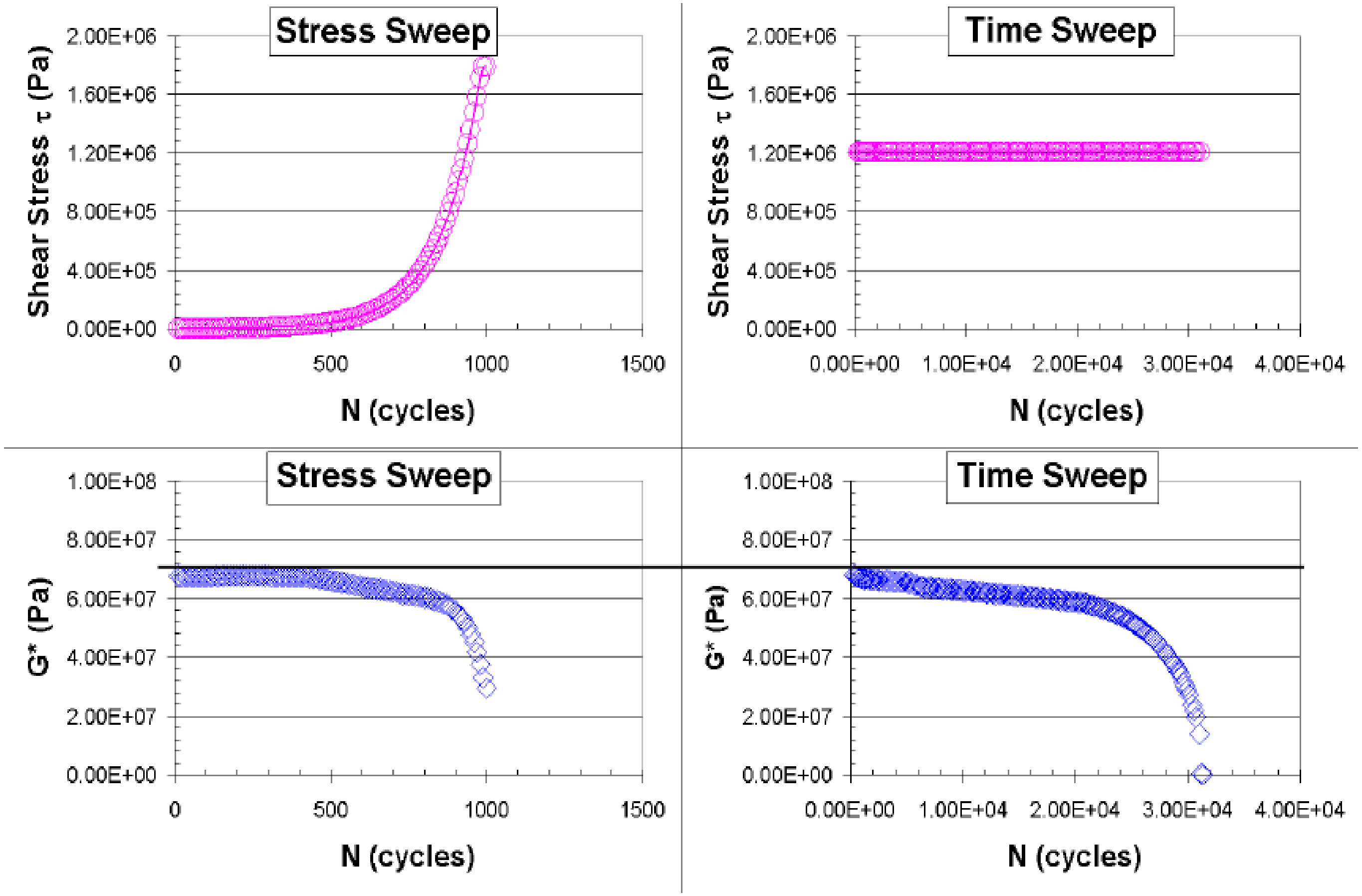
Fatigue – Direct Tension (low temp) Failure Strain



Fatigue – Creep m-value BBR (low temp)



Binder Cyclic Fatigue – Time and Stress Sweep



Binder Cyclic Fatigue – Time and Stress Sweep

Binder	% Strain	Beginning of Test		Conditions at Failure		Number of Cycles to Failure, N_F (x1,000)
		|G*| (MPa)	Phase Angle (deg)	|G*| (MPa)	Phase Angle (deg)	
70-22	3	23.11	45.46	12.73	46.97	49.63
	5	18.16	50.28	9.35	51.51	11.77
	7	15.54	53.67	7.65	54.68	4.64
Air Blown	3	12.71	44.99	6.48	46.75	108.97
	5	10.57	49.06	5.46	51.1	26.02
	7	9.36	51.94	4.87	54.18	10.12
SBS LG	5	6.05	49.41	3.02	57.05	1167.1
	7	4.99	52.5	2.5	58.58	236.48
	9	4.32	54.95	2.16	59.76	71.16
CR-TB	3	5.35	54.21	2.85	55.45	845.43
	5	4.37	57	2.24	58.03	51.73
	7	3.66	59.1	2.11	60.13	12.63
Terpolymer	3	6.25	50.5	3.29	53.62	532.63
	5	5.82	52.74	3.47	55.74	158.67
	7	5.17	55.46	3.16	57.79	45.68

Binder Cyclic Fatigue – Time and Stress Sweep

Binder	Beginning of Test		Point of Failure				
	|G*| (MPa)	Phase Angle (deg)	Stress τ (MPa)	Strain γ (%)	|G*| (MPa)	Phase Angle (deg)	Number of Cycles to Failure, N_F (x1,000)
Terpolymer	6.92	47.3	0.33	10.14	3.46	58.87	6.35
CR-TB	5.02	52.07	0.39	16.5	2.51	63.1	6.49
SBS LG	8.9	40.64	0.39	9.17	4.45	54.15	6.5
Air Blown	15.22	41.65	0.68	9.11	7.64	54.2	7.09
70-22	25.3	41.41	1.05	8.5	12.65	55.63	7.57

Fatigue – Large Strain Time Sweep Surrogate

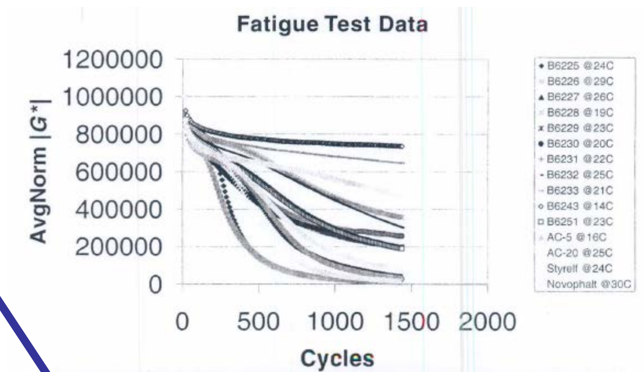
T=15ºC $\gamma = 0.1\%$ → $\gamma = 80\%$

T=20ºC $\gamma = 0.1\%$ → $\gamma = 80\%$

T=25ºC $\gamma = 0.1\%$ → $\gamma = 80\%$

T=30ºC $\gamma = 0.1\%$ → $\gamma = 80\%$

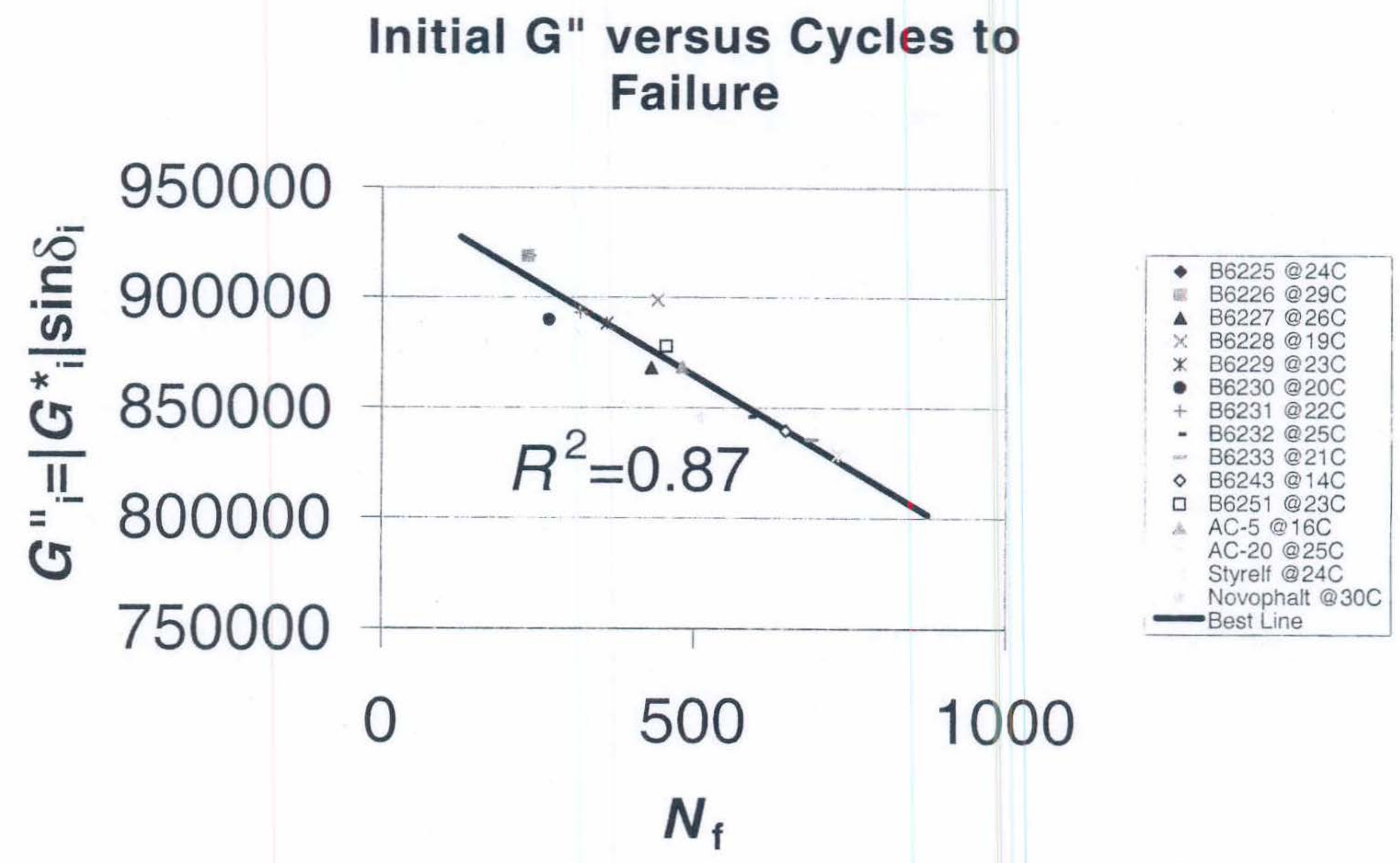
T ºC
where
$\gamma = 25\%$
&
|G*| = 1 MPa



X62 larger than PG

Shenoy, A., (July 2002) "Fatigue Testing and Evaluation of Asphalt Binders Using the Dynamic Shear Rheometer," *ASTM Journal of Testing and Evaluation*, Vol. 30, No. 4, pp 303-312

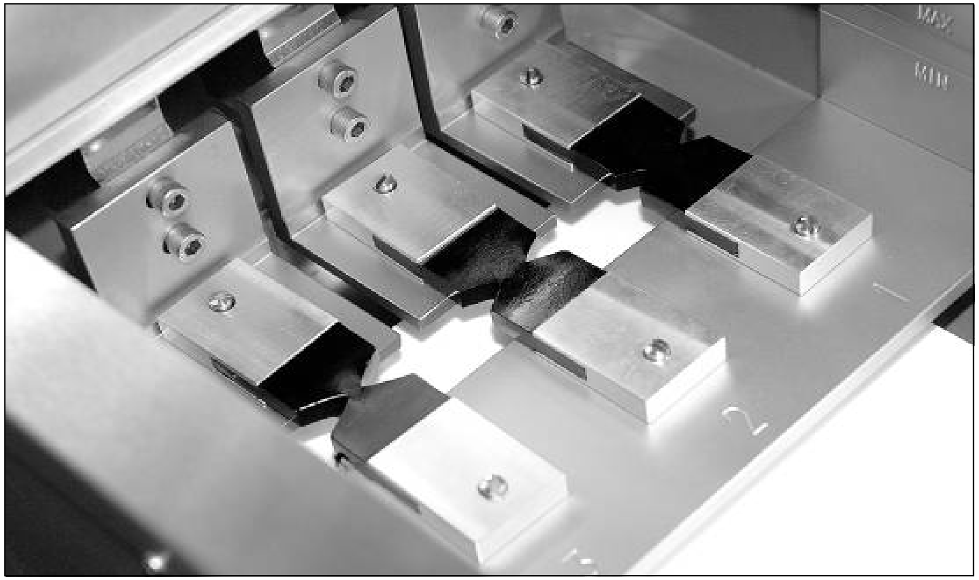
Fatigue – Large Strain Time Sweep Surrogate

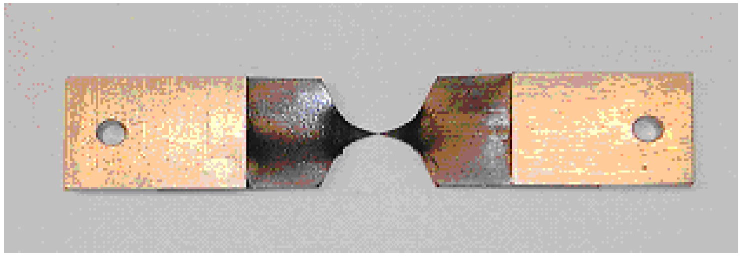


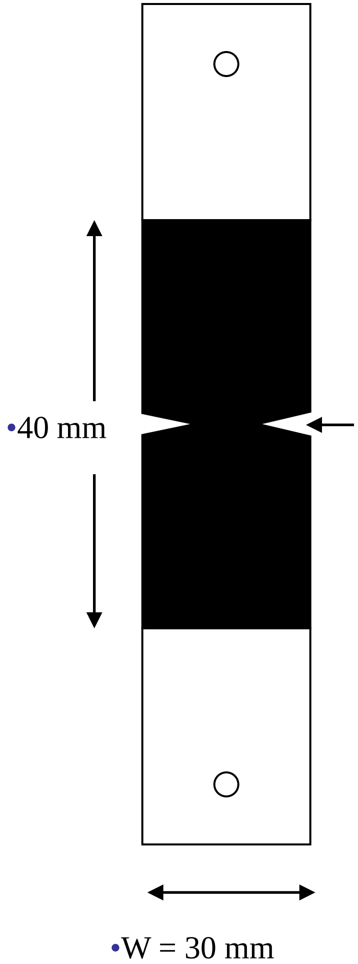
Fatigue – Large Strain Time Sweep Surrogate

Binder	$\|G^*\|\sin\delta$ [Pa] 19°C, 10 rads/s, 25% strain, RTFOT	$T_E\sin\delta_s$ [^oC] T_E @ $\|G^*_s\| = 1$ MPa 10 rads/s, 25% strain, RTFOT
Control 70-22	3,940,000	28.1
Air Blown	2,390,000	24.8
CR-TB	1,280,000	19.1
SBS-LG	1,360,000	19.2
Terpolymer	910,000	16.8
SBS 64-40	489,000	11.3

Fatigue – Critical Tip Opening Displacement



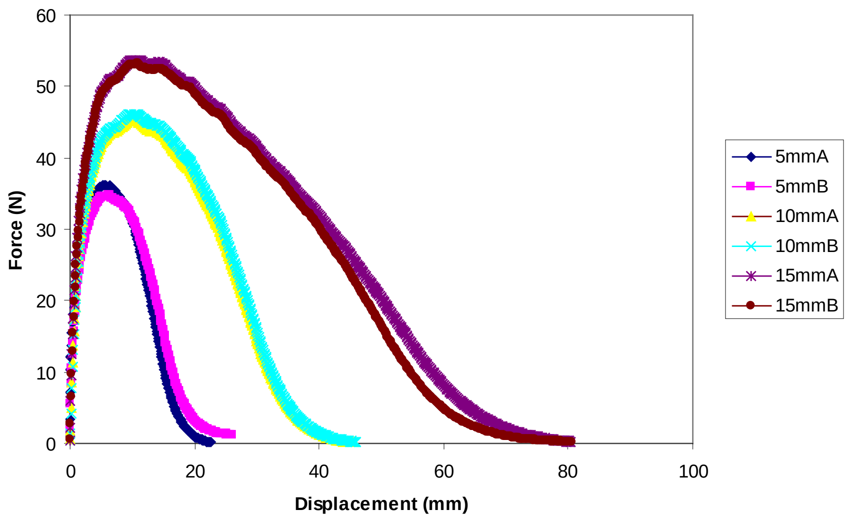


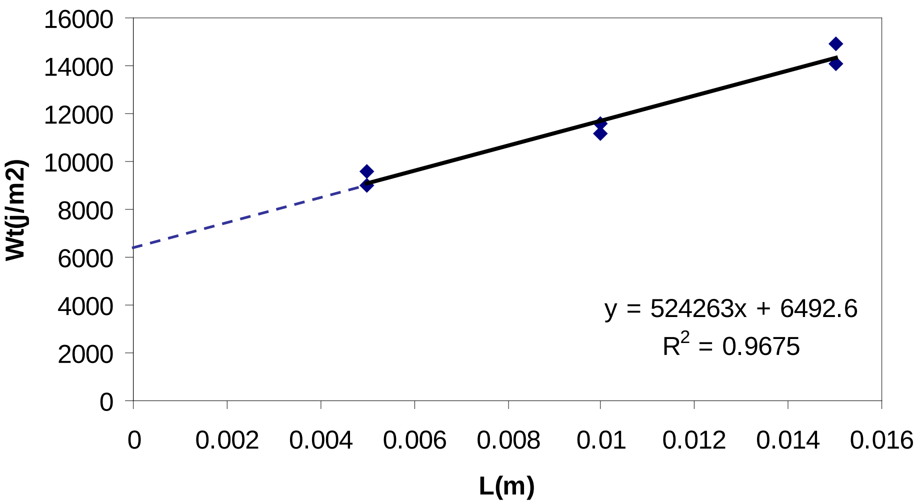


Fatigue – Critical Tip Opening Displacement

- **CTOD is a measure of strain tolerance in the presence of a crack**

Ontario **MTO Test Method LS-299**



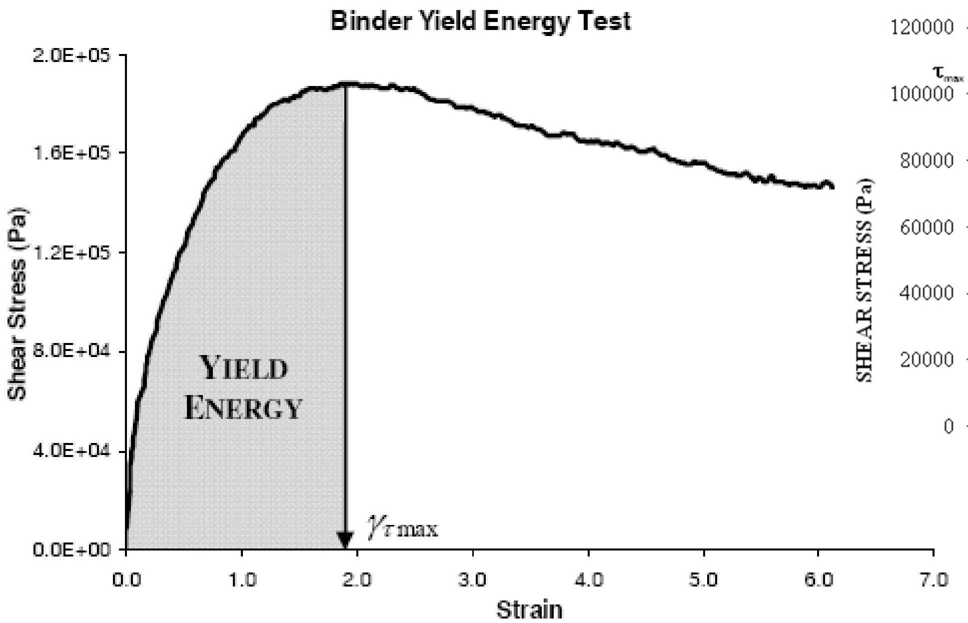


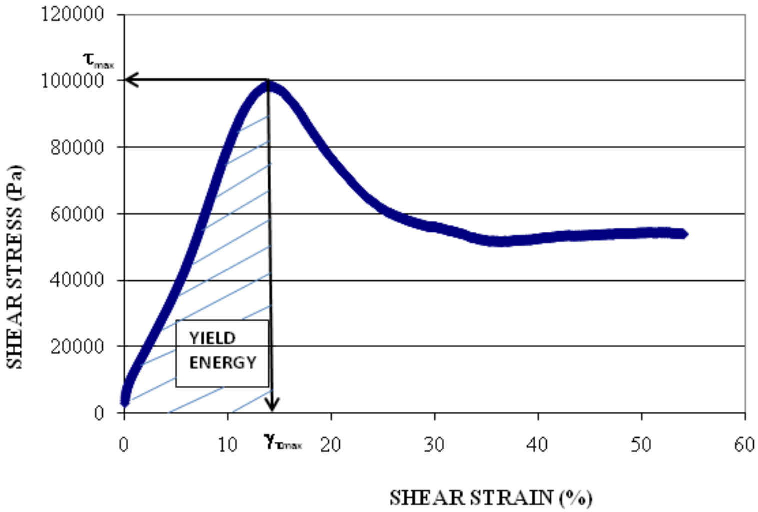
Fatigue – Critical Tip Opening Displacement

Binder	Essential Work of Fracture (EWF) [kJ/m2]	Yield Stress [kPa]	Calculated Critical Tip Opening Displacement (CTOD) [mm]
SBS 64-40	4.4	102	43.1
SBS-LG	1.02	43	24.0
Terpolymer	0.85	54	15.7
CR-TB	0.60	71	8.5
Control	0.97	129	7.5
Air Blown	0.70	103	6.8

Fatigue – Binder Yield Energy

Binder	Yield Energy [MPa] RTFO aged, 19°C, 0.0075 rad/sec
Terpolymer[1]	2.393
SBS-LG[1]	1.921
CR-TB[1]	1.759
Control[1]	0.342
Air Blown[1]	0.231
SBS 64-40[2]	0.0157





Statistical Scoring to Identify Stronger Tests

Binder Parameters for Rutting

100mm Lanes WITH Lane 6 Terpolymer

Binder Test for Rutting	Comparative Data	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Low Shear Viscosity	Flow Number	95%	-1.00	99%	-0.87	0.81
	ALF Rutting	82%	-0.40	76%	-0.71	
Zero Shear Viscosity	Flow Number	94%	-1.00	99%	-0.87	0.81
	ALF Rutting	82%	-0.40	76%	-0.71	
MSCR Non-recovered Compliance	Flow Number	99%	1.00	99%	0.97	0.72
	ALF Rutting	37%	0.40	76%	0.29	
Oscillatory-based Non-recovered Stiffness	Flow Number	88%	-0.8	96%	-0.78	0.69
	ALF Rutting	71%	-0.2	59%	-0.59	
$\lvert G^*\rvert/\sin\delta$ @ 0.25 rad/sec	Flow Number	89%	-0.40	76%	-0.79	0.63
	ALF Rutting	78%	-0.20	59%	-0.66	
Material Volumetric Flow Rate	Flow Number	77%	0.60	88%	0.66	0.59
	ALF Rutting	35%	0.40	76%	0.28	
$\lvert G^*\rvert/\sin\delta$ @ 10 rad/sec	Flow Number	59%	-0.20	59%	-0.48	0.56
	ALF Rutting	81%	-0.40	76%	-0.69	

Binder Parameters for Rutting

100mm Lanes WITHOUT Lane 6 Terpolymer

Binder Test for Rutting	Comparative Data	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Low Shear Viscosity	Flow Number	88%	-1.00	96%	-0.88	0.90
	ALF Rutting	98%	-0.67	83%	-0.98	
Zero Shear Viscosity	Flow Number	89%	-1.00	96%	-0.89	0.89
	ALF Rutting	95%	-0.67	83%	-0.95	
Oscillatory-based Non-recovered Stiffness	Flow Number	78%	-1.00	96%	-0.78	0.87
	ALF Rutting	95%	-0.67	83%	-0.95	
MSCR Non-recovered Compliance	Flow Number	99%	1.00	96%	0.99	0.86
	ALF Rutting	73%	0.67	83%	0.73	
|G*|/sinδ @ 0.25 rad/sec	Flow Number	80%	-0.67	83%	-0.80	0.73
	ALF Rutting	90%	-0.33	63%	-0.90	
Material Volumetric Flow Rate	Flow Number	68%	0.33	63%	0.68	0.68
	ALF Rutting	82%	0.67	83%	0.82	
|G*|/sinδ @ 10 rad/sec	Flow Number	56%	-0.33	63%	-0.56	0.44
	ALF Rutting	52%	0.00	38%	-0.52	

Binder Parameters for Rutting

- 150 mm lane rutting was simply too similar for useful statistical scores

- Zero and Low Shear Viscosities identified as strongest
  - ***However***, still physically a measure of viscosity
  - Apparent improvements can be achieved by means of stiffening from fillers or polyphosphoric acid that do not impart comparable performance improving characteristics of polymer modification

Binder Parameters for Fatigue Cracking

100mm Lanes

Binder Test for Fatigue Cracking	Comparative Data	*1-p_Reg_*	τ_K	*1-p_τK_*	*R*	Composite Score
Critical Tip Opening Displacement	Axial Fatigue	99%	1.00	99%	0.95	0.99
	ALF Cracking	100%	1.00	99%	0.98	
Binder Yield Energy	Axial Fatigue	94%	0.80	96%	0.87	0.88
	ALF Cracking	90%	0.80	99%	0.80	
Time Sweep	Axial Fatigue	89%	0.80	96%	0.79	0.88
	ALF Cracking	95%	0.80	96%	0.88	
Failure Strain in Low Temperature Direct Tension Test	Axial Fatigue	92%	0.60	88%	0.83	0.81
	ALF Cracking	93%	0.60	88%	0.85	
Superpave |G*|sinδ	Axial Fatigue	84%	-0.60	88%	-0.73	0.75
	ALF Cracking	78%	-0.60	88%	-0.66	
Large Strain Time Sweep Surrogate	Axial Fatigue	85%	-0.40	76%	-0.74	0.67
	ALF Cracking	78%	-0.40	76%	-0.67	
Essential Work of Fracture	Axial Fatigue	53%	0.40	76%	0.43	0.55
	ALF Cracking	60%	0.40	76%	0.50	
m-value from Low Temperature Bending Beam Rheometer	Axial Fatigue	63%	0.40	76%	0.52	0.54
	ALF Cracking	47%	0.40	76%	0.38	
Stress Sweep	Axial Fatigue	89%	-0.40	76%	-0.79	0.69* *Incorrect trend direction*
	ALF Cracking	83%	-0.40	76%	-0.73	

Binder Parameters for Fatigue Cracking

150mm Lanes

Binder Test for Fatigue Cracking	Comparative Data	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Critical Tip Opening Displacement	Axial Fatigue	96%	0.80	96%	0.89	0.62
	ALF Cracking	12%	0.40	76%	0.10	
Failure Strain in Low Temperature Direct Tension Test	Axial Fatigue	94%	0.60	88%	0.86	0.55
	ALF Cracking	16%	0.20	59%	0.13	
Large Strain Time Sweep Surrogate	Axial Fatigue	78%	-0.80	96%	-0.67	0.54
	ALF Cracking	38%	0.00	41%	-0.30	
Superpave $\|G^*\|\sin\delta$	Axial Fatigue	74%	-0.80	96%	-0.63	0.53
	ALF Cracking	38%	0.00	41%	-0.31	

Binder Parameters for Fatigue Cracking

150mm Lanes without Lane 9 SBS 64-40

Binder Test for Fatigue Cracking	Comparative Data	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Binder Yield Energy	Axial Fatigue	79%	1.00	96%	0.79	0.83
	ALF Cracking	79%	0.67	83%	0.79	
Critical Tip Opening Displacement	Axial Fatigue	29%	0.67	83%	0.29	0.75
	ALF Cracking	100%	1.00	96%	1.00	
Large Strain Time Sweep Surrogate	Axial Fatigue	68%	-0.67	83%	-0.68	0.64
	ALF Cracking	65%	-0.33	63%	-0.65	
Superpave |G*|sinδ	Axial Fatigue	67%	-0.67	83%	-0.67	0.63
	ALF Cracking	61%	-0.33	63%	-0.61	
Failure Strain in Low Temperature Direct Tension Test	Axial Fatigue	24%	0.33	96%	0.24	0.39
	ALF Cracking	21%	0.33	63%	0.21	

Binder Parameters for Fatigue Cracking

Ontario Highway 655

Binder		Superpave $\|G^*\|\sin\delta$ [kPa][74] 16°C	25°C	Critical Tip Opening Displacement 25°C [mm][74]	Binder Yield Energy 15°C [Pa] *FHWA TFHRC*
A	Terpolymer (Elvaloy)	2218	550	16	399.5
B	Oxidized + SBS	2588	860	10	822.5
C	SBS	1954	670	15	365
D	SBS	2226	690	13	504
E	SBS	2273	590	38	499
F	Oxidized	1820	690	7	818.5
G	Unmodified	1542	350	10	302.5

- **Designed to identify low temperature thermal cracking**
- **Contains load associated cracking**

Binder Parameters for Fatigue Cracking

Ontario Highway 655

(NB-SB) Total Number of All Cracks

Binder Test	Expected Trend	Correct	Regression Slope	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Critical Tip Opening Displacement	inverse	Yes	(-)	63%	-0.43	88%	-0.41	0.59
$\lvert G^*\rvert \sin\delta$ 25°C	proportional	Yes	(+)	7%	0.24	72%	0.04	0.27
Binder Yield Energy	inverse	No	(+)	18%	0.05	50%	0.10	0.21
$\lvert G^*\rvert \sin\delta$ 16°C	proportional	No	(-)	46%	-0.24	72%	-0.28	0.42

(NB-SB) Total Length of All Cracks

Binder Test	Expected Trend	Correct	Regression Slope	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Critical Tip Opening Displacement	inverse	Yes	(-)	79%	-0.62	97%	-0.54	0.73
Binder Yield Energy	inverse	No (somewhat)	(-) (+)	18%	0.05	50%	-0.11	0.21
$\lvert G^*\rvert \sin\delta$ 25°C	proportional	No (mostly)	(-)	63%	0.24	72%	-0.40	0.50
$\lvert G^*\rvert \sin\delta$ 16°C	proportional	No	(-)	80%	-0.43	88%	-0.55	0.66

Binder Parameters for Fatigue Cracking

Ontario Highway 655

(NB-SB) Total Length of Transverse Cracks

Binder Test	Expected Trend	Correct	Regression Slope	$1\text{-}p_{Reg}$	τ_K	$1\text{-}p_{\tau K}$	R	Composite Score
Critical Tip Opening Displacement	inverse	Yes	(-)	50%	-0.05	50%	-0.31	0.34
Binder Yield Energy	inverse	Yes	(-)	22%	-0.14	61%	-0.13	0.28
$\|G^*\|\sin\delta$ 25°C	proportional	Yes	(+)	6%	0.05	50%	0.04	0.16
$\|G^*\|\sin\delta$ 16°C	proportional	No	(-)	35%	-0.24	72%	-0.21	0.38

Binder Parameters for Fatigue Cracking

- 150 mm lanes were a challenge
  - SBS 64-40 mix tests indicated very good fatigue performance but ALF tests showed actual fatigue cracking sooner
  - Necessity to use engineering judgment on rank order between uncracked lane 12 and Lane 11.
- Binder Yield Energy scored high as well
  - but University of Wisconsin researchers had postponed further development for alternative techniques;
  - some modified binder produce two peaks; a first yield and ultimate yield which complicates the parameter
- Nonetheless, Critical Tip Opening Displacement was the most discriminating; ALF and Ontario

Q & A

FHWA Accelerated Load Facility Transportation Pooled Fund Studies

TPF-5(019) Full-Scale Accelerated Performance Testing for Superpave and Structural Validation

SPR-2(174) Accelerated Pavement Testing of Crumb Rubber Modified Asphalt Pavements

1st Closeout Webinar
August 16-17, 2010
11am – 2pm

Key Findings
and Recommendations

- **This study provided a critical evaluation of the Superpave specification |G*|/sinδ and |G*|sin δ as controlling parameters for rutting and fatigue cracking.**

- **A variety of candidate binder specification tests were evaluated based on the ability to discriminate permanent deformation and fatigue damage at the laboratory scale and rutting and fatigue cracking in full scale test pavements**

Key Findings

Binder Specification Parameters

- **Polymer modified asphalts clearly improve rutting and fatigue cracking performance.**

- Polymer modified binders can provide improved fatigue cracking performance compared to unmodified binders with similar high temperature PG grades

Key Findings

Binder Specification Parameters

- There are more discriminating binder tests for fatigue cracking and rutting than standard Superpave $|G^*|\sin\delta$ and $|G^*|/\sin\delta$
- **Strongest Implementable Parameters:**
  - **MSCR and similar Oscillatory-based non-recoverable stiffness for rutting**
  - **calculated Critical Tip Opening Displacement for fatigue cracking**

Key Findings

Binder Specification Parameters

- On the other hand, the statistically similar rutting in mixes having binders chosen based on similar $|G^*|\sin\delta$ has another interpretation

$|G^*|\sin\delta$ is 'not bad'

Key Findings

Binder Specification Parameters

- Increasing polymer content in relatively softer base asphalt binders to achieve higher temperature PG grades does not necessarily provide increased fatigue cracking resistance (SBS “64-40”)
  - An important caveat of this conclusion is this may only be applicable for the particular structural configuration of the ALF pavements in this experiment.

Key Findings

Crumb Rubber Modified Asphalt

- Gap graded crumb rubber modified asphalt mix (Arizona 'wet process') placed in a composite pavement structure exhibited excellent resistance to bottom-up fatigue cracks.
  - Benefited from a stiffer mix below
  - Fatigue cracks initiated and propagated up through two inches of conventional dense graded asphalt on the bottom but did not progress through any of the two inches of the gap-graded crumb rubber mix on top.

Key Findings

Fiber Reinforced HMA

- The fatigue cracking of this section was measurably better than those of the polymer modified sections even though a less resistant unmodified asphalt binder was used in the mix.
- The presence of fiber had no significant impact on the rutting performance.
- All relevant mixture tests had trouble reflecting good performance

Key Finding

Asphalt Mix Performance Tester (AMPT)

- AMPT Flow Number and SST Repeated Shear at Constant Height were the two strongest indicators of ALF rutting. The AMPT Flow Number test is a stronger predictor and more implementable.
- Most Flow Number tests did not achieve tertiary flow and showed simpler two-stage curves but still adequately discriminated performance.

Key Finding

Axial Fatigue Test

- An alternative test for flexural beam fatigue was assessed which used axial, direct tension-compression cyclic loading to capture fatigue damage modulus reduction.
- Axial fatigue with VECD can be used to generate fatigue properties at multiple conditions with a smaller experimental program than beam fatigue.

Key Finding

Axial Fatigue Test

- This test is a strong, implementable (is being done in the AMPT) indicator of fatigue cracking and correcting the tests results for true strain control using VECD theory strengthened the test's abilities further.

Key Finding

Axial Fatigue Test

- Easily used to generate material properties which are compatible with MEPDG

$$N_F = f(\varepsilon_T, E) \quad 0.00432\, C\, k_1 \left(\frac{1}{\varepsilon_T} \right)^{k_3} \left(\frac{1}{E} \right)^{k_4}$$

- Key material input for FHWA's "Developing Performance Related Specifications for Asphalt Mixtures", North Carolina State University (DTFH61-08-H-00005)

Key Finding

Mixture Characterization Tests

- The importance of testing asphalt mixture to confirm performance cannot be understated and should not rely entirely on binder tests because additives such as fibers will always challenge specification tests at the binder scale
- Mixture test are best suited to accommodate pavement structural attributes and volumetric mix design characteristics.

Key Finding

Mechanistic Empirical Pavement Design Guide

- Additional mixture-specific characterization inputs are needed above and beyond the |E*| dynamic modulus to be able to better discriminate and rank performance of modified and unmodified asphalt.

- Results confirm NCHRP 9-30A approach for mixture-specific tests to improve rutting prediction

Recommendations

- These tests are recommended based on the analysis of the data:
  - Binder Critical Tip Opening Displacement
  - (Re-affirm MSCR as a $|G^*|/\sin\delta$ companion binder specification for rutting)
  - Oscillatory based non-recovered stiffness
  - AMPT Axial Cyclic Fatigue with VECD
  - AMPT Triaxial Repeated Load Permanent Deformation (Flow Number)
    - Confined: 10 psi confinement, ~70-120 psi deviator
    - Unconfined: ~ 30 psi

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Day 2

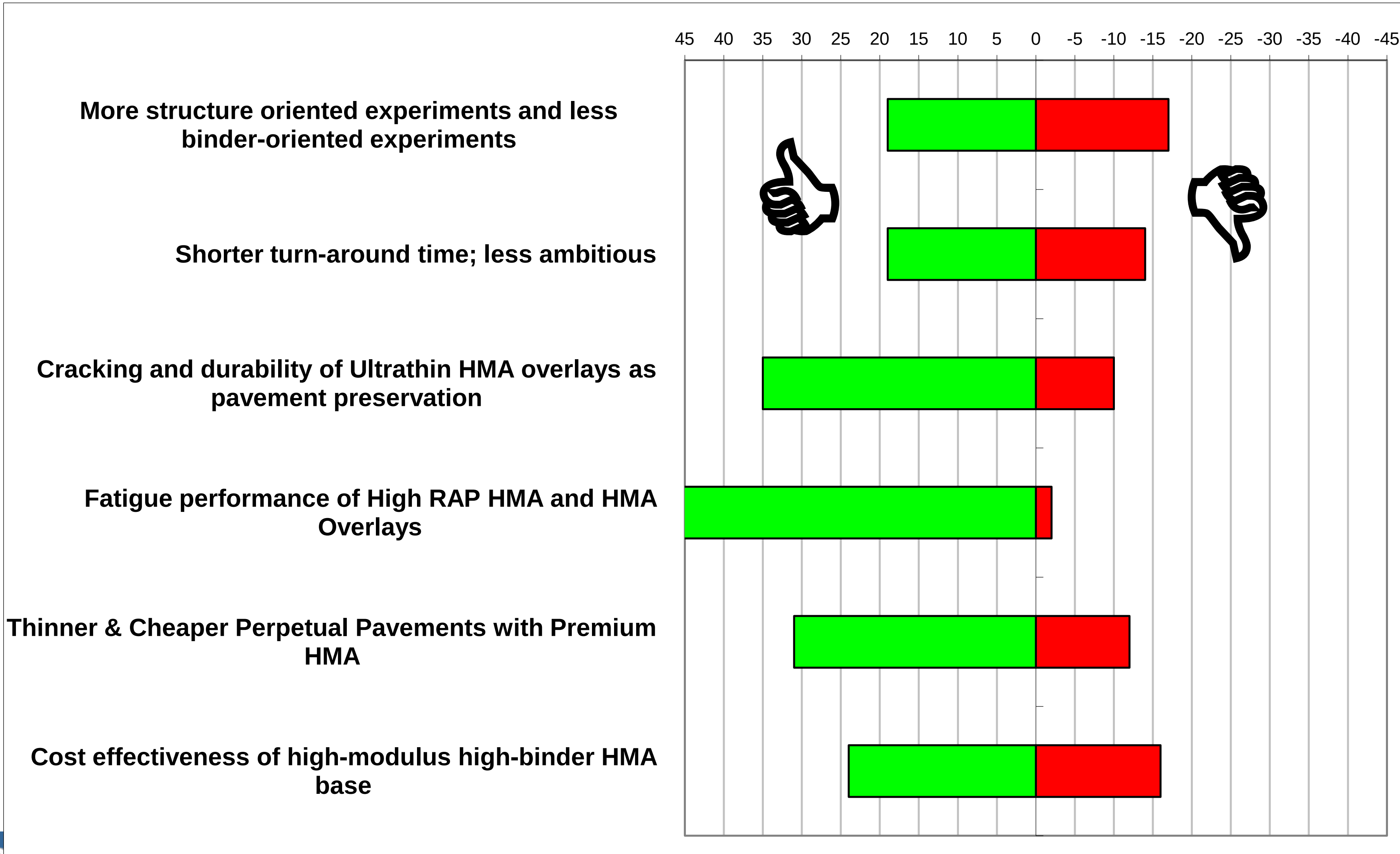
Stakeholder Input

Future ALF Studies

Polled Agency, Industry Academia

- Southeast Asphalt User Producer Group
- Nebraska Asphalt Paving Conference
- Asphalt ETGs

Combined Results



Also added the following:

- Cost effectiveness of high-modulus high-binder HMA base
- Performance of Reclamation Techniques and Changes in Emulsified Binder
- Lower-quality RAP as Rehabilitation Layer
- Impact of Construction Techniques (roller pattern, QC) on Performance

Partial Results with New Questions