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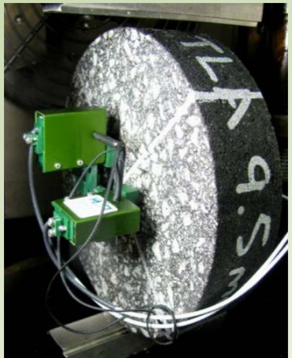
NCHRP 9-46

Improved Mix Design, Evaluation, and Materials Management Practices of HMA with High RAP Content

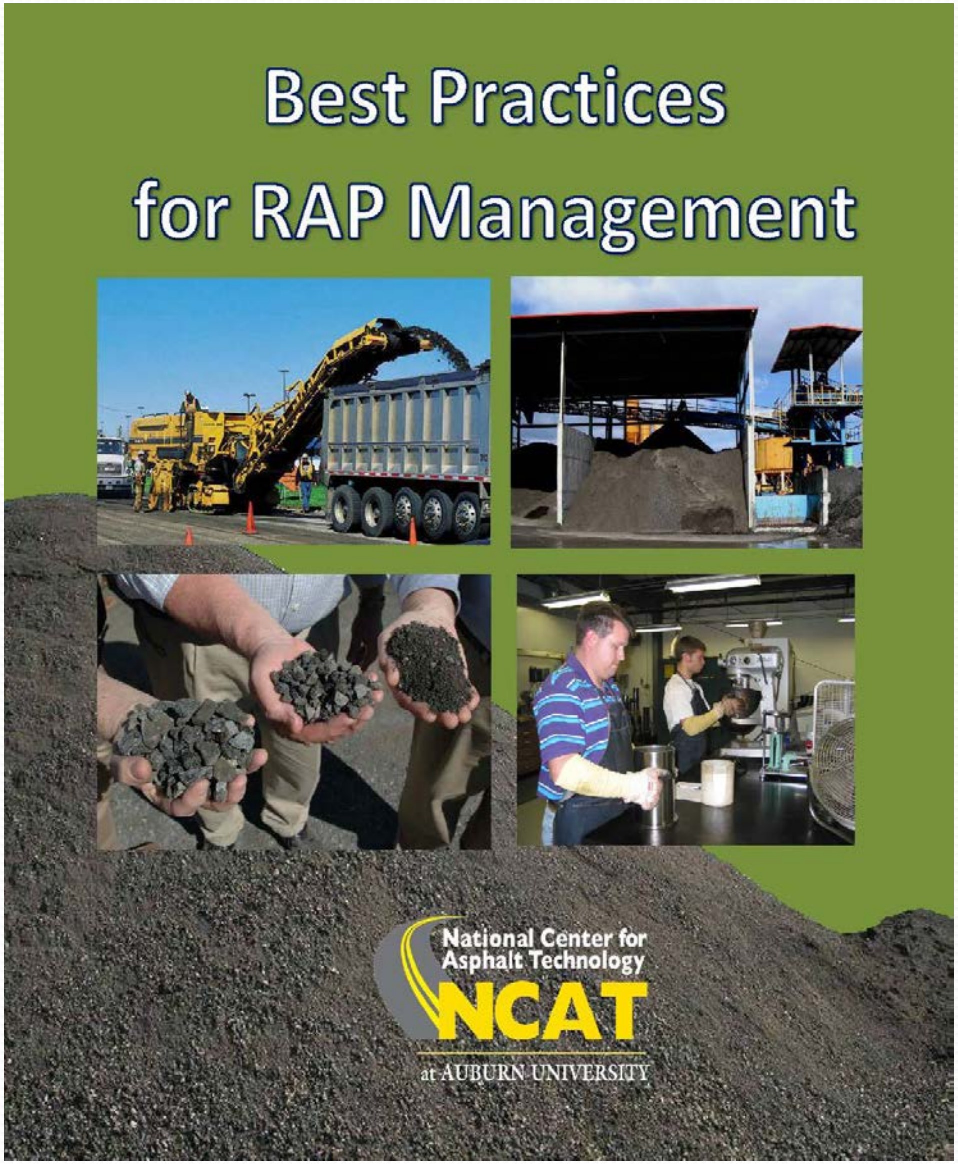




Presentation Outline

- Review of Objectives
- Best Practices for RAP Management
- Mix Design Sample Preparation Guidelines
- Experimental Plan
- Results and Analysis
- Recommendations

Project Objectives

- Provide Guidance on Characterizing RAP
- Revise Mix Design Procedure for High RAP Contents
- Recommend Performance Tests
  - Modulus
  - Moisture Sensitivity
  - Rutting Resistance
  - Fatigue Cracking Resistance
  - Low Temperature Cracking Resistance



Contents

- Sources of RAP
- Processing
- Inventory Analysis
- Sampling Guidelines
- Handling RAP in the Lab
- Testing Options
- Consistency Guidelines

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Experimental Plan

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

Volumetric Results

- Fractionated RAP was necessary to get 55% RAP in the mixes. The coarse RAP fraction was used exclusively in some cases.
- Percent binder replacement ranges:
  - 25% RAP (by weight of agg.): 25 to 27% binder repl.
  - 55% RAP (by weight of agg.): 33 to 49% binder repl.
- Changing the virgin binder source or PG does not appear to affect volumetric properties.
  - "Bumping" the binder grade should not effect Opt. Pb.
  - Incompatibility of binders may not be evident in volumetric mix design.

Performance Tests

Dynamic Modulus (E*) Testing

Two purposes:

1. To try to estimate the "effective" (combined RAP and virgin) binder properties.
2. To assess how RAP content influences mix stiffness through the range of temperatures expected in service.

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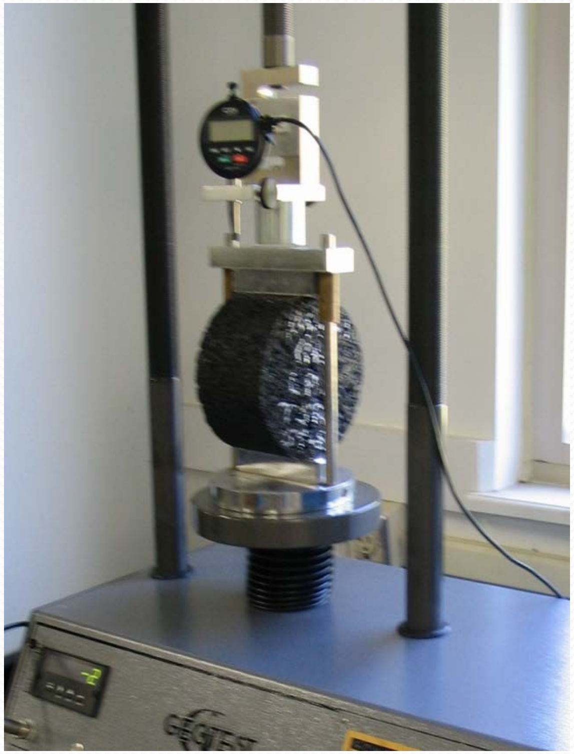
Summary of E* Statistical Analyses

- RAP content had a significant effect on E* at all temperatures. E* of high RAP content mixes were significantly higher than for virgin mixes.
- Virgin binder **grade** did not have a significant effect on E* at low temperatures. The influence of the virgin binder grade on E* increased with higher test temperatures.
- Virgin binder **source** was significant on E* only at the lowest and highest temperatures.

Moisture Damage Susceptibility

- AASHTO T 283
- Increasing RAP contents generally increased conditioned and unconditioned tensile strengths
- TSR can be misleading. Although both conditioned and unconditioned tensile strengths increase, TSR values can decrease. A lower TSR criterion (e.g. 0.75) with a minimum conditioned tensile strength (e.g. 100 psi) can help.
- Low TSRs can generally be improved with the addition of an antistripping agent.



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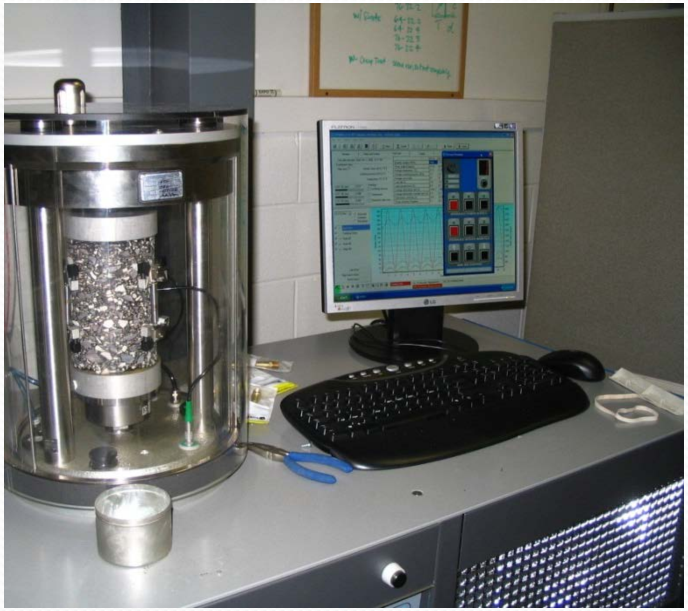
Flow Number Procedure

- Rutting Test
- FHWA original protocol
  - Confining stress = 10 psi
  - Deviator stress = 70 psi
  - Test to 20,000 cycles
- No tertiary deformation
- No difference in TOTAL deformation for high RAP and virgin mixes
- Recommend unconfined Fn



Summary of Flow Number Testing

- High RAP content mixes had statistically equal deformation compared to virgin counterparts in 8 of 9 cases.
- Although not statistically significant, using a lower virgin PG binder grade generally resulted in greater deformation.
- Recommend using unconfined flow number test and criteria from NCHRP Report 673

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Tests Considered for Fatigue Cracking

Test	Method	Disadvantages
Bending Beam Fatigue	AASHTO T 321	Challenging spec. prep, time consuming test
Simplified Viscoelastic Continuum Damage	NCSU	Time consuming, Complex analysis, lacks validation
Texas Overlay Tester	TEX-248-F	Unrealistically high strains
Semi-Circular Bend	LTRC	Method still in development
IDT Fracture Energy	UF	National standard needed

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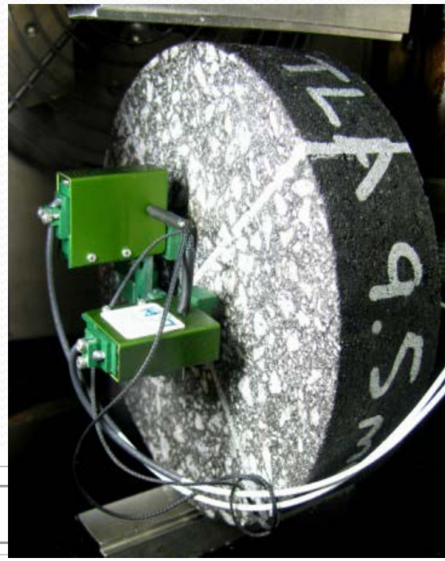
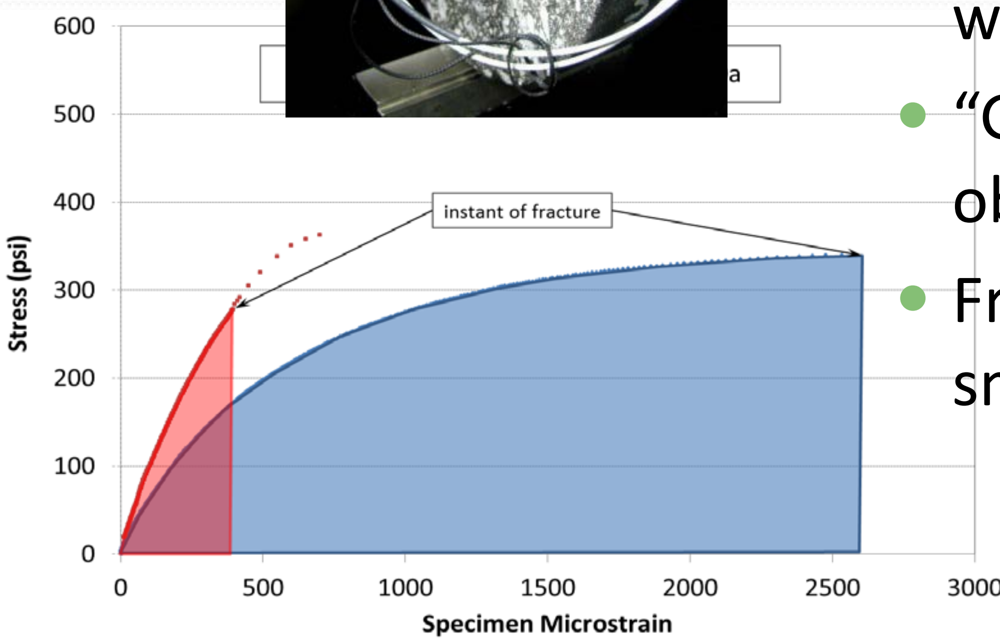
Fracture Energy (FE)



- Simple sample preparation
- Quick test, 10°C
- 4 strain measurements
- In most cases, FE decreased with increasing RAP content
- "Good" FE results can be obtained with high RAP mixes.
- Fracture Energy was higher for smaller NMAS mixes



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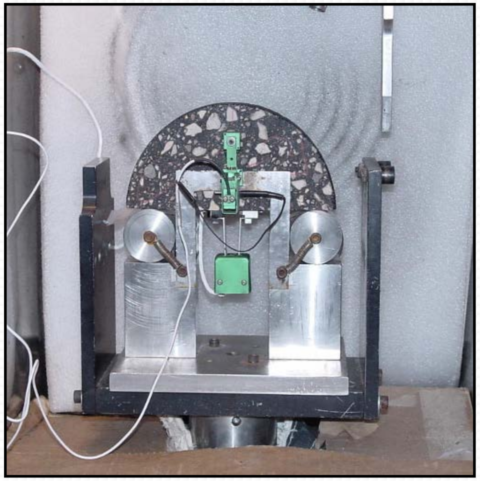
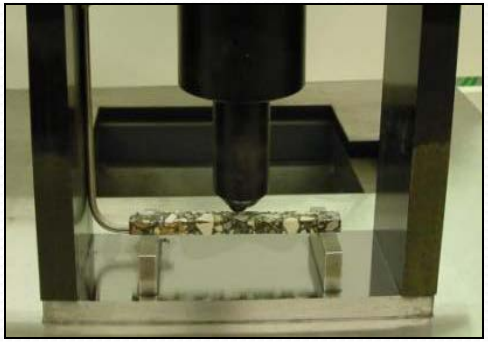
Low Temperature Cracking

- Testing and Analysis by Univ. of Minn.
- Semi-Circular Bend (SCB) test
  - Fracture Toughness (K_{IC}) ↑RAP
  - Fracture Energy (G_f) ↓RAP
- BBR on Mix Beams
  - Creep Stiffness ↑RAP
  - m-value ↓RAP
- Critical thermal cracking temperature is dominated by the virgin binder low PG
- Adequate thermal cracking resistance can be obtained with high RAP content mixes





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Recommendations

General Guidelines

- Definitions: Processing, Fractionation, RAP Content, RAP Binder Ratio, Warm Mix Asphalt
- Sources of RAP – open, just meet Superpave aggregate requirements for the mix design
- Continuously replenished RAP stockpiles allowed provided they meet variability limits

Quality Control of RAP

- Method of sampling
- Multiple samples required – do not combine
- Reducing samples to test portions
- Inspected for deleterious materials, QC results reviewed for stockpile approval

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Sampling and Testing Guidelines

Property	Test Method(s)	Frequency	Minimum Number of Tests per Stockpile	Maximum Standard Deviation
Asphalt Content	AASHTO T 164 or AASHTO T 308	1 per 1000 tons	10	0.5
Recovered Aggregate Gradation*	AASHTO T 30	1 per 1000 tons	10	5.0 all sieves 1.5 on 75 micron
Recovered Aggregate Bulk Specific Gravity	AASHTO T 84 and T 85	1 per 3000 tons	3	0.030
Binder Recovery and PG Grading	ASTM D 5404 and AASHTO R 29	1 per 5000 tons	1	n.a.

* Samples for Superpave aggregate consensus properties or other aggregate testing needs may be obtained by combining the tested aggregates following sieve analyses.

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High RAP Content Mix Design

- Aggregates properties – meet Superpave criteria
- Virgin Binder Selection: based on RAP Binder Ratio
  - RBR < 0.15 - use binder grade required for environment, traffic, and structural layer (i.e. may include polymer modified binder)
  - RBR 0.15 to 0.25 - use the standard binder grade for the climate (no polymer modification). If the mix is produced 25°F lower than equiviscous mixing temperature, the RAP Binder Ratio may be increased to 0.35 with the standard binder grade.

- Virgin Binder Selection:
  - If the RAP Binder Ratio exceeds 0.25 (or 0.35 for WMA), then determine the virgin binder grade using the formula:

$$T_{crit}(\text{virgin}) = \frac{T_{crit}(need) - (RBR \times T_{crit}(RAP\ Binder))}{(1 - RBR)}$$

T_{crit} *(virgin)* = critical temperature (high, intermediate, or low) of the virgin asphalt binder

T_{crit} *(need)* = critical temperature (high, intermediate, or low) needed for the climate and pavement layer.

RBR = the percentage of RAP binder in the mix divided by the mixture's total binder content. The mixture's total binder content is an unknown prior to mix design but can be estimated based on historical data for the aggregate type and NMAS.

T_{crit} *(RAP Binder)* = Critical temperature (high, intermediate, or low) of the RAP binder determined from extraction, recovery, and PG grading.

Mix Design for High RAP Contents

- Design mix to meet M 323
  - Moisture Susceptibility (always)
    - TSR or Hamburg
  - Permanent Deformation (mixes within top 50 mm)
    - AMPT Flow Number or APA
  - Fatigue (surface or base mixes) *for information purposes only*
    - Fracture Energy or other cracking test
  - Low Temperature (for cold climates)
    - IDT Creep Compliance & Strength, SCB, or BBR with mix beams

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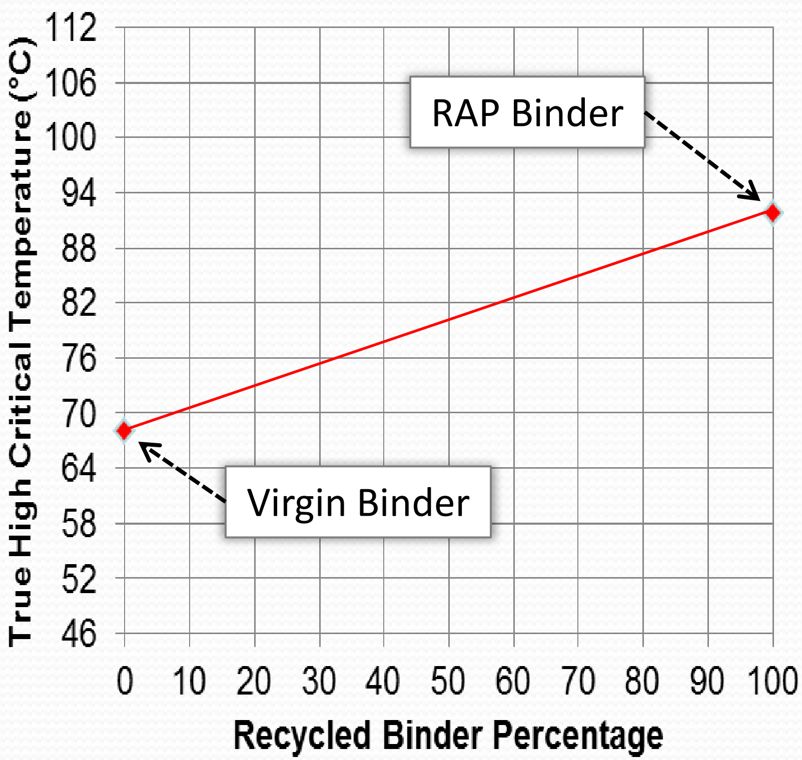
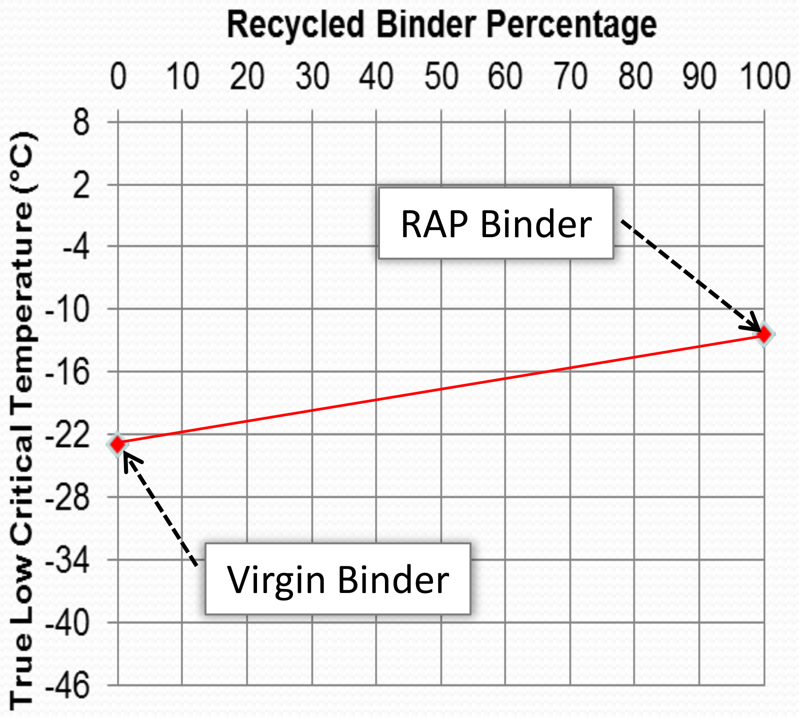
Thank You

Blending of Virgin and Recycled Binders





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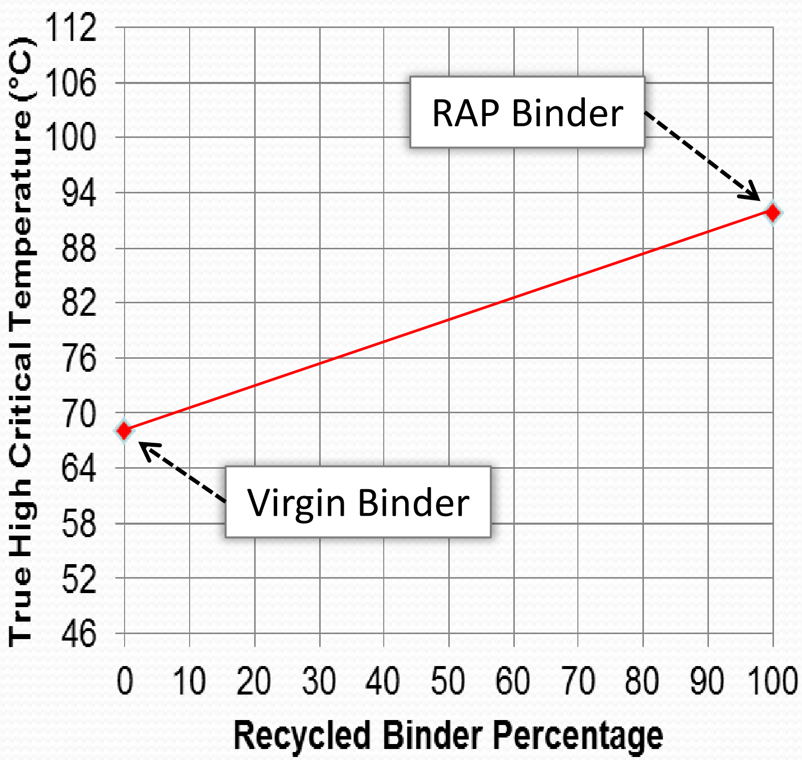
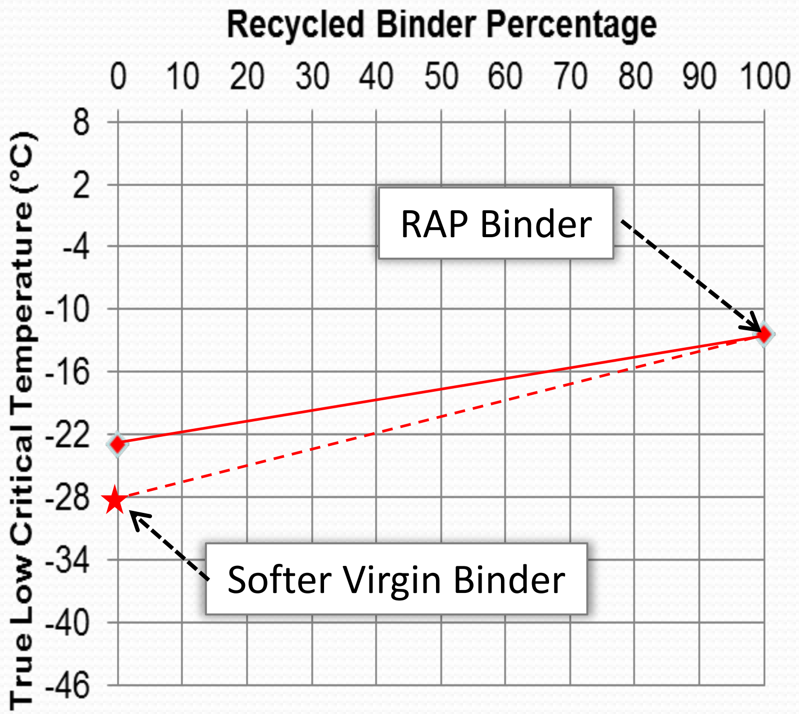
Blending of Virgin and Recycled Binders





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A New Approach to Selecting and Evaluating Alternate Blends

- The following method of calculating aggregate blends is well established:

$$p = Aa + Bb + Cc + \ldots.$$

- which can be rewritten as:

$$p_{sieveS} = \sum_{i=1}^{n} P_i \bar{x}_i$$

$p_{sieve\ S}$ = *percent passing any sieve "S"*
P = *proportion of component "i" in the total blend*
$\bar{x}$ = *average percent passing sieve "S" for component "i"*
n = *total number of aggregate components*

Blend Variability Analysis: a New Approach

- Similarly, the expected variance of the aggregate blends can be calculated as:

$$\mathrm{var}_{sieve\ S} = \sum_{i=1}^{n} P_i^2 \sigma_i^2$$

$\mathrm{var}_{sieve\ S}$ = *expected variance of percent passing any sieve "S"*

P = *proportion of component "i" in the total blend*

σ^2 = *variance of percent passing sieve "S" for component "i"*

n = *total number of aggregate components*

Assuming that the proportions "P_i" are constants

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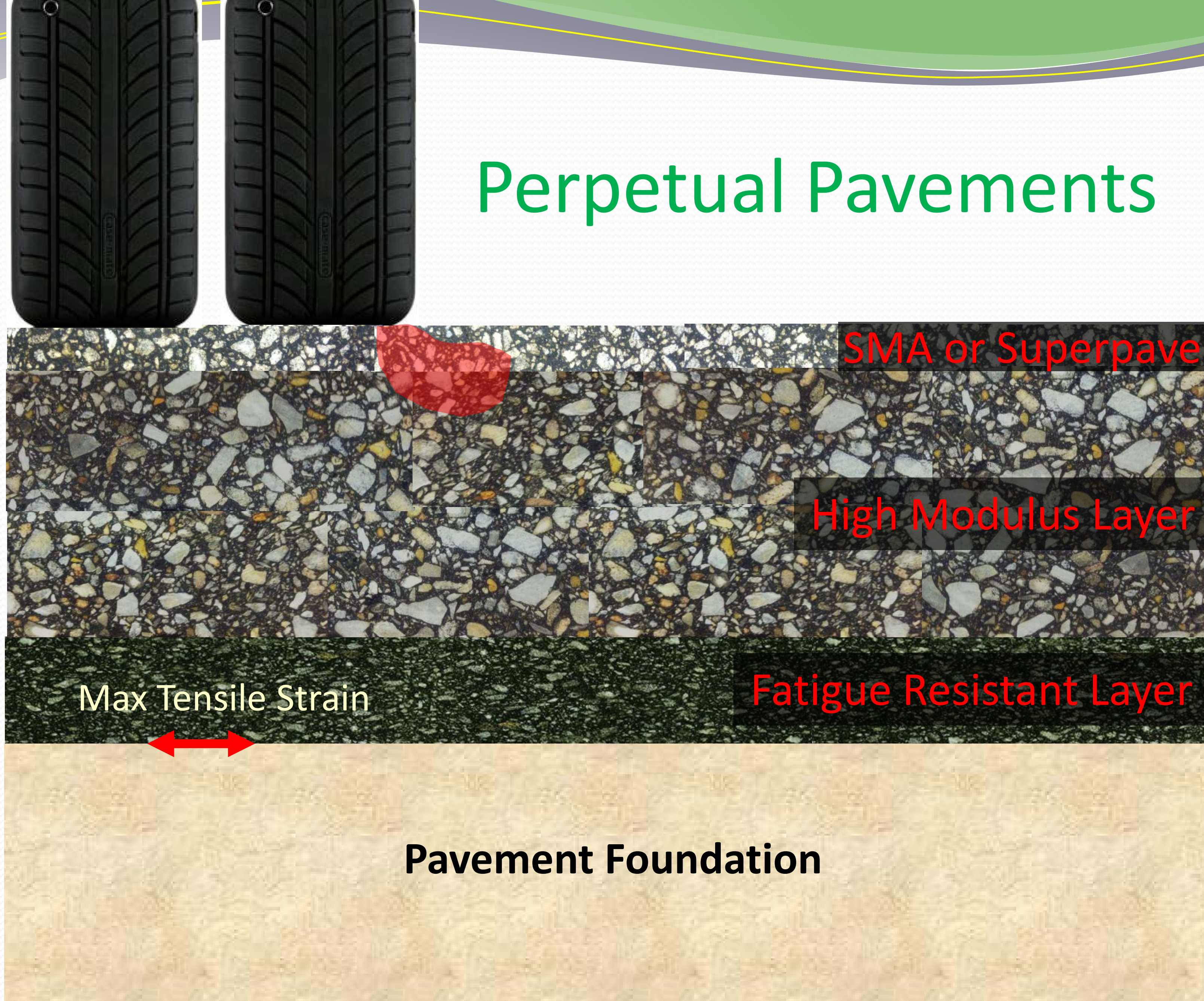
Blend Variability Analysis: a New Approach

$$std.dev._{sieve\ S} = sqrt(\sum_{i=1}^{n} P_i^2 \sigma_i^2)$$

- Actually, the proportions (P_i's) are not constants, they are also random variables.
- This complicates the matter, but the exact solution can be incorporated in a blending type spreadsheet.
- The worksheet uses the simplified equation above that does not account for variations in the proportions.
- It can be used to select alternate trial gradations that will help evaluate the sensitivity of the mix to normal variations in materials.

Perpetual Pavements



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Panel Meeting

September 15, 2011

NAS Keck Center

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Presentation Outline

- Status of Final Report
- Review of Objectives
- Best Practices for RAP Management
- Mix Design Sample Preparation Guidelines
- Experimental Plan
- Results and Analysis
- Preliminary Conclusions and Recommendations

Project Objectives

- Provide Guidance on Characterizing RAP
- Revise Mix Design Procedure for High RAP Contents
- Recommend Performance Tests
  - Dynamic Modulus
  - Moisture Sensitivity
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  - Fatigue Cracking Resistance
  - Low Temperature Cracking Resistance

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Best Practices for RAP Management

Best Practices for RAP Management

- Keep large milling stockpiles separate, no additional processing to minimize $P_{0.075}$
- Multi-source stockpiles can be made into a consistent RAP through processing. Avoid over-crushing by screening material prior to crusher.
- Variability guidelines should be used rather than method specifications for processing
- Fractionation is helpful for mix designs with high RAP contents
- Sampling & testing frequency should be consistent with aggregate QC (typically 1 per 1000 tons of RAP)
- Use a loader to build mini-stockpiles for sampling
- RAP aggregate can be recovered for testing using solvent extraction or ignition method

Handling RAP for Mix Designs

RAP Drying

Oven Drying @230F	Start	1 Hr	2 Hr
Moisture Content	5.6%	4.2%	2.9%
Recovered RAP Binder, True Grade	97.2 (33.7) -7.3		102 (37.9) – 9.7

Fan Drying @ Ambient	Start	17 Hrs	96 Hrs
Moisture Content	5.5%	0.9%	0.2%

RAP Heating Results

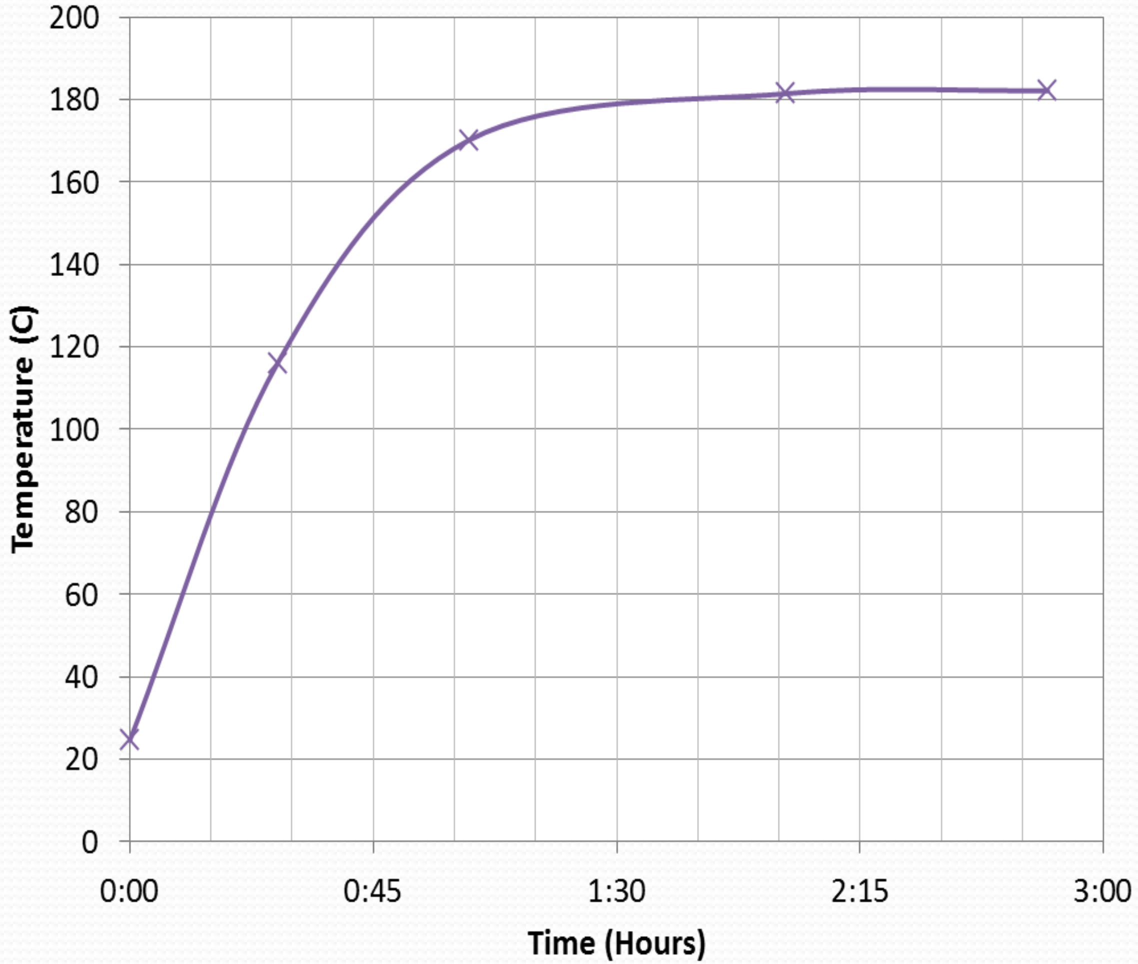
Theoretical Asphalt Content = 2.44%

RAP binder True Grade: 85.1-15.7

Virgin Heating Time	Virgin Temp.	RAP Heating Time	RAP Oven Temp.	Average Asphalt Content	Recov. PG
3 hours	355 °F	30 min	355 °F	1.98	85.0-17.8
3 hours	355 °F	3 hrs	355 °F	2.11	89.3-13.9
16 hours	355 °F	16 hours	355 °F	0.79	*
3 min	500 °F	0	Room Temp.	2.35	95.0-10.0

**** Majority of binder could not be extracted***

RAP Heating Time



RAP Aggregate Properties

RAP Aggregate Properties

- Gradation, Specific Gravity, Consensus Properties, Source Properties, Polishing/Friction
- How to recover the aggregate?
  - Solvent extraction, AASHTO T 164
  - Ignition method, AASHTO T 308
- A joint UNR-NCAT study examined many aggregate characteristics before and after solvent extraction and the ignition method using a limited set of materials. Most characteristics are not affected significantly by either method.

RAP Aggregate Bulk Specific Gravity

Option 1: Estimated G_{sb} from G_{mm} & P_{ba}

1. Determine G_{mm} (w/ dryback) of RAP sample
2. Calculate G_{se} using the formula:

$$G_{se(RAP)} = \frac{100 - P_{b(RAP)}}{\frac{100}{G_{mm(RAP)}} - \frac{P_{b(RAP)}}{G_b}}$$

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RAP Aggregate Bulk Specific Gravity

Option 1: Estimated G_{sb} from G_{mm} & P_{ba}

3. Estimate the absorbed asphalt, P_{ba} , based on historical values for the plant location.
4. Calculate G_{sb} using the formula:

$$G_{sb(RAP)} = \frac{G_{se(RAP)}}{\frac{P_{ba} \times G_{se(RAP)}}{100 \times G_b} + 1}$$

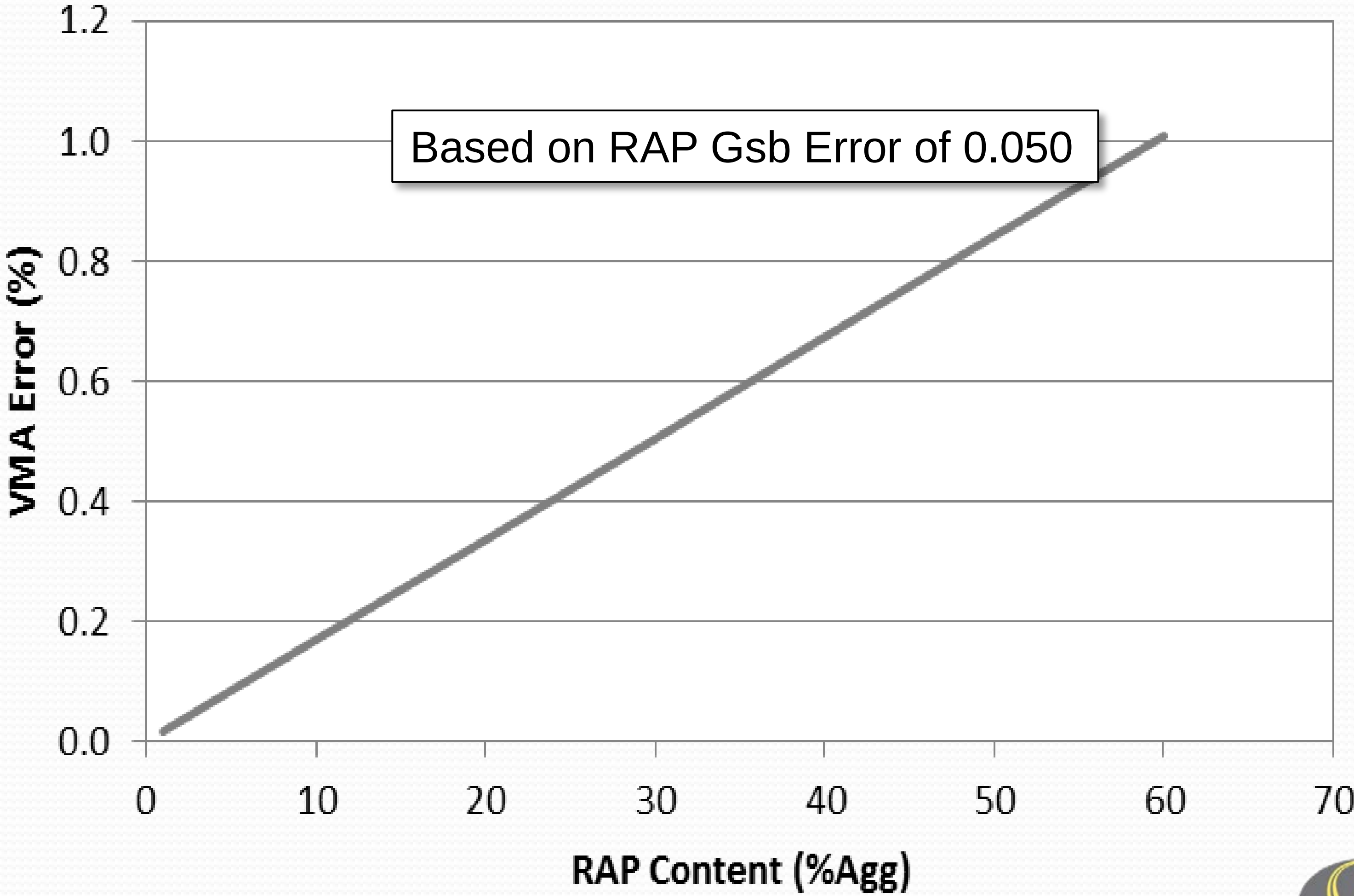
RAP Aggregate Bulk Specific Gravity

Option 2: Recover aggregate using a solvent extraction or ignition method, then conduct AASHTO T84 and T85 on the fine and course fractions like any other aggregate.

RAP Aggregate Gsb Results

RAP Desc.	Centrifuge	Ignition	Gmm→Gsb (C)	Gmm→Gsb (I)	Max.-Min.
FL Coarse	2.563	2.592	2.616	2.604	0.053
FL Fine	2.565	2.574	2.581	2.566	0.016
MN Coarse	2.628	2.623	2.681	2.591	0.090
MN Fine	2.618	2.606	2.656	2.585	0.071
NH Coarse	2.662	2.653	2.630		0.030
NH Fine	2.636	2.629	2.671	2.667	0.042
UT Coarse	2.567	2.599	2.693	2.622	0.126
UT Fine	2.583	2.579	2.624	2.641	0.062

Potential VMA Error



Comparison of VMA Using different Gsb's

RAP Source	RAP content	NMAS (mm)	Centrifuge - T84/85	Ignition - T84/85	Backcalculated
New Hampshire	25%	12.5	16.1	16.1	16.5
	55%	12.5	15.9	15.8	16.3
Utah	25%	12.5	14.0	13.9	14.4
	55%	12.5	15.1	14.8	16.0
Minnesota	40%	9.4	15.5	15.4	16.9
		19.0	13.3	13.3	14.7
Florida	40%	9.5	15.0	15.2	16.2
		19.0	13.6	13.8	15.0

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Experimental Plan

Experimental Plan

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

Volumetric Properties

New Hampshire Mixes with PG58-28 Virgin Binder	0% RAP	0% RAP	25% RAP	55% RAP Original	55% RAP Original	55%RAP Redesign
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	58-28A	58-28B	58-28A	58-28A	58-28B	58-28A
+ #4 Scrnd RAP (Pb=3.2) %	0	0	0	55	55	31
- #4 Scrnd RAP (Pb=6.05) %	0	0	25	0	0	24
Percent Passing 4.75 mm	56.0	56.0	63.1	51.1	51.1	44.7
Percent Passing 0.075 mm	3.8	3.8	5.2	4.6	4.6	5.3
Optimum AC, %	5.5	5.6	5.9	5.2	5.3	6.1
AC from virgin binder, %	5.6	5.6	4.4	3.4	3.5	3.7
AC from RAP, %	0	0	1.51	1.76	1.76	2.44
RAP Binder / Total Binder, %	0	0	26	34	33	40
Va, %	4.0	3.7	4.0	4.0	4.1	4.0
VMA, %	15.8	15.5	16.1	14.4	14.4	15.5

New Hampshire Mixes with PG70-28 Virgin Binder	0% RAP	0% RAP	25% RAP	55% RAP Original	55% RAP Original
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	70-28A	70-28B	70-28A	70-28A	70-28B
+ #4 Scrnd RAP (Pb=3.2) %	0	0	0	55	55
- #4 Scrnd RAP (Pb=6.05) %	0	0	25	0	0
Percent Passing 4.75 mm	56.0	56.0	63.1	51.1	51.1
Percent Passing 0.075 mm	3.8	3.8	5.2	4.6	4.6
Optimum AC, %	5.6	5.6	5.9	5.2	5.2
AC from virgin binder, %	5.6	5.6	4.4	3.4	3.4
AC from RAP, %	0	0	1.51	1.76	1.76
RAP Binder / Total Binder, %	0	0	26	34	34
Va, %	3.8	3.7	4.0	4.0	4.0
VMA, %	15.5	15.4	16.2	15.5	14.4
Vbe, %	11.7	11.7	12.2	10.5	10.4
VFA, %	75.7	75.9	75.0	72.7	73.0
Effective AC, %	5.0	5.0	5.2	4.5	4.5
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

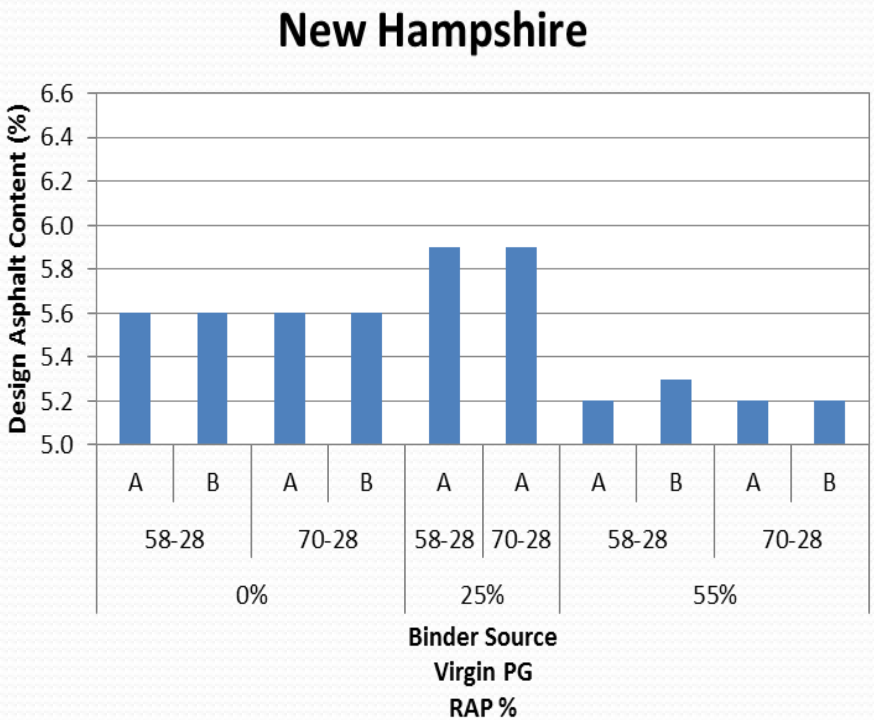
Utah Mixes with PG58-34 Virgin Binder	0% RAP	0% RAP	25% RAP	55% RAP WMA	55% RAP	55%RAP
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	58-34A	58-34B	58-34A	58-34A	58-34A	58-34B
Fine RAP (Pb=6.72), %	0	0	12	15.5	15.5	15.5
Coarse RAP (Pb=5.32), %	0	0	13	39.5	39.5	39.5
Percent Passing 4.75 mm	48.5	48.5	44.9	43.5	43.5	43.5
Percent Passing 0.075 mm	5.2	5.2	5.6	6.1	6.1	6.1
Optimum AC, %	5.5	6.0	5.7	6.5	6.5	6.1
AC from virgin binder, %	5.5	6.0	4.2	3.5	3.5	3.1
AC from RAP, %	0	0	1.54	3.0	3.0	3.0
RAP Binder / Total Binder, %	0	0	27	46	46	49
Va, %	3.9	4.1	3.7	4.1	3.7	3.7
VMA, %	14.0	15.2	14.1	15.3	15.1	15.0
Vbe, %	10.1	11.1	10.4	11.2	11.4	11.3

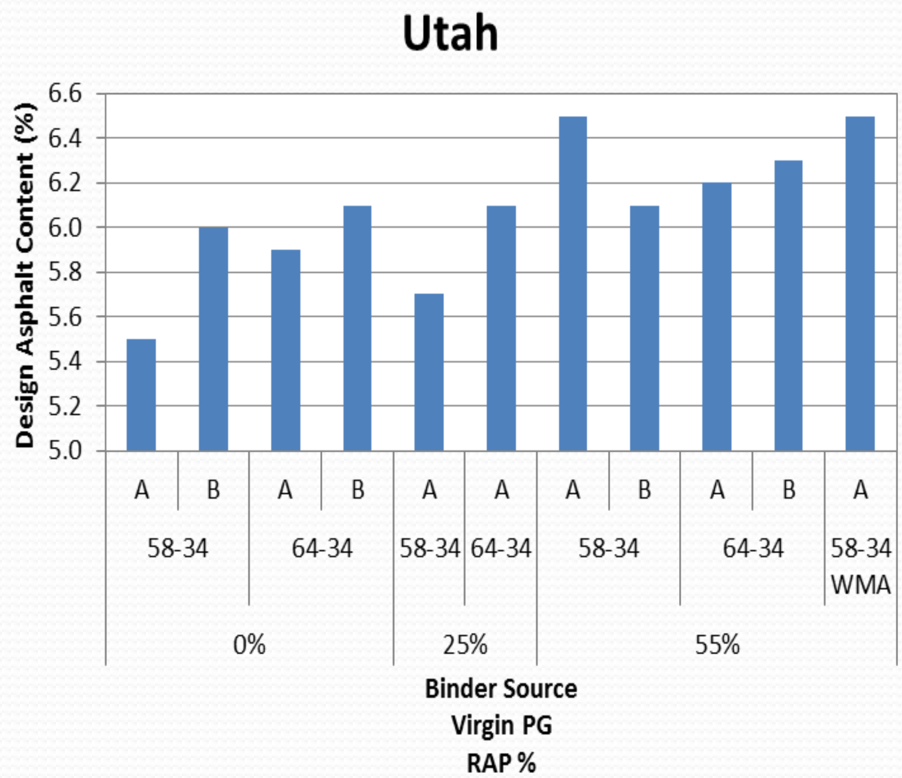
Utah Mixes with PG64-34 Virgin Binder	0% RAP	0% RAP	25% RAP	55% RAP	55% RAP
Nominal Max. Agg. Size, mm	12.5	12.5	12.5	12.5	12.5
Virgin Binder Grade	64-34A	64-34B	64-34A	64-34A	64-34B
Fine RAP (Pb=6.72), %	0	0	12	15.5	15.5
Coarse RAP (Pb=5.32), %	0	0	13	39.5	39.5
Percent Passing 4.75 mm	48.5	48.5	44.9	43.5	43.5
Percent Passing 0.075 mm	5.2	5.2	5.6	6.1	6.1
Optimum AC, %	5.9	6.1	6.1	6.2	6.3
AC from virgin binder, %	5.9	6.1	4.6	3.2	3.3
AC from RAP, %	0	0	1.54	3.0	3.0
RAP Binder / Total Binder, %	0	0	25	48	48
Va, %	4.2	4.0	4.0	3.8	4.8
VMA, %	15.2	15.1	15.3	15.4	15.4
Vbe, %	11.0	11.1	11.3	11.6	10.6
VFA, %	71.9	72.7	73.3	75.3	74.0
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Minnesota Mixes with PG58-28 Virgin Binder	0% RAP	40% RAP	0% RAP	40% RAP
Nominal Max. Agg. Size, mm	9.5	9.5	19.0	19.0
Virgin Binder Grade	58-28	58-28	58-28	58-28
Coarse RAP (Pb=4.31), %	0	30	0	40
Fine RAP (Pb=4.67), %	0	10	0	0
Percent Passing 4.75 mm	51.0	48.0	45.1	51.8
Percent Passing 0.075 mm	4.1	3.6	3.6	3.8
Optimum AC, %	6.3	6.1	5.0	5.1
AC from virgin binder, %	6.3	4.1	5.0	3.0
AC from RAP, %	0	2.0	0	2.1
RAP Binder / Total Binder, %	0	33	0	42
Va, %	4.0	4.0	4.1	4.0
VMA, %	16.1	15.5	13.6	13.4
Vbe, %	12.1	11.5	9.5	9.4
VFA, %	75.0	74.7	69.4	70.6
Effective AC, %	5.3	5.0	4.1	4.0

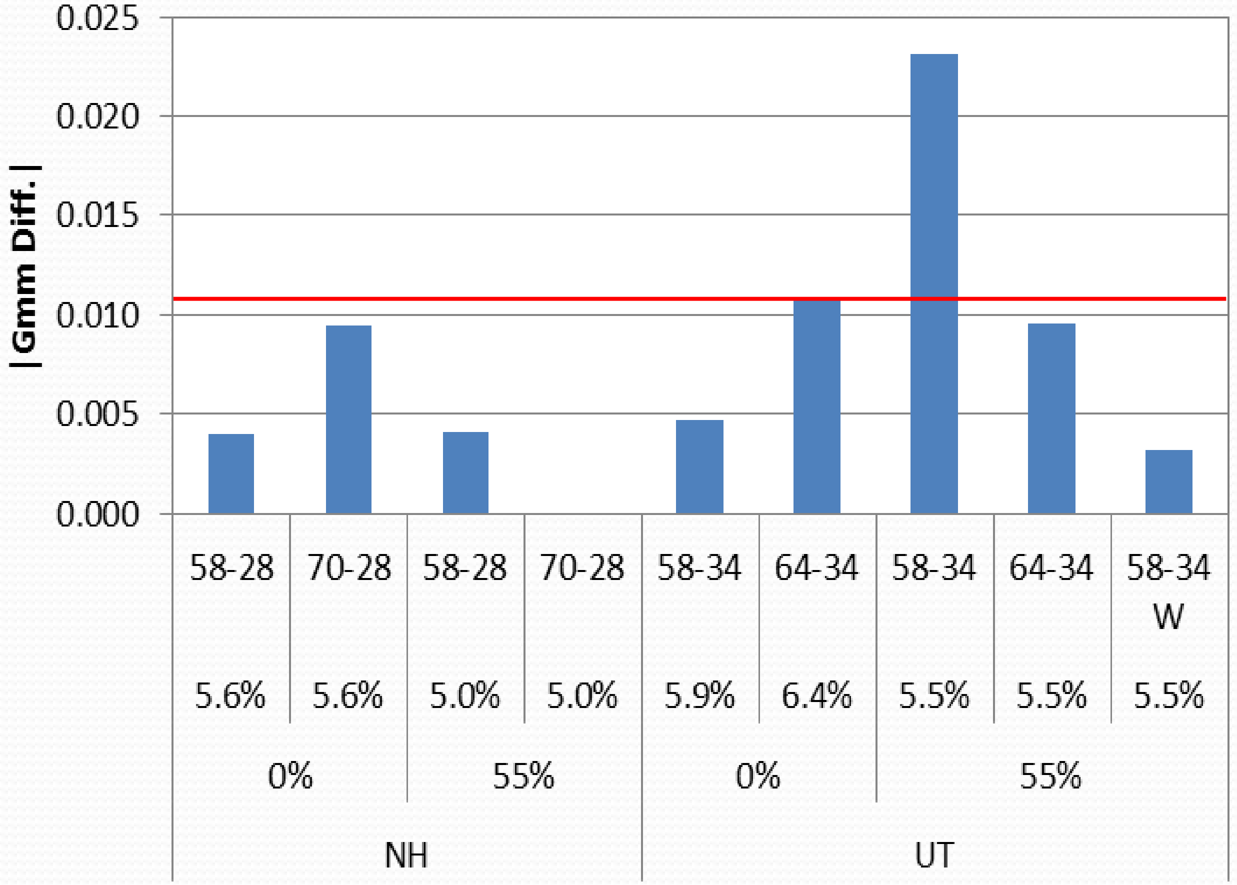
Florida Mixes with PG64-22 Virgin Binder	0% RAP	40% RAP	0% RAP	40% RAP
Nominal Max. Agg. Size, mm	9.5	9.5	19.0	19.0
Virgin Binder Grade	64-22	64-22	64-22	64-22
Coarse RAP (Pb=5.27), %	0	35	0	20
Fine RAP (Pb=5.95), %	0	5	0	20
Percent Passing 4.75 mm	71.3	70.5	51.8	50.9
Percent Passing 0.075 mm	4.6	4.5	4.0	4.0
Optimum AC, %	5.4	3.5	4.5	2.9
AC from virgin binder, %	5.4	5.6	4.5	5.1
AC from RAP, %	0.0	2.1	0.0	2.2
RAP Binder / Total Binder, %	0	38	0	44
Va, %	3.8	4.2	4.1	4.1
VMA, %	15.1	15.0	13.5	13.6
Vbe, %	11.3	10.8	9.4	9.5
VFA, %	72.6	71.8	70.3	70.4
Effective AC, %	4.6	4.6	4.0	4.0

Comparison of Design Binder Contents

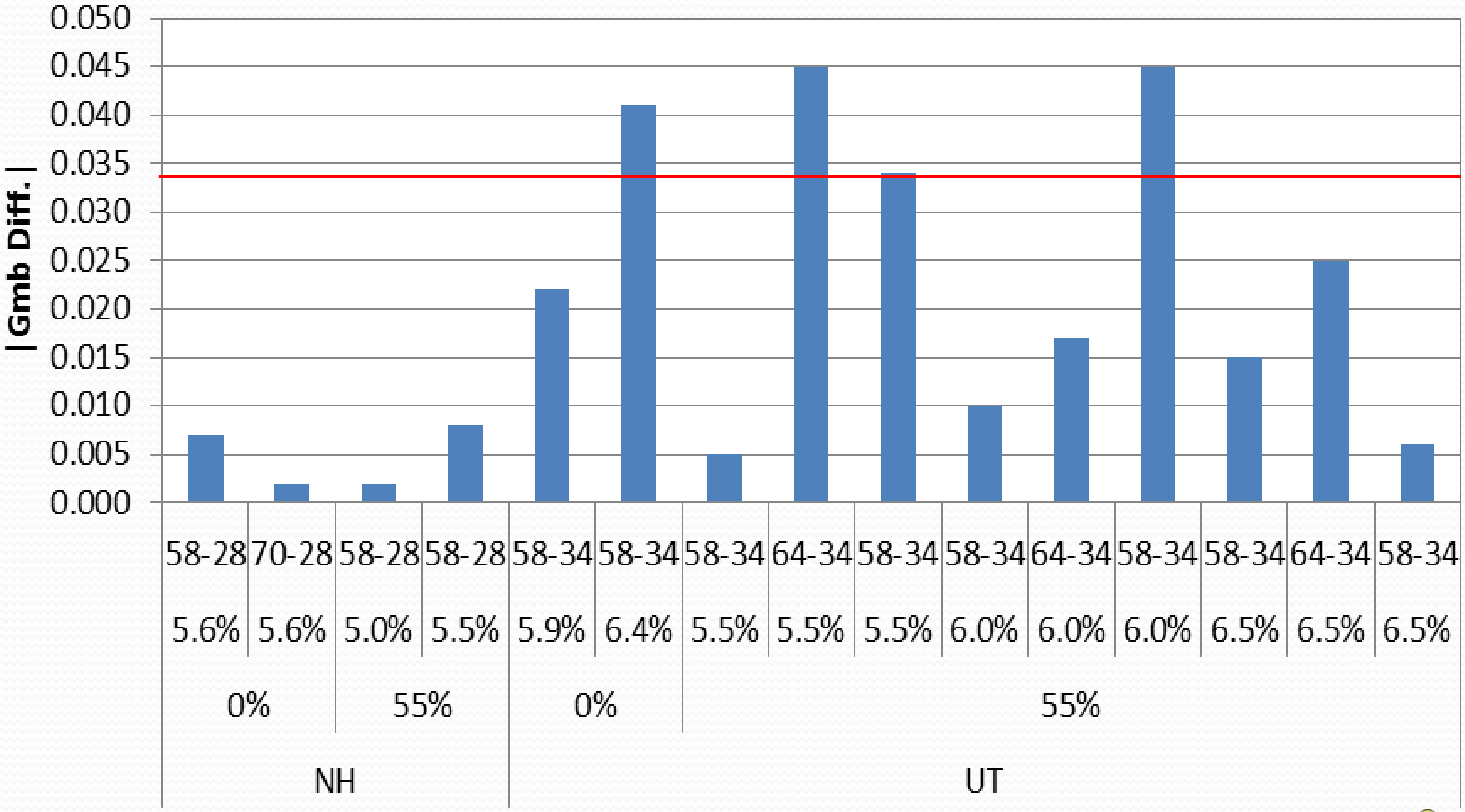




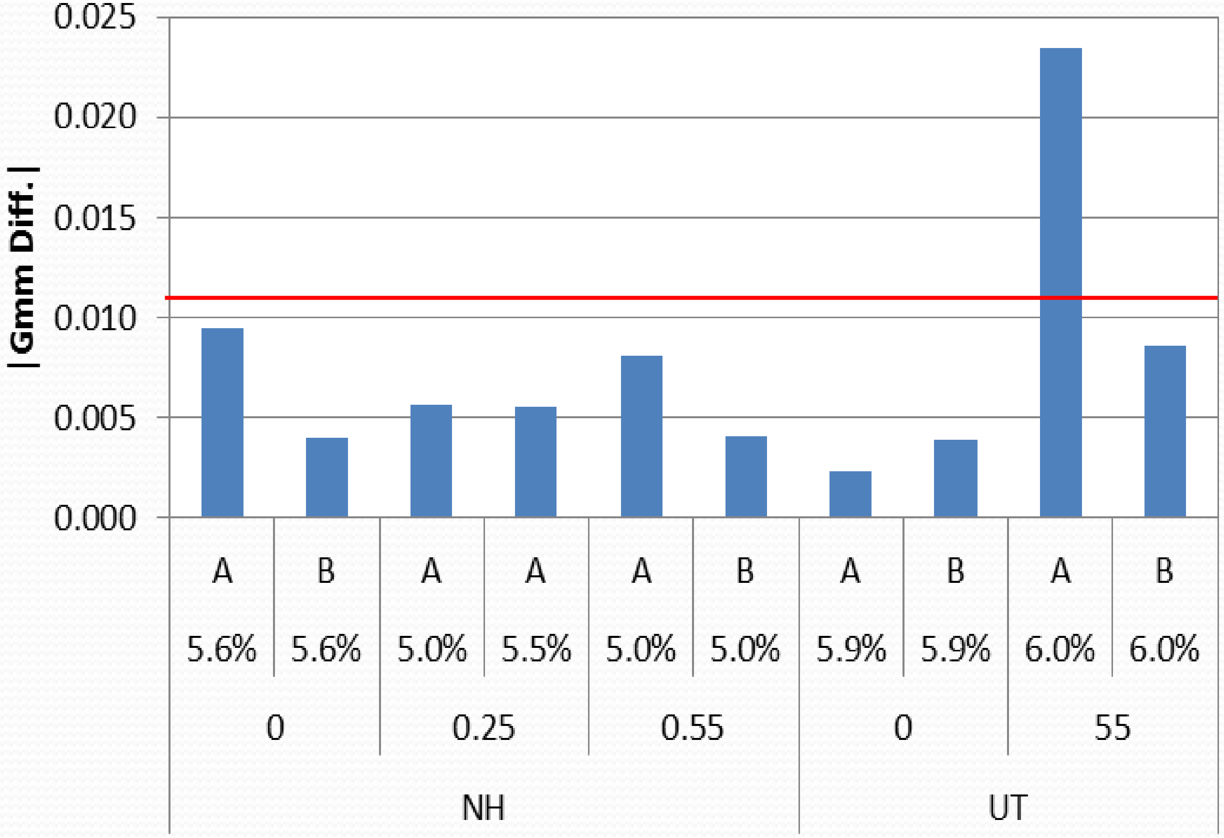
Effect of Binder Source on Gmm



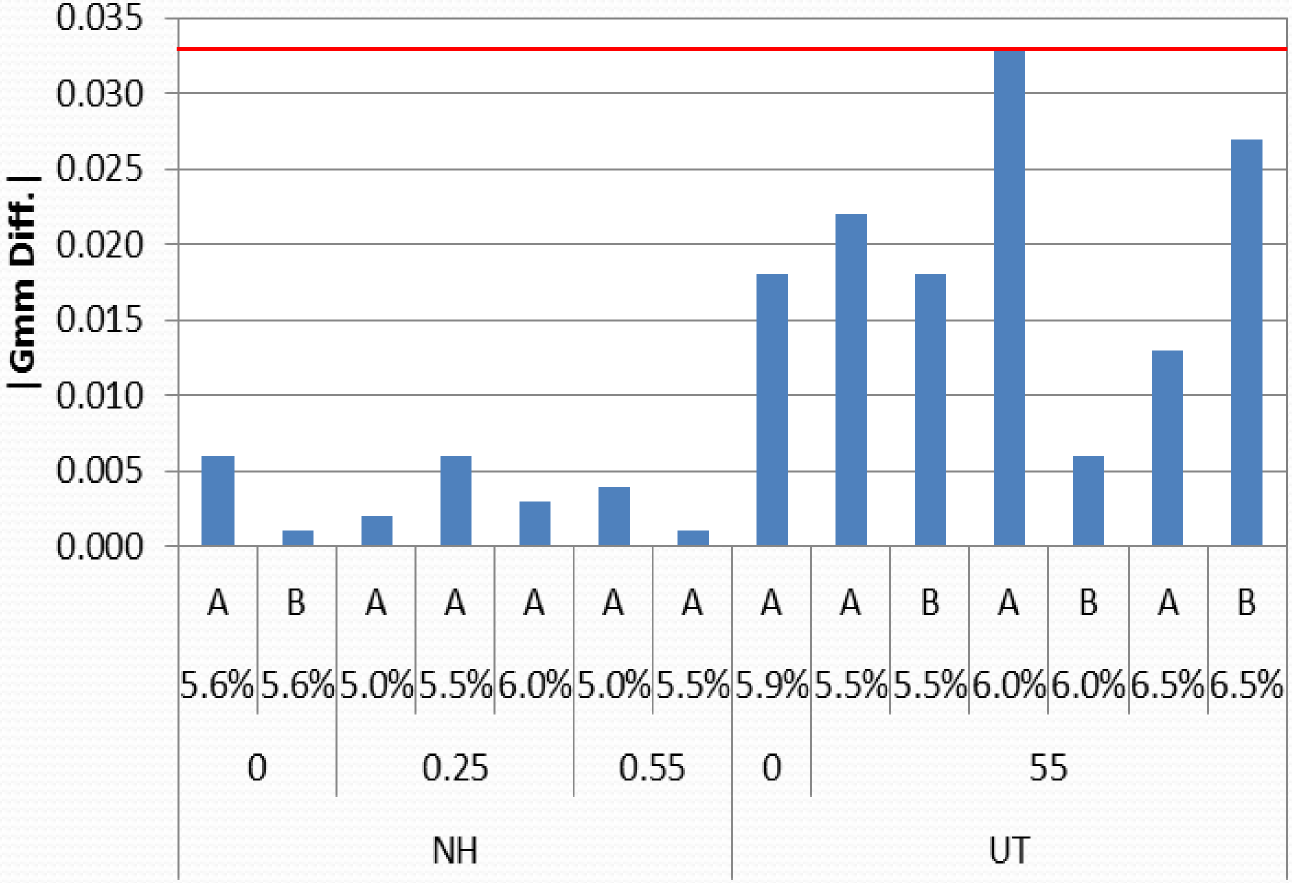
Effect of Binder Source on Gmb



Effect of Binder Grade on Gmm



Effect of Binder Grade on Gmb



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Analysis of Binder Source and Grade on Volumetric Properties

- Changing binder source and PG grade affected the optimum asphalt content for one set of materials (Utah), but not the other (New Hampshire).
- Comparisons of Gmm and Gmb data were analyzed to try to isolate if differences could be due to adsorption or lubrication during compaction.
  - No apparent cause can be assigned to differences. This is probably not related to binder compatability since the optimum asphalt content was also affected for the virgin mix.

Theoretical Blending Analysis

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PG Grading of Binders

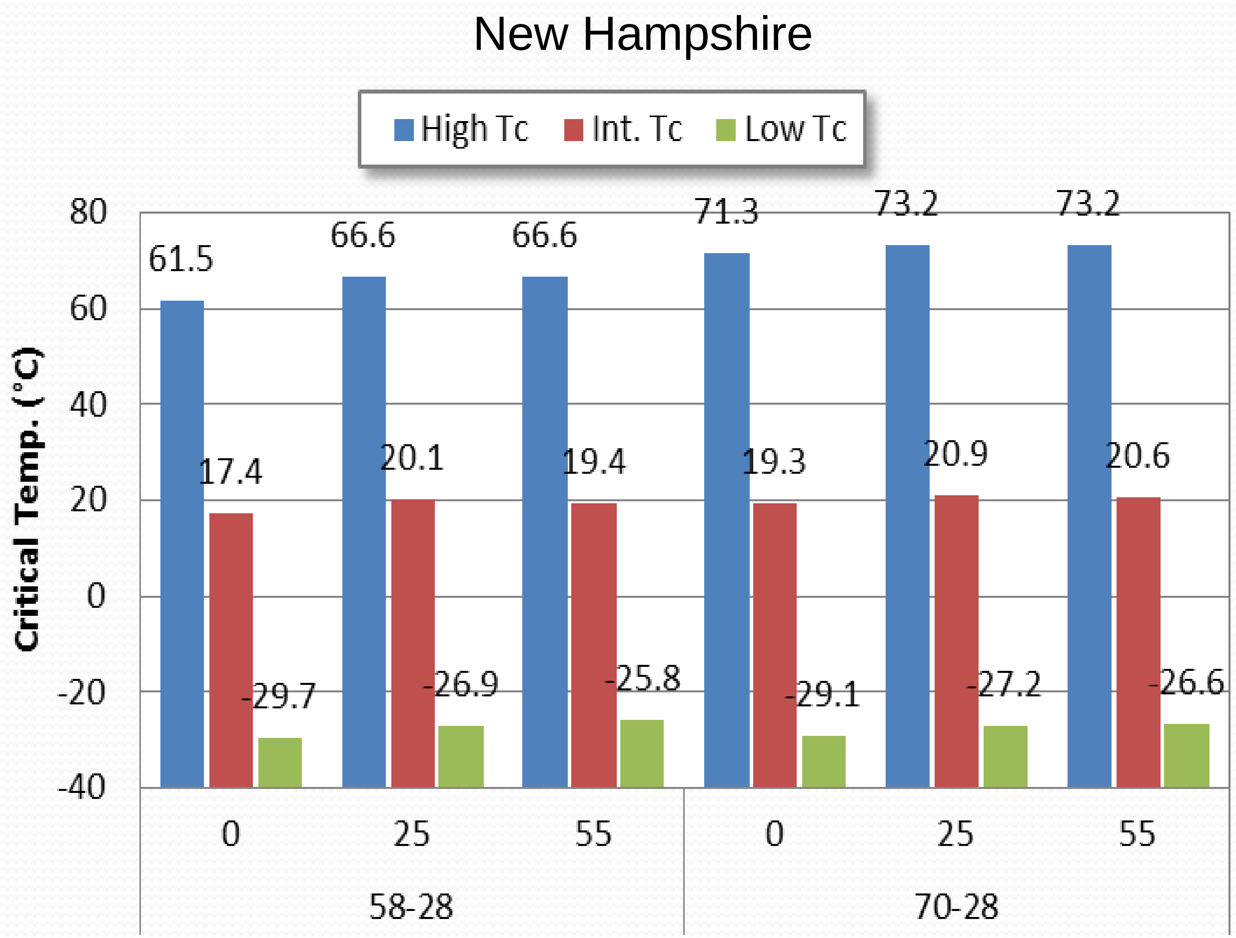
Virgin Binders

Source	ID	T_{crit} High	T_{crit} Int	T_{crit} Low	PG
NH	70-28 A	71.3	19.3	-29.1	70 - 28
	70-28 B	71.4	15.6	-31.9	70 - 28
	58-28 A	61.5	17.4	-29.7	58 - 28
UT	64-34 A	68.2	9.3	-35.5	64 - 34
	64-34 B	70.6	13.9	-34.5	70 - 34
	58-34 A	63.0	11.7	-34.9	58 - 34
	58-34 B	61.2	9.9	-35.9	58 - 34
	58-28				

Recovered RAP Binders

Source	Size	T_{crit} High	T_{crit} Int	T_{crit} Low	PG
NH	Coarse	77.3	23.5	-21.4	76 - 16
	Fine	81.3	28.0	-18.8	76 - 16
	Non-fract.	80.2	28.1	-20.2	76 - 16
UT	Coarse	83.8	29.3	-17.0	82 - 16
	Fine	89.0	32.7	-12.6	88 - 10
MN	Coarse	72.8	23.7	-22.7	70 - 22
	Fine	89.2	38.1	-9.3	88 - 4
FL	Coarse	73.8	23.6	-24.8	70 - 22
	Fine	71.1	21.7	-26.3	70 - 22

Theoretical Blending Analysis



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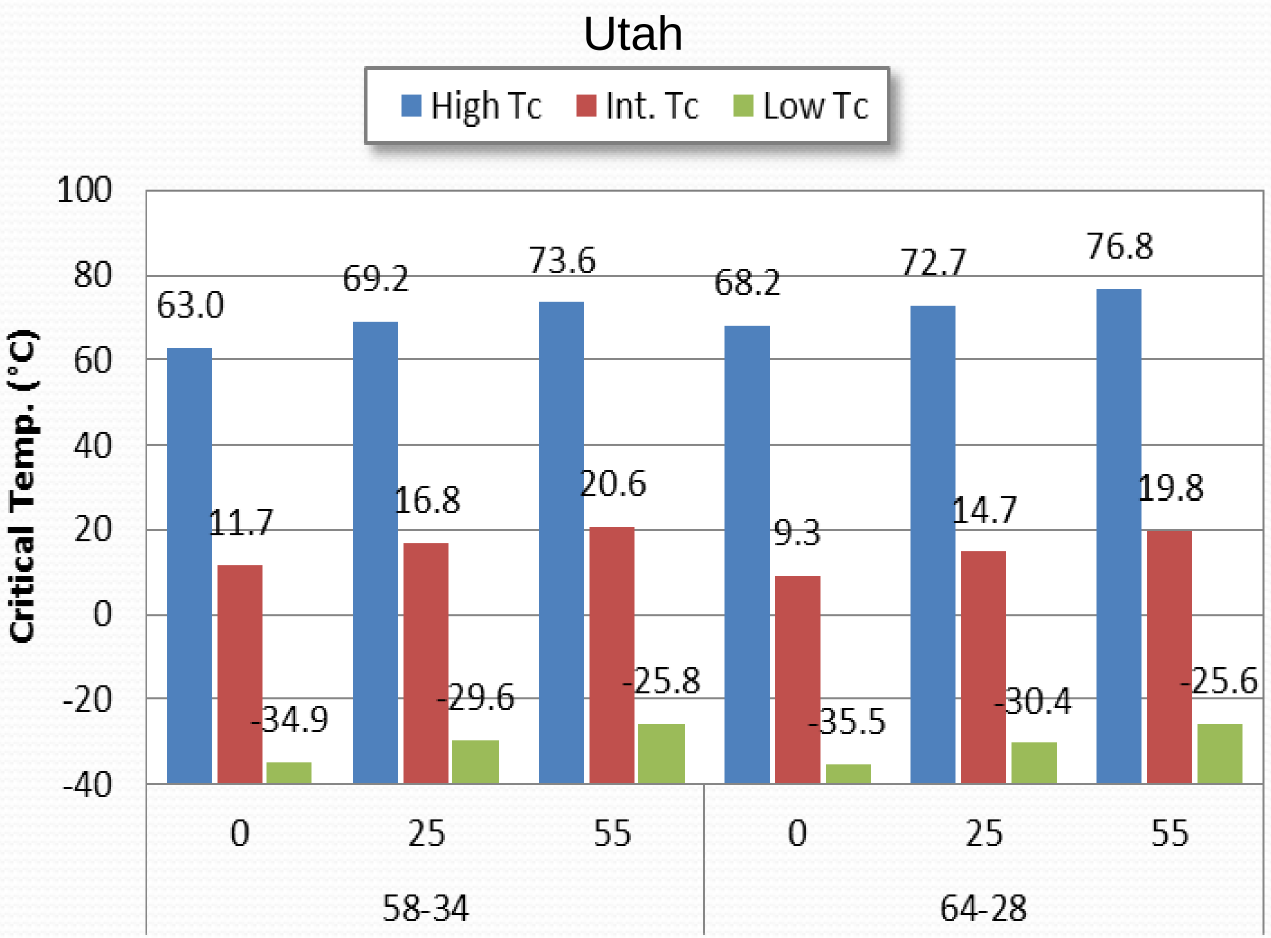
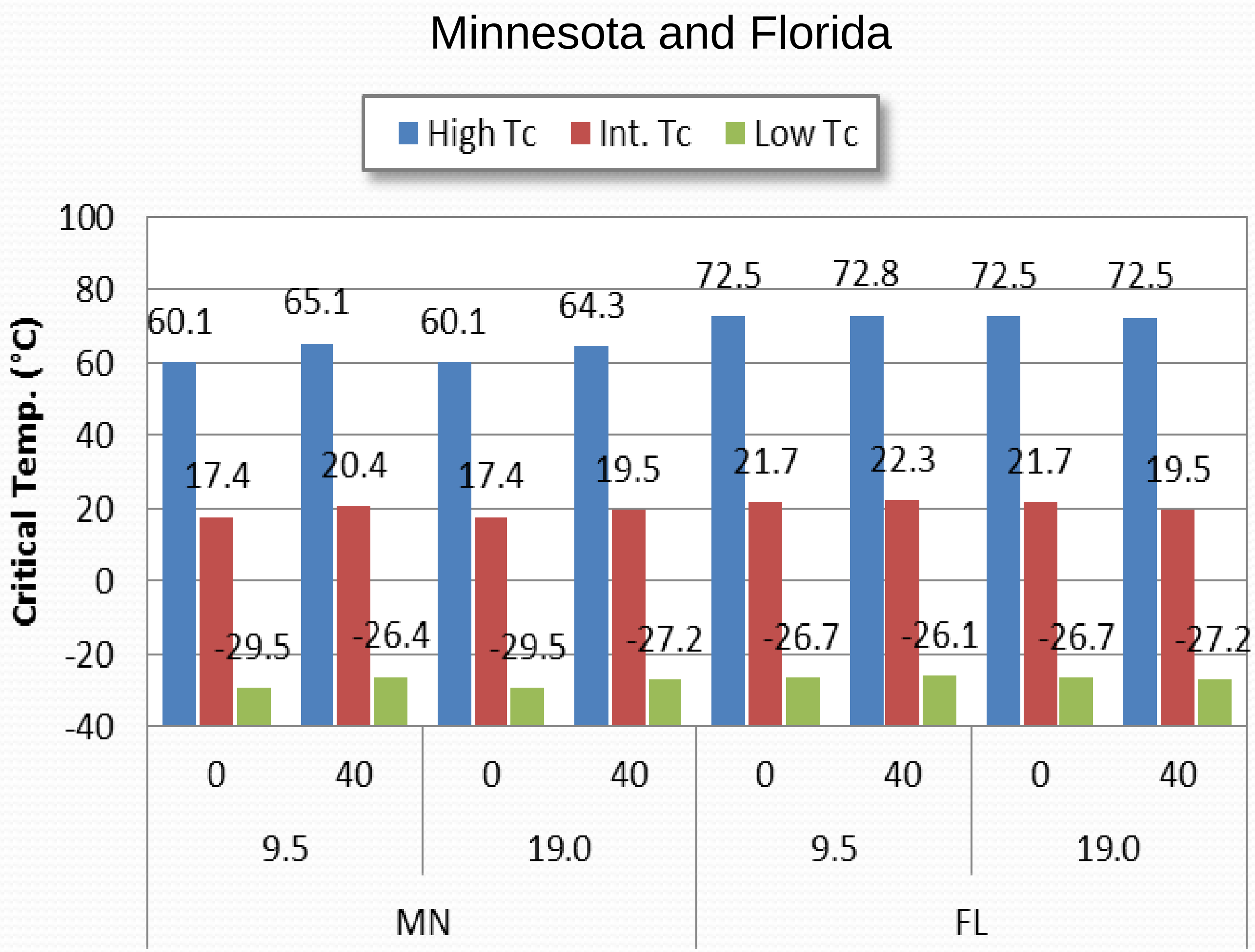
Theoretical Blending Analysis



Theoretical Blending Analysis



Dynamic Modulus and Back-calculation of Binder Properties

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) and Unconfined
- Target Strain: 100με
- Sigmoidal function to create mastercurves

AMPT

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Back-calculation 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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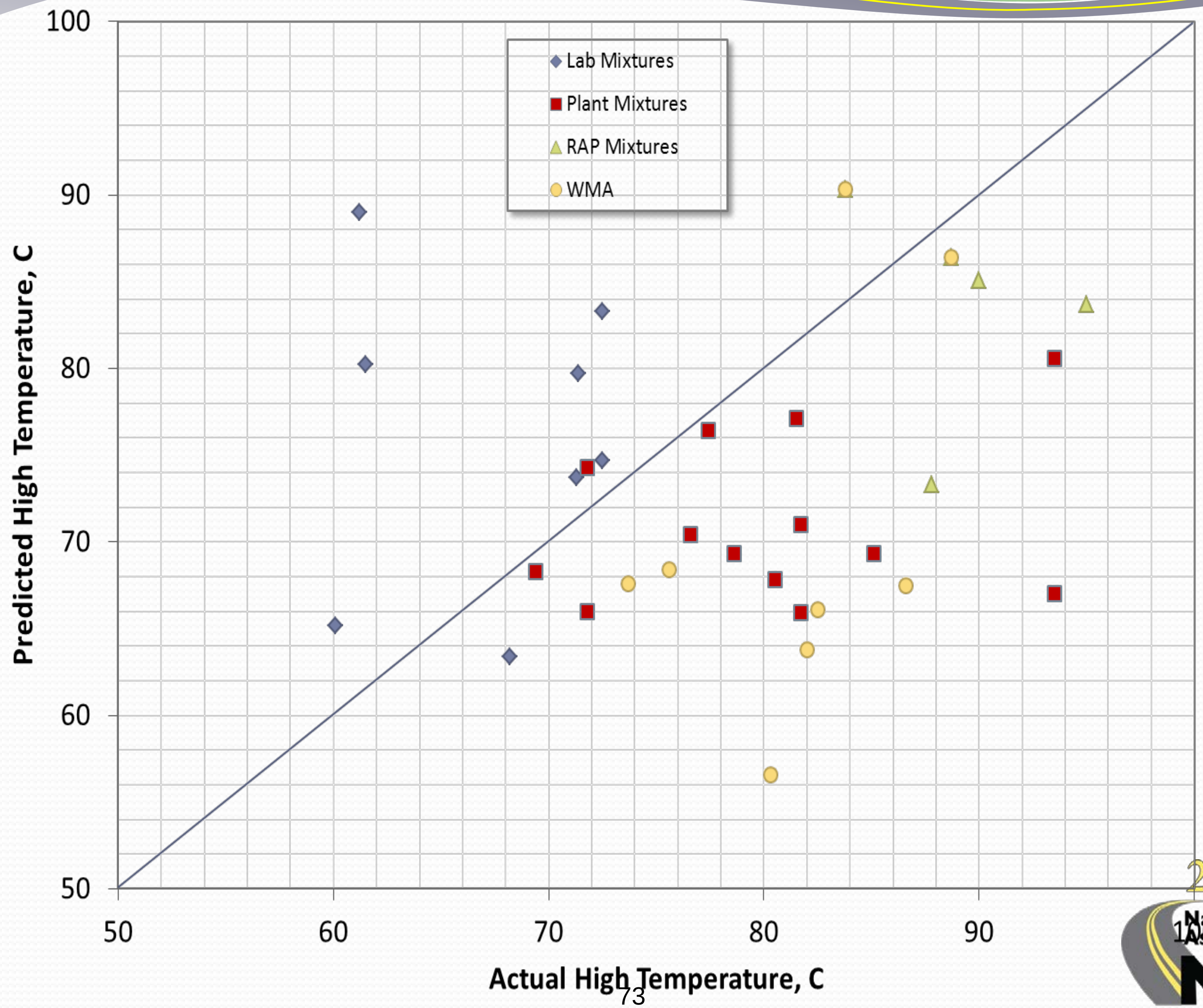
Back-calculation of Binder Properties

- 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(δ) = 2.2 kPa
  - Intermediate temp: G*sin(δ)= 5,000 kPa


Lab Mixtures
Plant Mixtures
RAP Mixtures
WMA
Predicted High Temperature, C
Actual High Temperature, C
100
90
80
70
60
50
50
60
70
80
90
100

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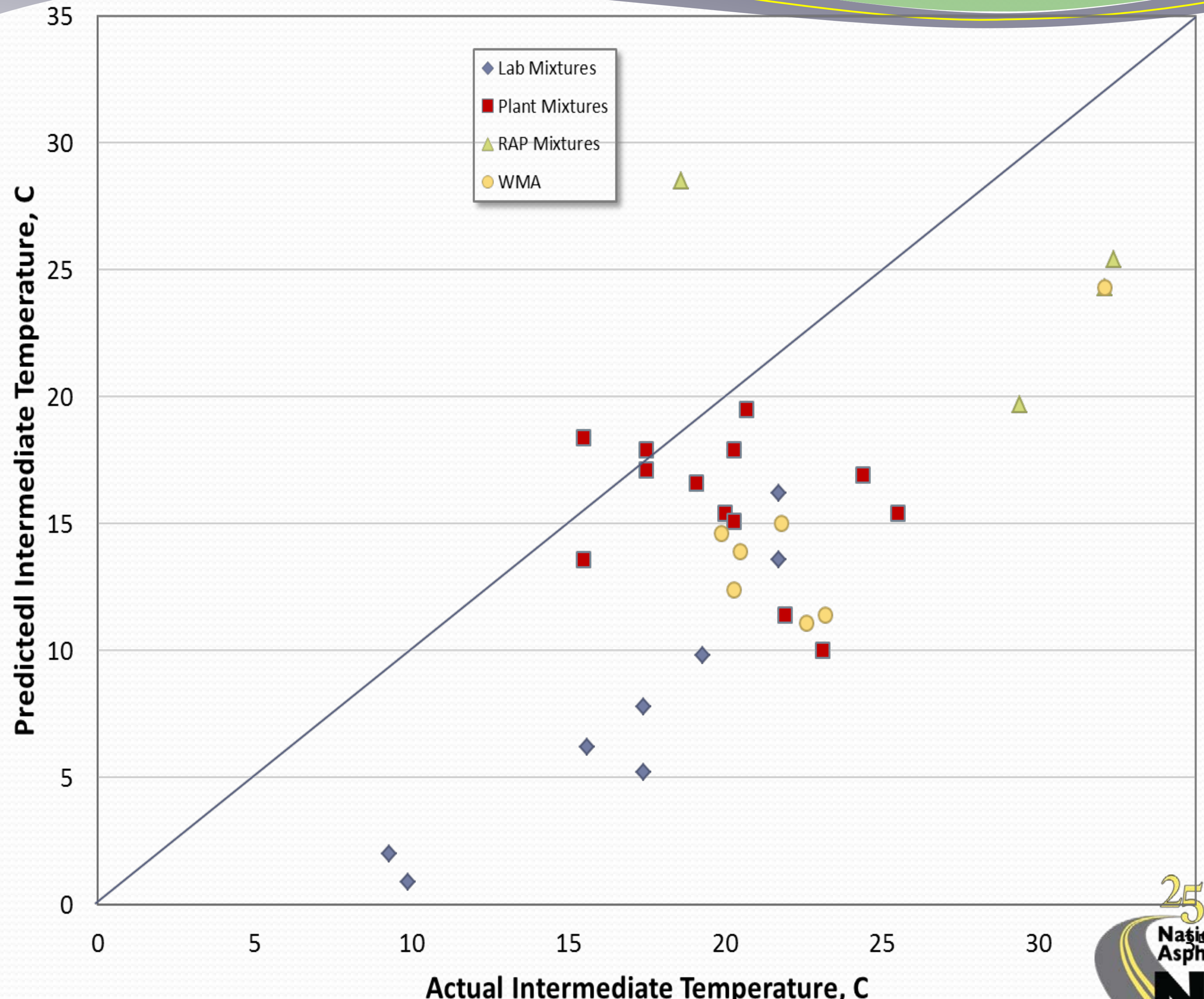

Lab Mixtures
Plant Mixtures
RAP Mixtures
WMA
35
30
25
20
15
10
5
0
Predictedl Intermediate Temperature, C
0
5
10
15
20
25
30
Actual Intermediate Temperature, C

Summary of Back-Calculation Analyses

- The procedure is not reliable for critical high temperature prediction.
  - Both G* and δ erroneous
- The procedure under-predicts the intermediate critical temperature.
  - Procedure under-predicts G*
  - Procedure over-predicts δ
- Recovered binder G* frequency sweeps were not performed to allow for forward calculation of E* and analysis of blending

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Other Potential Methods for Estimating the Properties of Recycled & Virgin Binders

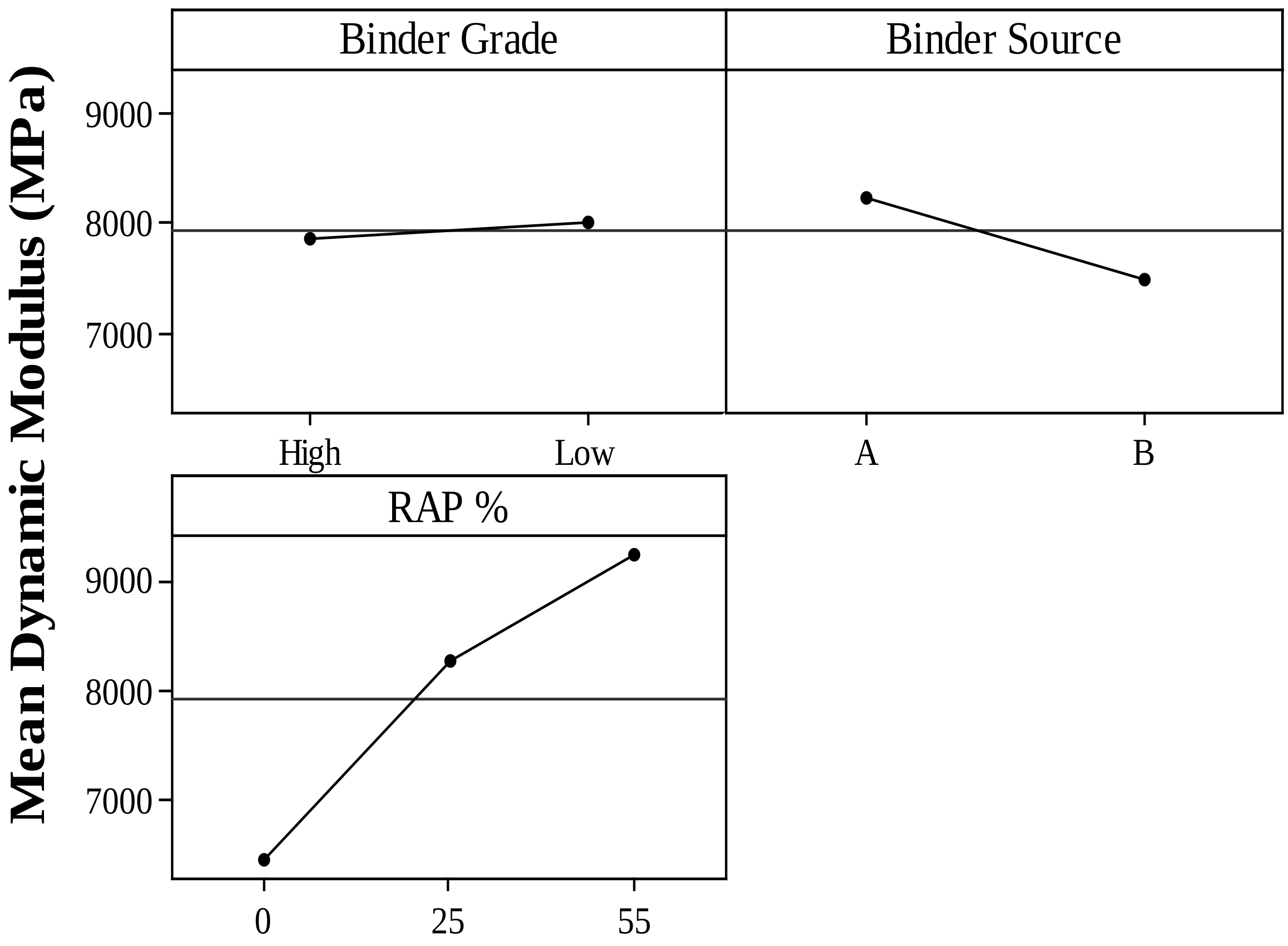
- Use Artificial Neural Network analysis in place of the Hirsch model to solve for binder properties from E* mastercurves
- Bahia's method using BBR on bars of RAP fines and Virgin Binder may provide low temperature properties.
- Use the same approach to make mini cores from SGC specimens for Dynamic Mechanical Analysis using a research grade DSR

Statistically Significant Factors for E*

Region	Variables	4.4C	21.1C	37.8C	54.4C
FL	% RAP	% RAP	% RAP	% RAP	% RAP
MN	% RAP	% RAP		%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)

E* @ 4.4°C, Main Effects Plot



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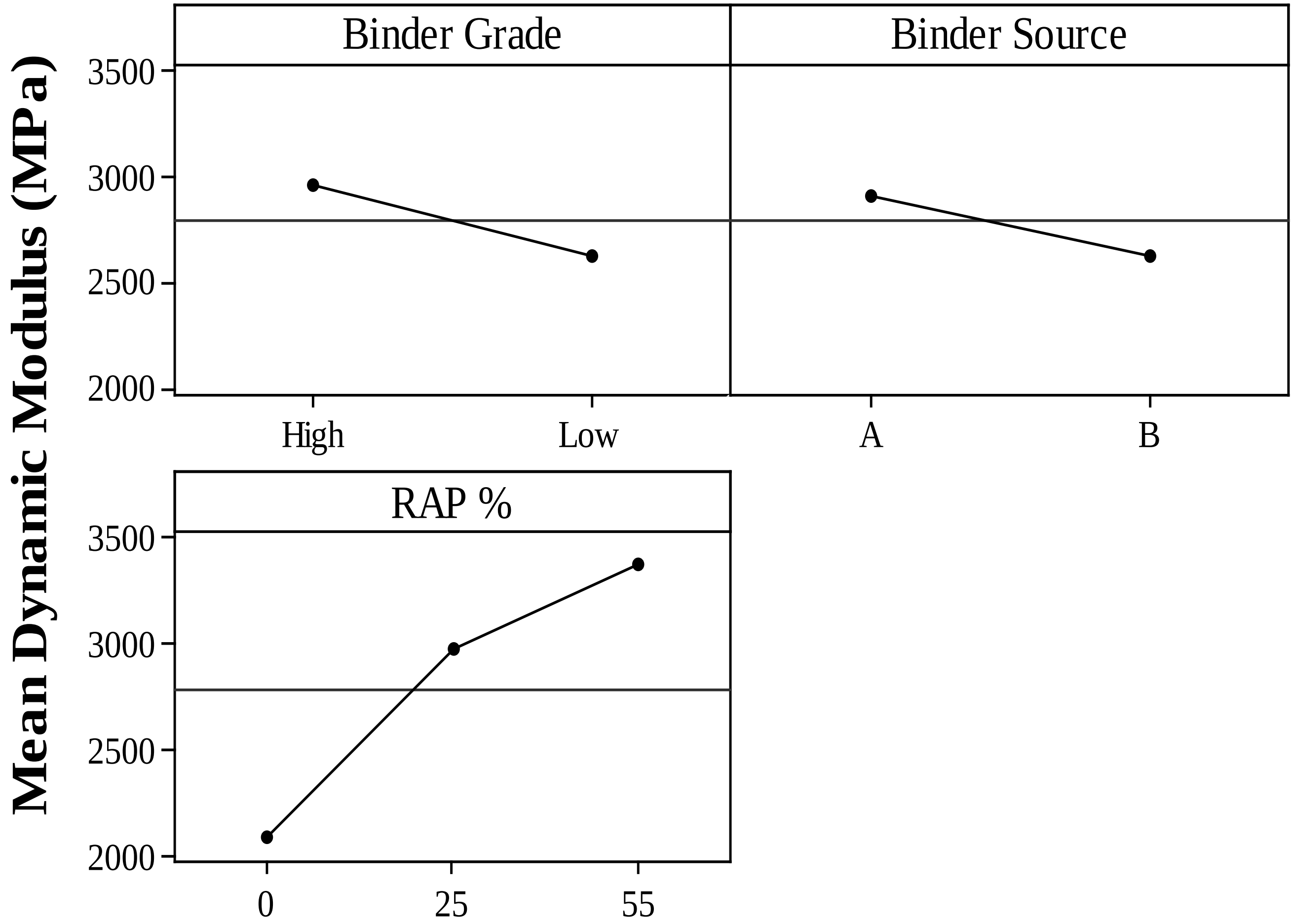
E* @ 21.1°C, Main Effects Plot



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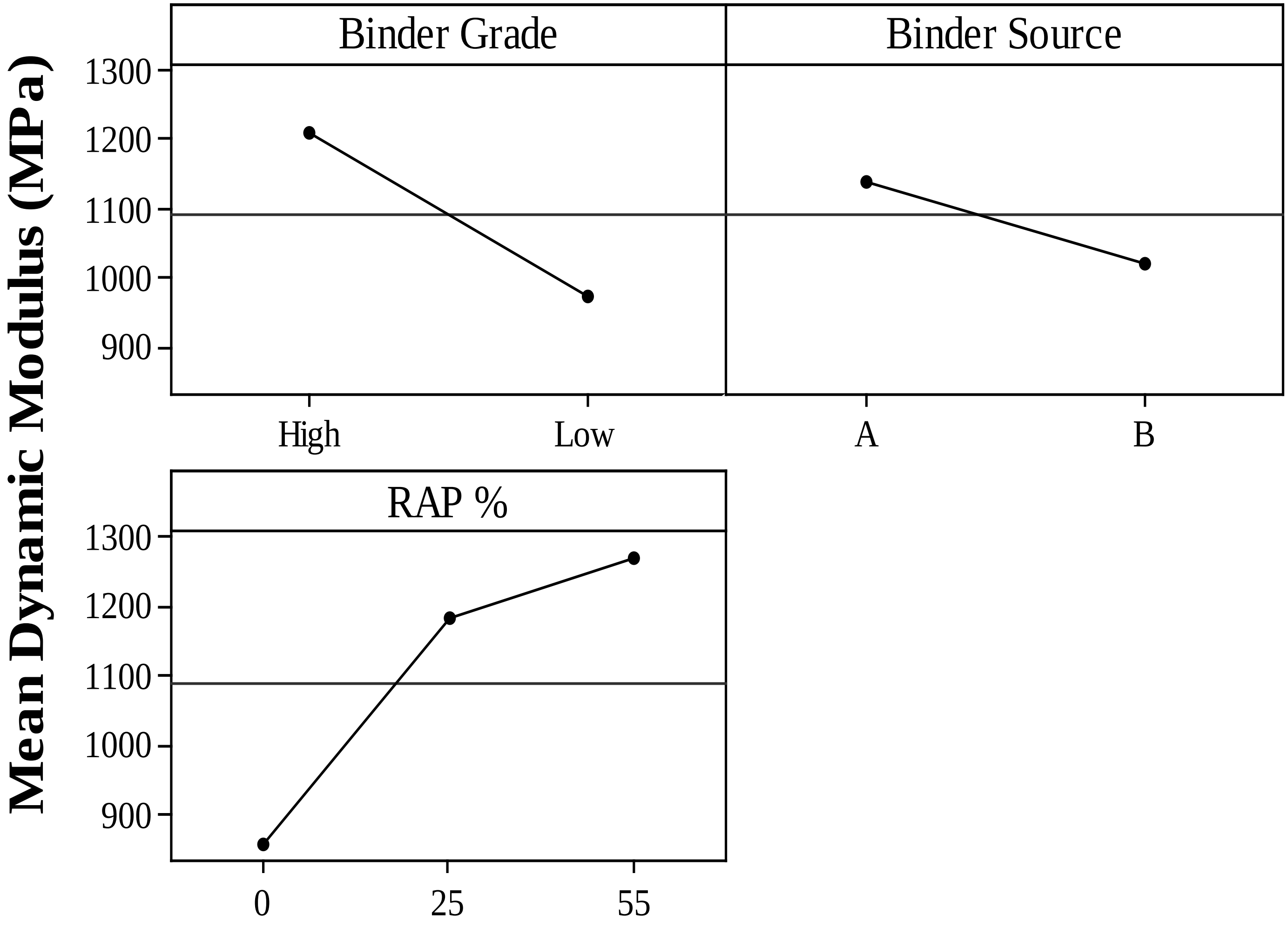
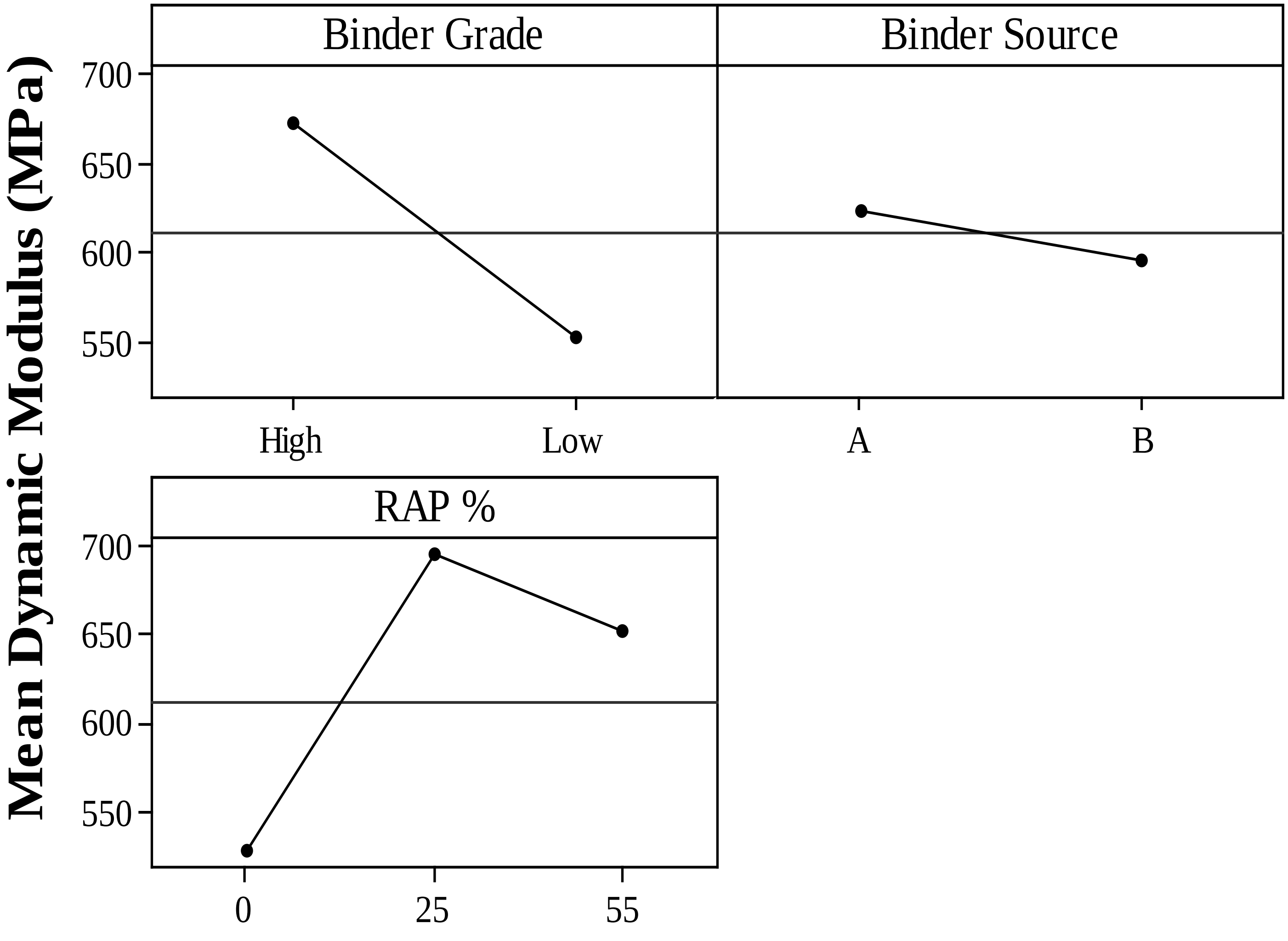
E* @ 37.8°C, Main Effects Plot



E* @ 54.4°C, Main Effects Plot



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Summary of E* Statistical Analyses

- Virgin binder **grade** did not have a significant effect on E* at low temperatures. This is logical since the virgin binder grades were only different at the high PG. The influence of the virgin binder grade on E* increased with higher test temperatures.
- Virgin binder **source** was significant on E* only at the lowest and highest temperatures.
- RAP content had a significant effect on E* at all temperatures. E* of high RAP content mixes were significantly higher than for virgin mixes.

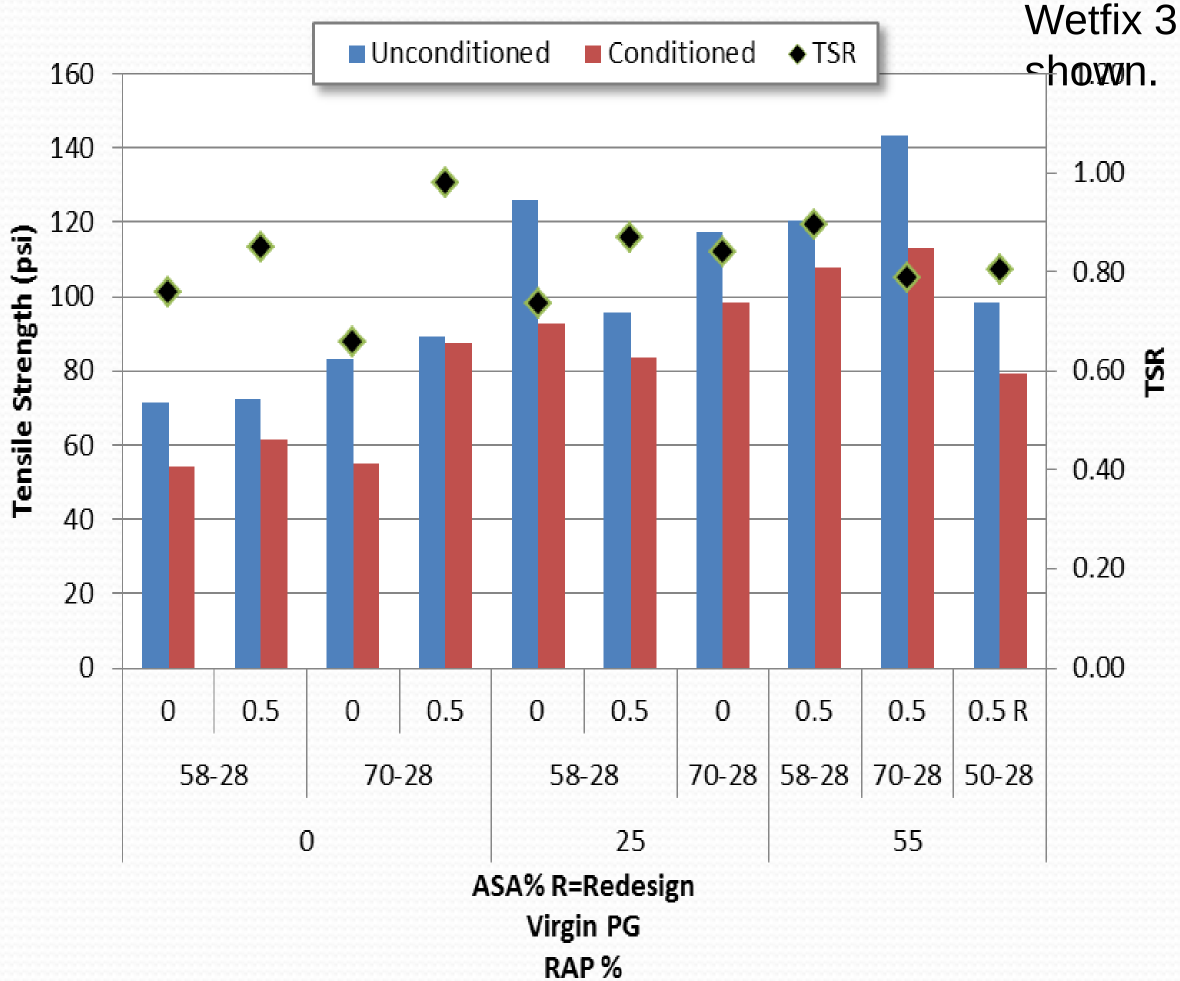
Performance Tests

Moisture Damage Susceptibility

T 283 Results

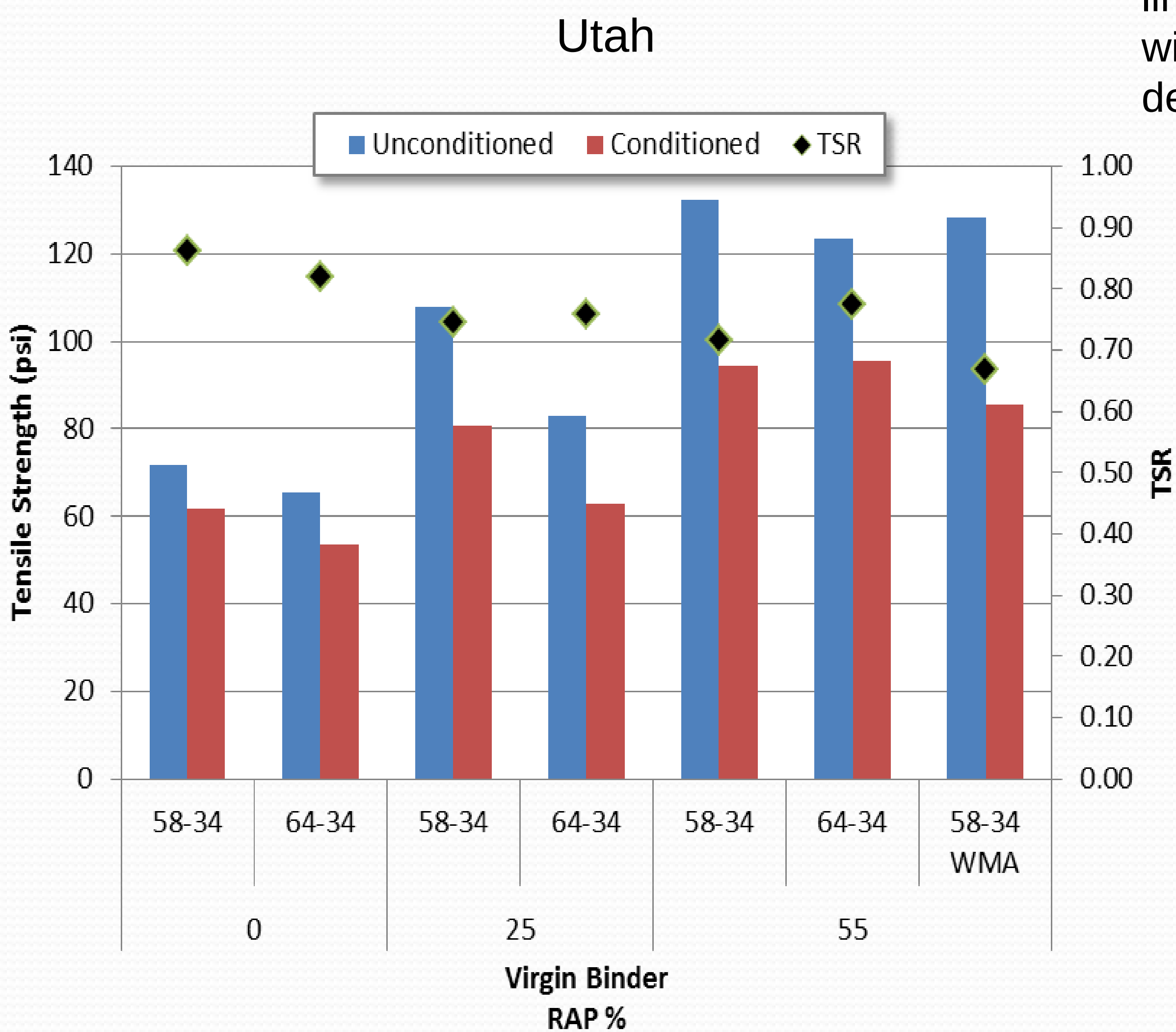
No antistrip additives are used by the contractor who supplied these materials. AkzoNobel Wetfix 312 was used as shown.

New Hampshire



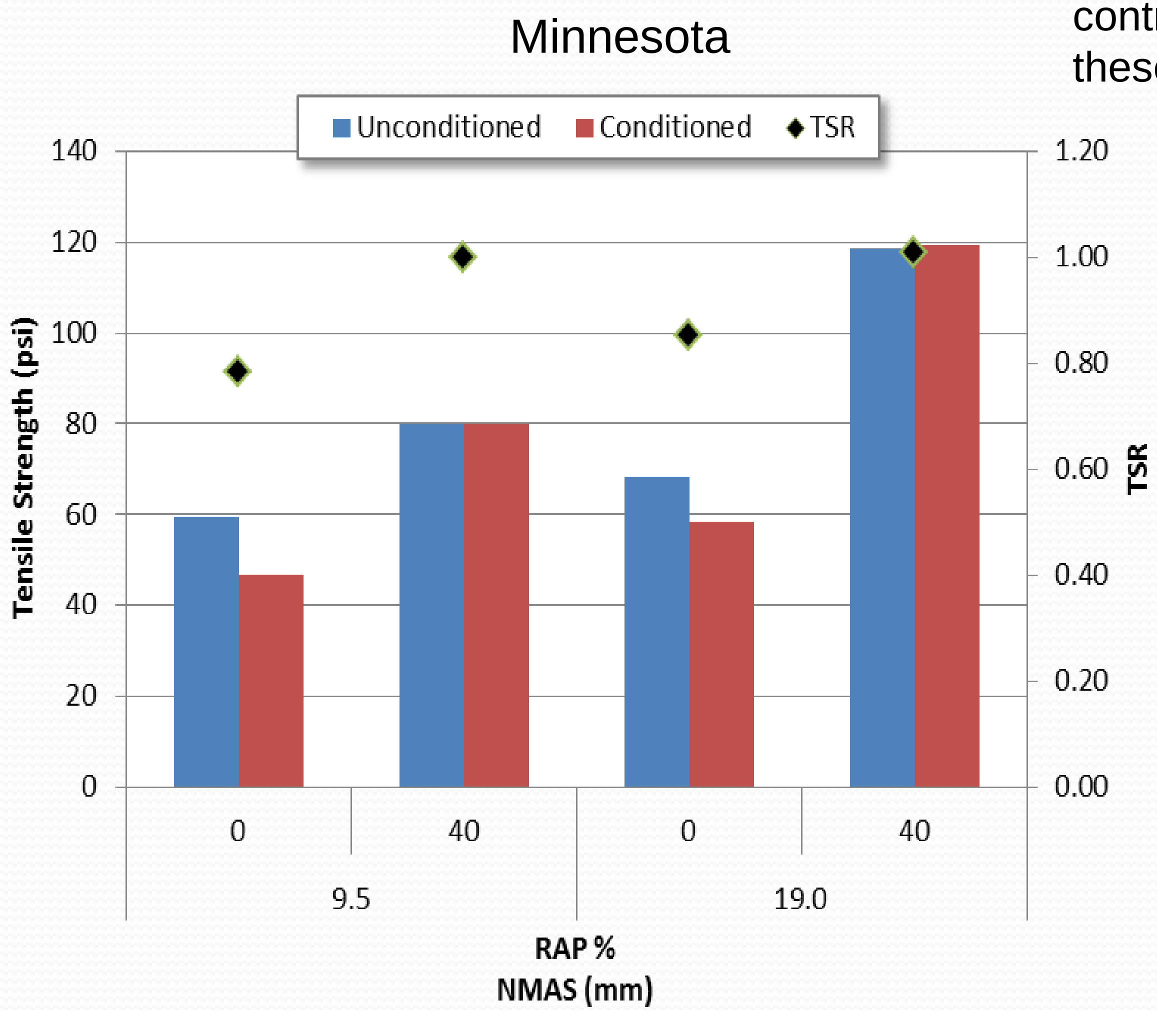
T 283 Results

1% hydrated lime was used with these mix designs



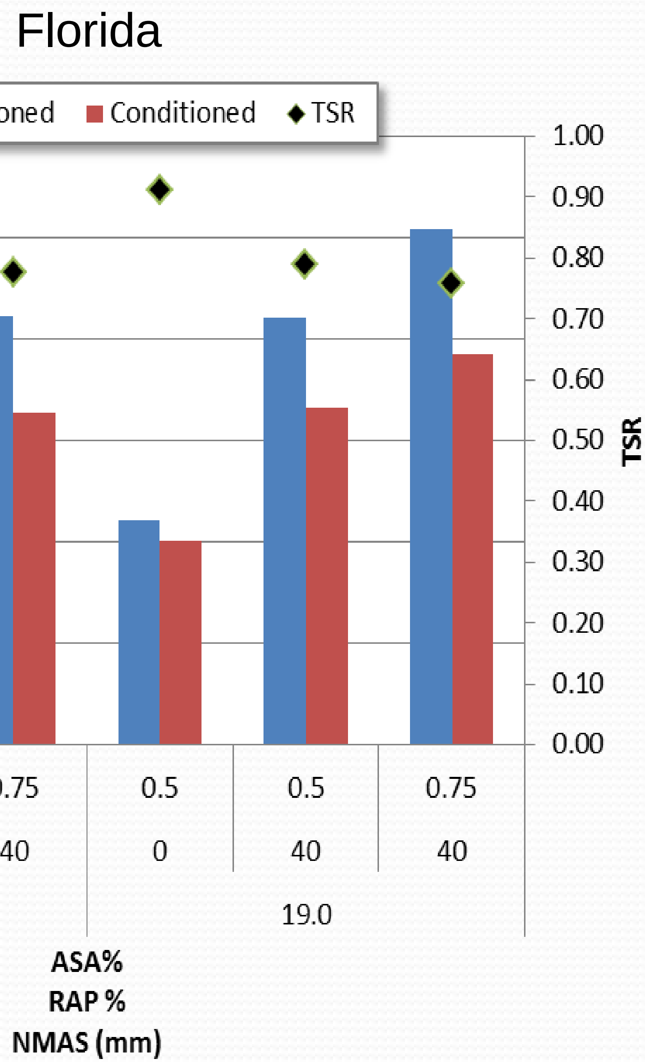
T 283 Results

No antistrip additives are used by the contractor who supplied these materials



T 283 Results

AARMAZ LOF 6500 was used as shown



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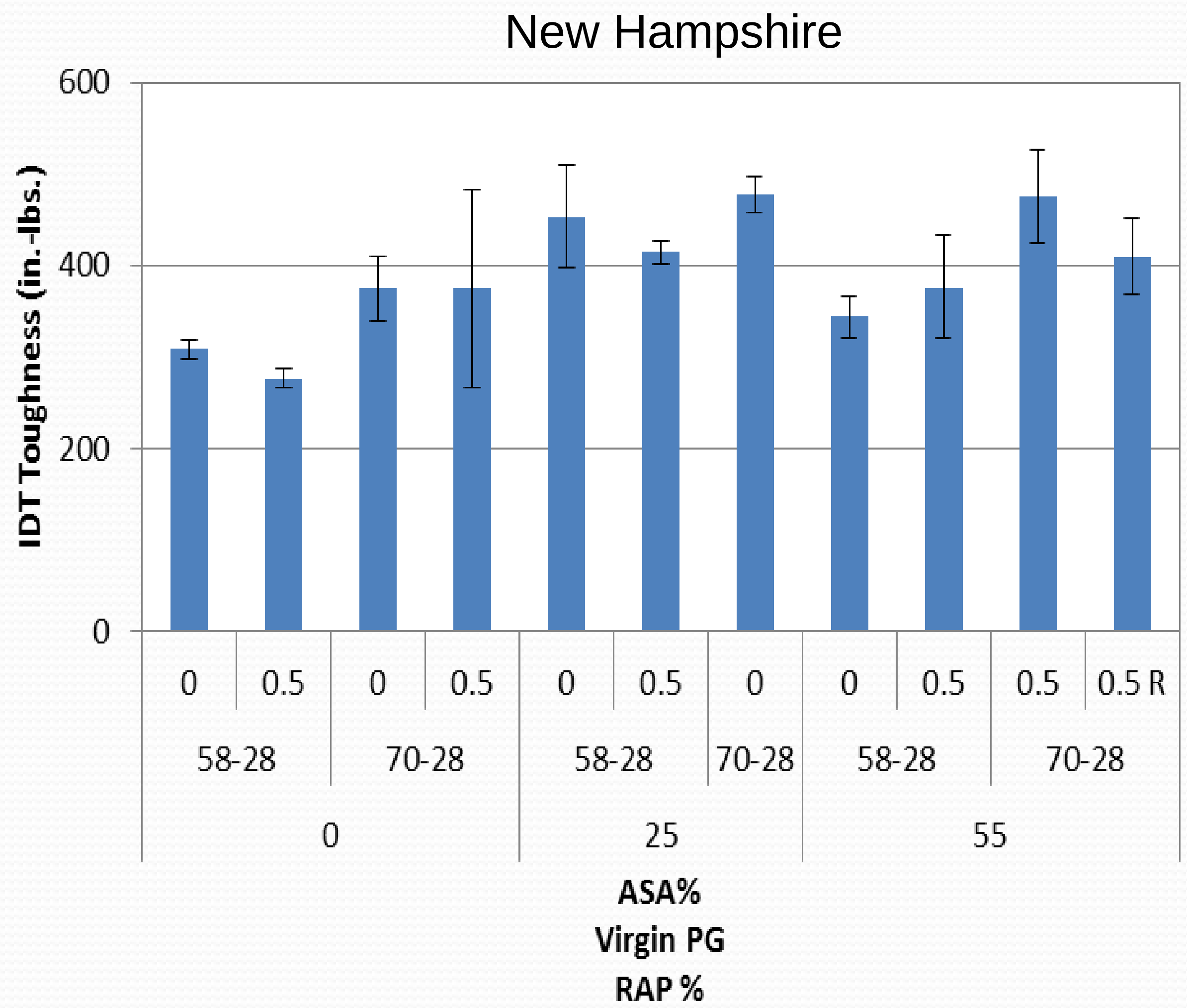
IDT Toughness



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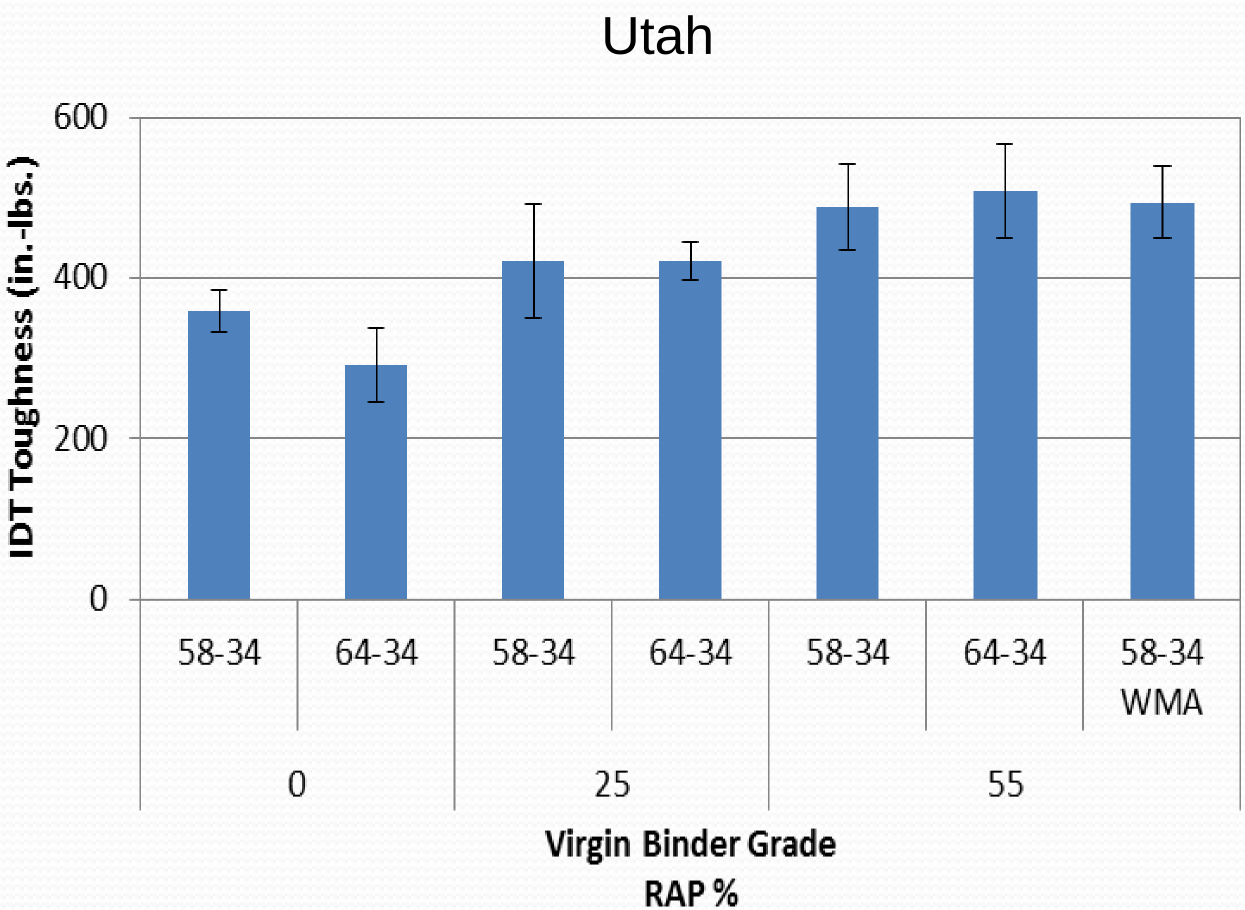
IDT Toughness



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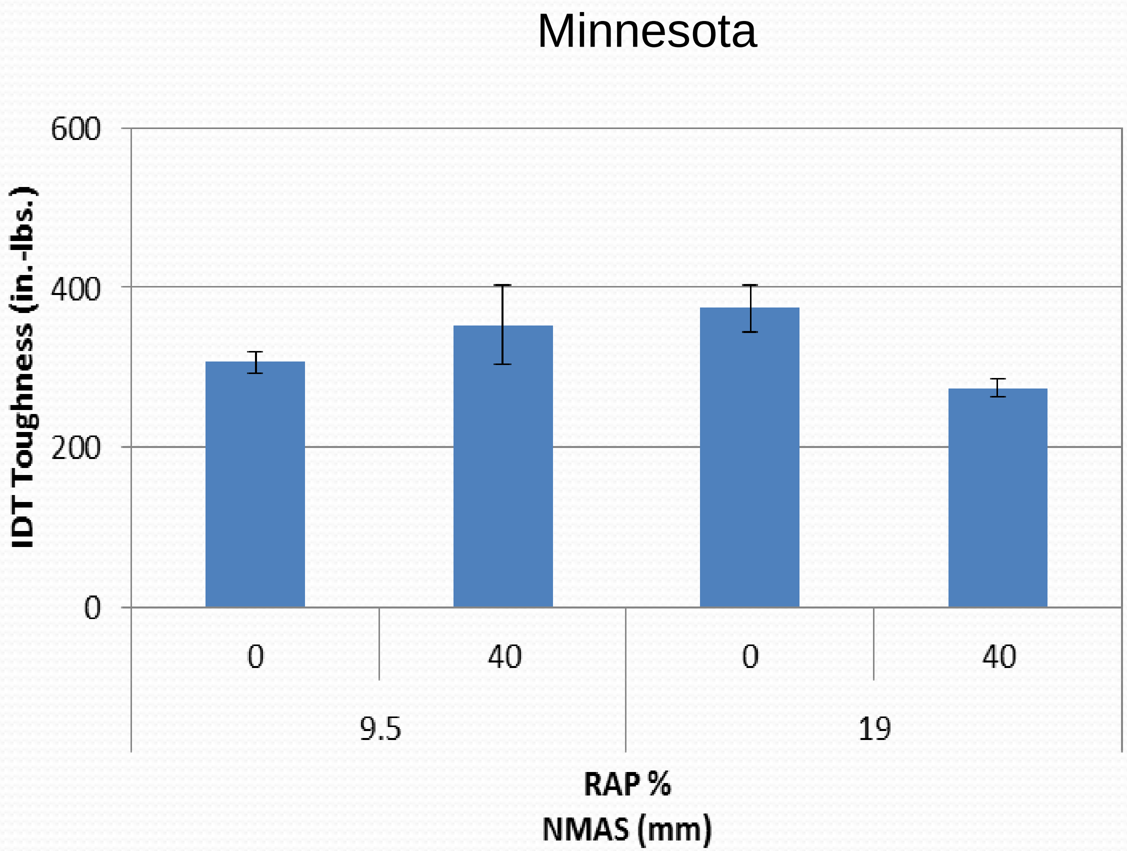
IDT Toughness



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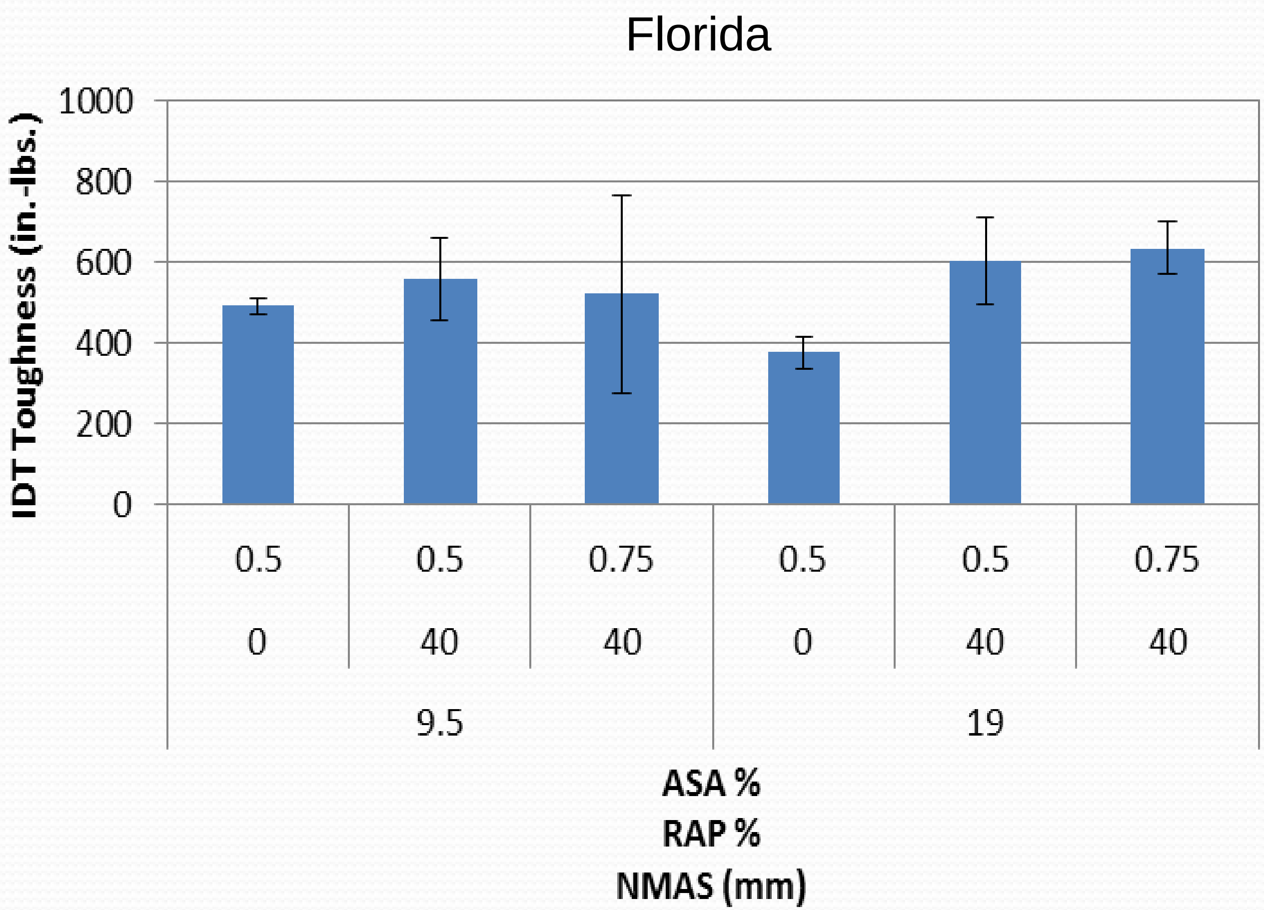
IDT Toughness



Summary of Moisture Damage Testing

- Increasing RAP contents generally increased conditioned and unconditioned tensile strengths
- Low TSRs can generally be improved with the addition of an antistripping agent.
- TSR can be misleading. Although using RAP may increase both conditioned and unconditioned tensile strengths, TSR values can decrease, sometimes below 0.80. High TSR can also results when both conditioned and unconditioned strengths are extremely low.

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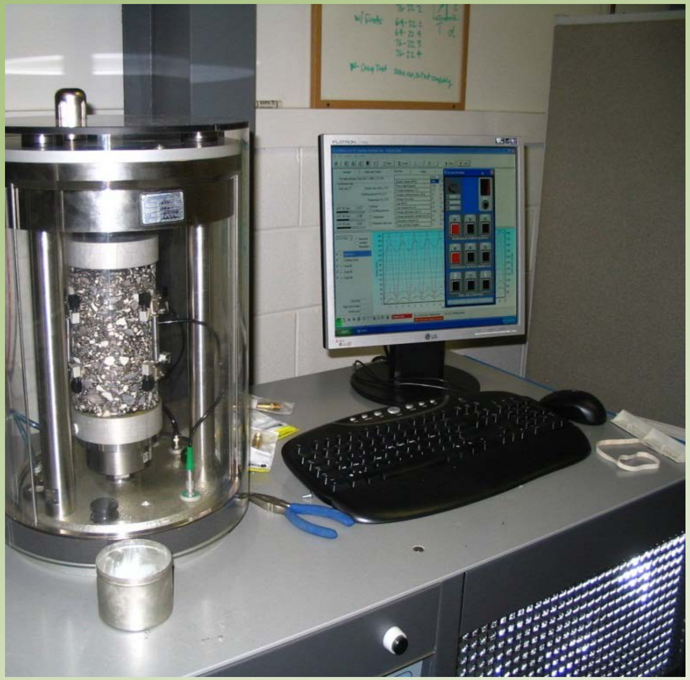
Flow Number

Rutting Resistance Test



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Flow Number Procedure

- Protocol originally recommended by FHWA.
- Loose mix aged for 4 hrs. at 135°C (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%.
- Specimens were preheated to the 50% reliability high-temperature from LTPP Bind for the location of the respective materials.
- The deviator stress = 70 psi; confining stress = 10 psi. Test to 20,000 cycles.

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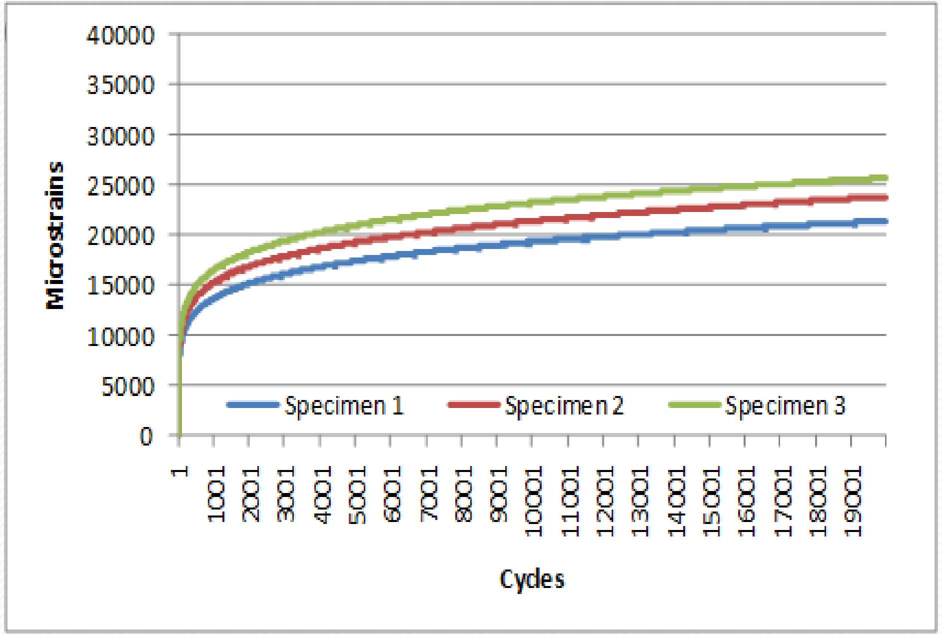
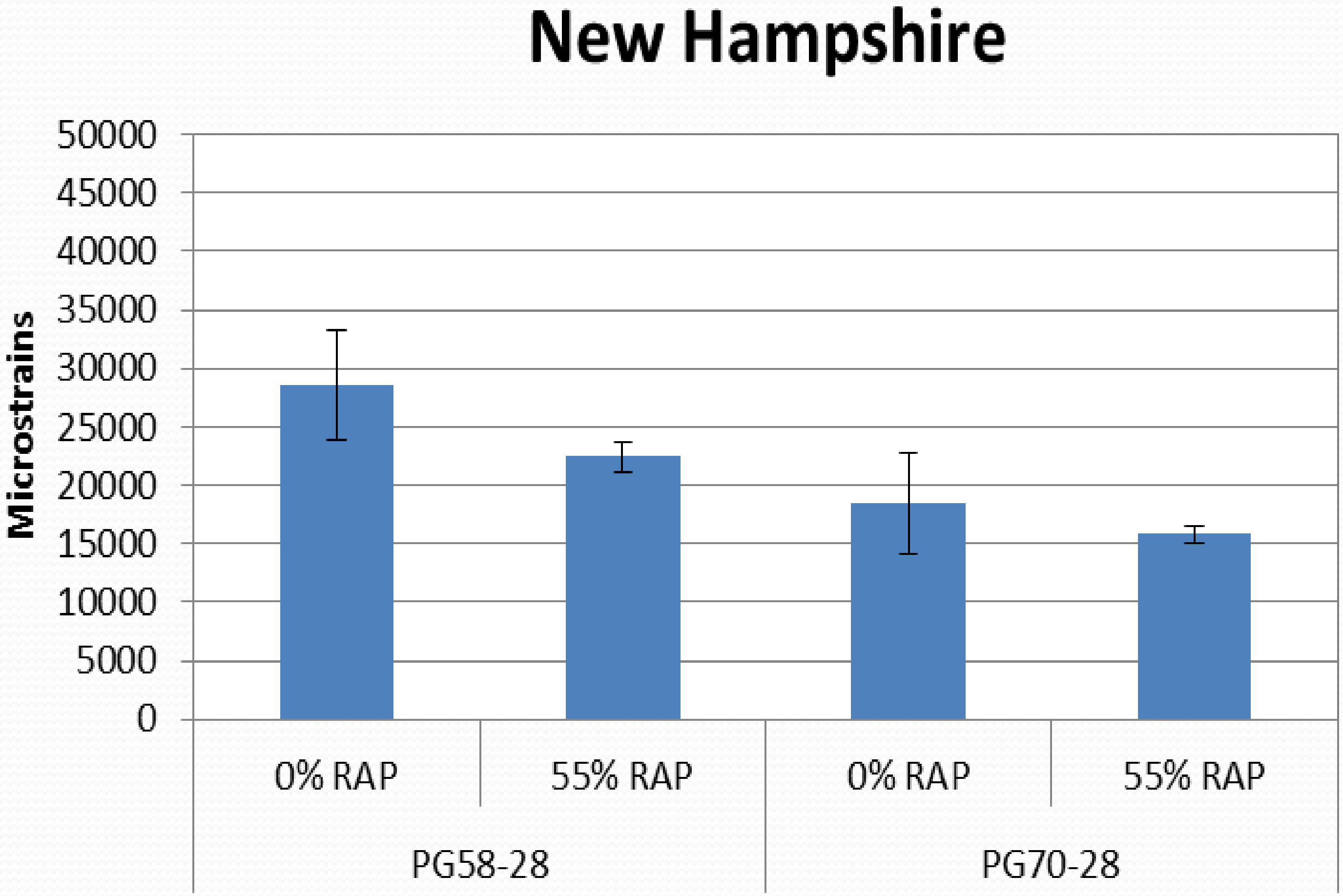
Flow Number Results

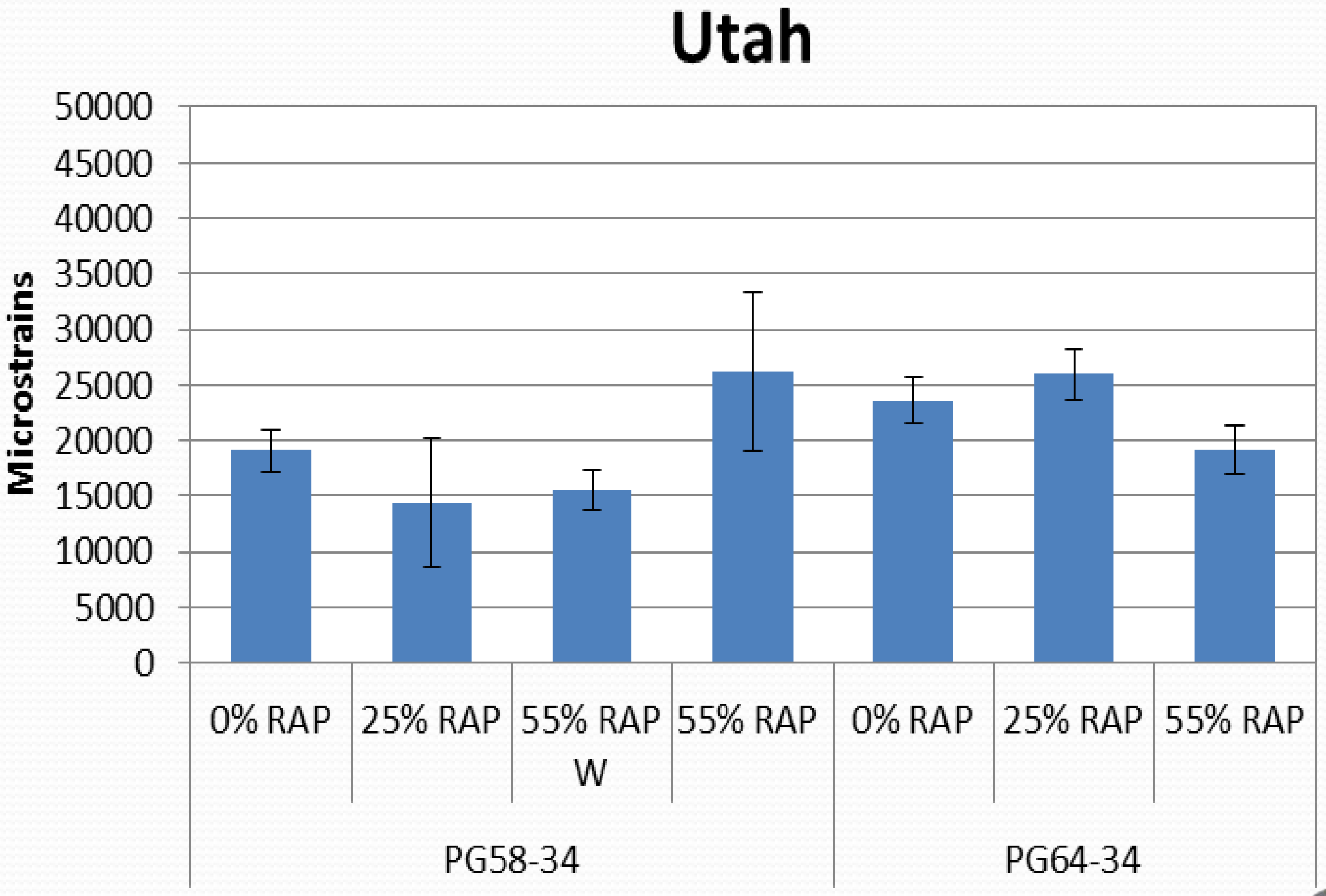
- Tertiary flow was not visually evident for any mixture
- Flow Numbers were identified using the Power model, but could not be determined with the Franken model.
- Analysis was conducted using total accumulated strain at 2



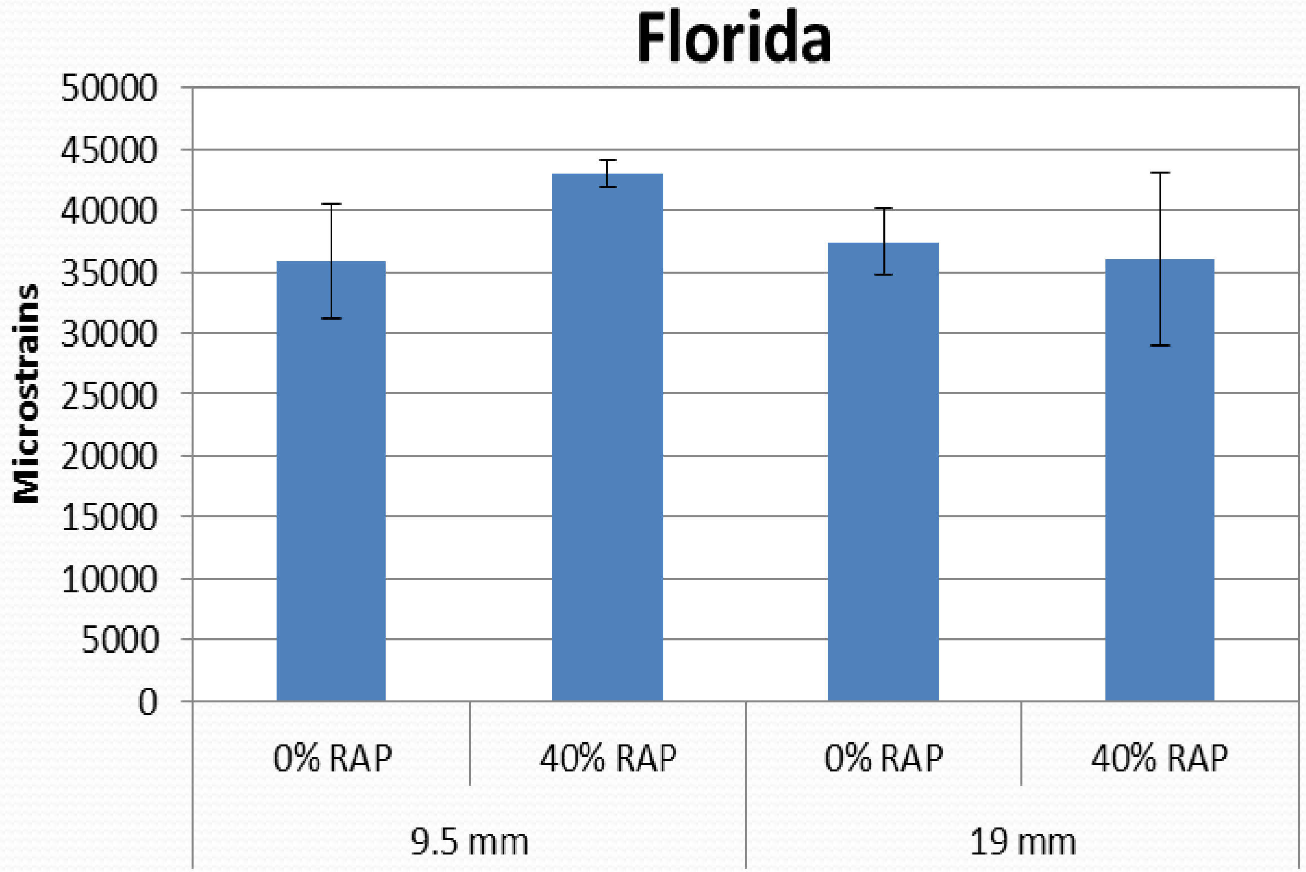
Flow Number Test Results



Flow Number Test Results



Flow Number Test Results



Summary of Flow Number Testing

- High RAP content mixes had statistically equal deformation compared to virgin counterparts in 8 of 9 cases.
- Although not statistically significant, using a lower virgin PG binder grade generally (but not always) resulted in greater deformation.
- Recommend using unconfined flow number test and criteria from NCHRP Report 673

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Fatigue Cracking

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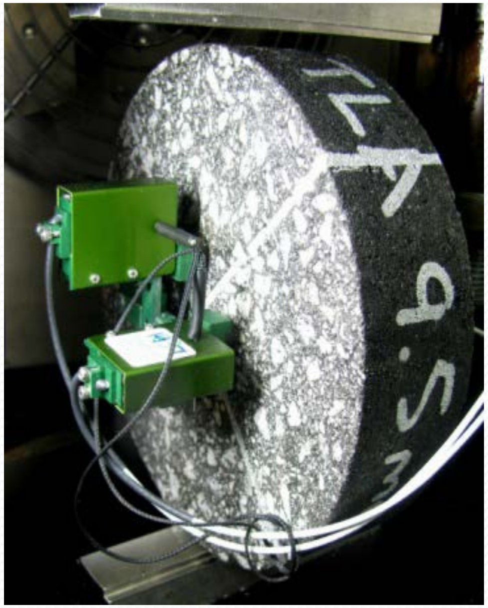
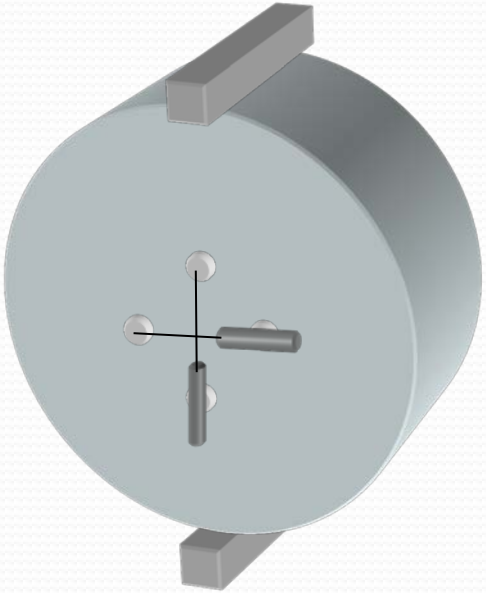
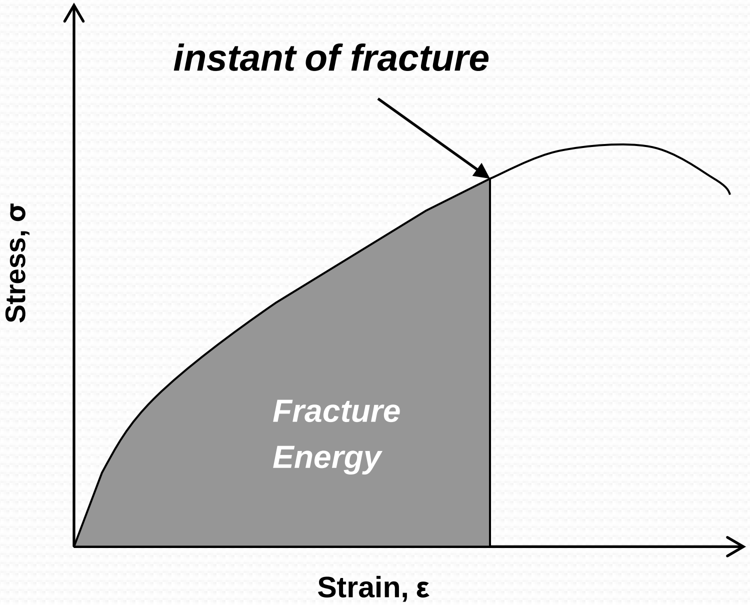
Tests Evaluated for Fatigue Cracking

Test	Method	Disadvantages
Bending Beam Fatigue	AASHTO T 321	Challenging spec. prep, time consuming test
Simplified Viscoelastic Continuum Damage	NCSU	Method still in development, Complex analysis
Texas Overlay Tester	TEX-248-F	Current method uses unrealistically high strains
Semi-Circular Bend	LTRC	Method still in development
IDT Fracture Energy	UF	National standard needed

Fracture Energy





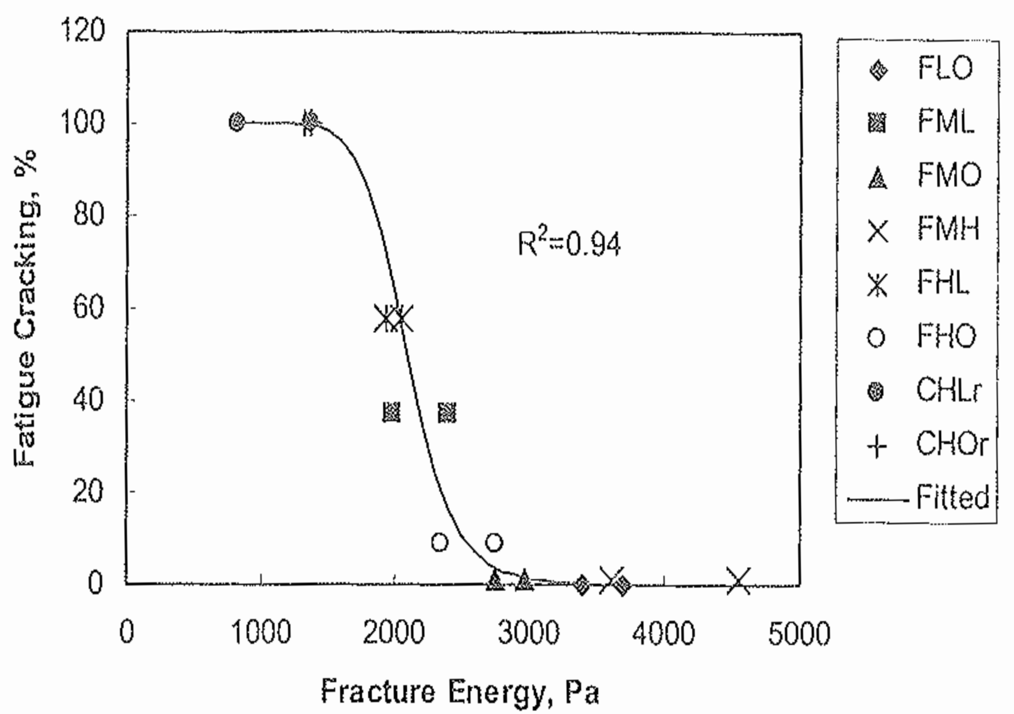


IDT Fracture Energy at 10°C

IDT Fracture Energy (10°C)Summary

- Fairly simple test except for strain measurements
  - Simple sample preparation
  - Monotonic loading, 4 strain measurements
  - 10°C test temperature
  - Quick test
  - Analysis is straight forward
- Specimens were long-term aged prior to testing

Indirect Tensile Fracture Energy



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

2006 High RAP Test Sections

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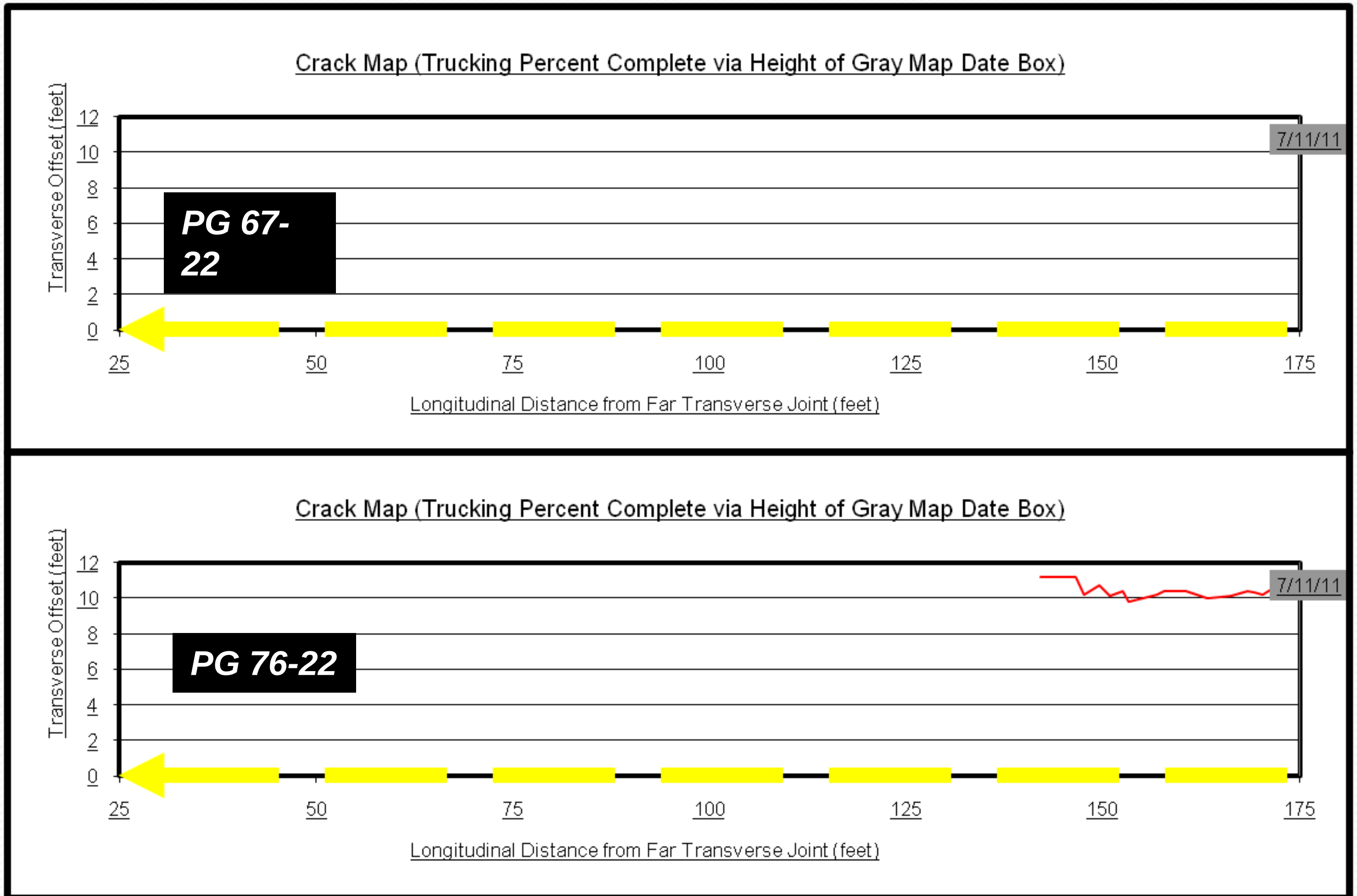
2006 20% RAP



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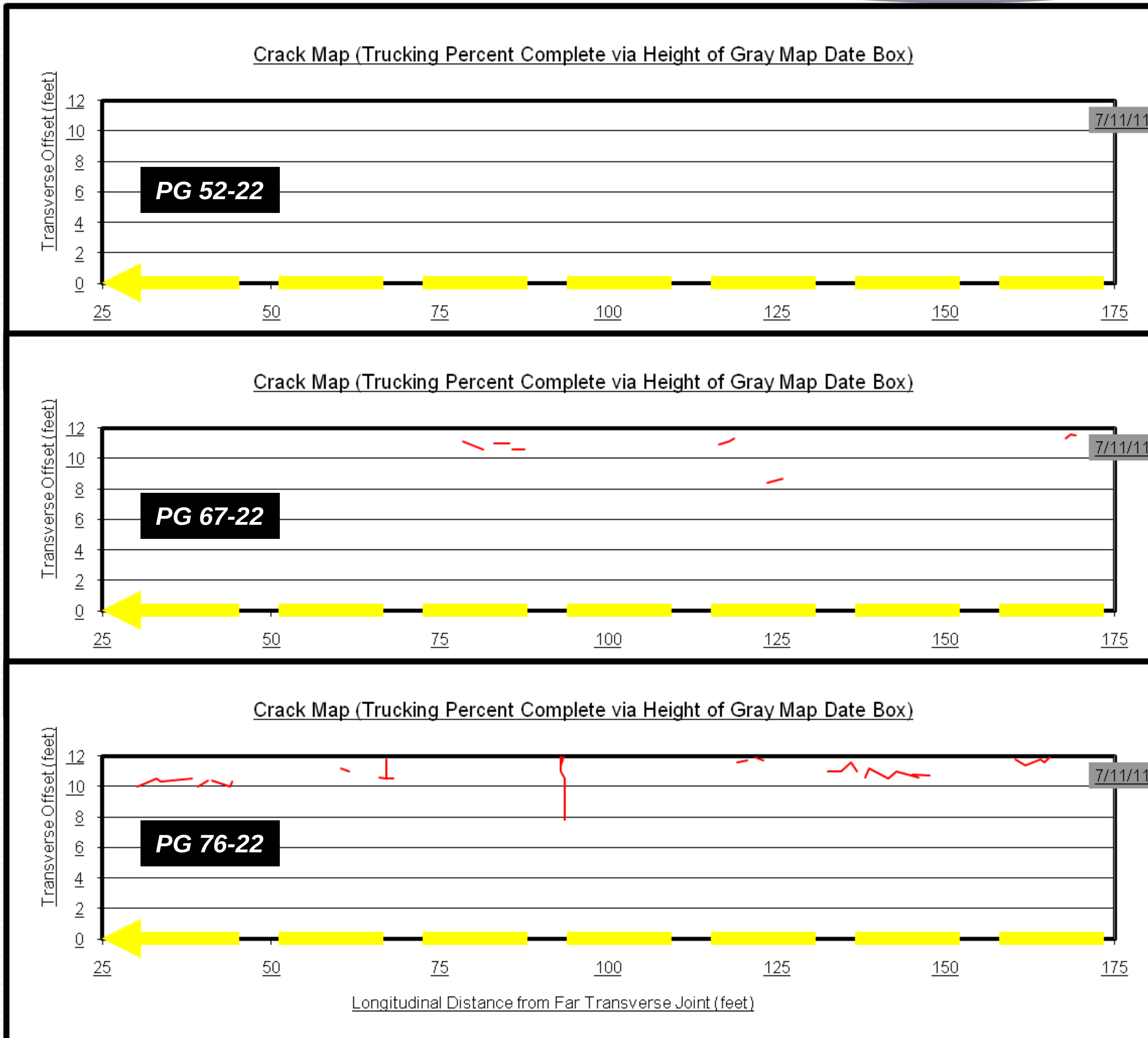
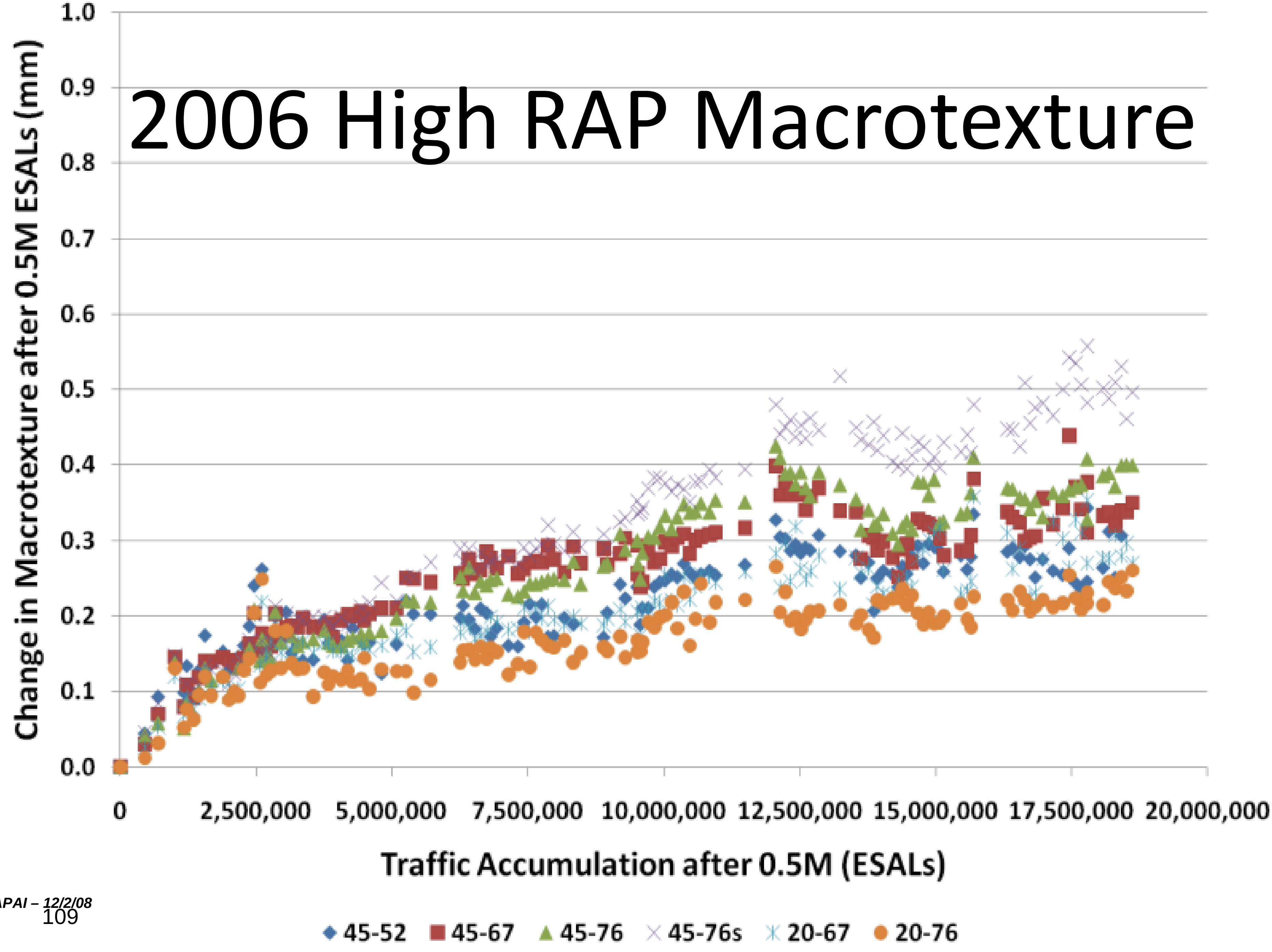
2006 45% RAP

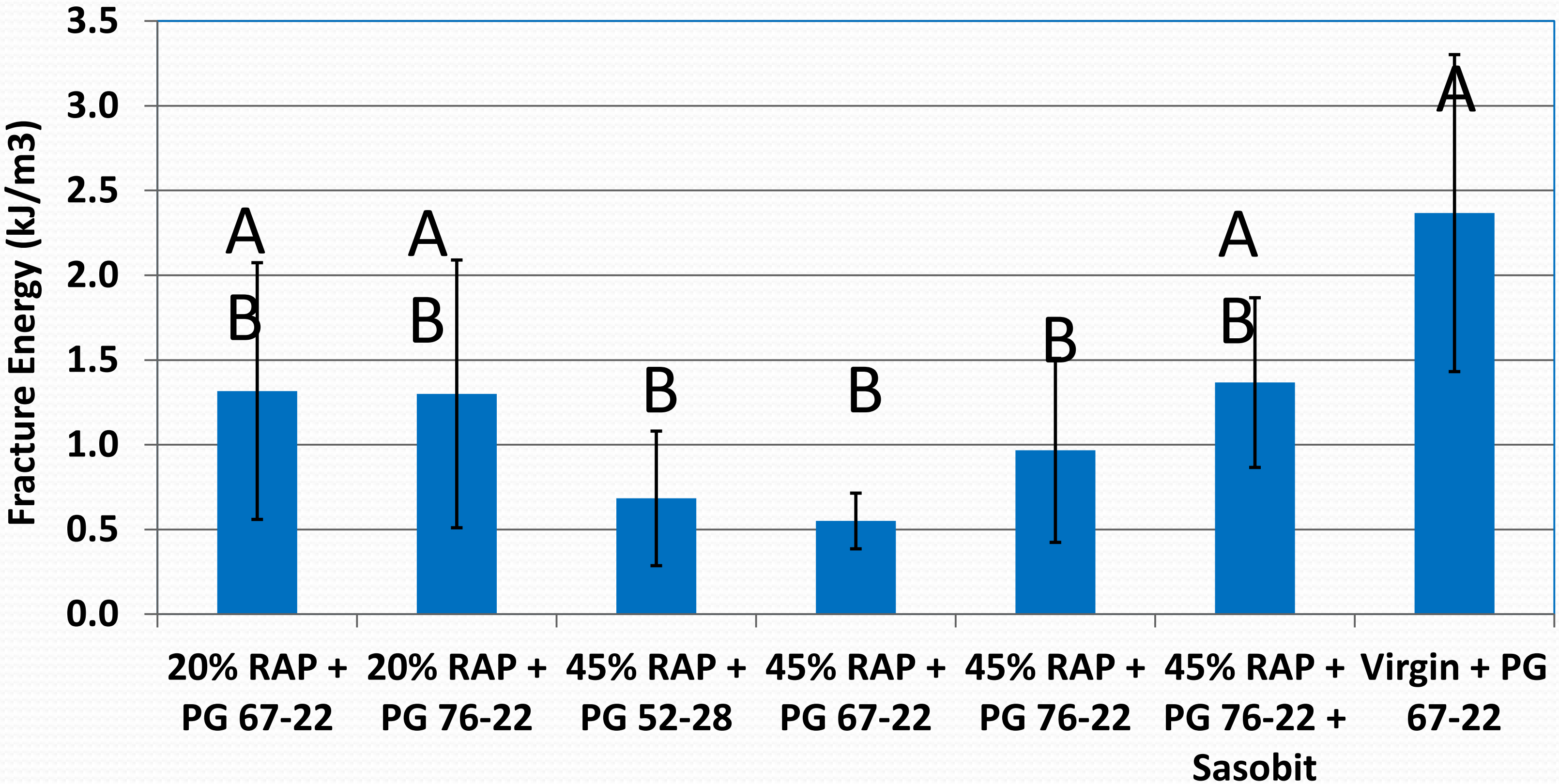


Crack Map (Trucking Percent Complete via Height of Gray Map Date Box)
PG 52-22
Transverse Offset (feet)
7/11/11
0
2
4
6
8
10
12
25
50
75
100
125
150
175
Crack Map (Trucking Percent Complete via Height of Gray Map Date Box)
PG 67-22
Transverse Offset (feet)
7/11/11
Crack Map (Trucking Percent Complete via Height of Gray Map Date Box)
PG 76-22
Transverse Offset (feet)
7/11/11
Longitudinal Distance from Far Transverse Joint (feet)

2006 High RAP Macrotexture



FE Results, 2006 NCAT Test Track



Vbe (%) 12.3 12.4 10.8 10.6 10.4 10.3
13.0

1 kJ/m^3 = 1000 Pa

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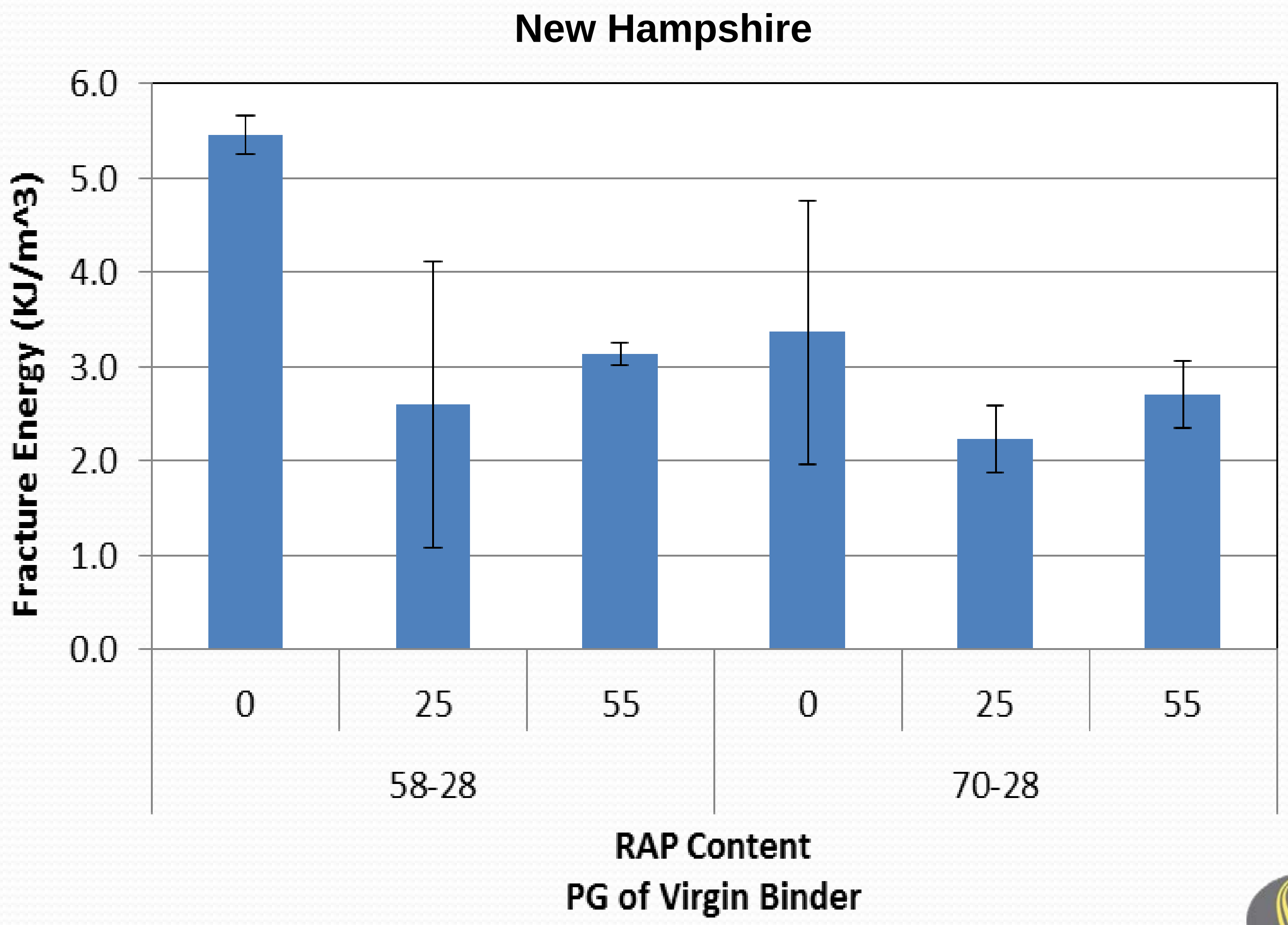
IDT Fracture Energy (10°C) Results



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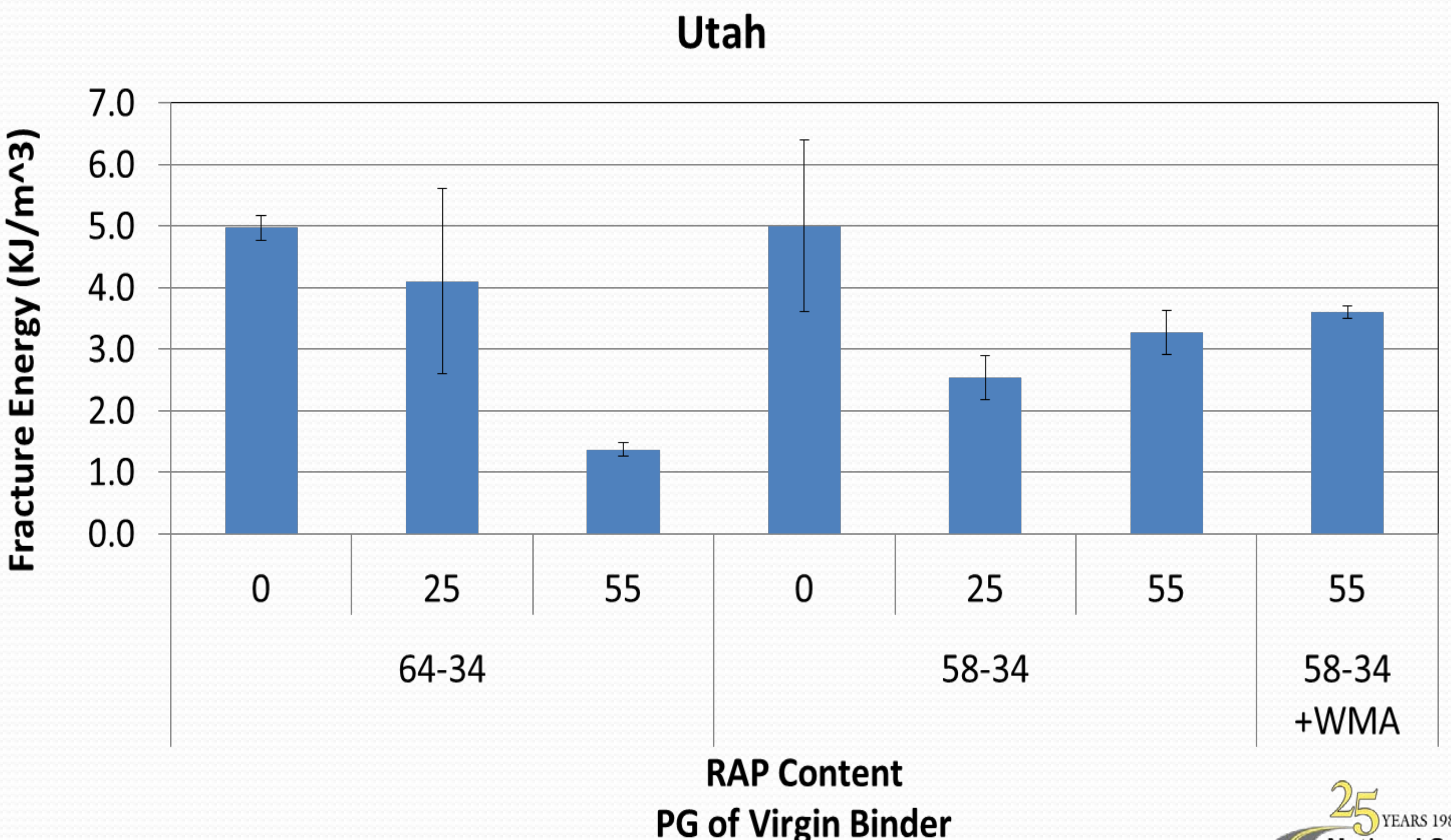
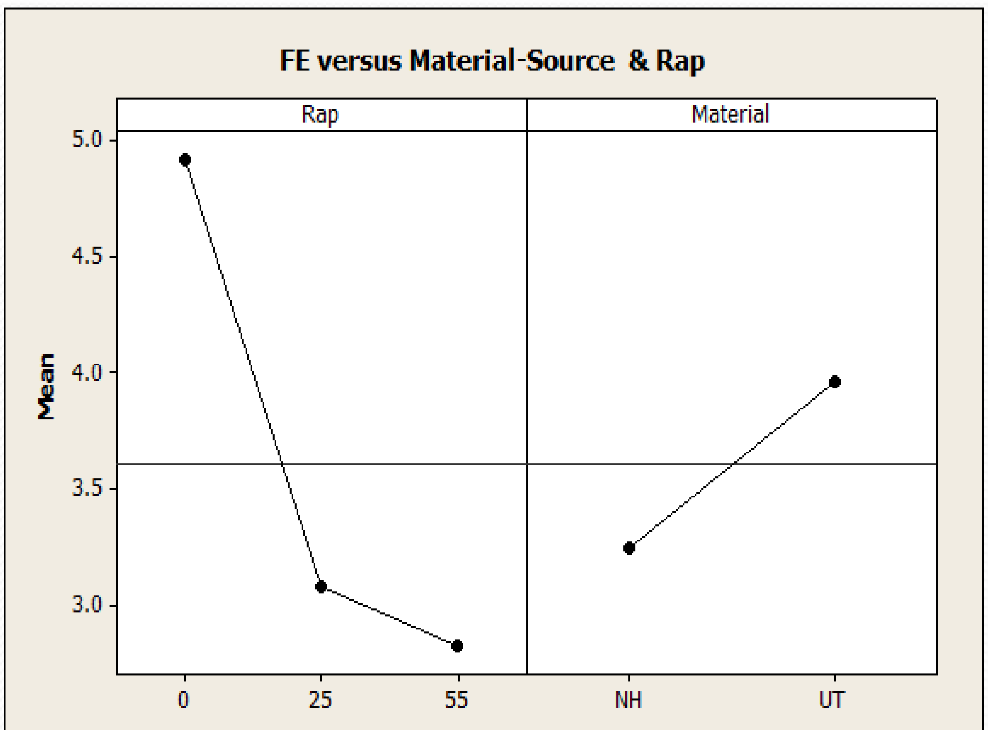
IDT Fracture Energy (10°C) Results



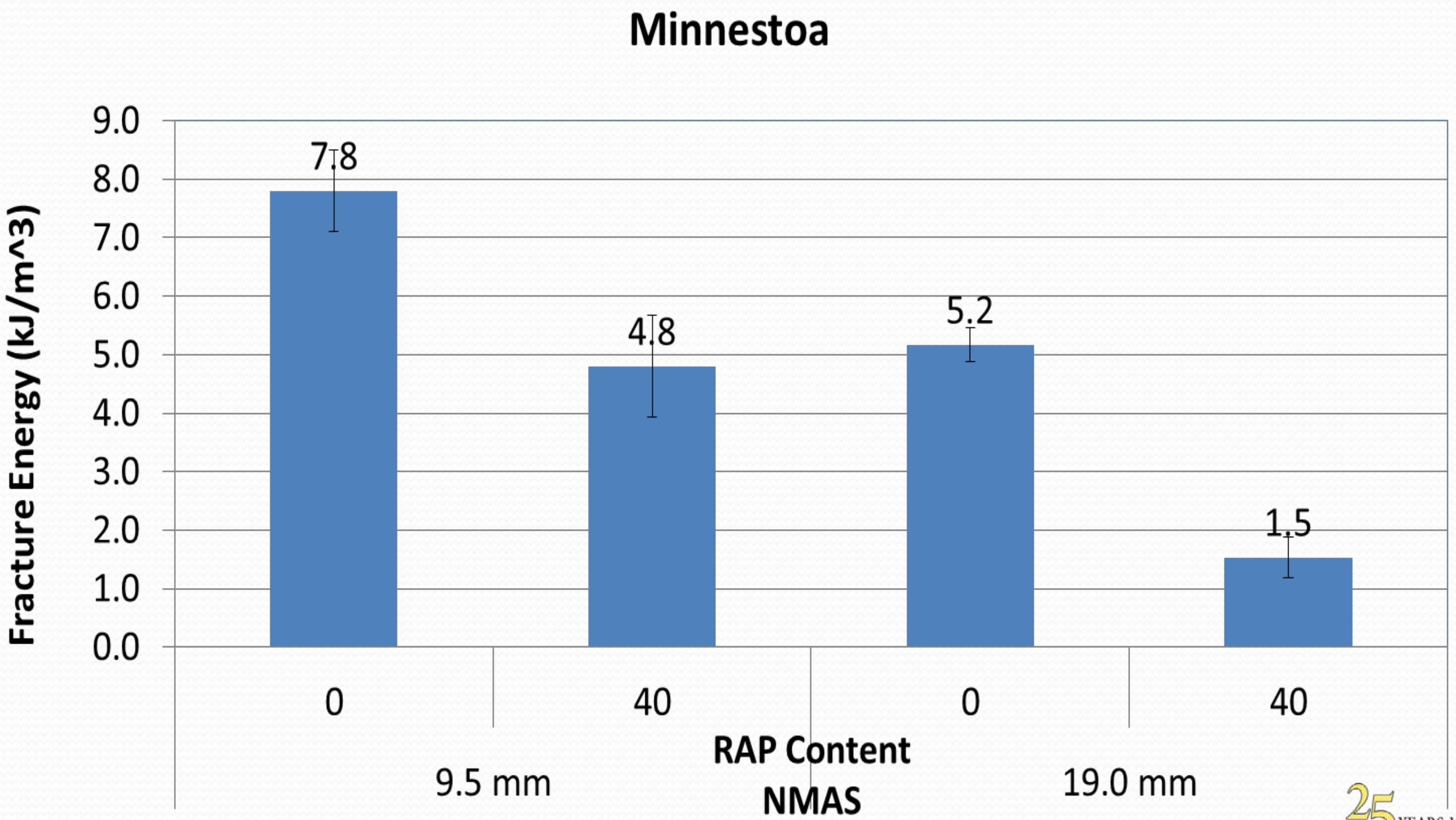
Statistical Analysis of FE@10°C

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Material Source	1	0.8585	3.9621	3.9621	4.35	0.046
Virgin Binder Grade	3	4.2818	7.5661	2.5220	2.77	0.059
RAP %	2	31.0556	31.0556	15.5278	17.04	0.000
Material Source*RAP%	2	3.7222	3.7222	1.8611	2.04	0.147
Error	30	27.3378	27.3378	0.9113		
Total						



NCHRP 9-46

IDT Fracture Energy (10°C) Results



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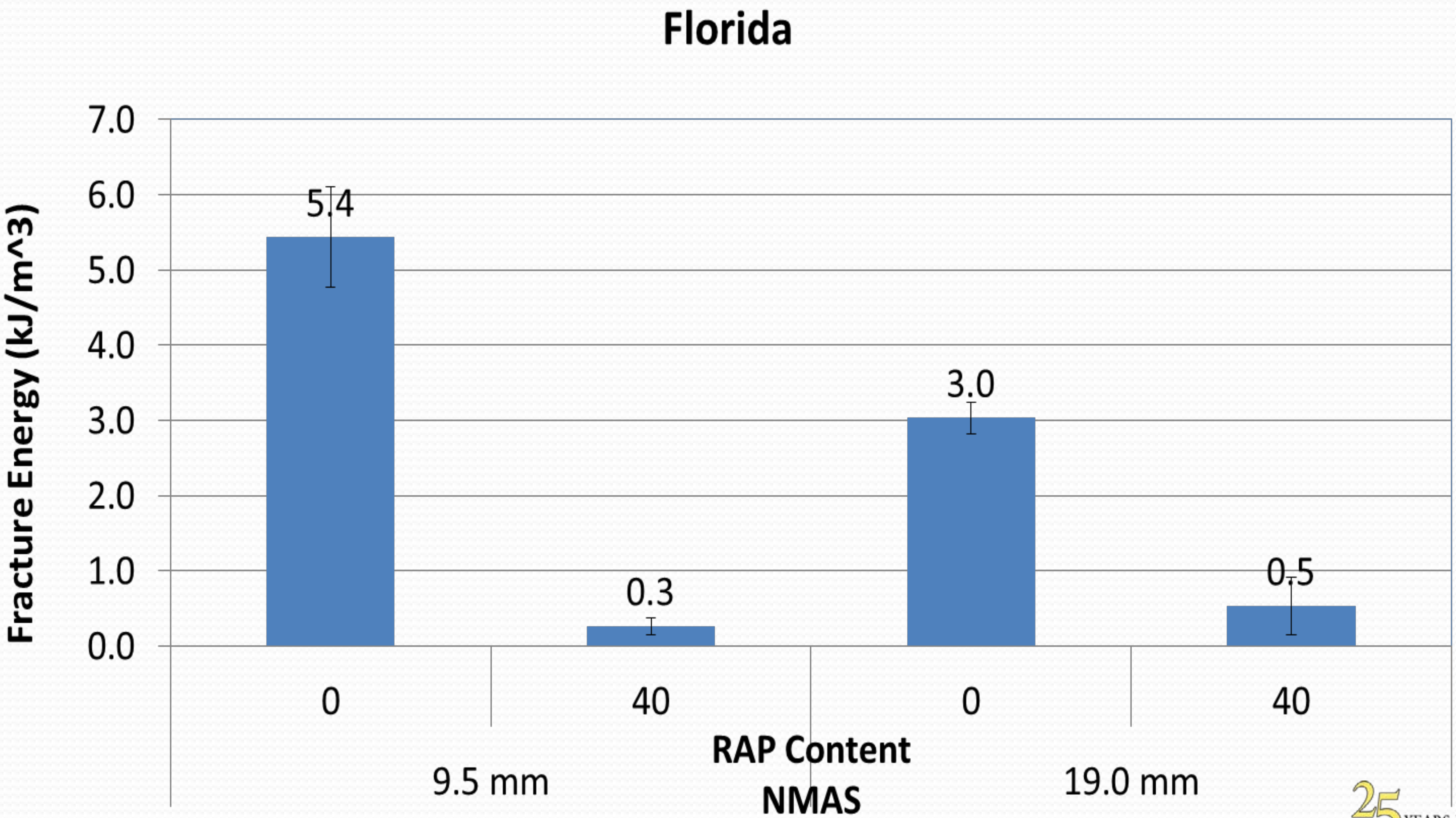
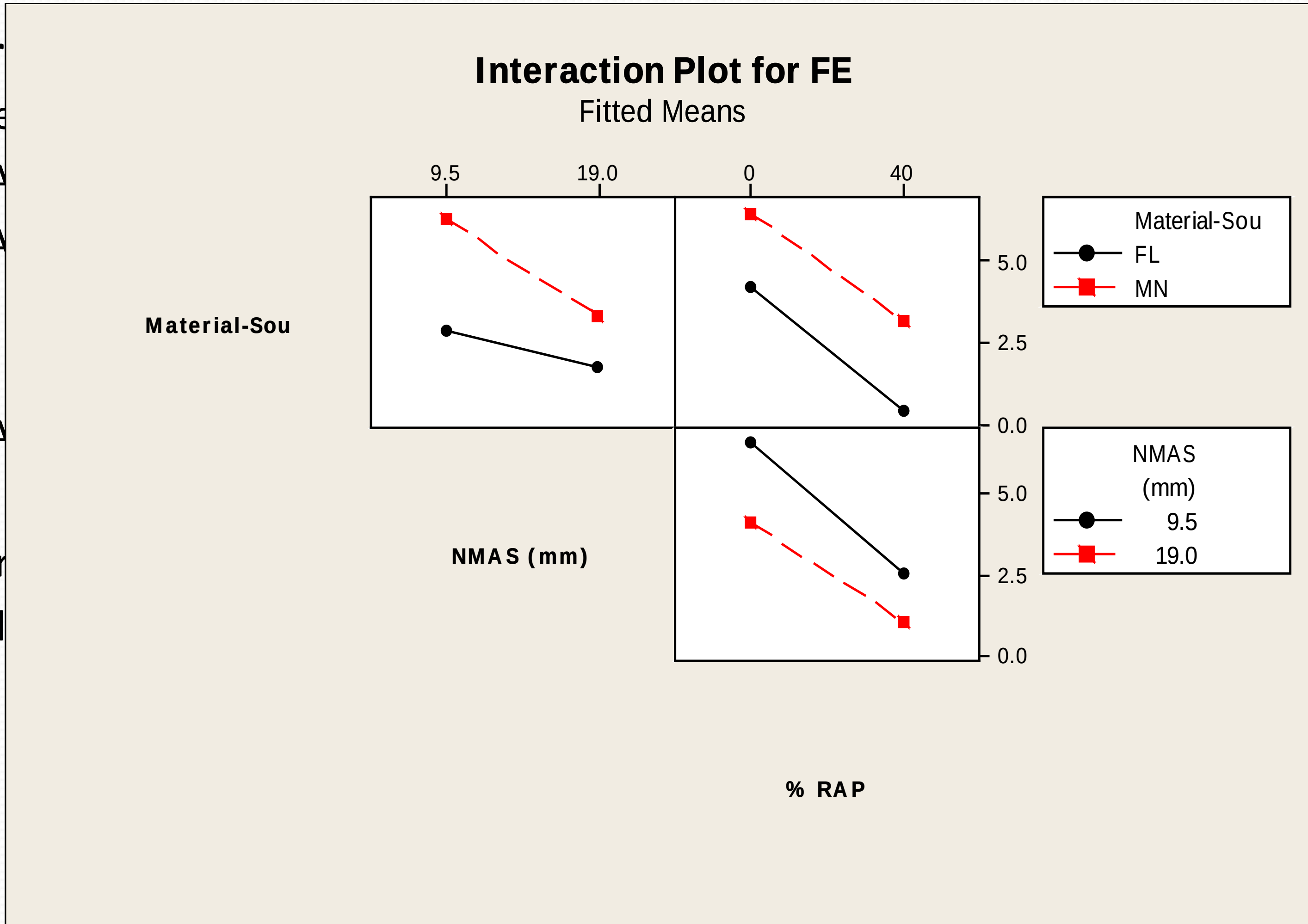


Statistical Analysis of FE@10°C

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Material-Source	1	37.750	37.750	37.750	147.32	0.000
NMAS	1	24.200	24.200	24.200	94.44	0.000
% RAP	1	76.684	76.684	76.684	299.25	0.000
Matl-So*NMAS	1	5.320	5.320	5.320	20.76	0.000
Matl-So*% RAP	1	0.400	0.400	0.400	1.56	0.229
NMAS*% RAP	1	1.550	1.550	1.550	6.05	0.026
Matl-So*NMAS*%RAP	1	4.084	4.084	4.084	15.94	0.001
Error	16	4.100	4.100	0.256		
Total	23	154.090				

Statistical Analysis of FE@10°C

Sour	P
Mate	0.000
NMA	0.000
% RA	0.000
Matl	0.000
Matl	0.229
NMA	0.026
Matl	0.001
Error	
Total	



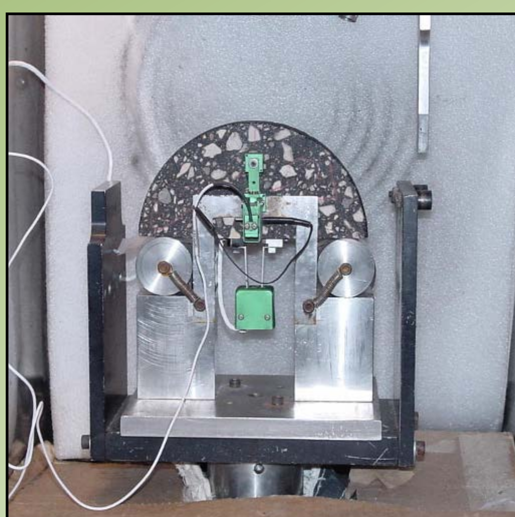
Summary of 10°C Fracture Energy Results

- High RAP content mixes have lower fracture energy results than their virgin mix counterparts.
- The relationship between fracture energy and field fatigue performance has not been thoroughly validated. Fatigue cracking involves material properties, structural and load-related factors, and several environmental factors. A simple criteria for fatigue cracking may not appropriate.

Low Temperature Cracking

Testing and Analysis by Dr. Mihai Marasteanu

University of Minnesota



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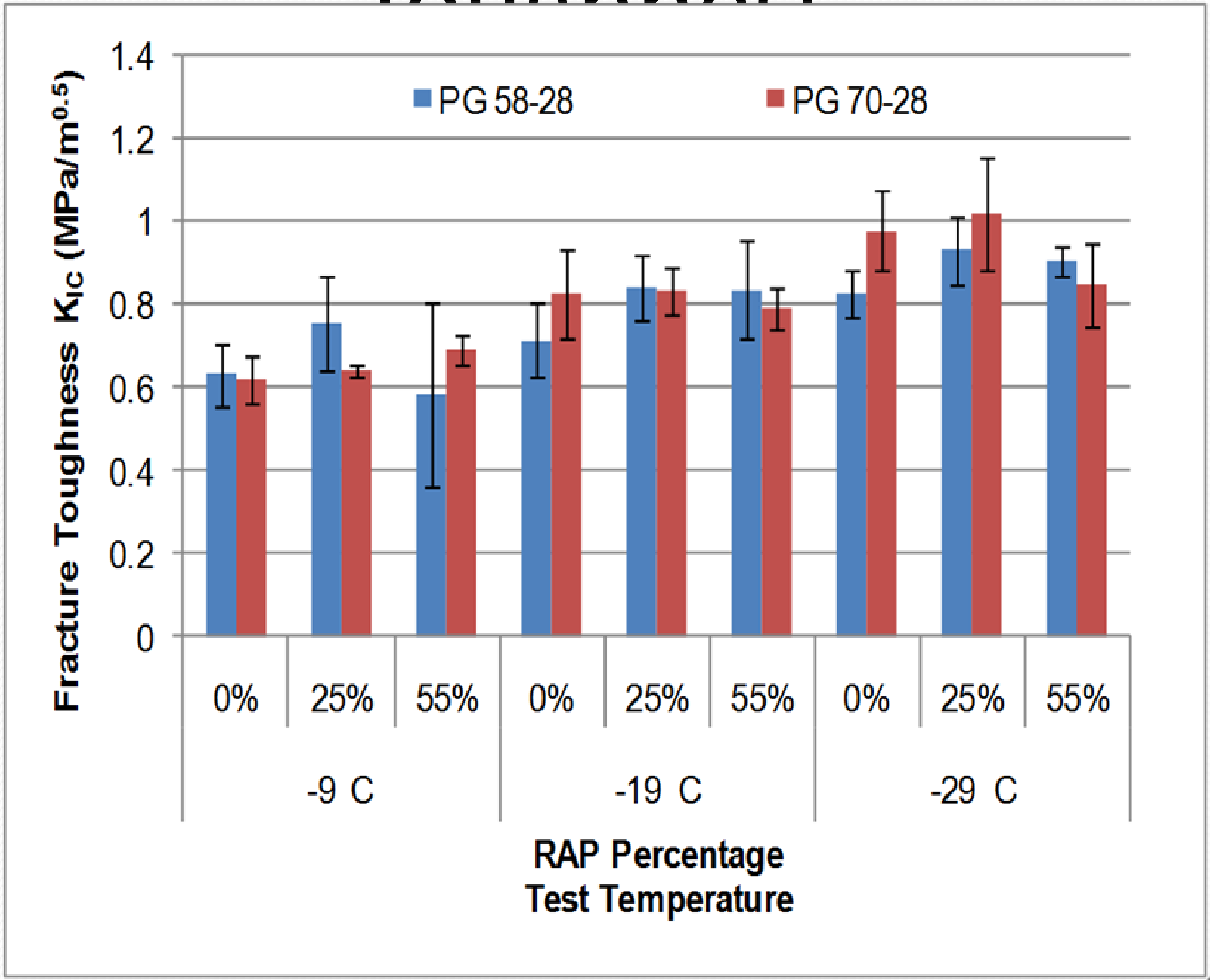
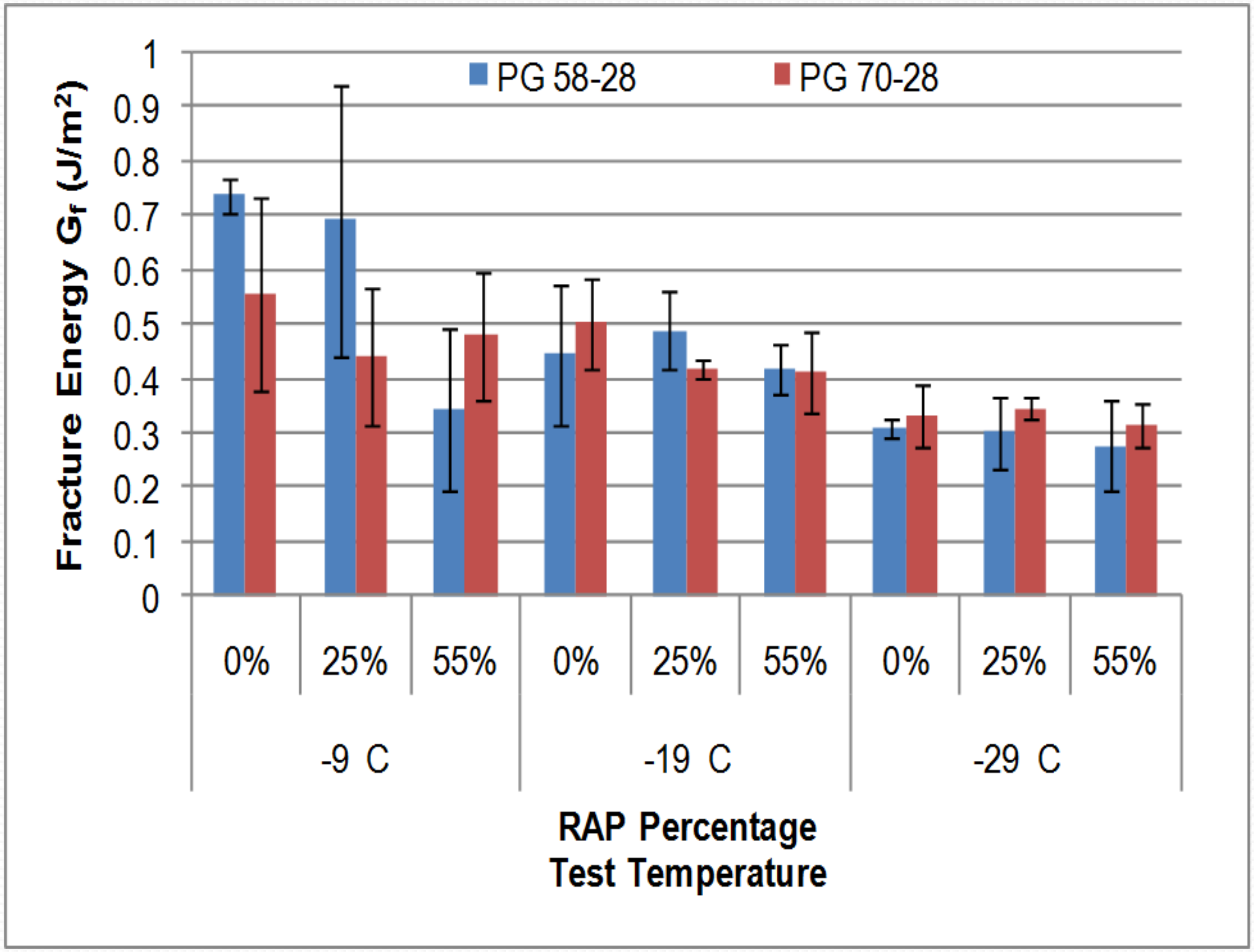
Low Temperature Cracking Analysis

- Semi-Circular Bend (SCB) test @ 3 temperatures
  - Fracture Toughness
  - Fracture Energy
- Bending Beam Rheometer on Mix Beams @ 2 temperatures
  - Creep Stiffness
  - m-value
- Mix Designs from MN, NH, and UT

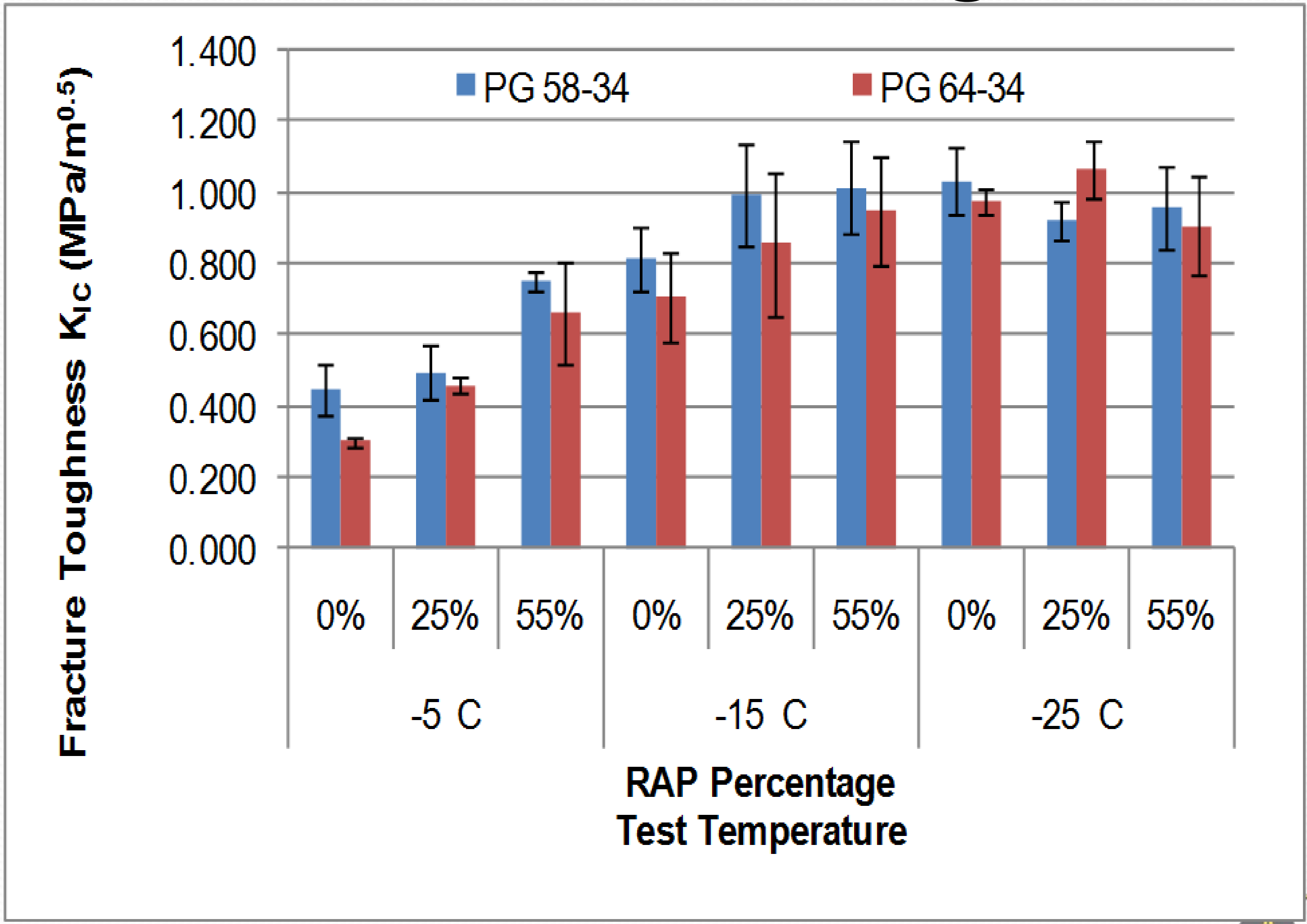
New Hampshire: Fracture Toughness



New Hampshire: Fracture Energy



Utah: Fracture Toughness



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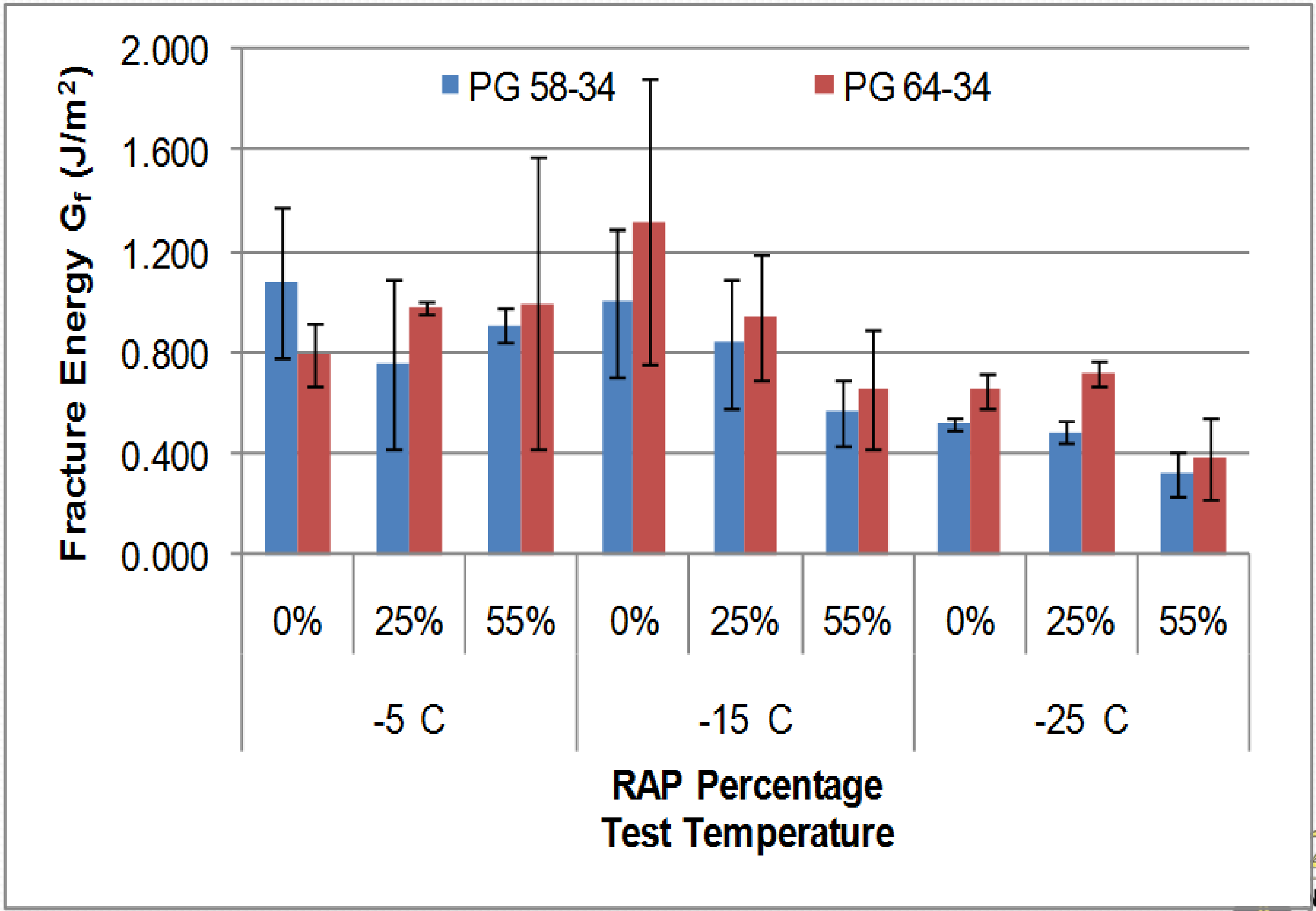
Utah: Fracture Energy



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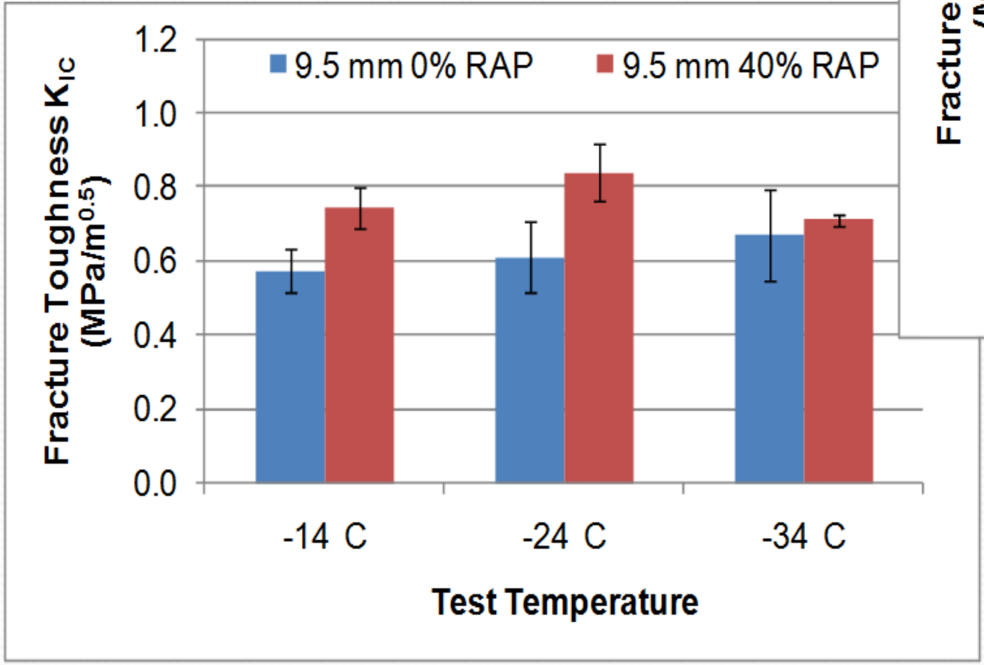
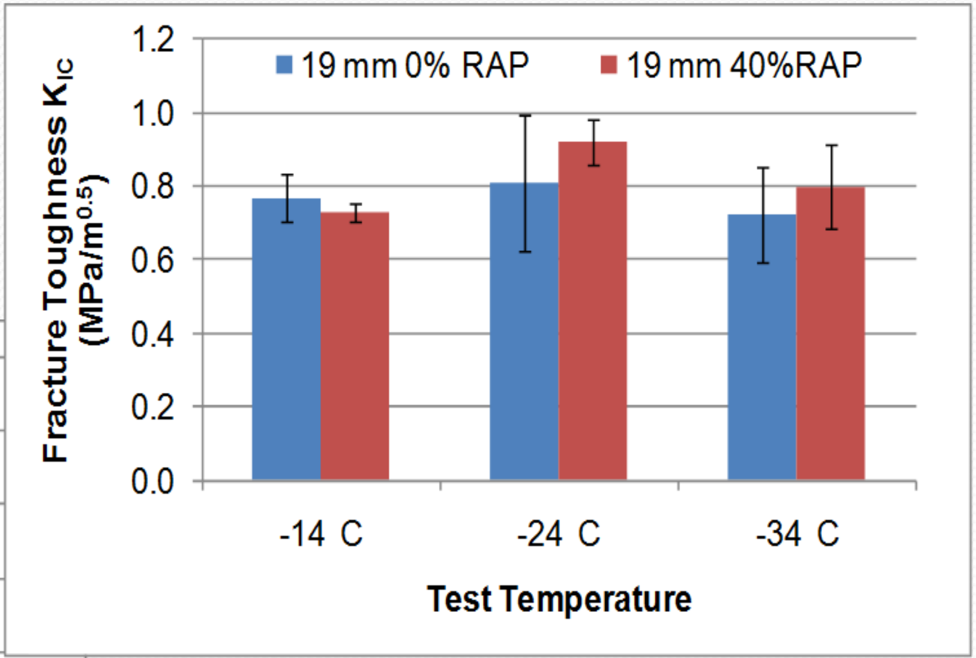
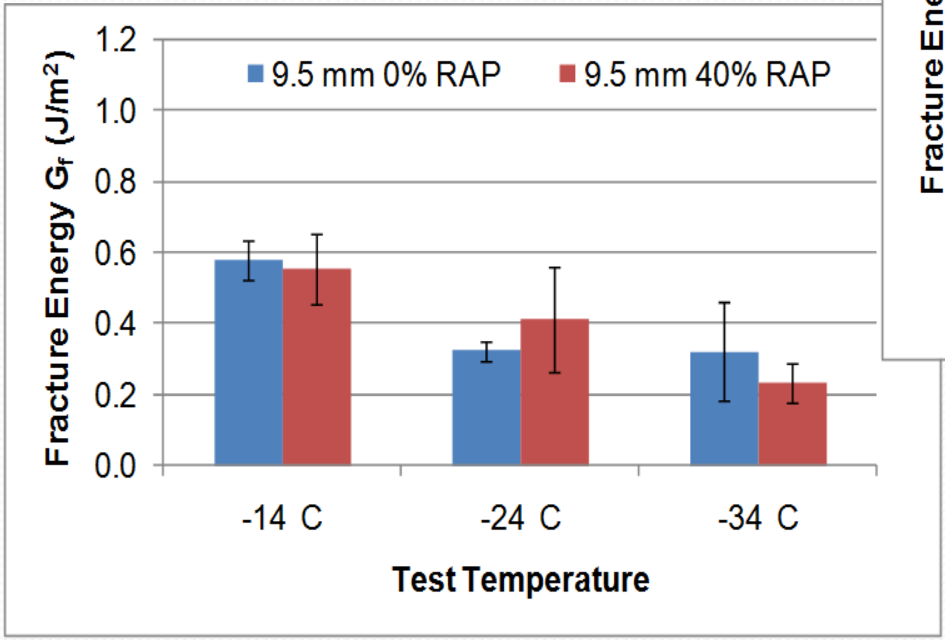
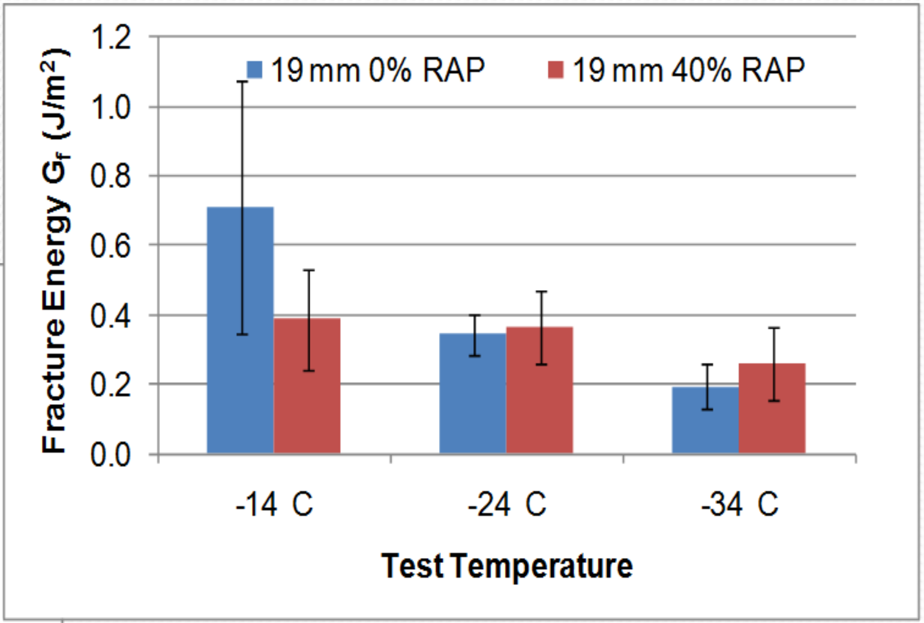
Minnesota: Fracture Toughness



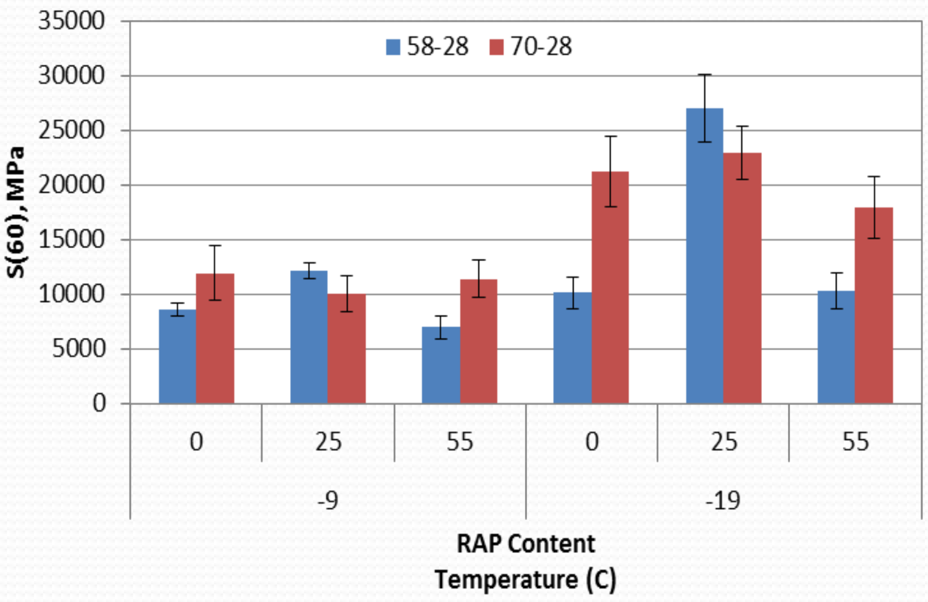


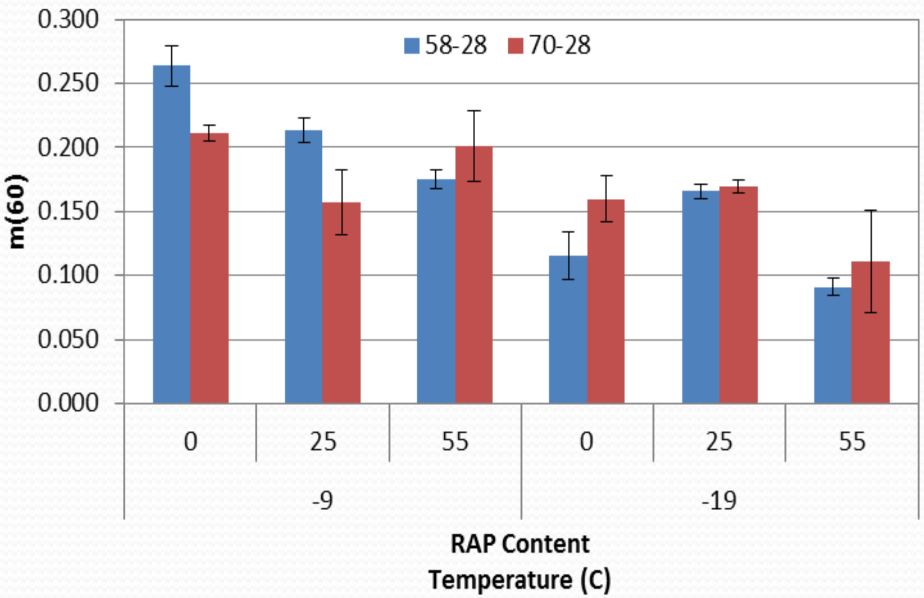
Minnesota: Fracture Energy



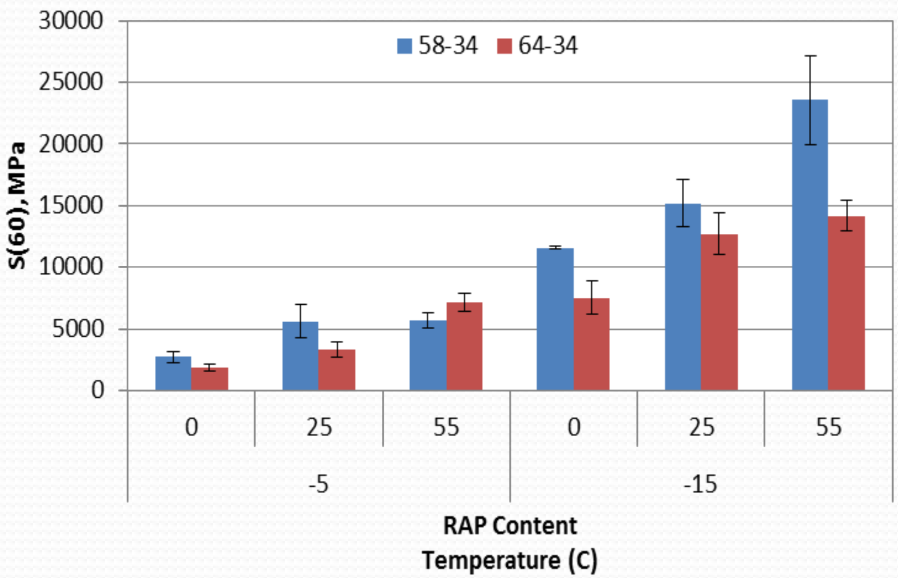


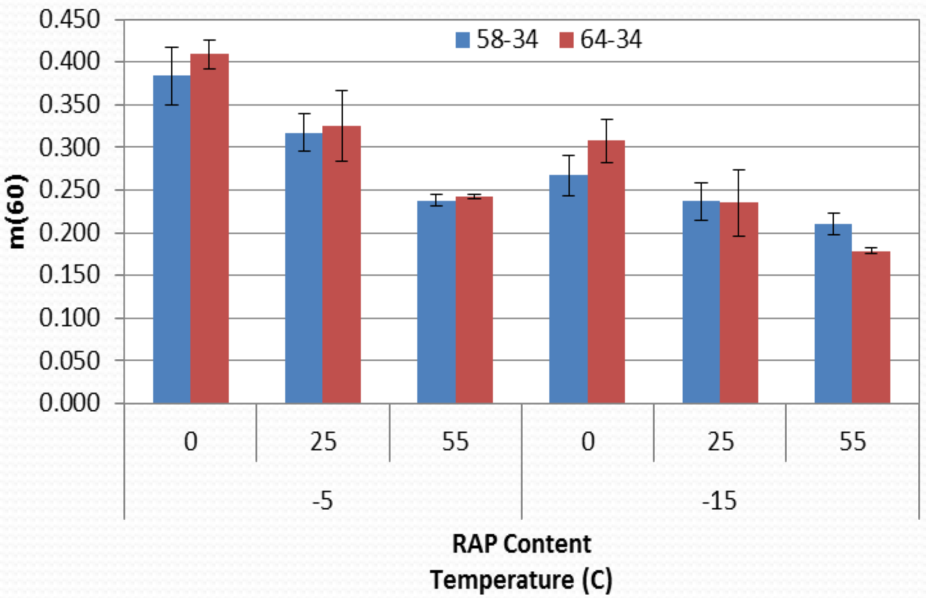
New Hampshire: BBR Results



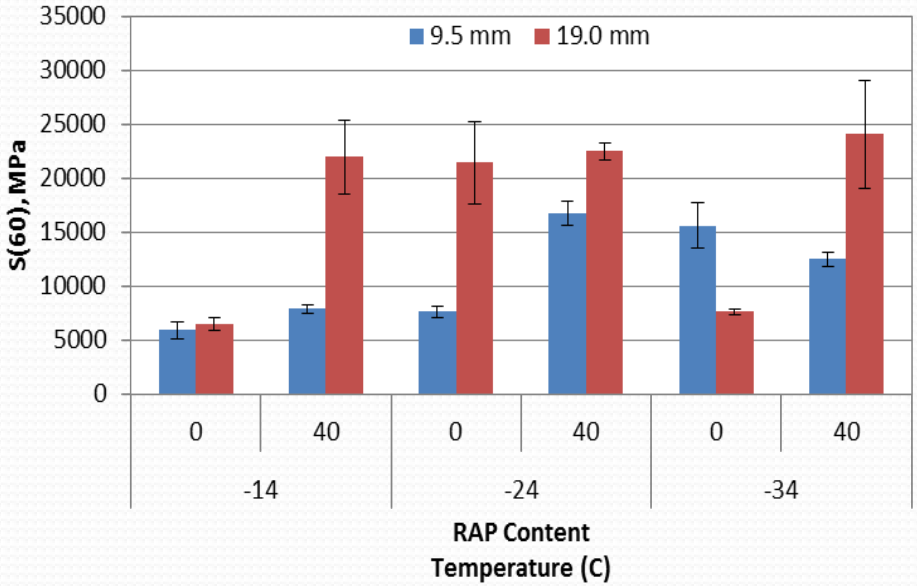


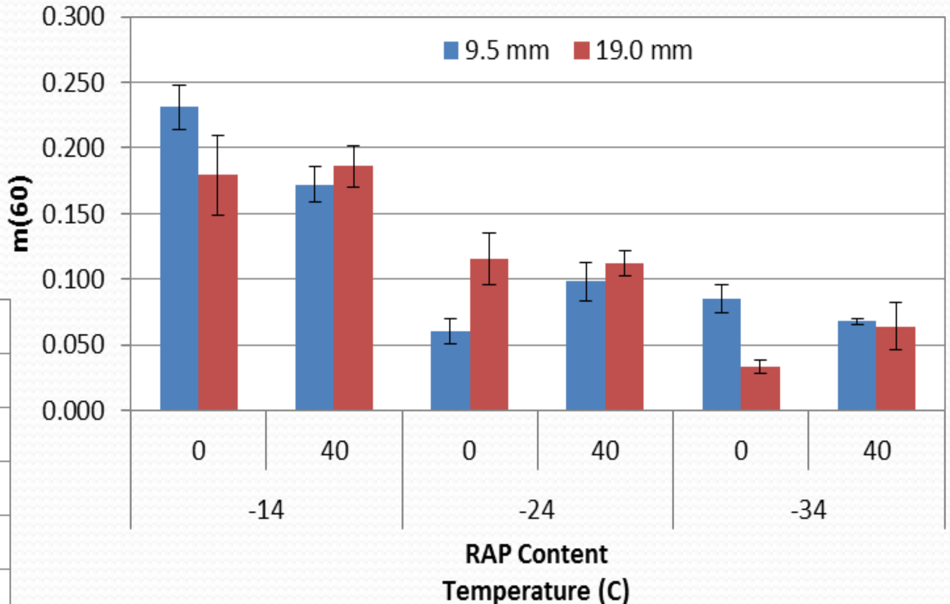
Utah: BBR Results





Minnesota: BBR Results





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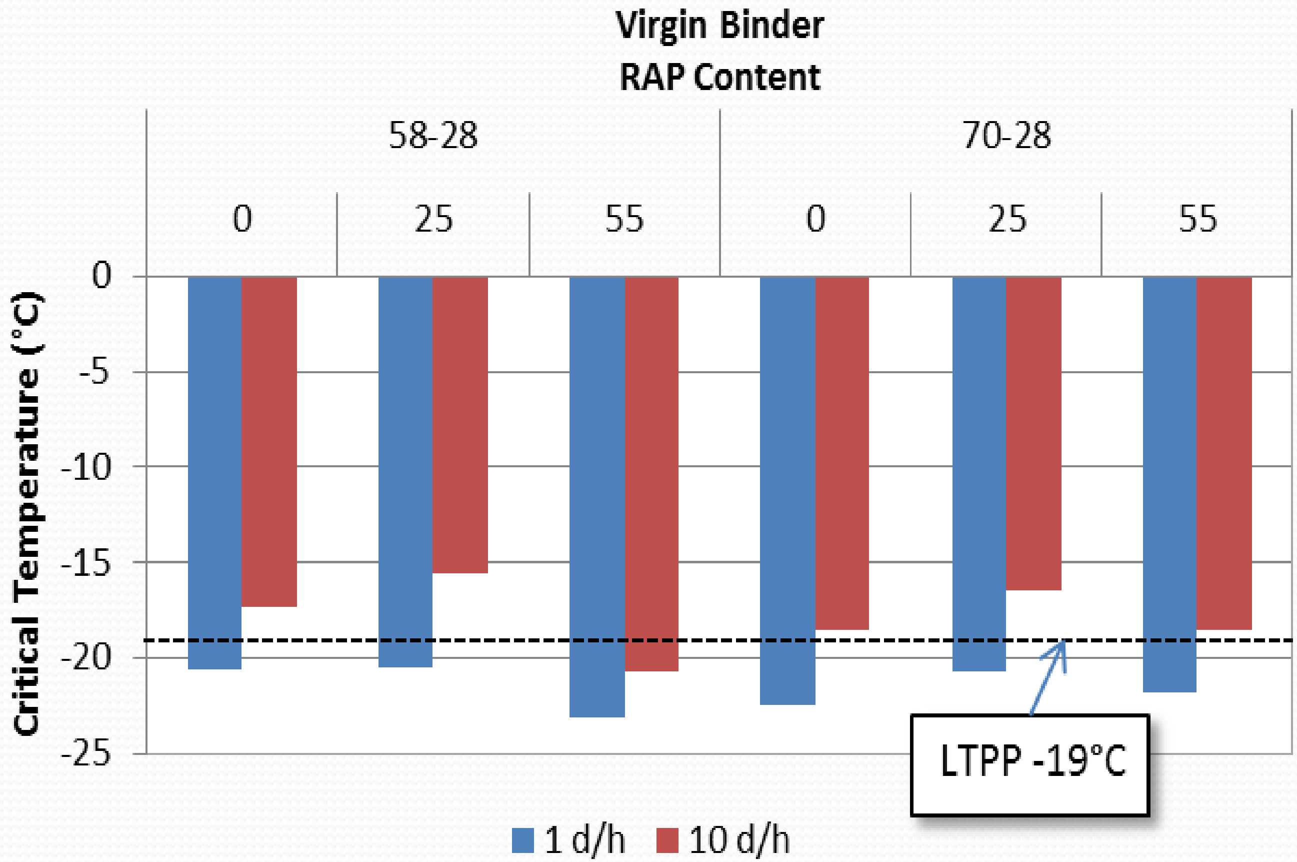
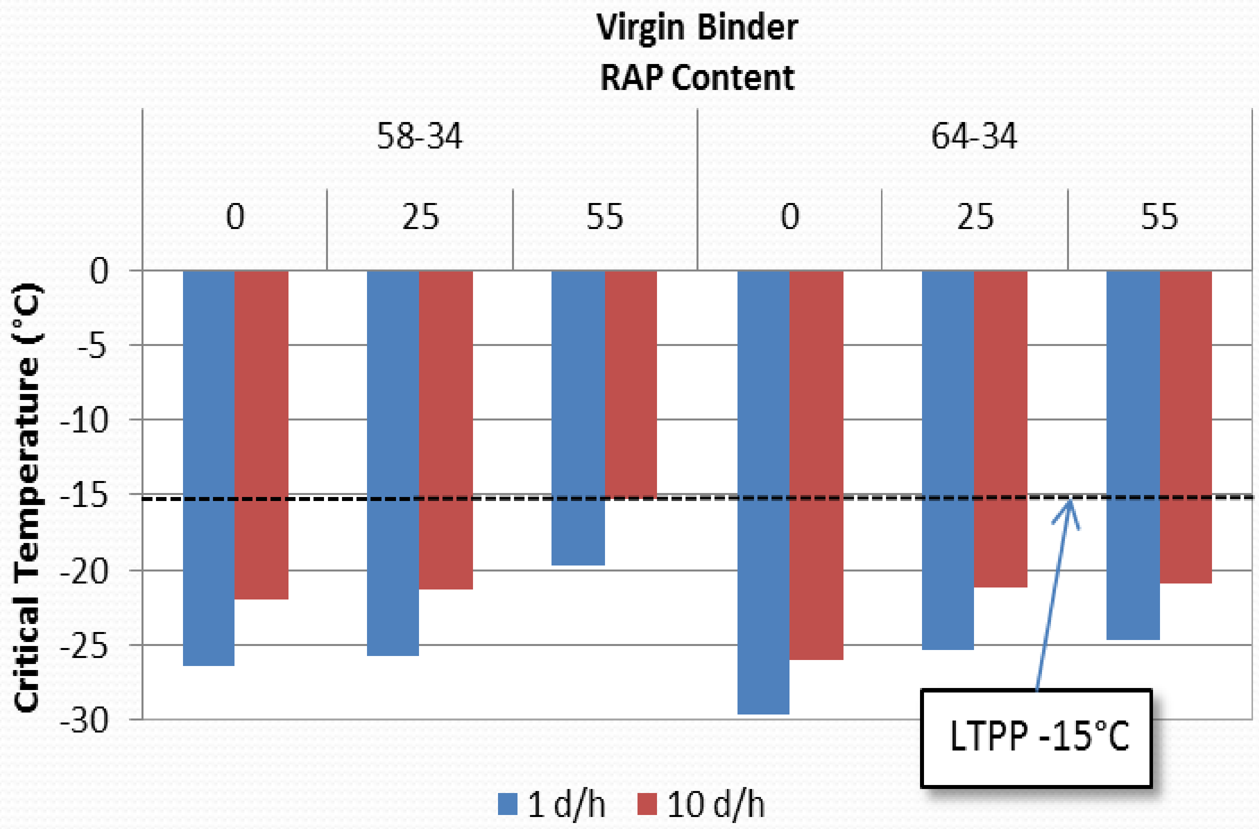
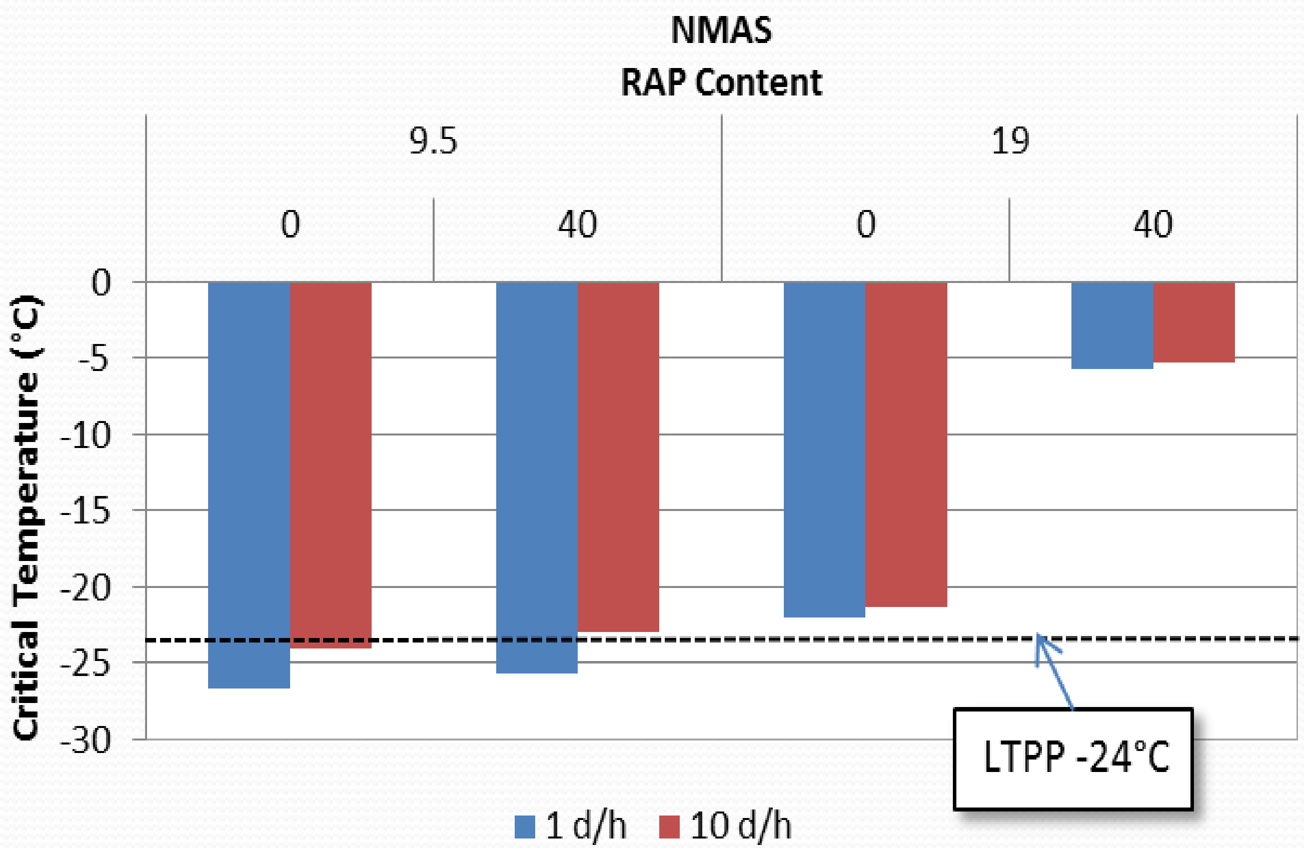
New Hampshire: Critical Cracking Temp.



Utah: Critical Cracking Temp.



Minnesota: Critical Cracking Temp.



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Summary of Effect of RAP Content on Low Temp. Properties

Virgin Binder	New Hampshire (NH)			
	K_{IC}	G_f	S(60s)	m(60s)
PG58-28A	55% ↑	Not significant	25% ↑	25&55% ↓
PG70-28A	Not significant	Not significant	Not significant	25% ↓

Virgin Binder	Utah (UT)			
	K_{IC}	G_f	S(60s)	m(60s)
PG58-34A	55% ↑	25&55% ↓	25&55% ↑	25&55% ↓
PG64-34A	55% ↑	55% ↑	25&55% ↑	25&55% ↓

Virgin Binder	Minnesota (MN)			
	K_{IC}	G_f	S(60s)	m(60s)
PG58-28B	40% ↑	Not significant	40% ↑	40% ↓

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Summary of Low Temperature Analysis

- In most cases, K_{IC} increases and G_f decreases as the temperature decreases. K_{IC} was also higher for 40 & 55% RAP mixes compared to virgin mixes. No trend was evident for the effect of RAP on G_f.
- BBR creep test results indicated that S(60s) increases as the temperature decreases and RAP content increases, whereas m(60s) decreases as the temperature decreases and RAP content increases.
- The effect of RAP content on critical cracking temperature was not consistent. The virgin binder grade appears to dominate the critical cracking temperature.

Preliminary Findings and Recommendations

Preliminary Recommendations

RAP Management

- The goal for RAP Management is to achieve good consistency of the material characteristics. To measure “consistency”, a QC plan must be used with a sampling and testing frequency commensurate with the proportion of the RAP in the mix design.

Preliminary Recommendations

Handling RAP in the Lab

- RAP should be fan dried, not oven dried, before testing.
- Heating RAP samples for preparation of mix design specimens for less than 3 hours. One and a half hours was sufficient to bring RAP batch up to mixing temperature.

Preliminary Recommendations
RAP Aggregate Gsb

- One method of determining RAP aggregate Gsb will not work for all material types. Agencies will need to evaluate options to find the best method for their materials. The method that gives the lowest Gsb will result in the lowest mix VMA. This is desirable since it will lead to higher asphalt contents and better durability.

Preliminary Recommendations

Selecting the Virgin Binder Grade

- Use a lower PG grade when the recycled binder content is 25 percent or more of the total binder for surface layers and mixes at the bottom of the pavement structure. Although blending charts or equations may not be completely accurate, they provide a reasonable method to the selection of virgin binders.
- Using the normal binder grade with high RAP content mixes for intermediate pavement layers provides a structural benefit (high modulus mix).

Mix Design for High RAP Contents

- Select the virgin binder grade using blending equations considering the mix location in the pavement structure.
- 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) *for information purposes only*
    - Fracture Energy

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Questions?