NCHRP 9-46
RAP ETG meeting

Irvine, CA

May 10, 2011

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Outline

- Mix Design Concept for High RAP Content Mixes
- Back-calculation Analyses
- Comparison of Dynamic Modulus results
- Flow Number
- Selection of a Fatigue Test

Mix Design for High RAP Contents

- Start mix design with bumped virgin binder grade
- Design mix to meet M 323
- Moisture Susceptibility (always)
  - TSR or Hamburg
- Permanent Deformation (mixes within top 100 mm)
  - AMPT Flow Number or APA
- Fatigue (surface or base mixes)
  - AMPT fatigue or Overlay Tester
- Low Temperature (for cold climates)
  - SCB and BBR with mix beams

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Experiment

- Mix Designs with 4 sets of materials: UT, MN, NH, FL
- RAP Contents: 0 & 40% or 0, 25, & 55%
- Two binder grades and two binder sources
- Volumetrics, E*, FN, TSR, SCB and BBR, and a fatigue test

Dynamic Modulus of RAP Mixtures and Backcalculation of Binder Properties

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E* Testing Methodology

- AASHTO TP 62-07
- Temperatures
  - 4.4, 21.1, 37.8, and 54.4 °C
- Frequencies
  - 25, 10, 5, 1, 0.5, 0.1 Hz
- Confined: 10 psi
- Target Strain: 100με
- Data quality assured
- Sigmoidal function to create mastercurves

AMPT

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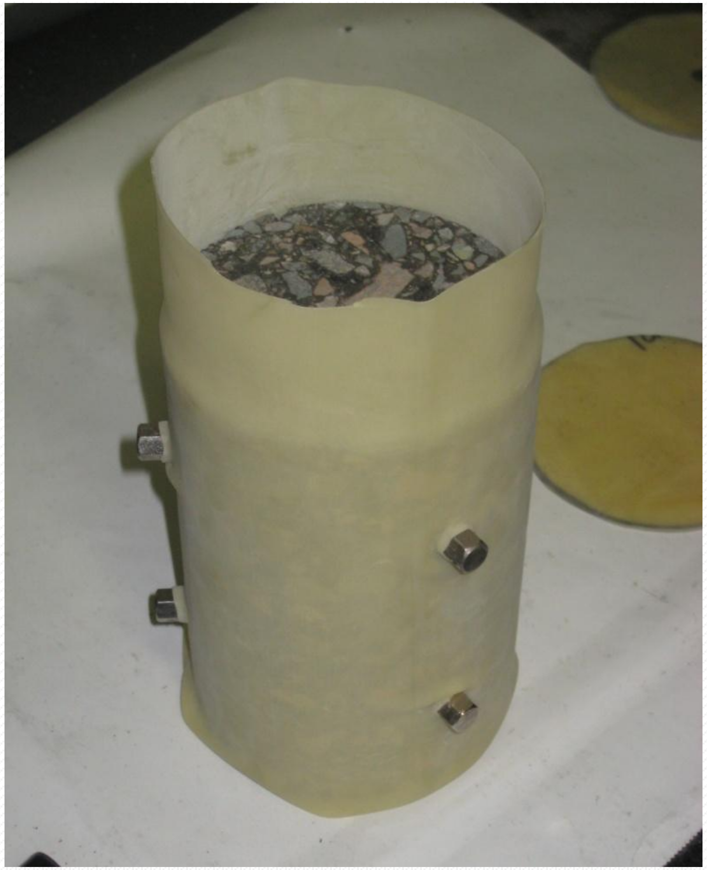
Error in Original Testing



- Holes were cut in membrane around LVDT mounting studs
- Eliminated sample confining pressure

Error in Original Testing

- Samples were not allowed to vent to atmospheric pressure
- Pore pressure in air voids counteracting the confining pressure

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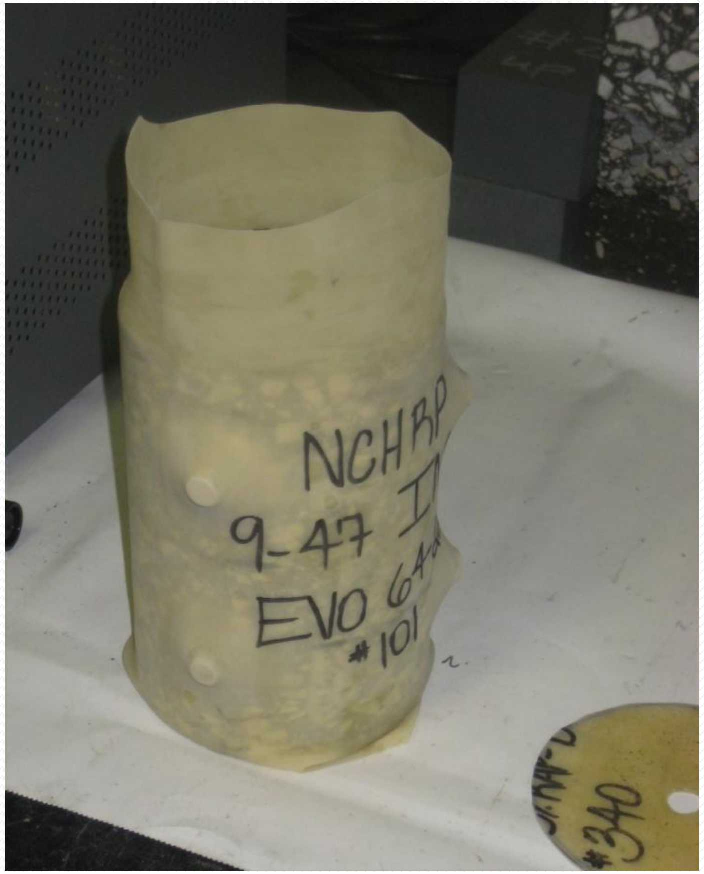
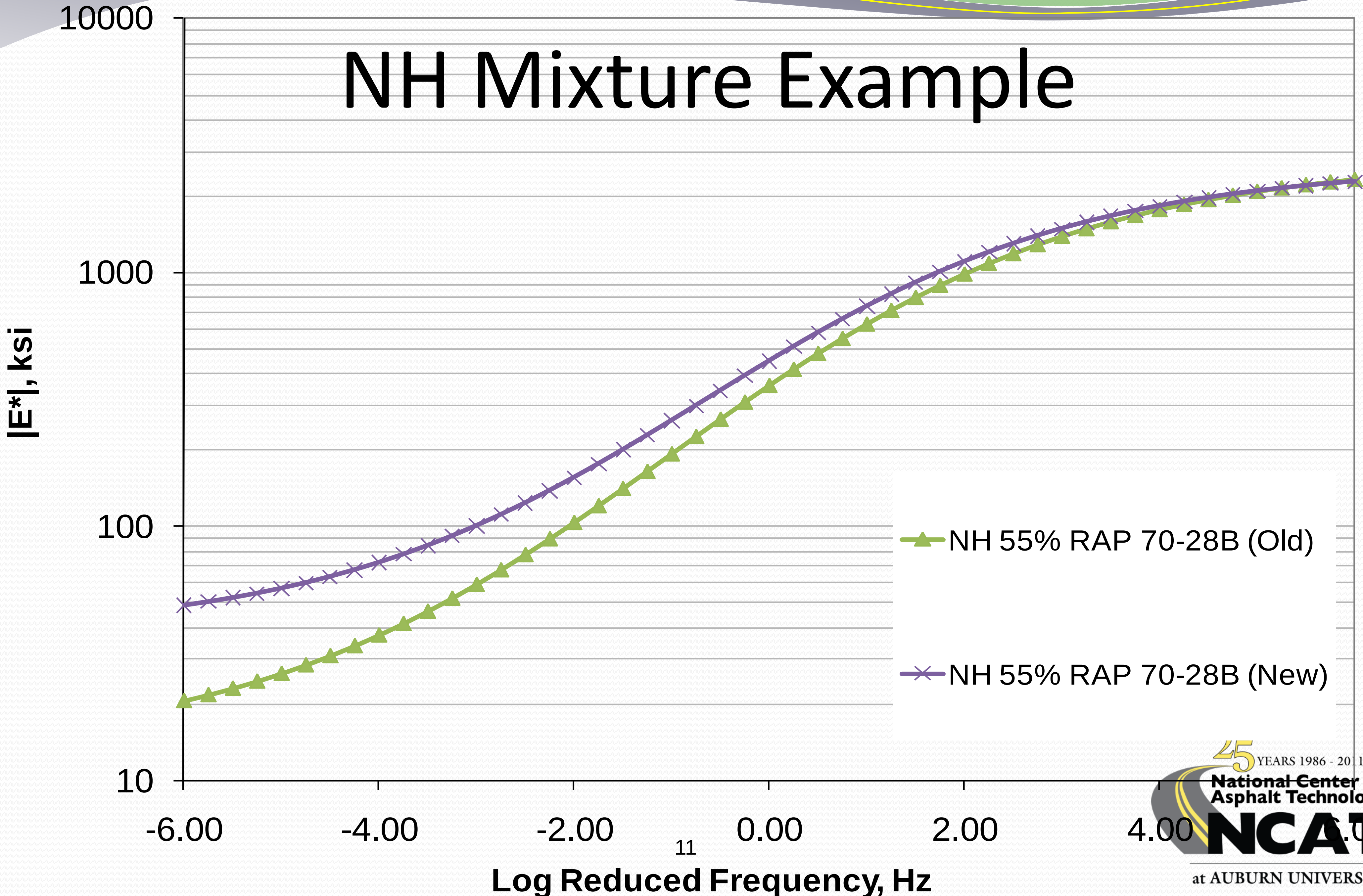
Correct Method



Dynamic Modulus
Effect of Confinement

NH Mixture Example



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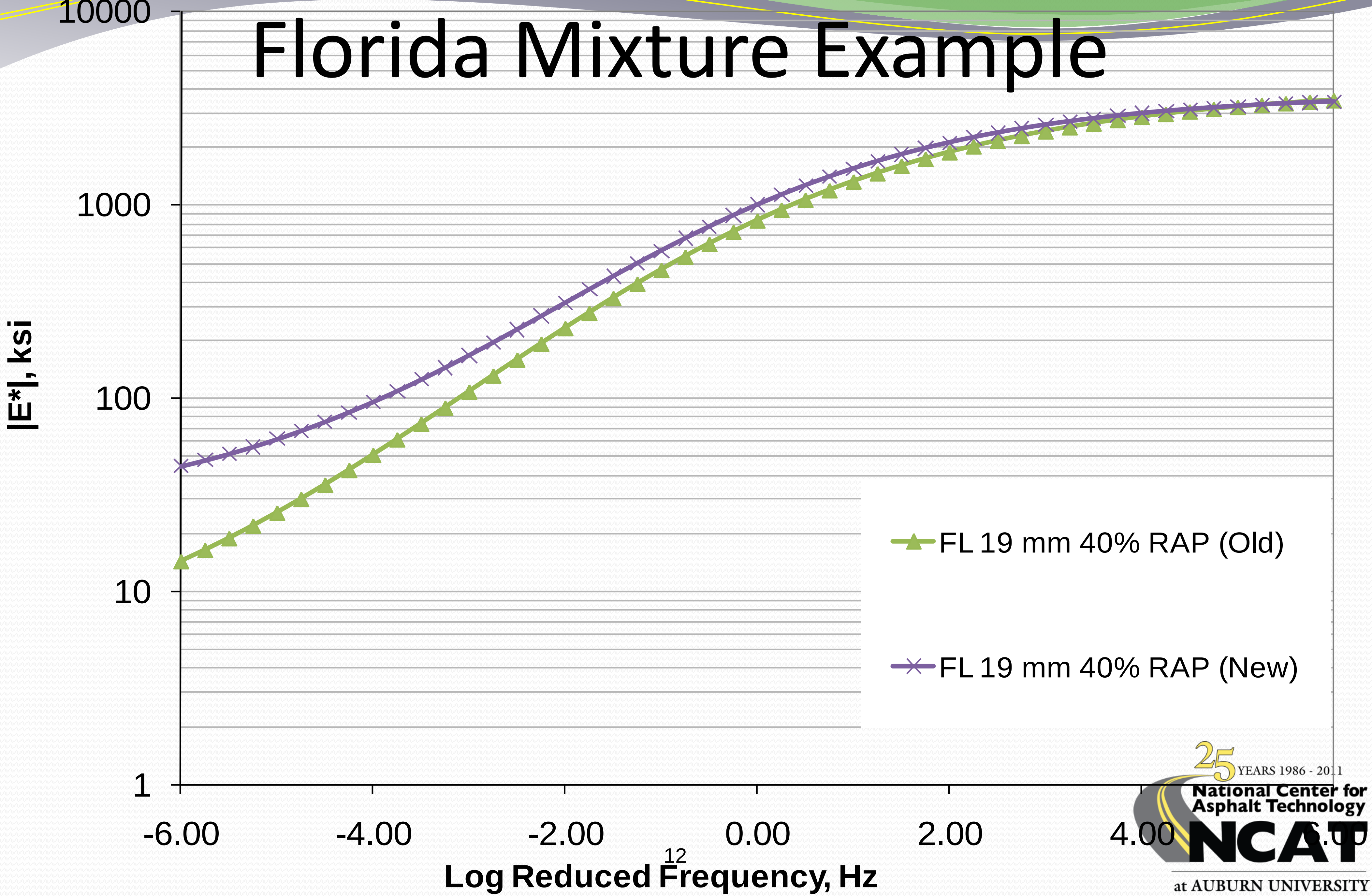
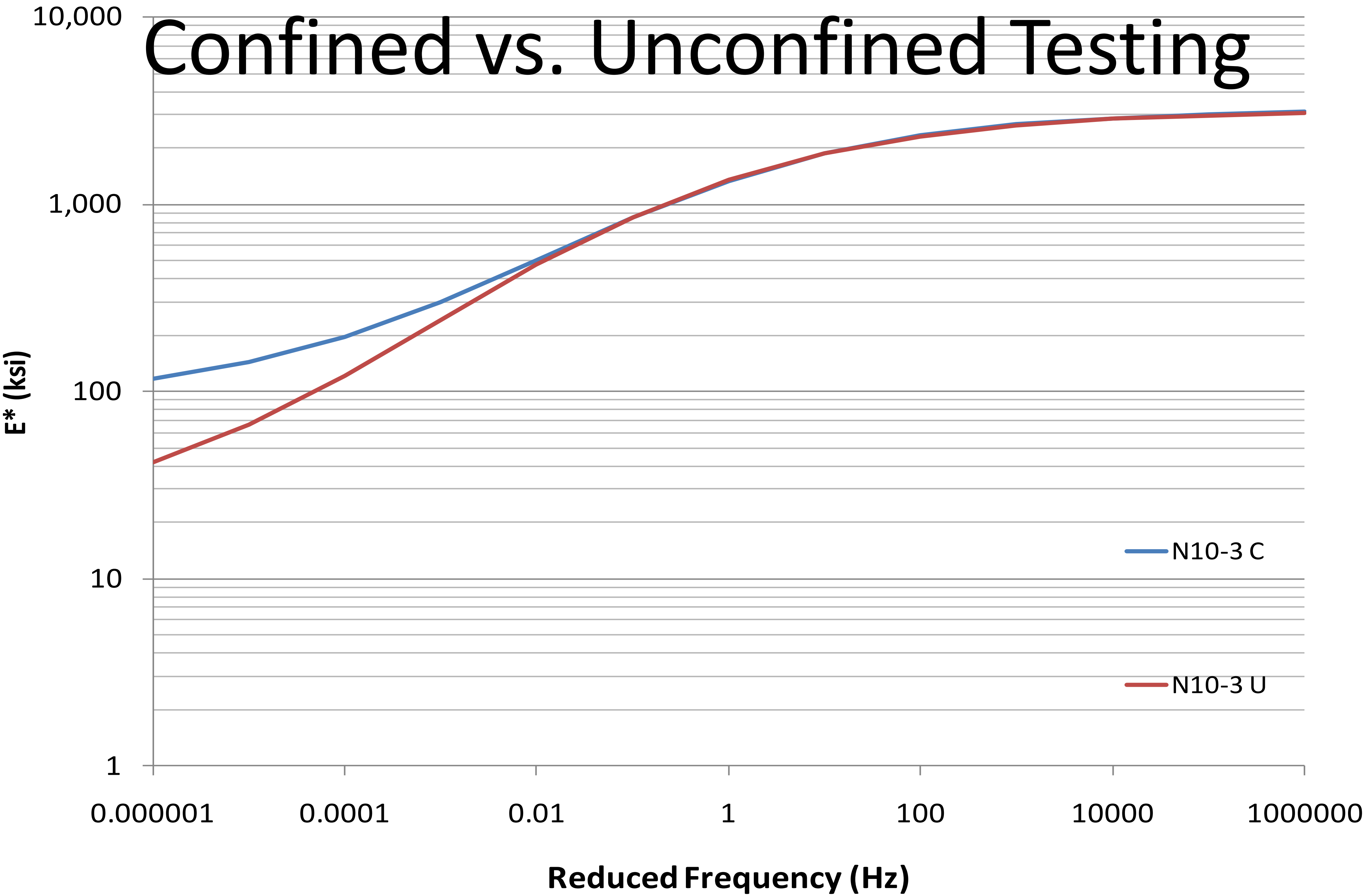
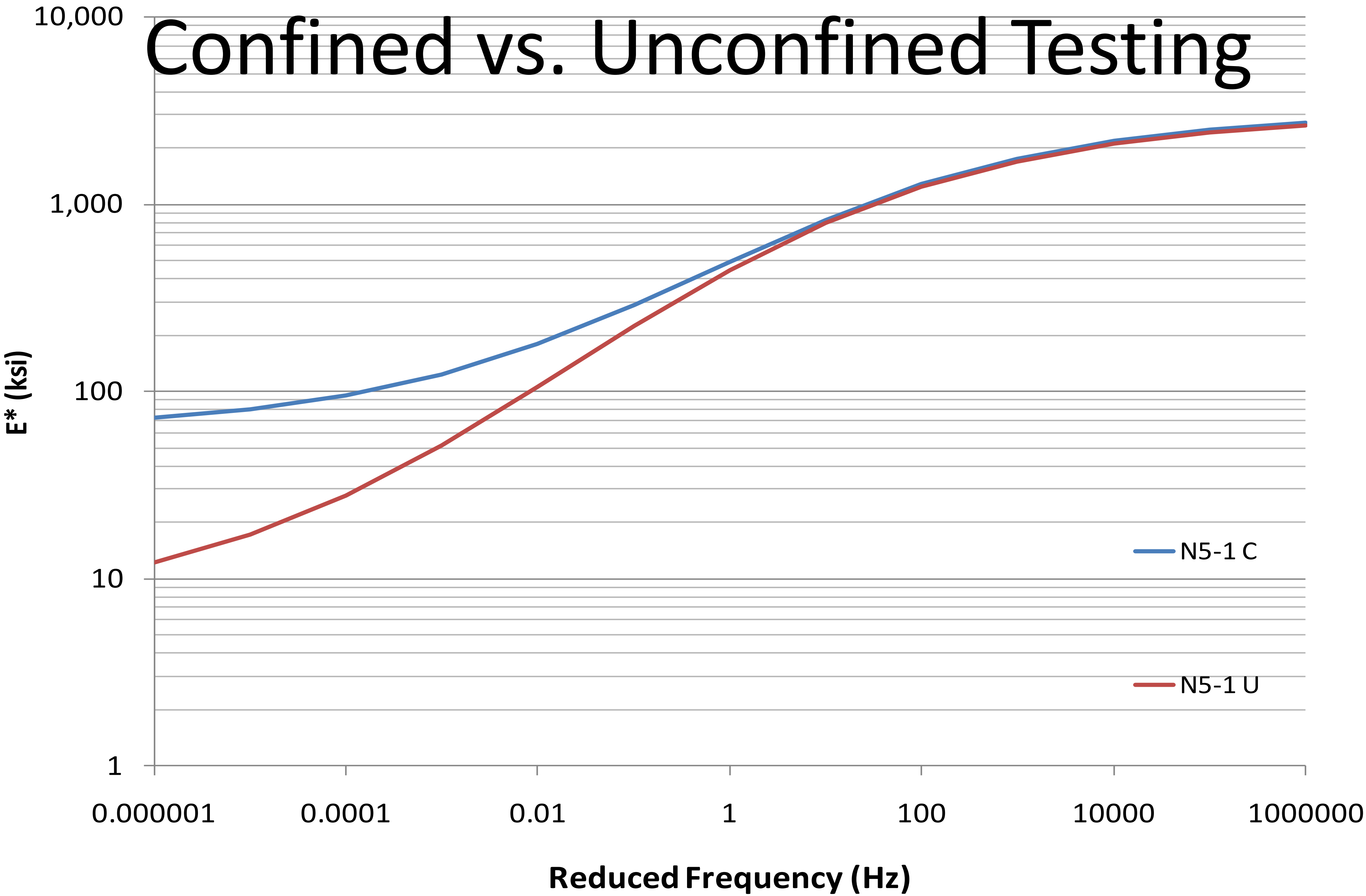
Florida Mixture Example



Confined vs. Unconfined Testing



Confined vs. Unconfined Testing



Statistical Comparisons of E* for 9-46 Mixes

Statistically Significant Factors for E*

Region	Variables	4.4C	21.1C	37.8C	54.4C
FL	% RAP	% RAP	% RAP	% RAP	% RAP
MN	% RAP	% RAP	None	%RAP	% RAP
NH	Binder Grade Binder Source % RAP	Source % RAP	Grade % RAP	Grade % RAP	Grade Source % RAP
UT	Binder Grade Binder Source % RAP	Source % RAP	Grade % RAP	Grade % RAP	Grade Source % RAP

Statistic: General Linear Model (α = 0.05)

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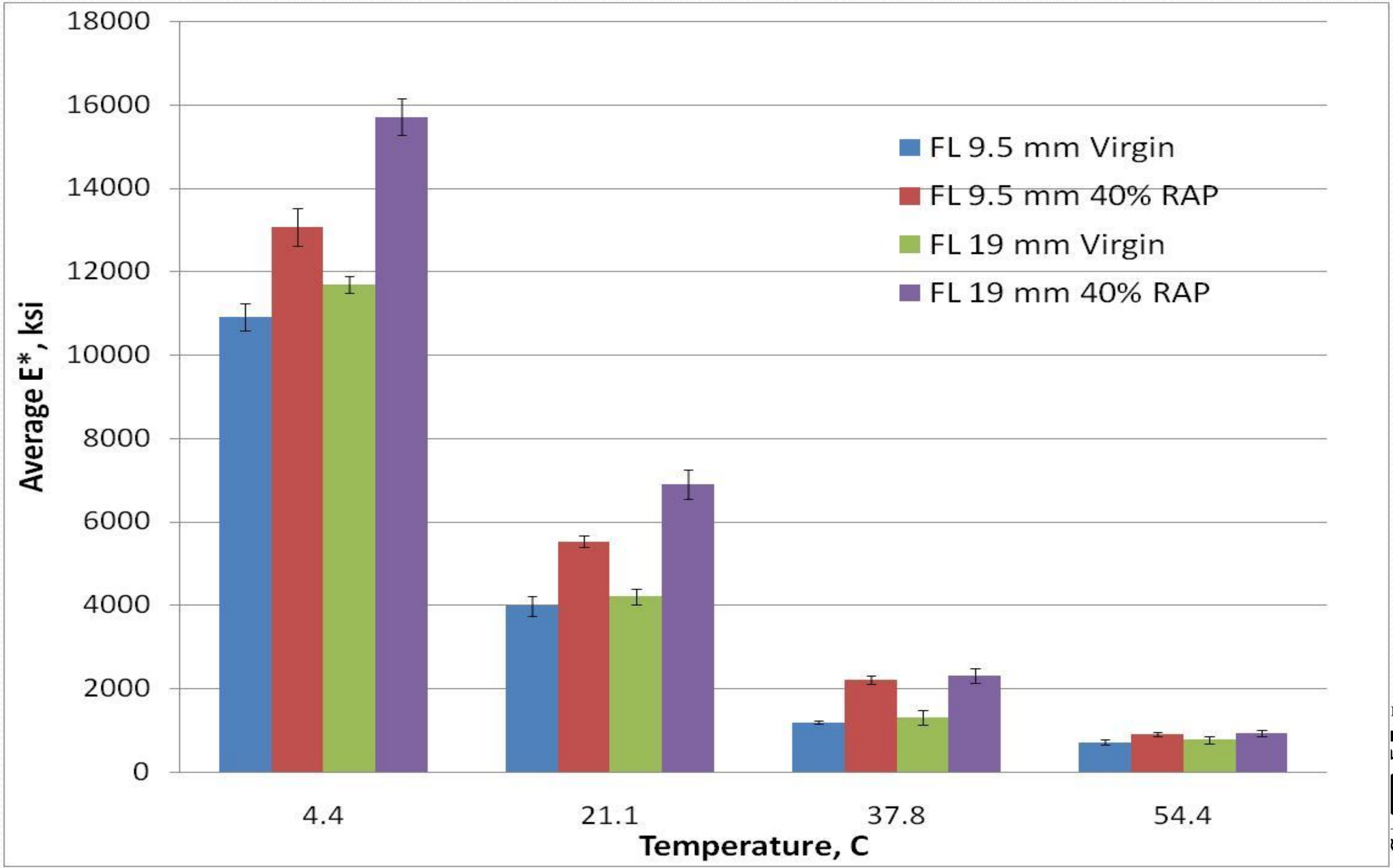
Florida Average E* Results at 1 Hz



Percent Difference in E* by % RAP

		% Difference @ Temperature, C			
Mix 1	***Mix 2***	4.4	21.1	37.7	54.4
FL 9.5mm Virgin	FL 9.5mm 40% RAP	19.8%	38.9%	85.3%	26.8%
FL 19mm Virgin	FL 19mm 40% RAP	34.5%	63.6%	77.3%	21.6%
MN 9.5mm Virgin	MN 9.5mm 40% RAP	60.5%	-5.4%	24.9%	33.5%
MN 19mm Virgin	MN 19mm 40% RAP	77.4%	229.5%	185.1%	51.5%

Percent Difference in E* by % RAP

		% Difference @ Temperature, C			
Mix 1	***Mix 2***	4.4	21.1	37.7	54.4
NH 58-28A Virgin	NH 58-28A 25% RAP	21.5%	49.0%	71.5%	43.9%
NH 58-28A Virgin	NH 58-28A 55% RAP	39.9%	77.2%	103.9%	30.1%
NH 58-28A 25% RAP	NH 58-28A 55% RAP	15.1%	18.9%	18.9%	-9.6%
NH 58-28B Virgin	NH 58-28B 55% RAP	12.7%	31.0%	14.4%	3.7%
NH 70-28A Virgin	NH 70-28A 25% RAP	8.2%	28.9%	21.1%	46.1%
NH 70-28A Virgin	NH 70-28A 55% RAP	17.8%	18.3%	10.8%	20.1%
NH 70-28A 25% RAP	NH 70-28A 55% RAP	8.9%	-8.2%	-8.5%	-17.8%
NH 70-28B Virgin	NH 70-28N 55% RAP	10.6%	13.6%	22.3%	15.1%

Percent Difference in E* by % RAP

		% Difference @ Temperature, C			
Mix 1	***Mix 2***	4.4	21.1	37.7	54.4
UT 58-34A Virgin	UT 58-34A 25% RAP	51.9%	66.2%	48.9%	21.9%
UT 58-34A Virgin	UT 58-34A 55% RAP	54.2%	87.3%	56.3%	40.1%
UT 58-34A 25% RAP	UT 58-34A 55% RAP	1.5%	12.7%	5.0%	14.9%
UT 58-34B Virgin	UT 58-34B 55% RAP	94.3%	101.7%	34.5%	2.8%
UT 64-34A Virgin	UT 64-34A 25% RAP	15.7%	15.2%	13.6%	29.8%
UT 64-34A Virgin	UT 64-34A 55% RAP	80.3%	136.3%	92.7%	33.3%
UT 64-34A 25% RAP	UT 64-34A 55% RAP	55.9%	105.2%	69.6%	2.7%
UT 64-34B Virgin	UT 64-34B 55% RAP	98.2%	150.2%	131.3%	53.9%

% Difference in E* by Binder Grade

		% Difference @ Temperature, C			
Mix 1	***Mix 2***	4.4	21.1	37.7	54.4
NH 58-28A Virgin	NH 70-28A Virgin	23.0%	55.0%	83.2%	45.2%
NH 58-28A 25% RAP	NH 70-28A 25% RAP	9.5%	34.0%	29.4%	47.5%
NH 58-28A 55% RAP	NH 70-28A 55% RAP	3.6%	3.4%	-0.5%	34.1%
NH 58-28B Virgin	NH 70-28B Virgin	-4.7%	21.8%	43.6%	28.2%
NH 58-28B 55% RAP	NH 70-28B 55% RAP	-6.5%	5.6%	53.6%	42.3%
UT 58-34A Virgin	UT 64-34A Virgin	-15.2%	-15.2%	-2.7%	-1.4%
UT 58-34A 25% RAP	UT 64-34A 25% RAP	-33.9%	-39.9%	-25.7%	5.0%
UT 58-34A 55% RAP	UT 64-34A 55% RAP	1.6%	9.5%	20.0%	-6.2%
UT 58-34B Virgin	UT 64-34B Virgin	2.3%	18.1%	-4.0%	-10.1%
UT 58-34B 55% RAP	UT 64-34B 55% RAP	4.3%	46.4%	65.1%	34.5%

% Difference in E* by Binder Source

		% Difference @ Temperature, C			
Mix 1	***Mix 2***	4.4	21.1	37.7	54.4
NH 58-28A Virgin	NH 58-28B Virgin	-12.9%	-21.4%	-20.9%	-26.0%
NH 58-28A 55% RAP	NH 58-28B 55%	9.0%	10.3%	32.2%	-0.4%
NH 70-28A Virgin	NH 70-28B Virgin	12.5%	4.6%	5.3%	-11.2%
NH 70-28A 55% RAP	NH 70-28B 55% RAP	17.9%	8.4%	-4.6%	-6.6%
UT 58-34A Virgin	UT 58-34B Virgin	25.0%	31.9%	13.0%	-0.1%
UT 58-34A 55% RAP	UT 58-34B 55% RAP	5.4%	26.6%	25.1%	26.6%
UT 64-34A Virgin	UT 64-34B Virgin	11.6%	7.4%	14.1%	8.8%
UT 64-34A 55% RAP	UT 64-34B 55% RAP	2.8%	2.0%	-3.0%	-5.3%

Tukey-Kramer Grouping of E* (MN and FL mixtures)

- No virgin mixtures from FL were grouped with RAP mixtures
- Both MN virgin and RAP mixtures were grouped together at 21.1C
- MN 9.5mm virgin and MN 9.5 mm 40% RAP were grouped together at 37.7C

Tukey-Kramer Grouping of E* (NH Mixtures)

- Changing the binder grade from a PG 58-28 to PG 70-28 statistically affected E* at 21.2, 37.8, and 54.4C
- E* was statistically different between binder sources at 21.2 and 37.8C
- E* of virgin and 25% RAP mixtures similar at 4.4C
- E* of 25 and 55% RAP mixtures only statistically different at 54.4C

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Tukey-Kramer Grouping of E* (UT Mixtures)

- Changing the binder grade from a PG 58-34 to PG 64-34 never statistically affected E*
- E* was statistically different between binder sources at 21.2C
- E* of virgin and 25% RAP mixtures similar at 37.8C
- E* of 25 and 55% RAP mixtures statistically similar at 54.4C

Back-calculation of Binder Properties from E*

Backcalculation of Binder Properties

- Methodology
  - Use Hirsch model to backcalculate G*

$$E^*_{\max} = P_C\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3G^*\left(\frac{VFA*VMA}{10{,}000}\right)\right]+(1-P_c)\left[\frac{1-(VMA/100)}{4{,}200{,}000}+\frac{VMA}{3(VFA)G^*}\right]^{-1}$$

  - E* = limiting maximum HMA dynamic modulus, psi
  - VMA = voids in mineral aggregate, %
  - VFA = voids filled with asphalt, %
  - G*= shear dynamic modulus of binder, psi

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Backcalculation of Binder Properties

- Average E* from three tests at each frequency and temperature
- Microsoft © Excel macro developed to backcalculate G* from Hirsch Model
- Christensen-Anderson Model model used to create G* master curves
- Solved for high and intermediate critical temperatures
  - High temp: $G^*/\sin(\delta) = 2.2$ kPa
  - Intermediate temp: $G^*\sin(\delta) = 5{,}000$ kPa

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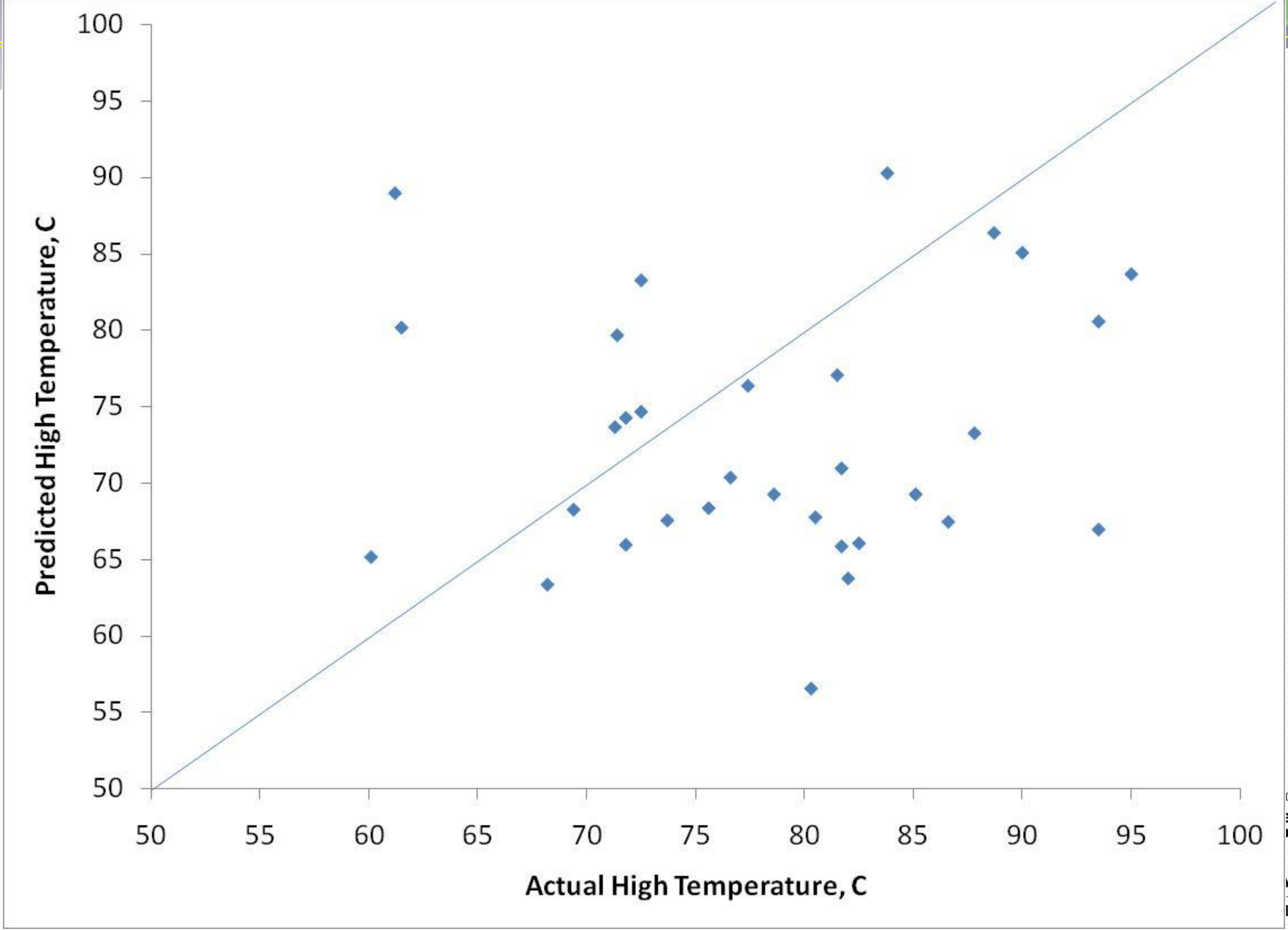
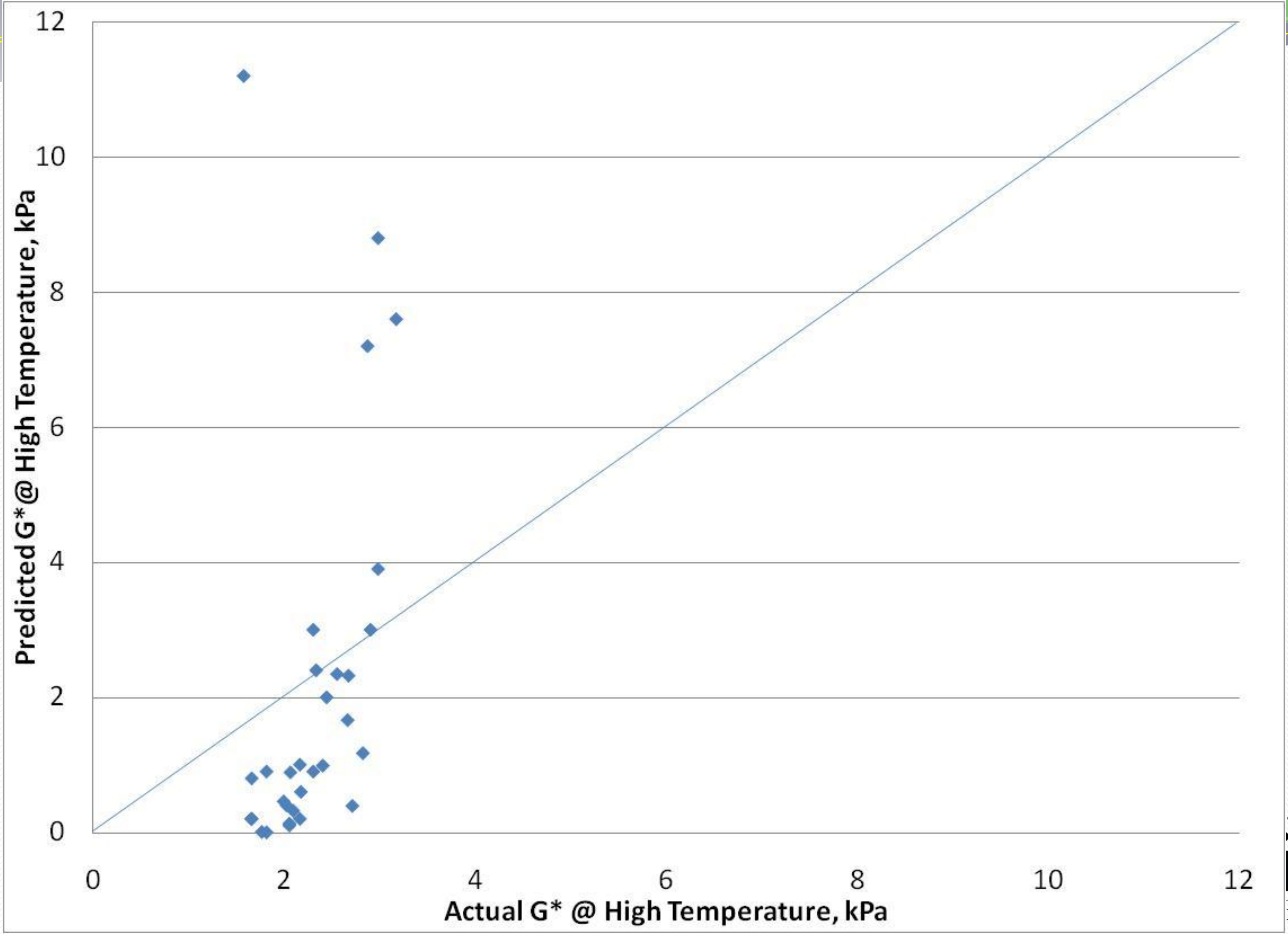
Mixtures Analyzed

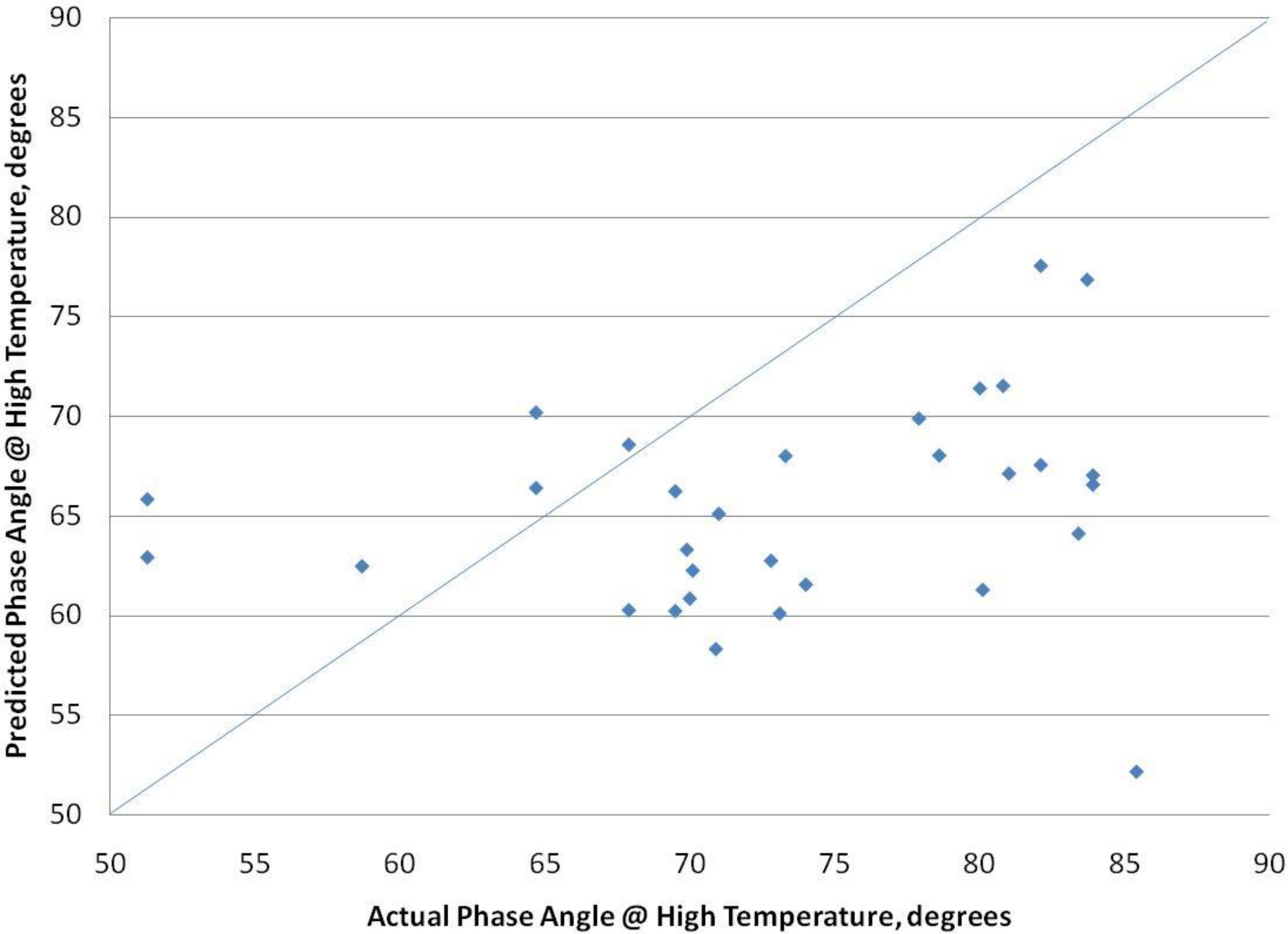
- FL 19 mm No RAP
- FL 9.5 mm No RAP
- NH 58-28A No RAP
- NH 58-28B No RAP
- NH 70-28A No RAP
- NH 70-28B No RAP
- UT 58-34B No RAP
- UT 64-34A No RAP
- 2009 Test Track Mixtures



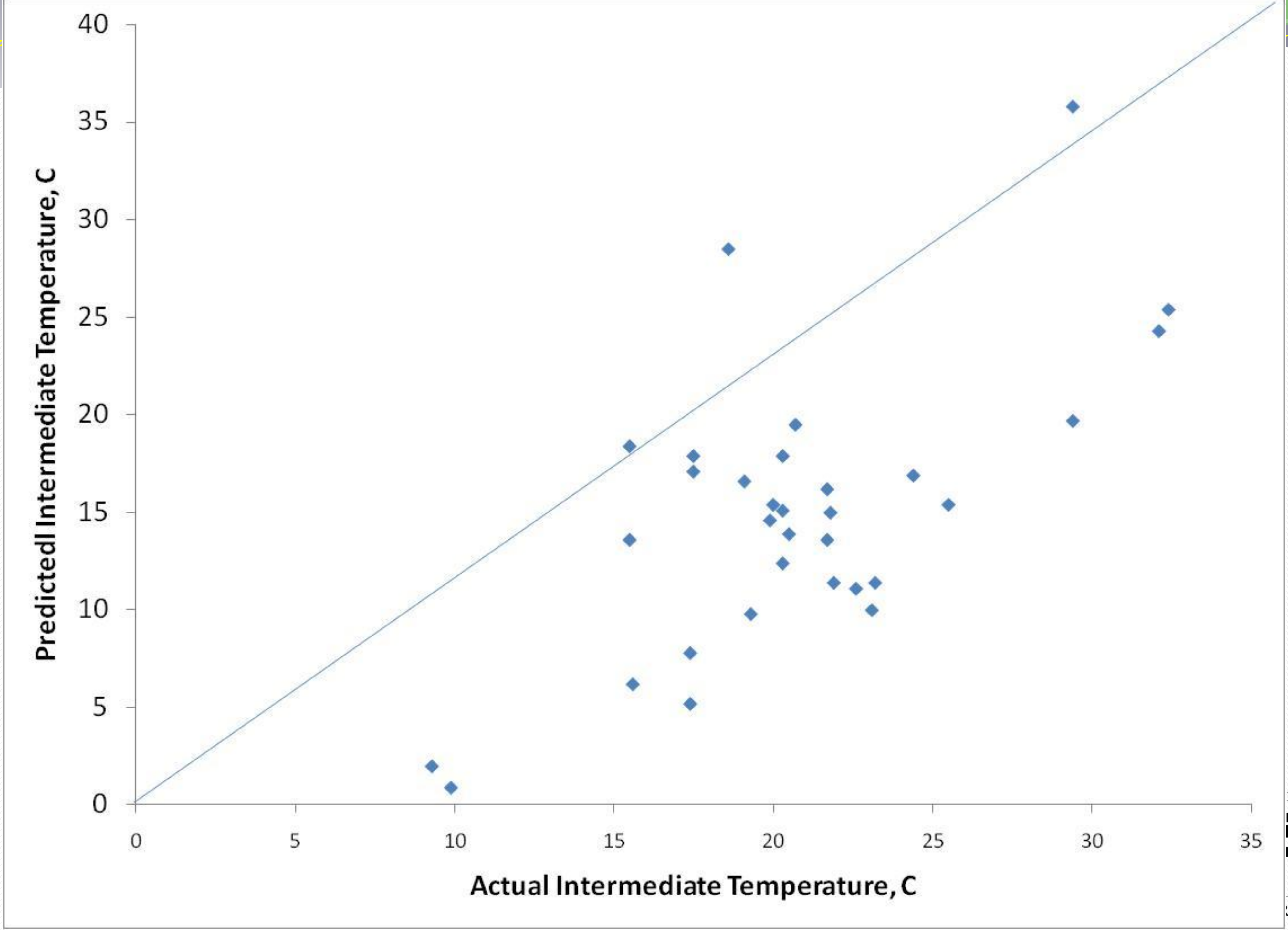
Predicted High Temperature, C
100
95
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
90
95
100
Actual High Temperature, C

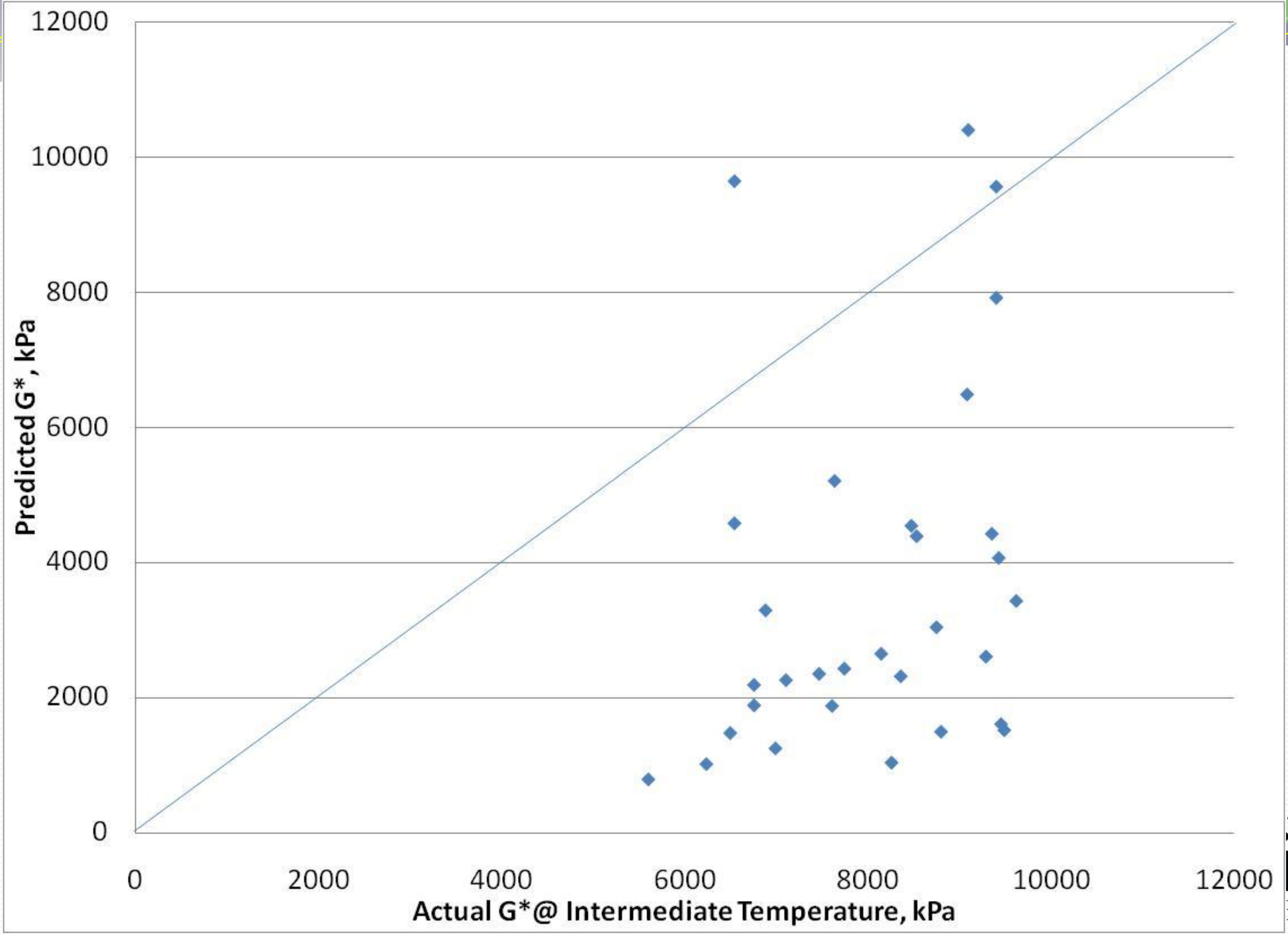


12
10
8
6
4
2
0
Predicted G*@ High Temperature, kPa
0
2
4
6
8
10
12
Actual G* @ High Temperature, kPa

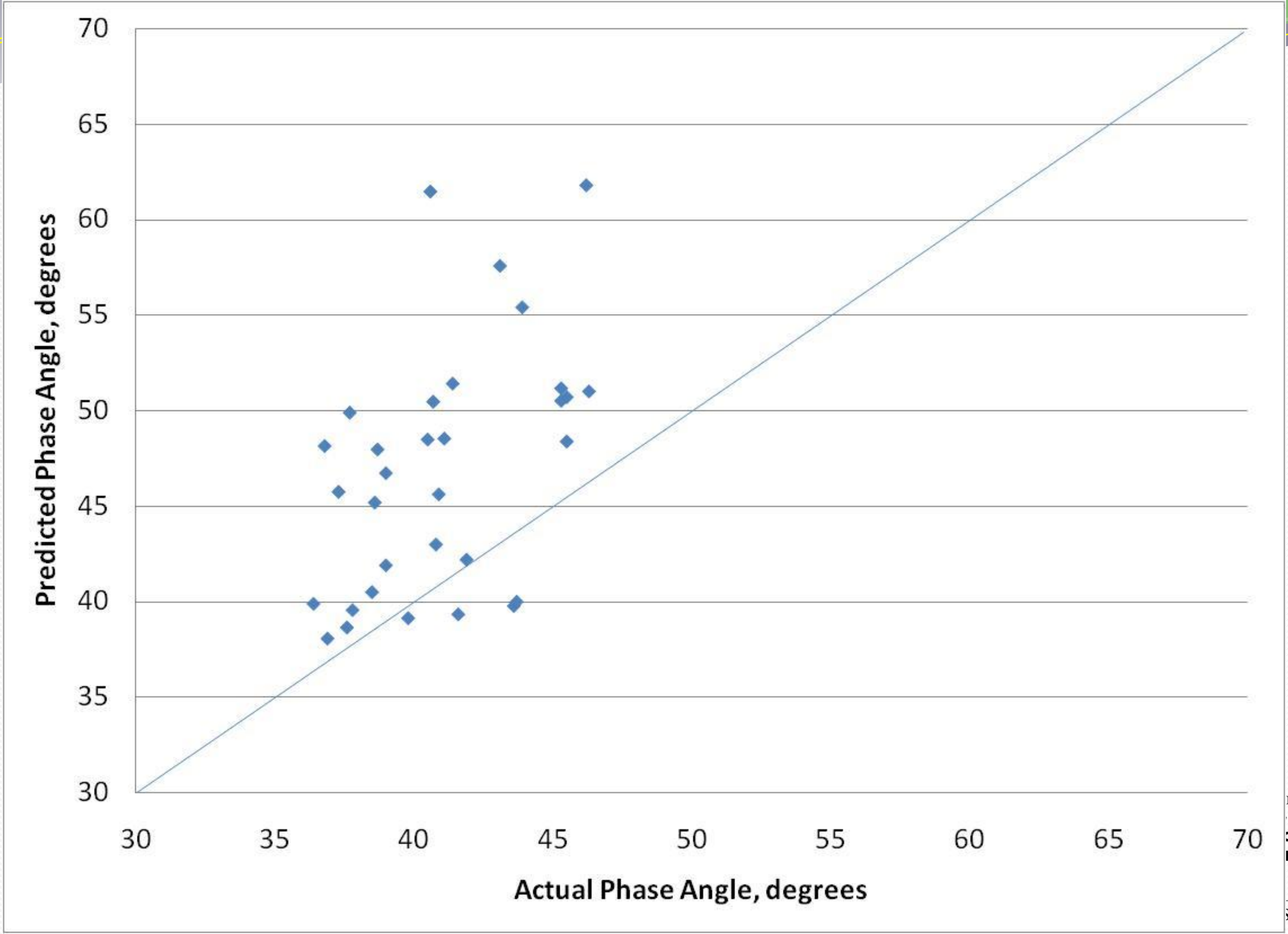


Predicted Phase Angle @ High Temperature, degrees
Actual Phase Angle @ High Temperature, degrees
90
85
80
75
70
65
60
55
50
50
55
60
65
70
75
80
85
90


Predictedl Intermediate Temperature, C
Actual Intermediate Temperature, C
0
5
10
15
20
25
30
35
40



12000
10000
8000
6000
4000
2000
0
Predicted G*, kPa
0
2000
4000
6000
8000
10000
12000
Actual G*@ Intermediate Temperature, kPa



Predicted Phase Angle, degrees
70
65
60
55
50
45
40
35
30
30
35
40
45
50
55
60
65
70
Actual Phase Angle, degrees

Summary

- Backcalculation procedure inconsistent for critical high temperature prediction
  - Both G* and δ erroneous
- Backcalculation procedure underpredicts the intermediate critical temperature
  - Procedure underpredicts G*
  - Procedure overpredicts δ

Flow Number

Fn Procedure

- Protocol originally recommended by FHWA.
- Loose mix aged for 4 hrs. at 135°C in accordance with AASHTO R 30.
- Specimens compacted to 150 x 170 mm, then cut and cored to 100 mm dia. x 150 mm ht. with a target V_a of 7±0.5%.
- Prior to testing, specimens were preheated to the 50% reliability high-temperature from LTPP for the location of the respective RAP materials.
- The deviator stress used was 70 psi, and the confining stress was 10 psi. Test to 20,000 cycles or until the specimen reached 5% strain.

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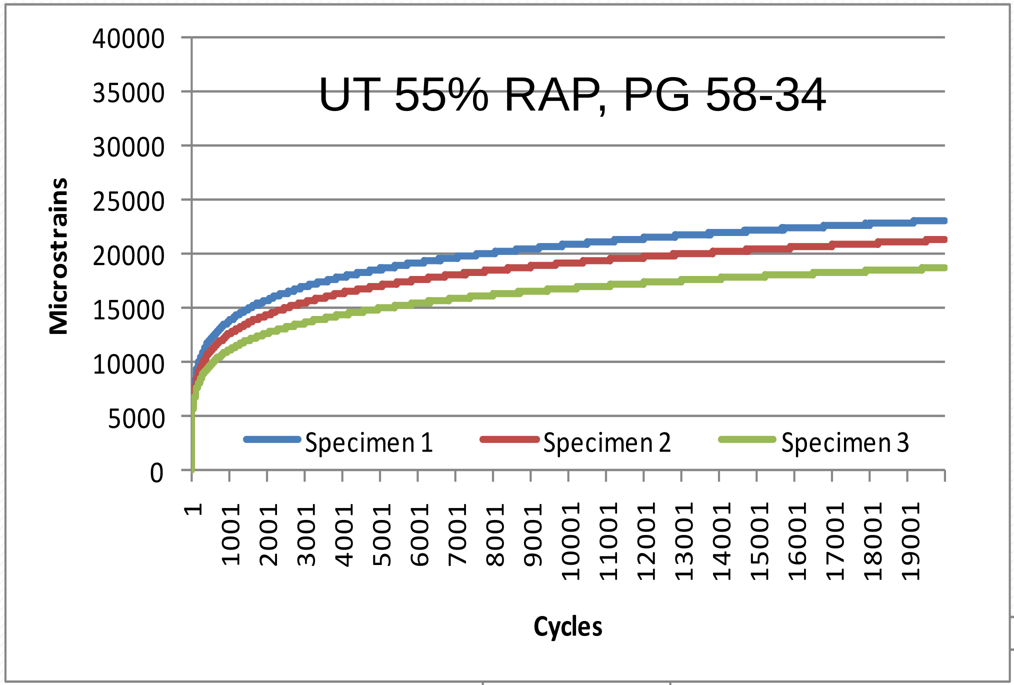

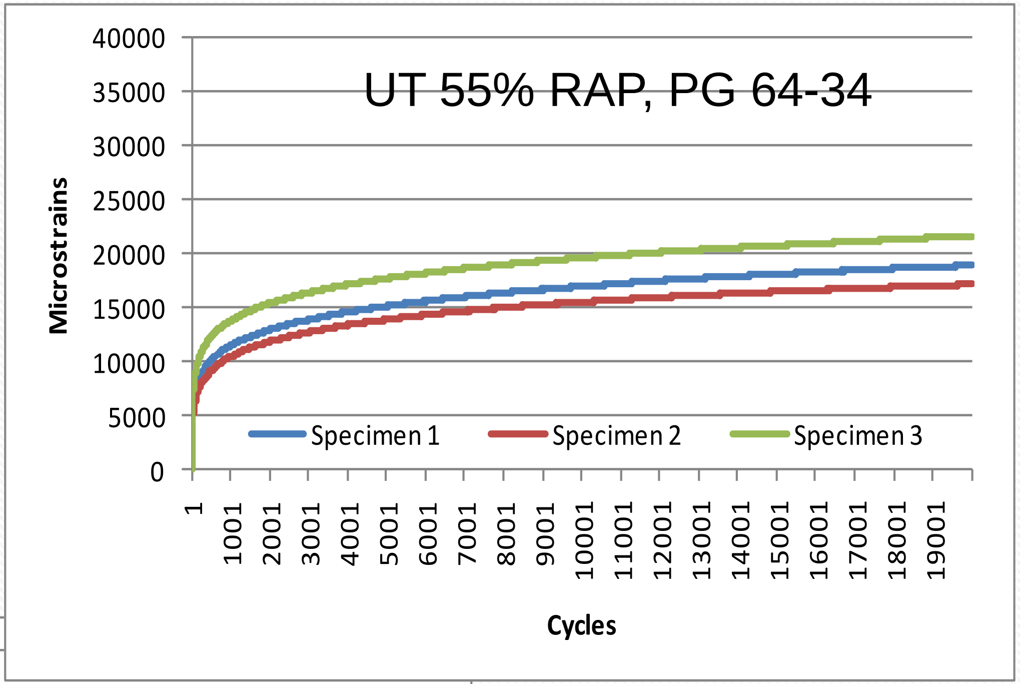

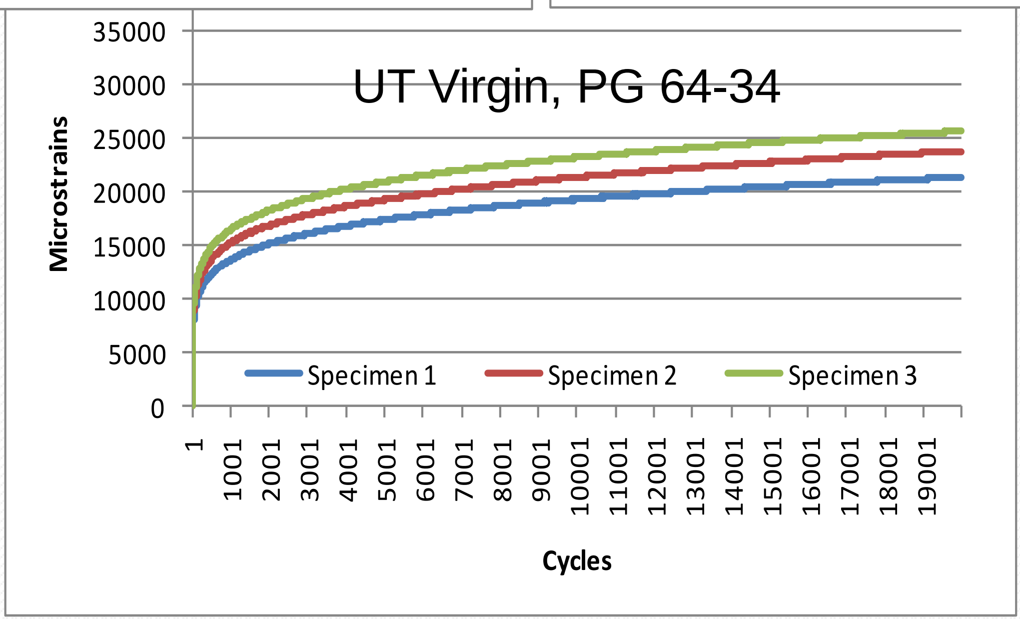

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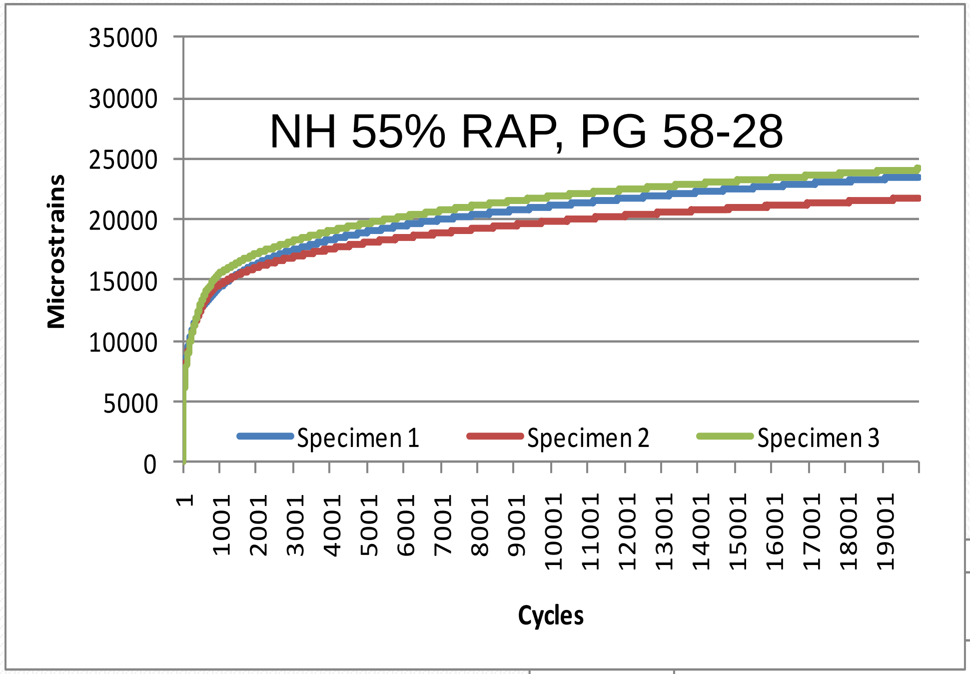

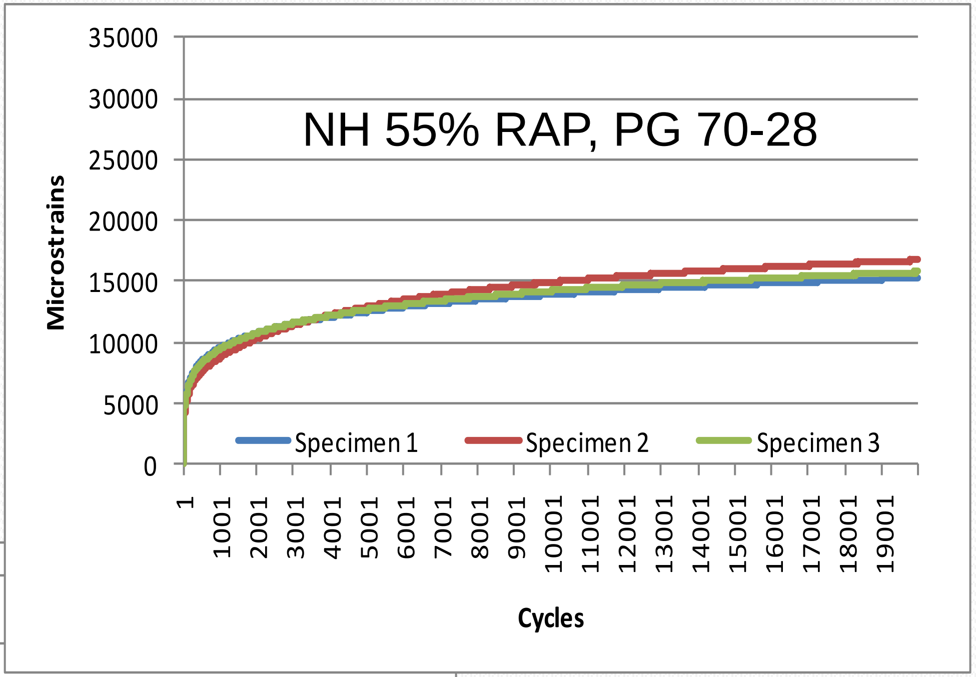

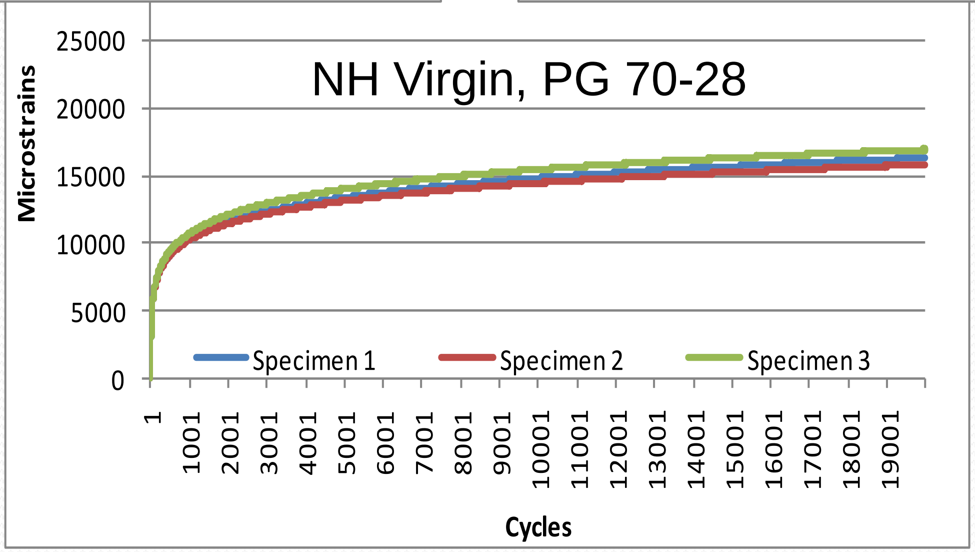

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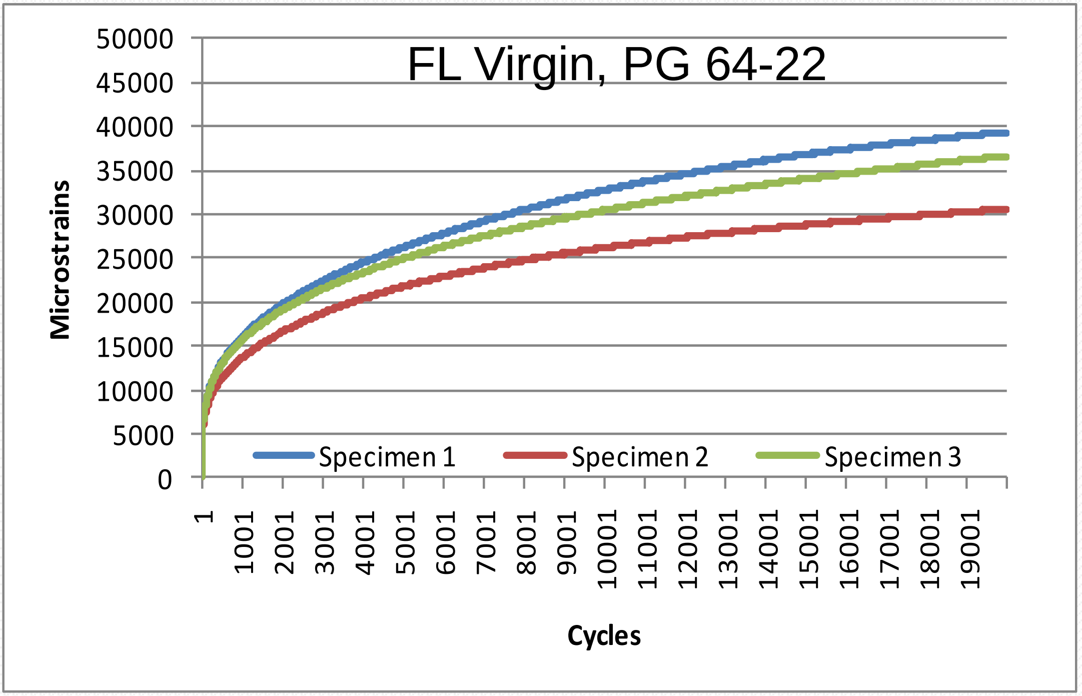
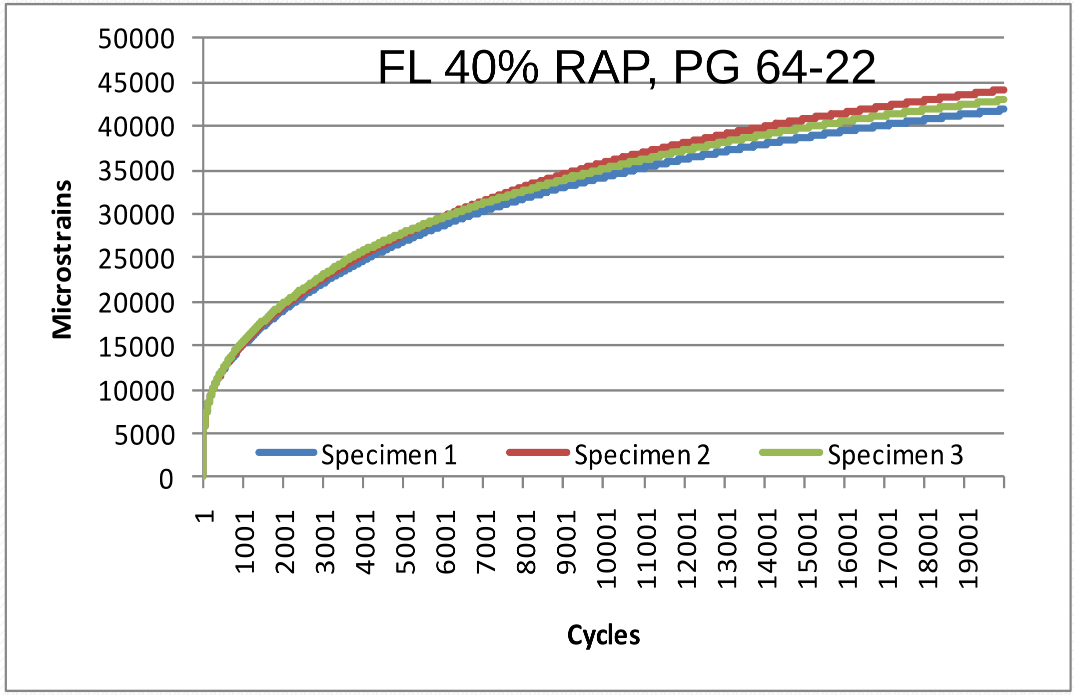
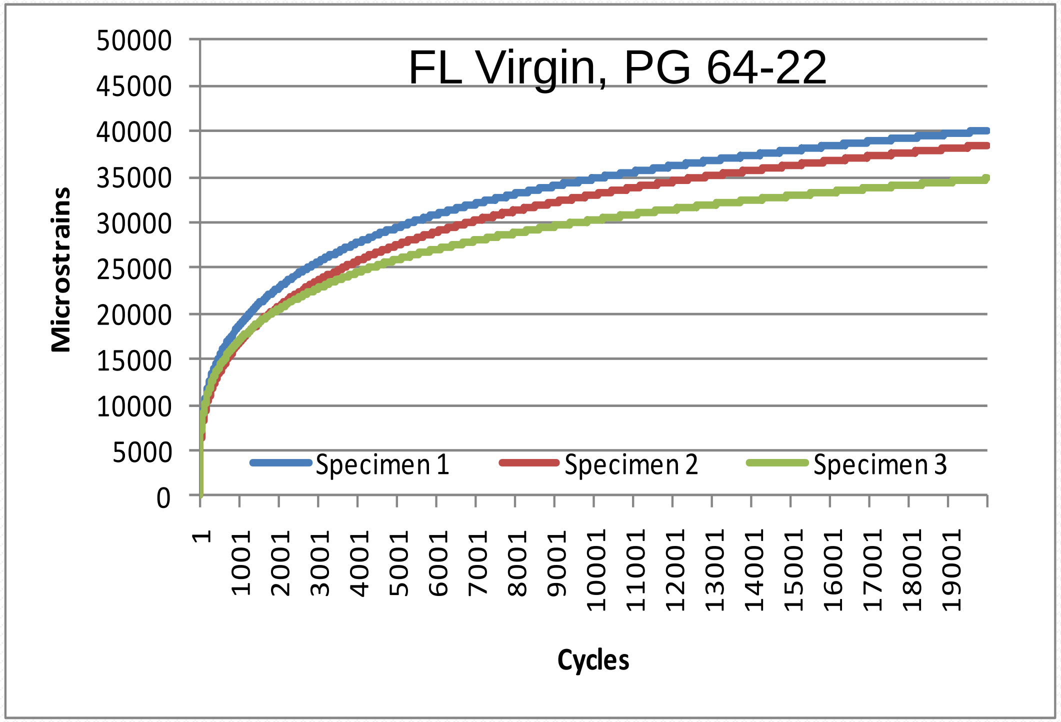
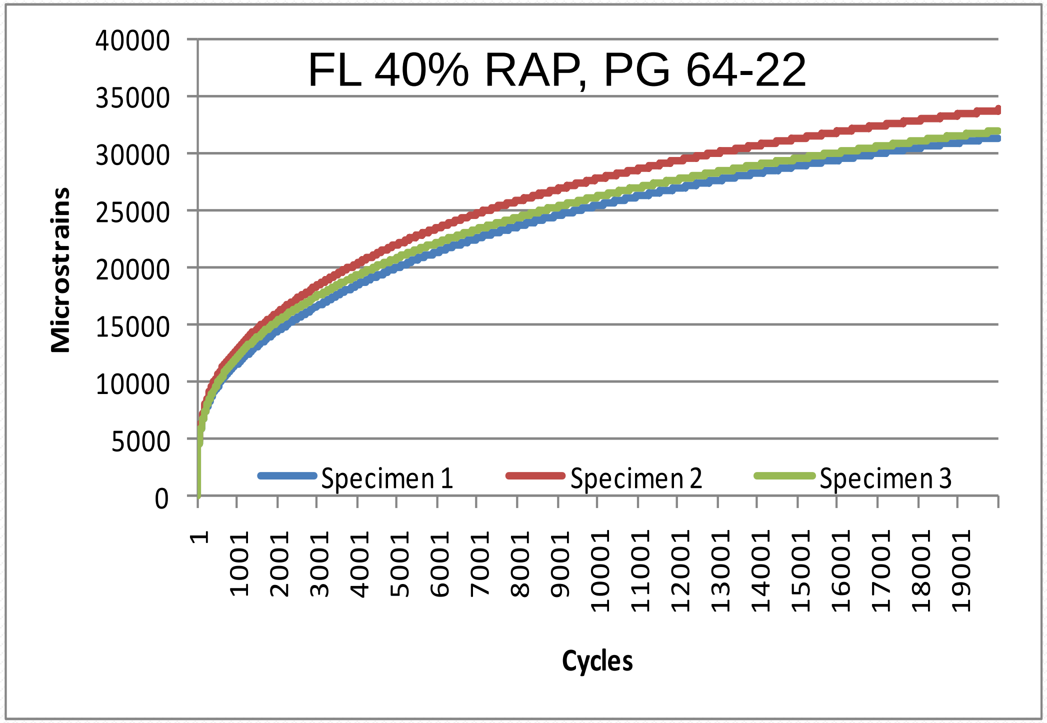
FL 9.5 mm NMAS


FL Virgin, PG 64-22
Microstrains
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Specimen 1
Specimen 2
Specimen 3
1
1001
2001
3001
4001
5001
6001
7001
8001
9001
10001
11001
12001
13001
14001
15001
16001
17001
18001
19001
Cycles


FL 40% RAP, PG 64-22
Microstrains
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Specimen 1
Specimen 2
Specimen 3
1
1001
2001
3001
4001
5001
6001
7001
8001
9001
10001
11001
12001
13001
14001
15001
16001
17001
18001
19001
Cycles

FL 19.0 mm NMAS





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Selection of a Cracking Test

Outline

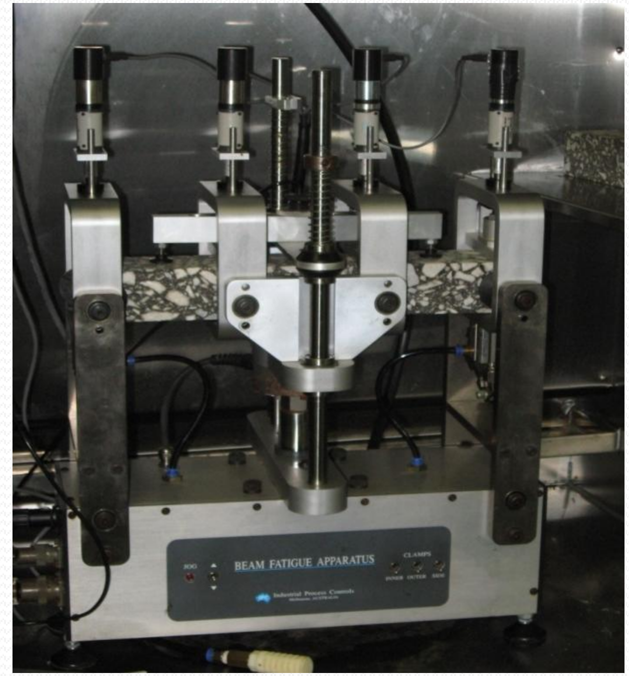
- Possible tests to consider
  - Bending Beam Fatigue
  - Push-Pull, Simplified Viscoelastic Continuum Damage
  - Texas Overlay Tester
  - Semi-Circular Bend
  - IDT Fracture Energy
- Advantages & Disadvantages
  - Specimen preparation
  - Equipment
  - Complexity

Bending Beam Fatigue

(AASHTO T 321 or ASTM D 7460)

Specimen and Parameters

- Beam size – 2.5” by 2” by 15”
  - Usually @ 7% air voids
- Loading
  - Haversine strain control
  - 0.1 sec load and 0.4 sec unload
  - 10 Hz
- Test temperature
  - 20 ± 0.5°C



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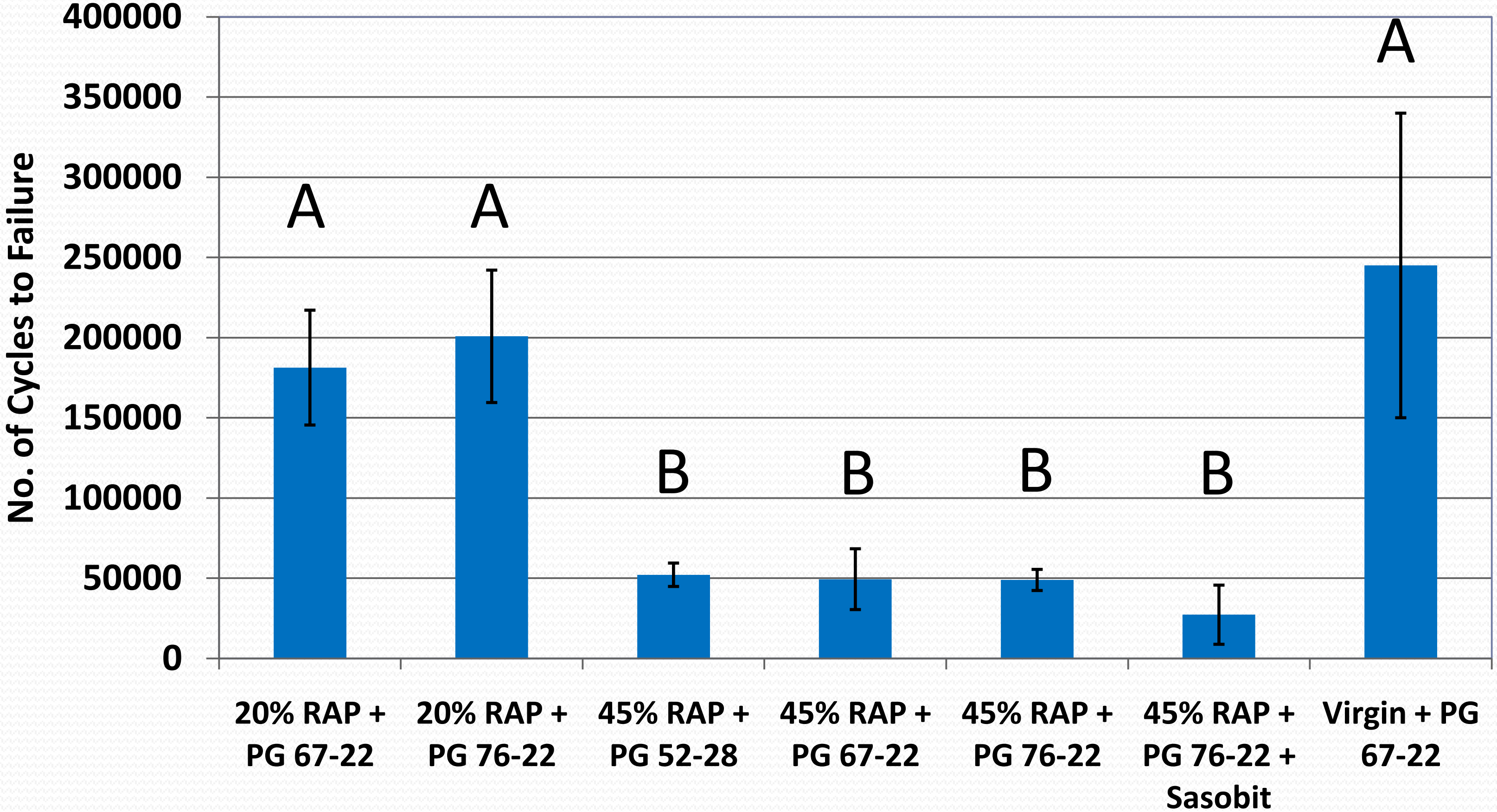
Test Results

- Test termination
  - 50% loss in initial beam stiffness
  - 70% loss in initial beam stiffness
  - Initial stiffness measured at 50^{th} cycle
- Determination of No. of cycles to failure
  - AASHTO T 321: 50% loss in initial beam stiffness
  - ASTM D 7460: max Normalized Modulus × Cycles
- Fatigue tests are usually plotted as log strain vs Log N (number of cycles)

BBF Results, 2006 RAP Test Sections



Vbe (%)	12.3	12.4	10.8	10.6	10.4	10.3	13.0

BBF Summary

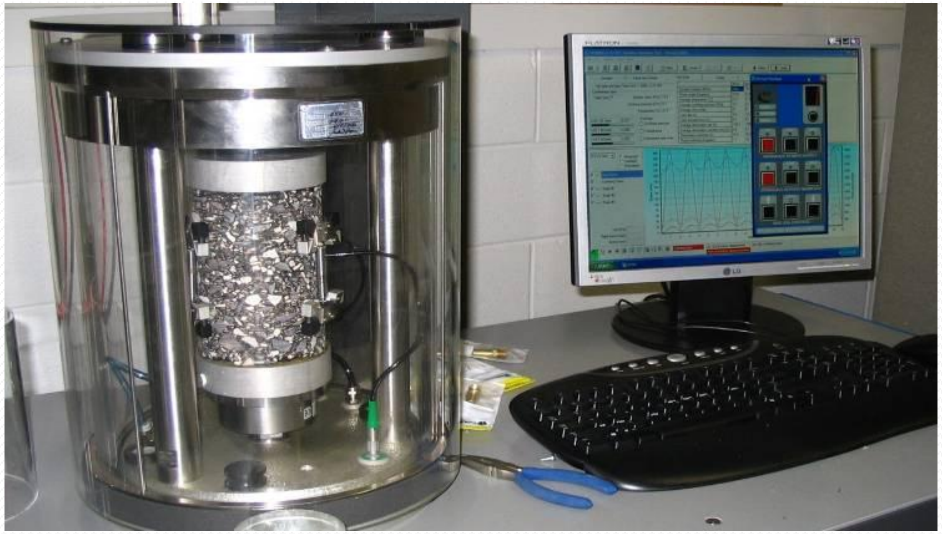
- Suitable for research, but not for routine usage
  - Specimen fabrication
  - Specialized equipment
  - Time consuming method

Push-Pull, Simplified Viscoelastic Continuum Damage

(Draft Procedure)

Push-Pull Fatigue

- Draft procedure by NCSU
- 4+ replicates
- Must have E* information for mixtures
- 19°C (or based on MAAT?)
- 10Hz
- 2 strain levels (tricky)
- Currently limited to one specimen per day

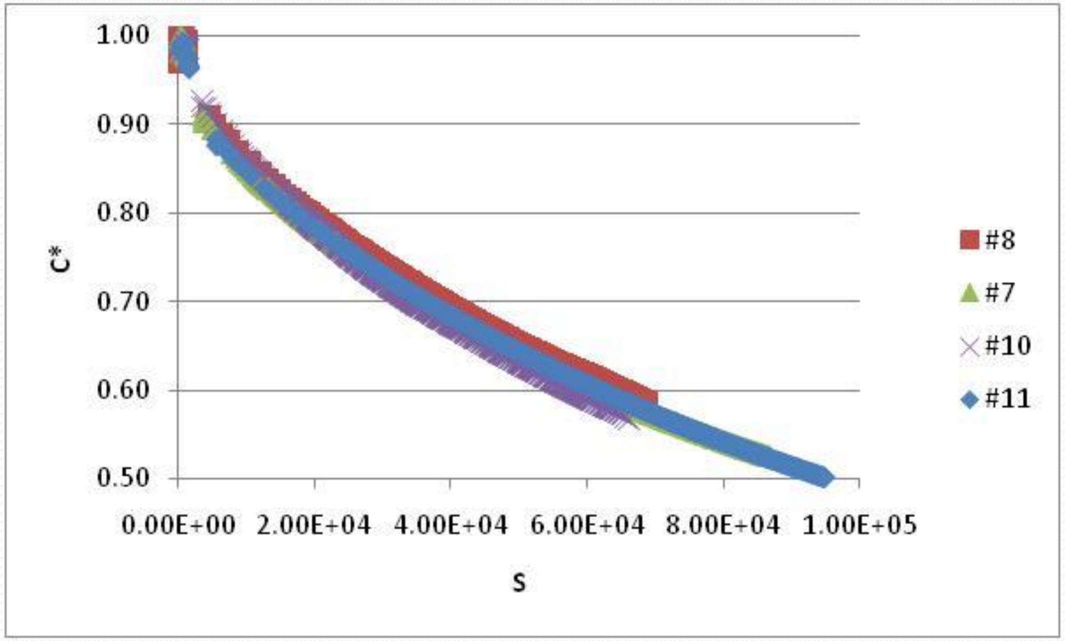


Push-Pull Fatigue

- Constant actuator displacement
- Failure defined as a sharp reduction in phase angle
- Two failure targets
  - N_f: 1,000 and 10,000
  - Two replicates each
- Estimate initial on-specimen microstrain to yield appropriate N_f

Push-Pull Fatigue

- Pseudostiffness versus damage curve (c vs. s)
- Uses NCSU program
  - Software calibrated below 15% RAP
- Allows user to characterize N_f at multiple strains, temperatures, and frequencies



S-VECD Testing Methodology

- IPC Global AMPT
- Software developed by NCSU to perform test by NCSU draft AASHTO Specification
- Data Analysis performed by NCSU ALPHA-F Software Package
  - Modified by NCSU to Accept AMPT Output Files
- Samples Prepared in Accordance with AASHTO PP60-09

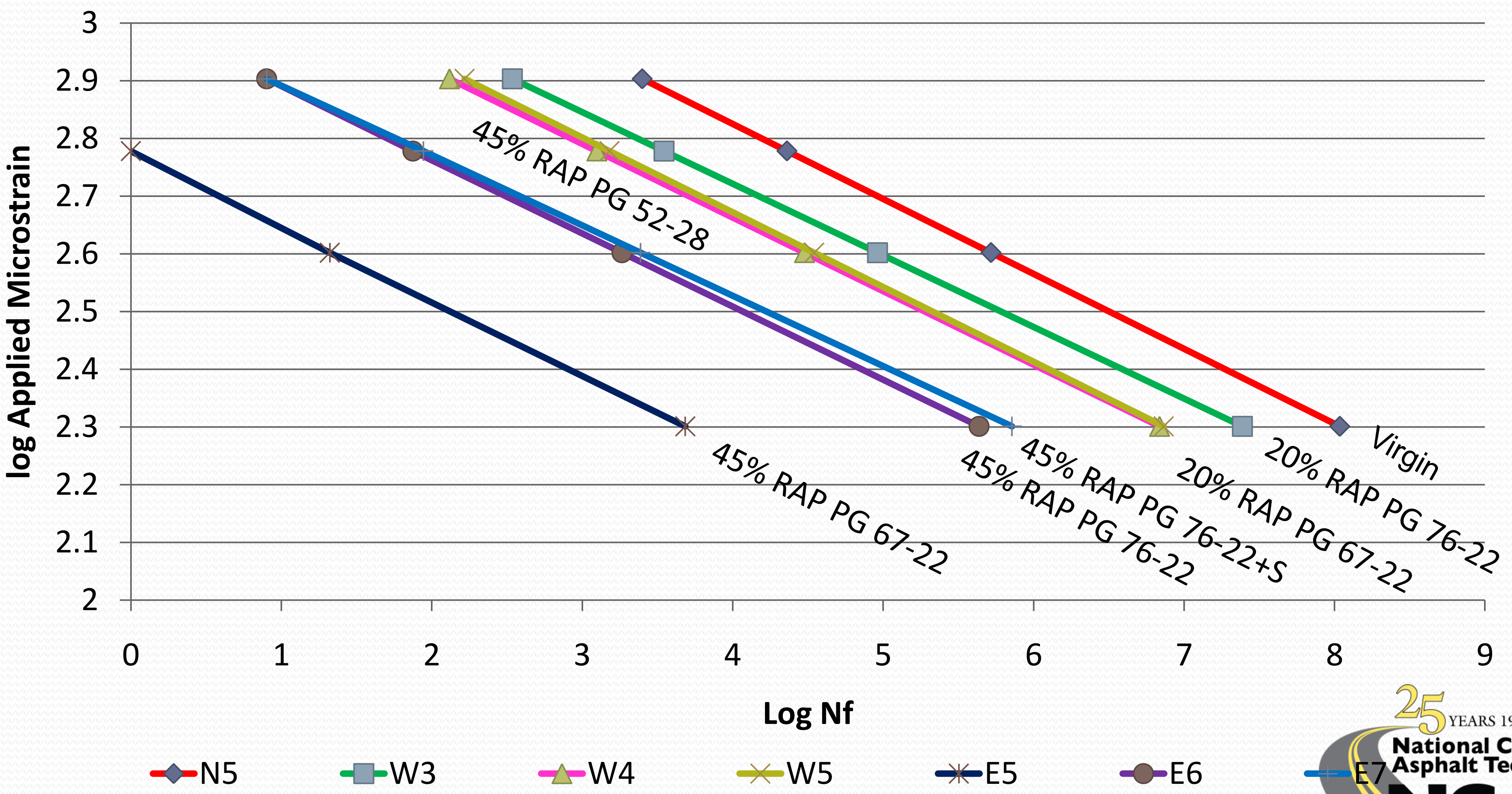
S-VECD Testing Methodology

- Use ALPHA-F software to develop C vs. S curves for tested samples
- Simple Power function used to model C vs. S curve for each mix
- Excel Sheet Developed for Fatigue Predictions
  - Hou et al. – AAPT – 2010
  - ALPHA-F Predictions not used
    - Equation Parameters calibrated to maximum 15% RAP
    - Parameters from Individual tests utilized for prediction

S-VECD Testing Prediction

- Controlled Strain Test Predictions Made for Each Mix
  - 200, 400, 600, 800 Target Microstrain
  - Developed Fatigue Curve for Each Mix
  - Relative Comparisons

Summary of S-VECD Fatigue Prediction



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Push-Pull Test Issues

- Must make educated 'guess' of target microstrain value to get desired cycles to failure
- Difficult to Find Acceptable Testing Strain Level with More Brittle Mixtures
  - Higher RAP, Lower AC
  - Small 'Window' of target microstrain between immediate fracture and perpetual behavior
- No automatic software cut-off at failure

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Push-Pull Fatigue Summary

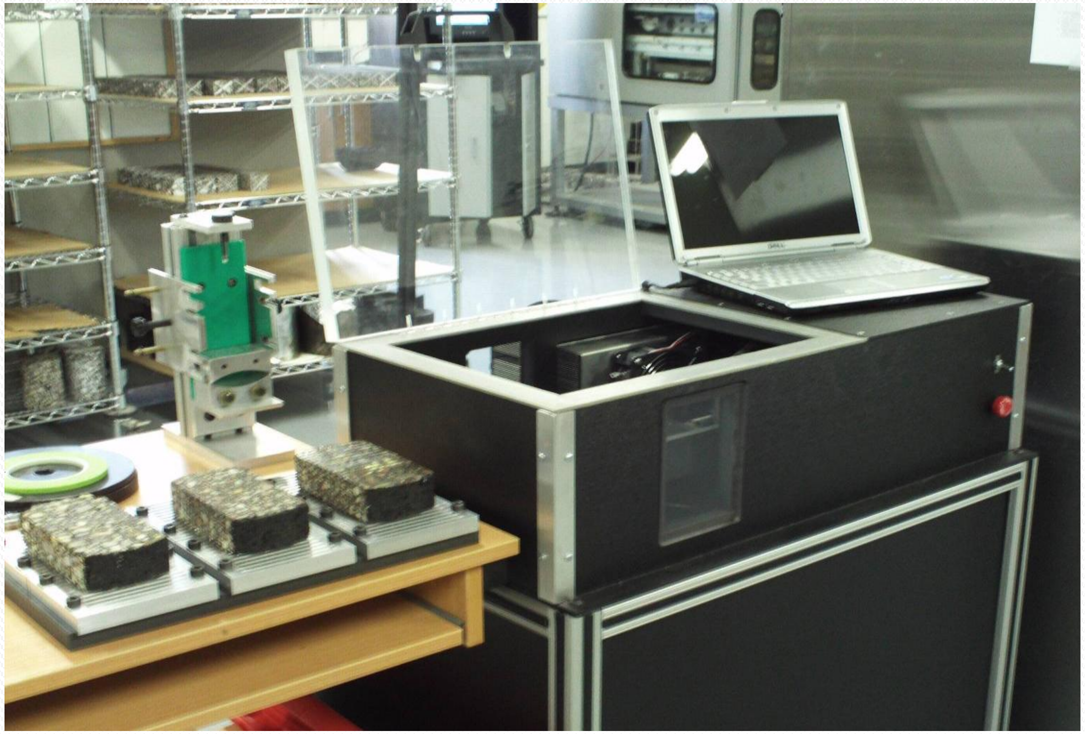
- Test method is complex
  - Challenging to choose appropriate strain magnitude
  - Time consuming test
  - Only one sample glued per day
- Field validation is necessary
- Can theoretically determine mixture's cycles until failure for numerous strain, temperature, and frequency combinations

Texas Overlay Tester

(Tex-248-F)

Texas Overlay Tester (OT) Test

- Specimen cut from field core or SGC specimen
  - 6" x 3" x 1"
- Two available procedures
  - Zhou et al
- Not as complex as Push-Pull fatigue



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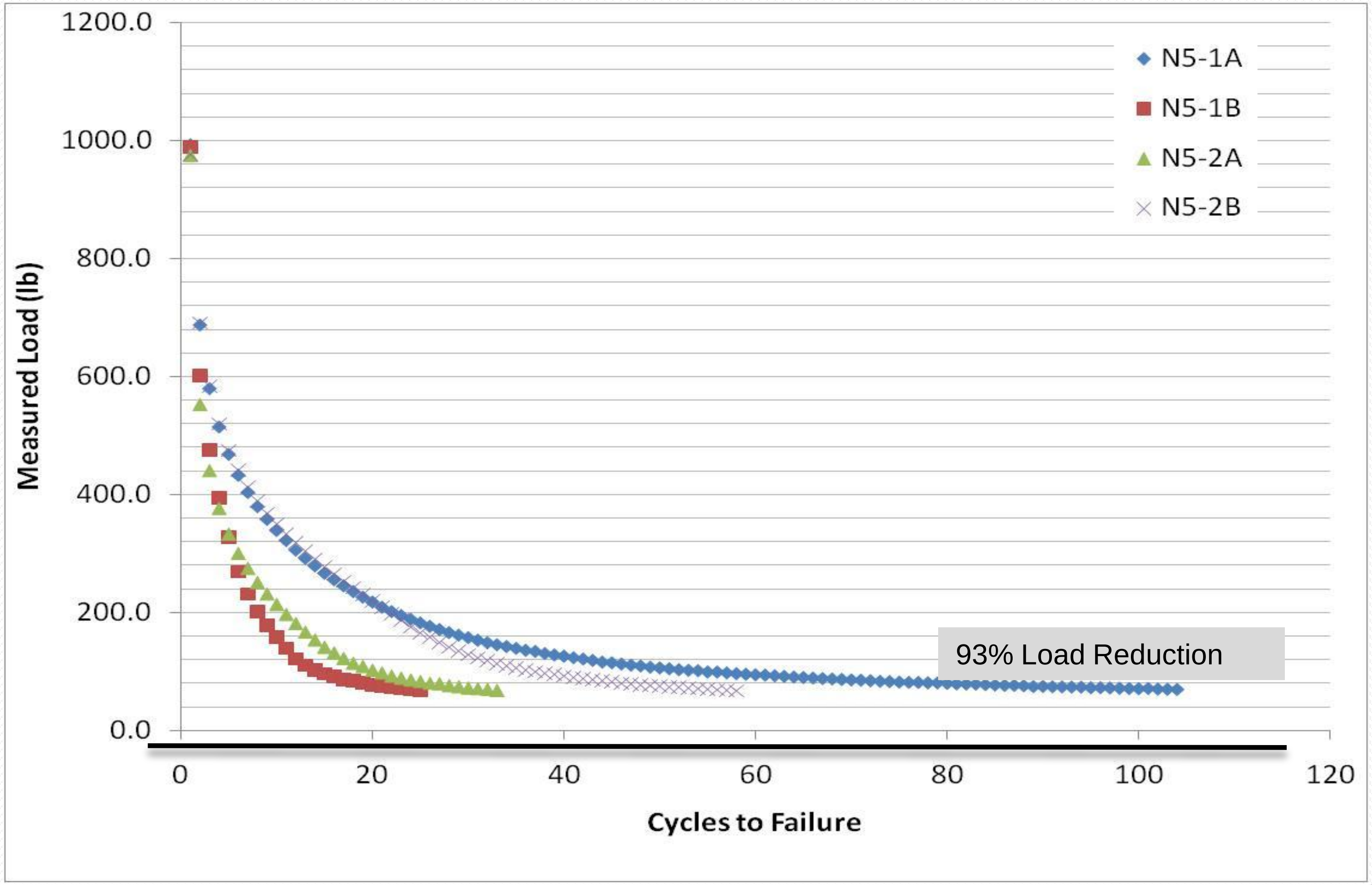
Testing Method

- Tex 248-F (January 2009)
  - Testing Temperature = 77°F
  - Cycle Length = 10 seconds (5 open/5 close)
  - Max Opening Displacement = 0.025”
  - Maximum Cycles = 1,200
  - Waveform = Sawtooth
- Parameters are Adjustable in the Software
  - Temperature
  - Crack opening

Overlay Tester Cycles to Failure



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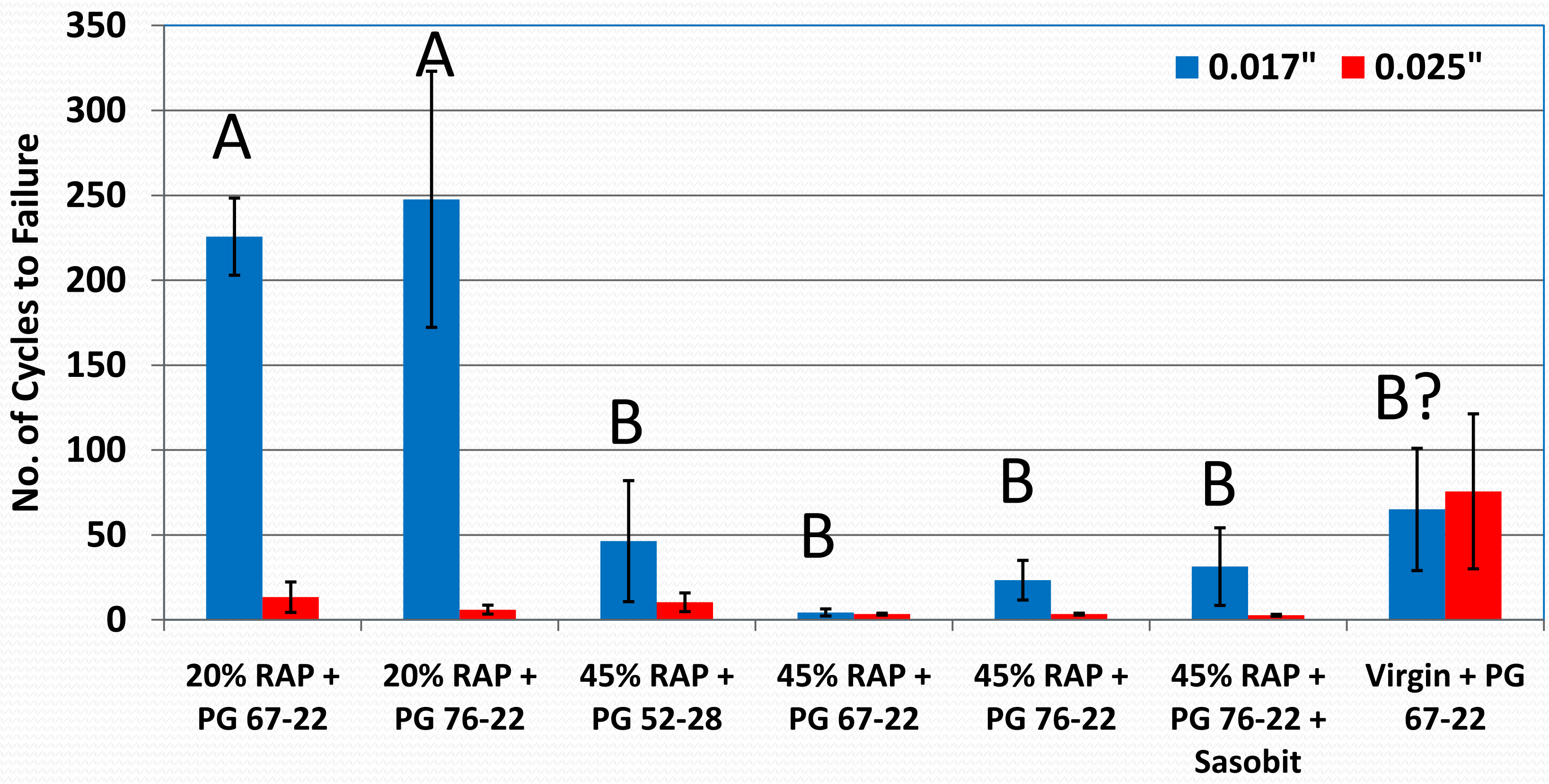
OT Results, 2006 RAP Test Sections



Vbe (%)	12.3	12.4	10.8	10.6	10.4	10.3	13.0

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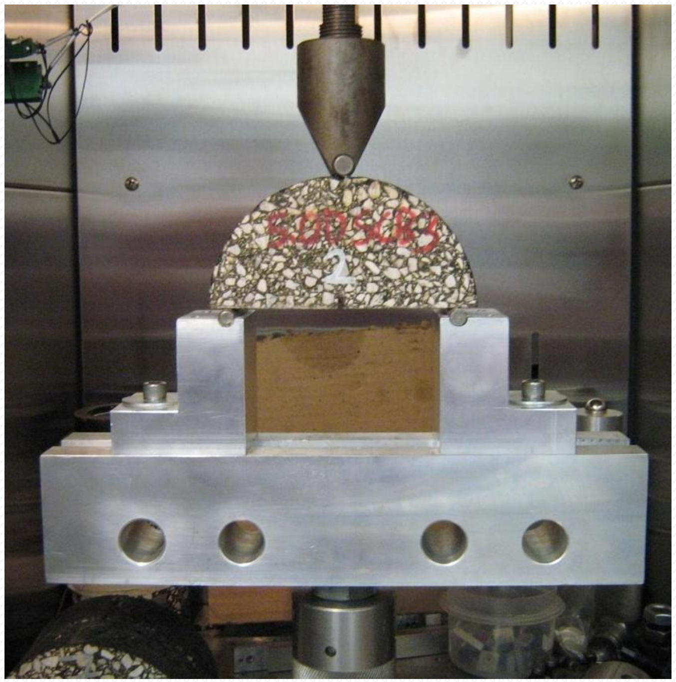
Semi-Circular Bend

(Draft Procedure)

Semi-Circular Bend (SCB) Test



- Half-moon specimens cut from SGC cylinders or cores
- Procedure al la Wu, et al
- Notches cut to three depths
- Not as complex as low-temperature SCB
- Constant cross-head rate of 0.5 mm/min.
- Capture load and vertical displacement

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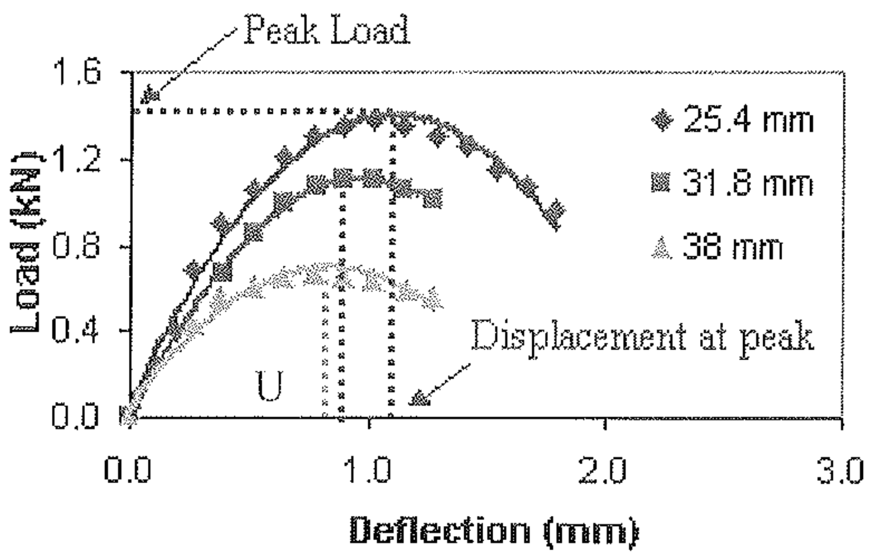
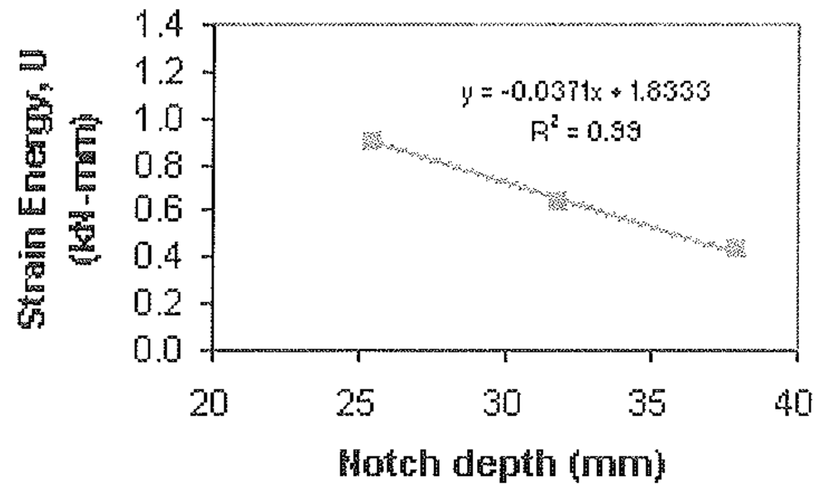
SCB Test

- Determine U, strain energy, for each notch depth, a
- Calculate Jc, Critical J-integral, as slope of U vs a divided by specimen thickness, b





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SCB Summary

- The method is simple
  - Moderately simple sample preparation
  - Simple monotonic loading and vertical displacement
  - Analysis is straight forward, but it sounds high tech
- Has been used by several asphalt research organizations (LTRC, FHWA, Delft) to rank fracture resistance of mixes
- Results seem to be sensitive to binder properties
- No link to field performance has been established

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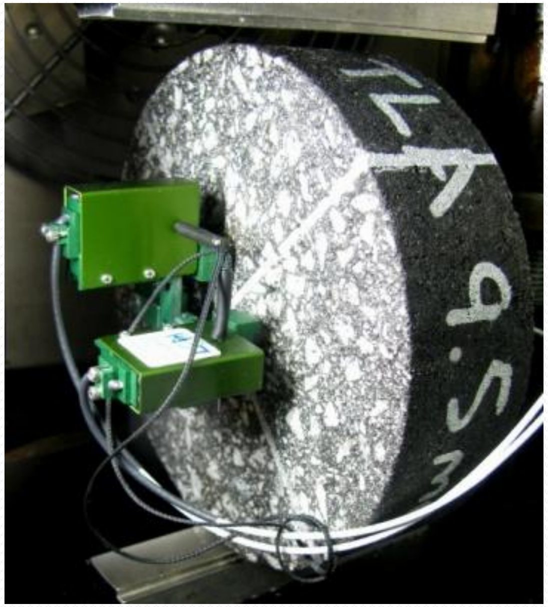
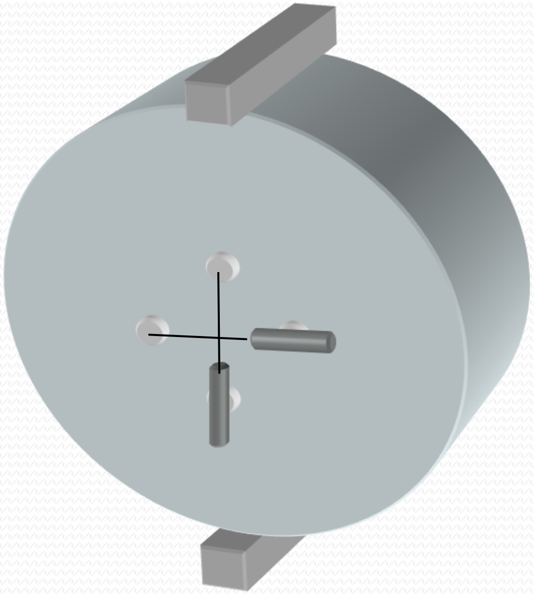
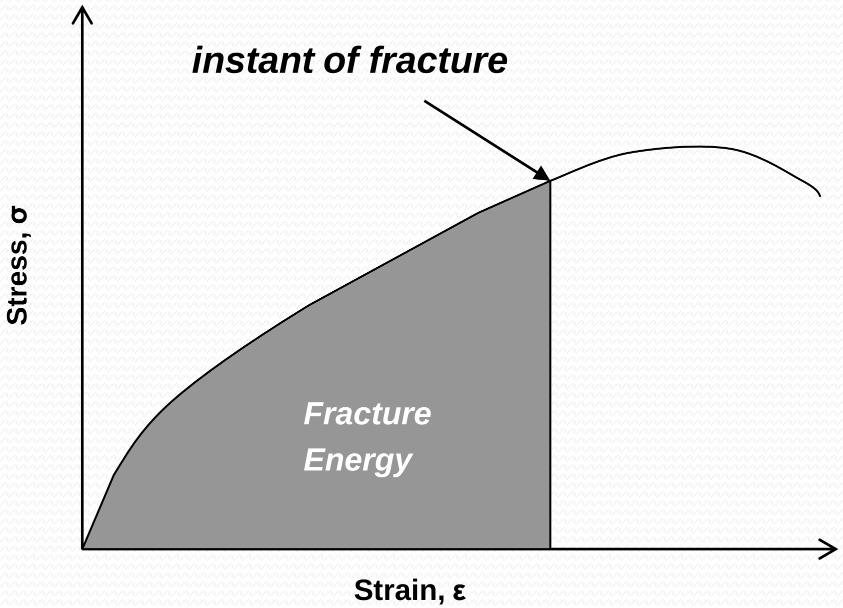
IDT Fracture Energy

Fracture Energy

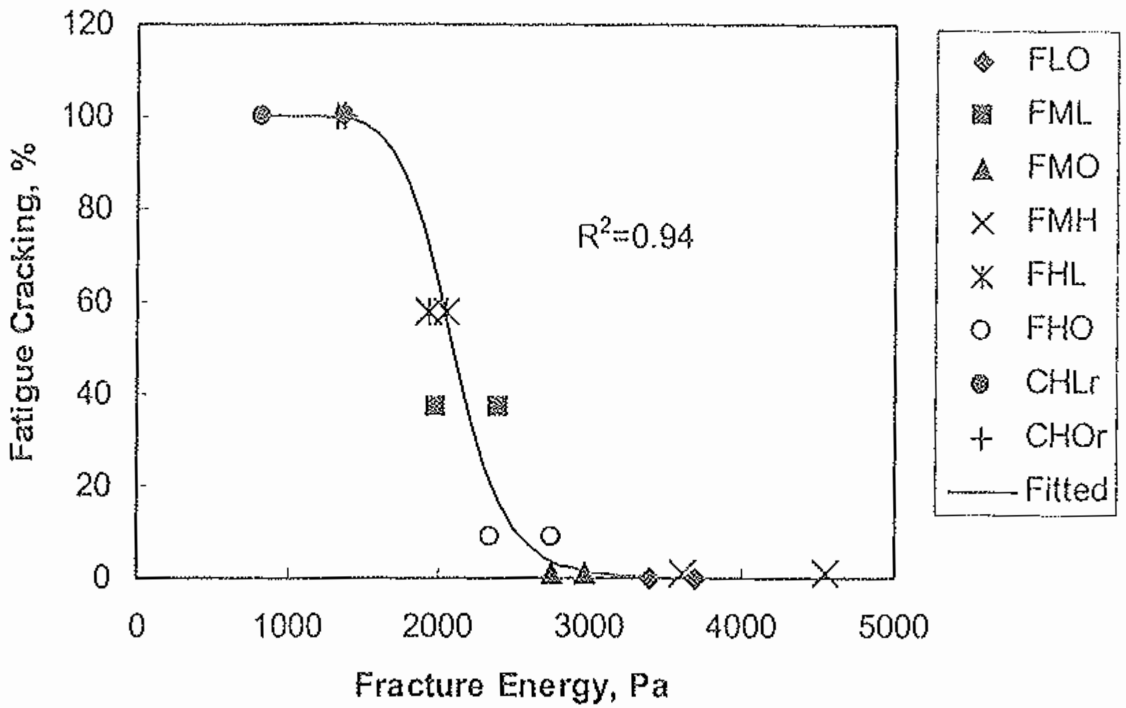






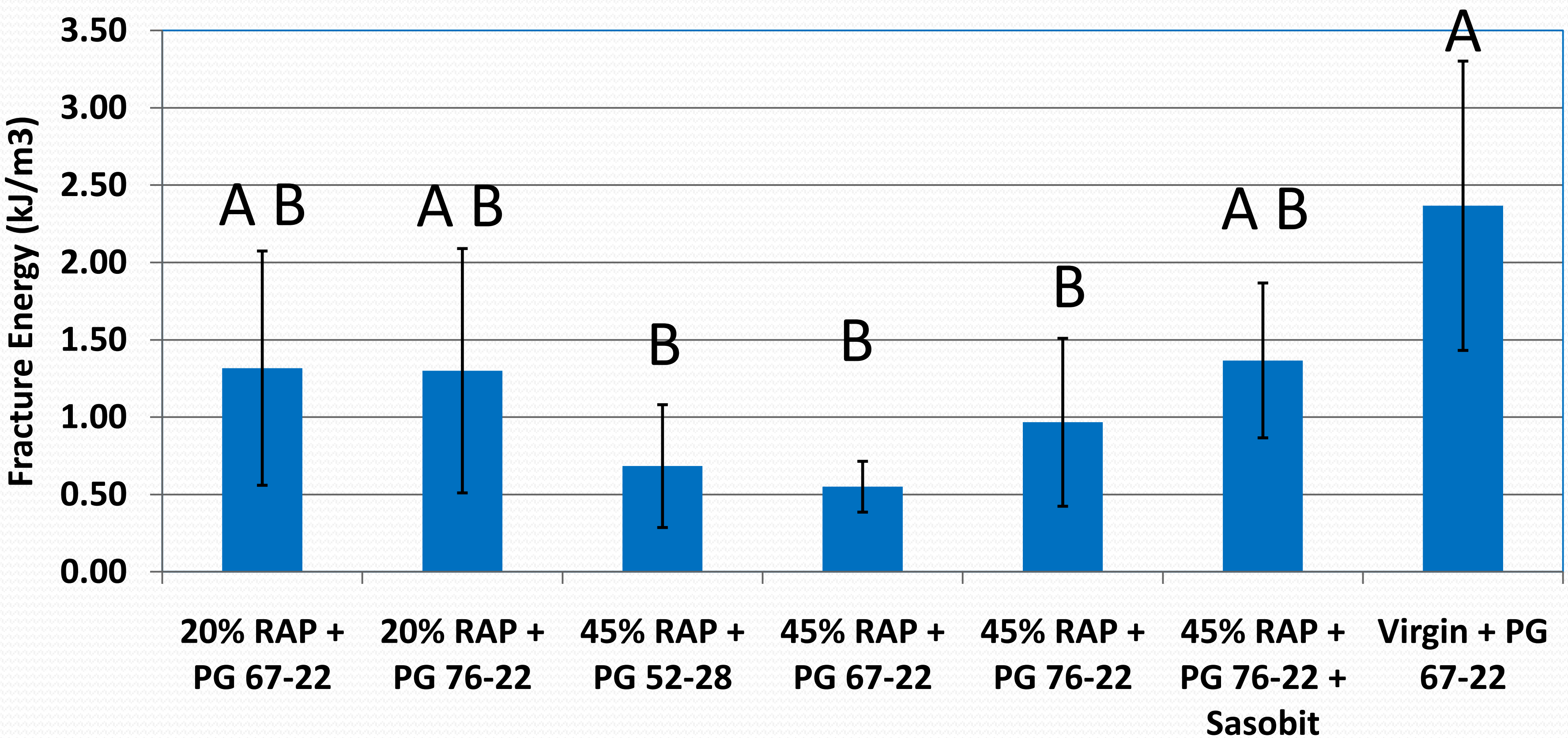
- IDT Fracture Energy at 20ºC

Indirect Tensile Fracture Energy



- R. Kim and H. Wen, AAPT 2002
- Correlation with fatigue cracking at WesTrack

FE Results, 2006 NCAT Test Track



Vbe (%)	12.3	12.4	10.8	10.6	10.4	10.3	13.0

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IDT Fracture Energy Summary

- Fairly simple test except for strain measurements
  - Simple sample preparation
  - Monotonic loading, 4 strain measurements
  - 20°C test temperature
  - Quick test
  - Analysis is straight forward
- Has been shown to be strongly related to fatigue cracking at one APT facility

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IDT Fracture Energy Testing

- All samples fabricated
- Long-term conditioning before testing
- Half of the tests are completed, remainder should be done in a few weeks.

Thank You