Building Crack-Resistance in Modern Mixes Including RAS using Performance Tests

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ILLINOIS

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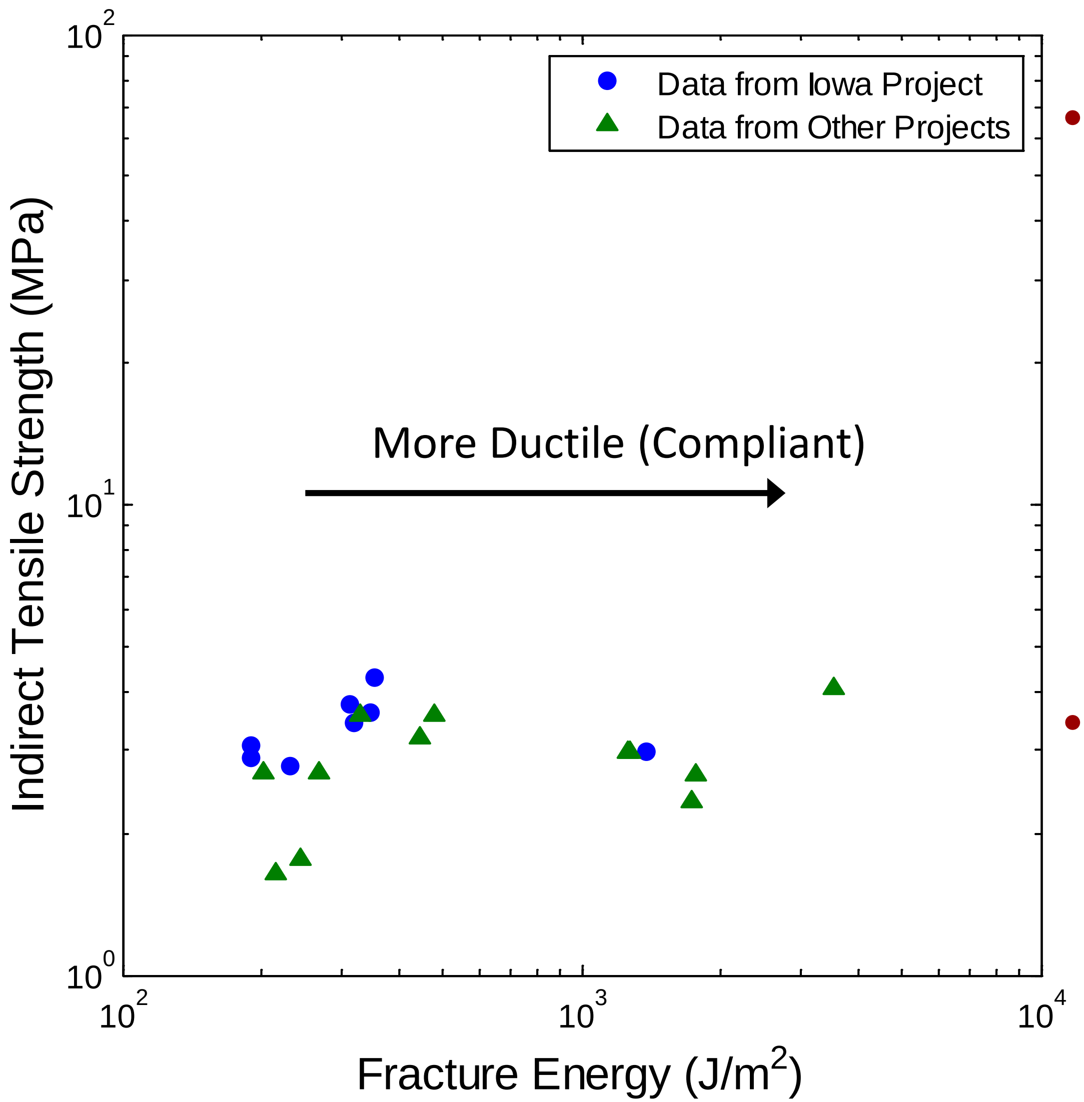
- If its not durable, its probably not sustainable
- Asphalt is much weaker in tension than in compression
- Asphalt becomes more brittle with age, low temps (glassy)

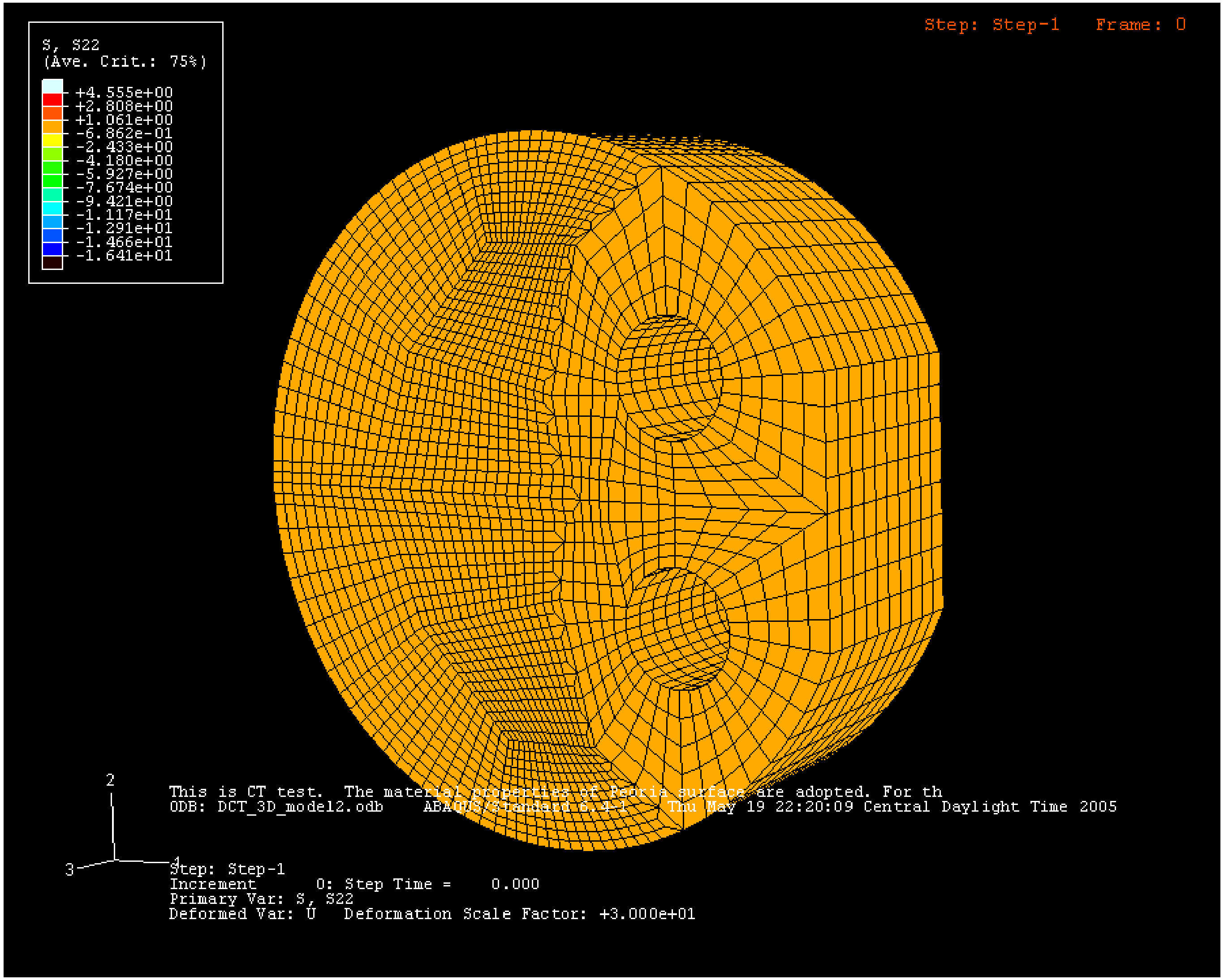
Tensile Strength is not Enough



Source: Wagoner and Buttlar, 2007

- Fracture energy appears to disseminate between mixes better than IDT strength
  - Large spread in data (<200 to > 2,000 J/m^2) for mixes with varied components (binder 'stretch', aggregate strength)
  - Especially prevalent with modified binders
- Data supported need for fracture mechanics approach

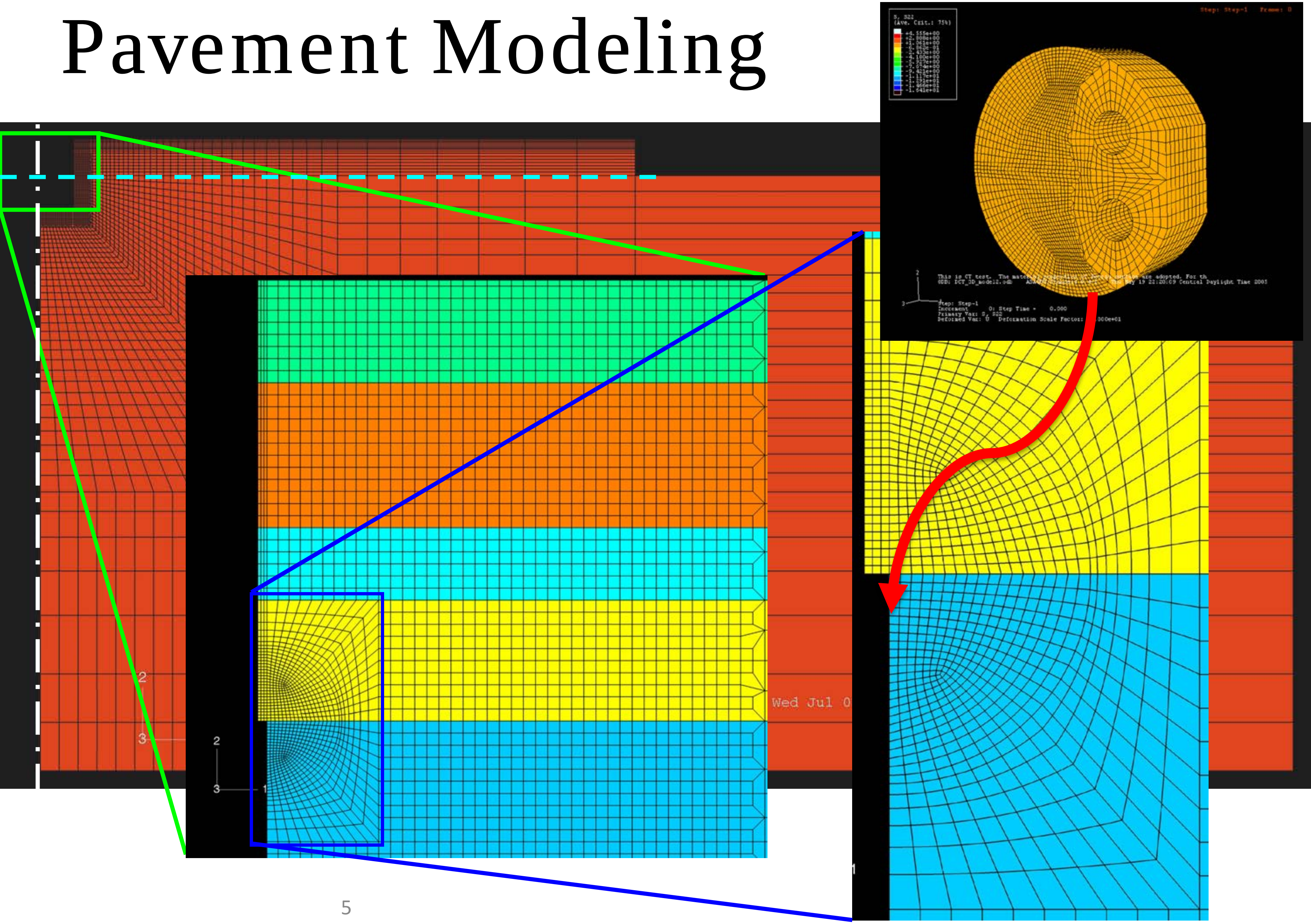
Three-dimensional fracture modeling



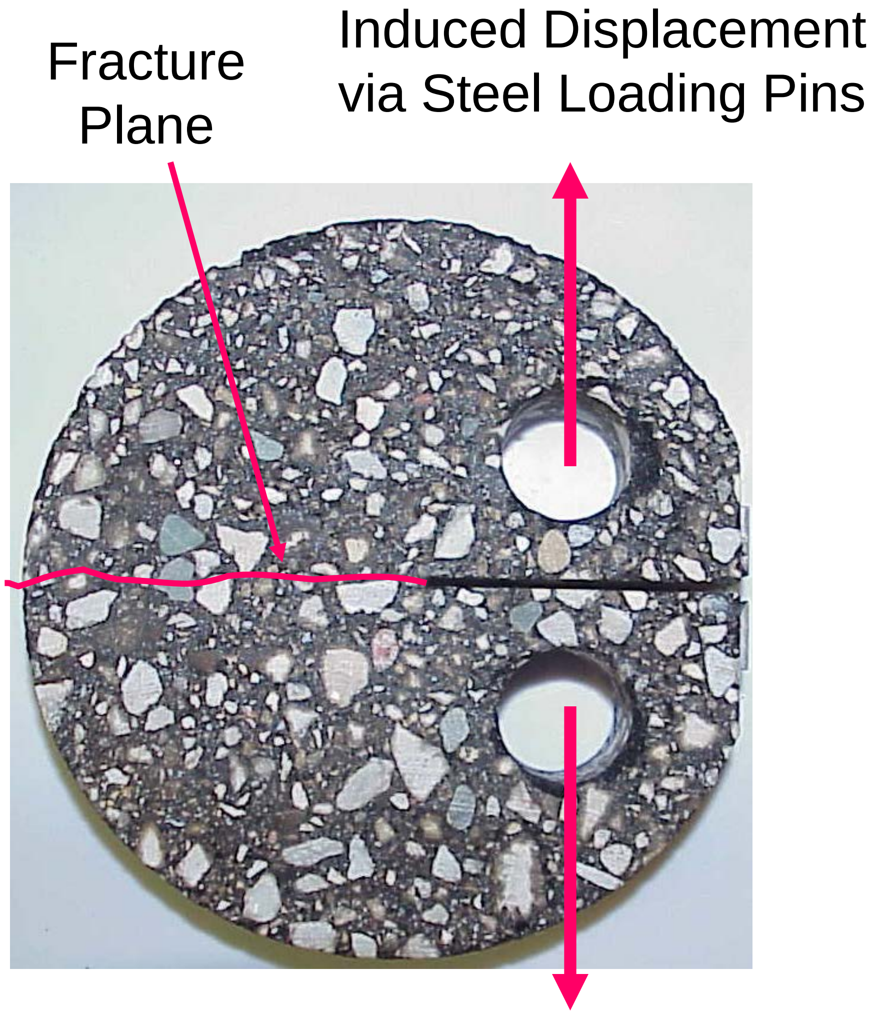
Fracture Behavior is f(Temp., time, specimen dimensions, test mode and boundary conditions, local strength, local energy, modulus)

Disk-Shaped Compact Tension Test (DC(T))

Pavement Modeling



Disk-Shaped Compact Tension - DC(T)



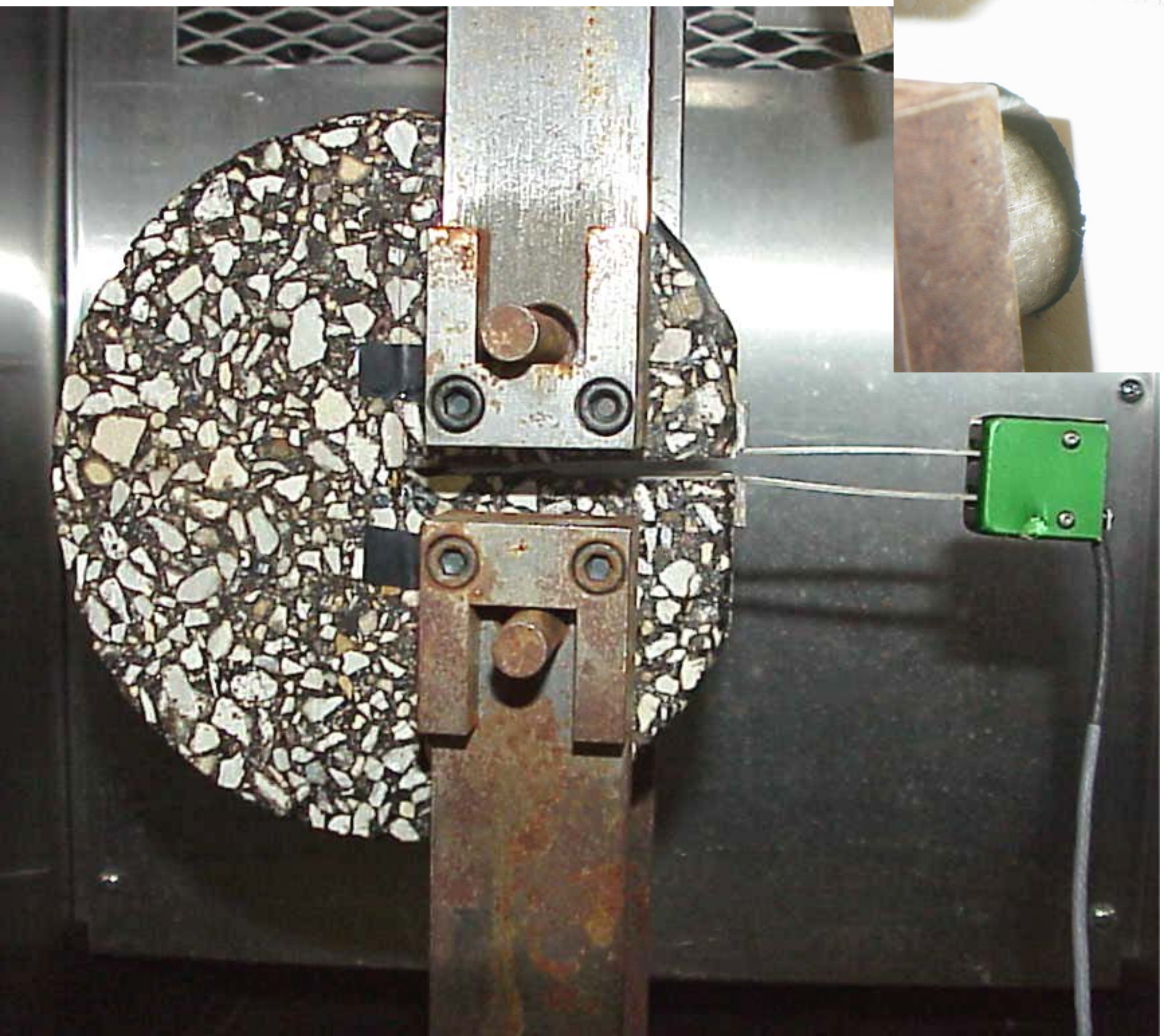
Motivation – measure fracture energy, use cylindrical specimens, maximize repeatability, use true fracture test

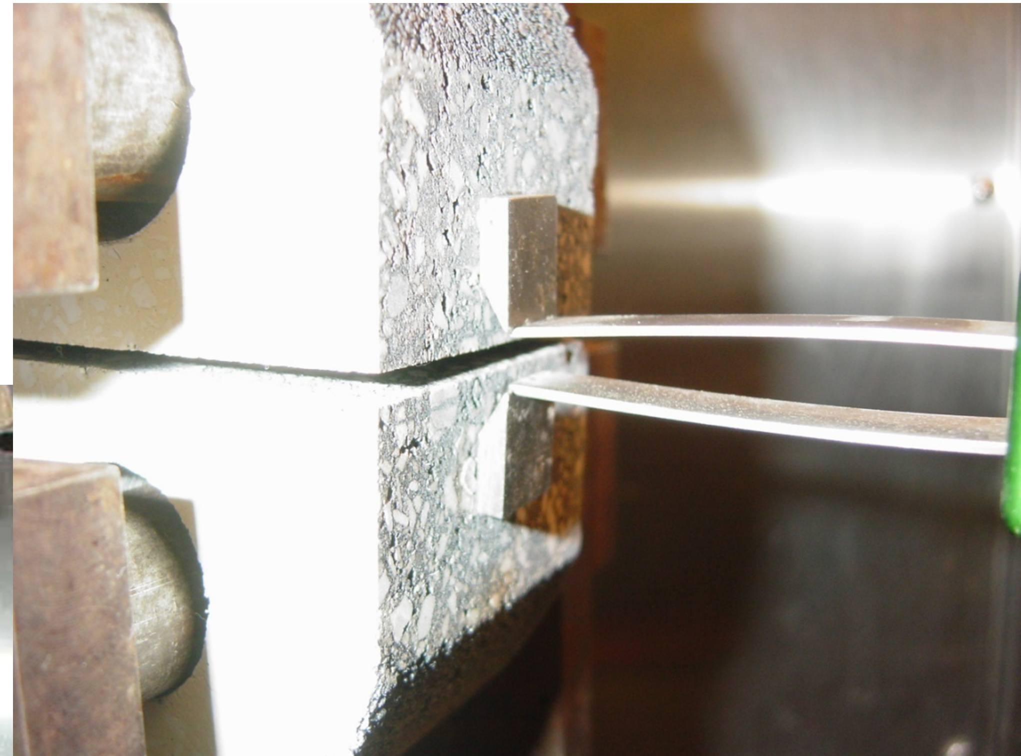
Based on ASTM E399 – Geometry slightly modified to account for differences in the fracture behavior of steel and asphalt concrete

Genesis was NSF GOALI study on reflective cracking: UIUC-NSF-Koch (2004)

Wagoner, M. P., Buttlar, W. G., and G. H. Paulino, "Disk-Shaped Compact Tension Fracture Test: A Practical Specimen Geometry for Obtaining Asphalt Concrete Fracture Properties," *Experimental Mechanics*, Vol. 45, No. 3, pp. 270-277, 2005.

Early DC(T) Test at U. of Illinois





CMOD Clip Gage Spring Mounted onto Knife-Edge Gage Points

CMOD = Crack Mouth Opening Displacement

ASTM Specification

Designation: D 7313 – 06

Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry[1]

This standard is issued under the fixed designation D 7313; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. *Scope*

1.1 This test method covers the determination of fracture energy (G_f) of asphalt-aggregate mixtures using the disk-shaped compact tension geometry. The disk-shaped compact tension geometry is a circular specimen with a single edge notch loaded in tension. The fracture energy can be utilized as a parameter to describe the fracture resistance of asphalt concrete. The fracture energy parameter is particularly useful in the evaluation of mixtures with ductile binders, such as polymer-modified asphalt concrete, and has been shown to discriminate between these materials more broadly than the indirect tensile strength parameter (AASHTO T322, Wagoner[2]). The test is generally valid at temperatures of 10°C (50°F) and below, or for material and temperature combinations which produce valid material fracture, as outlined in 7.4.

1.2 The specimen geometry and terminology (disk-shaped compact tension, DC(T)) is modeled after Test Method E 399 for Plane-Strain Fracture Toughness of Metallic Materials, Appendix A6, with modifications to allow fracture testing of asphalt concrete.

1.3 The test method describes the testing apparatus, instrumentation, specimen fabrication, and analysis procedures required to determine fracture energy of asphalt concrete and similar quasi-brittle materials.

1.4 The standard unit of measurement for fracture energy is Joules/meter^2 (J/m^2) [inch-pound/inch^2 (in.-lbf/in.^{2})].

1.5 The text of this standard references notes and footnotes

responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 *ASTM Standards:* [3]

D 8 Terminology Relating to Materials for Roads and Pavements

D 6373 Specification for Performance Graded Asphalt Binder

D 6925 Test Method for Preparation and Determination of the Relative Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor

E 399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials

E 1823 Terminology Relating to Fatigue and Fracture Testing

2.2 *AASHTO Standard:*

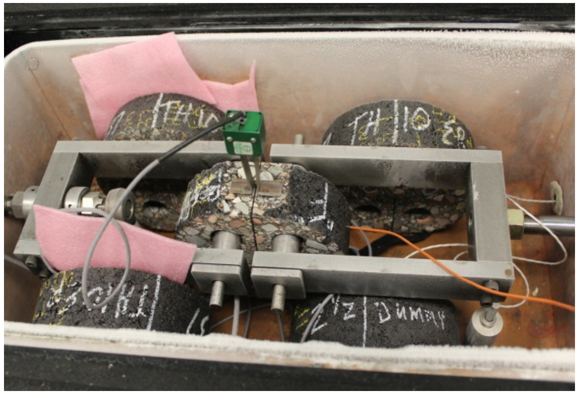
AASHTO T322 Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device[4]

3. Terminology

3.1 *Definitions*—Terminologies E 1823 and D 8 are applicable to this test method.

3.1.1 *crack mouth*—portion of the notch that is on the flat surface of the specimen, that is, opposite the notch tip (see Fig. 3).

DC(T) Test

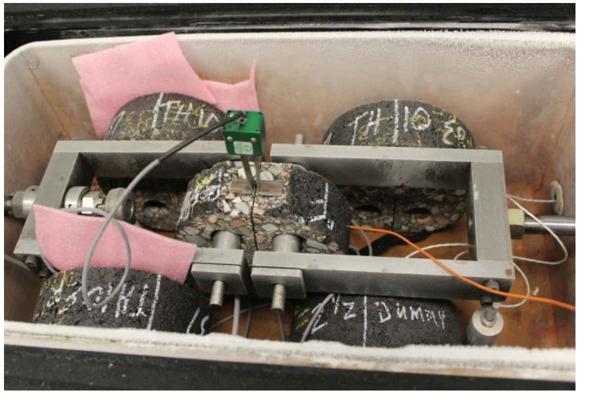


Test Quip DC(T)

- Test time: less than 10 minutes
- Turn-key test operation
- ~ $49k device
- 110V wall outlet

Testing

- The easy part!
- Less than 10 minutes
- Insert loading pins into specimen, affix CMOD gage, then turn-key operation



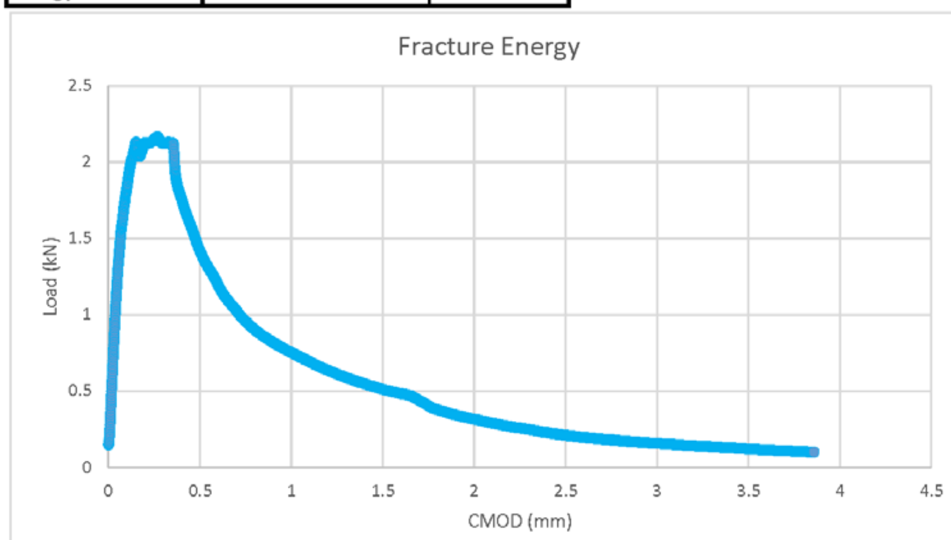
Test Quip DC(T (acknowledgement: Tom Brovold)

Automated Data Analysis

DCT Test Results

Tests perfomed in accordance with
IDOT Modified ASTM D7313-07

Test Date:	9/2/2014 3:12:58 PM		
Technician:	STATE TESTING		
Specimen ID:	SET 1		
Comments:	SPECIMEN 1L		In Compliance:
Diameter:	144.49	mm	
Thickness:	39.00	mm	
Ligament:	78.00	mm	
Cumulative Area:	2234.92	Nmm	
Max Load:	2.167 kN at 16.08 seconds		
Slope:	0.0170	mm/second	
Test Temperature:	C	°C	
Energy:	**734.690**	**J/m^2**	



Typical COV Data/Trends

Specimen ID	Test Temperature (°C)	Fracture Energy (J/m2)			
		Mean	Standard Deviation	COV	n
Mix 6	-10	289.3	3.5	1.2	3
Mix 3	-10	304.5	11.3	3.7	3
Mix 1	-10	333.6	16.0	4.8	3
Mix 7	-20	355.6	36.0	10.1	4
Mix 5	-10	436.5	21.2	4.9	4
Mix 4	-10	755.1	83.6	11.1	3
Mix 2	-10	798.2	69.9	8.8	2
Mix 23	0	841.9	98.6	11.7	3
Mix 12	-10	908.8	108.4	11.9	3
Mix 20	0	1047.1	89.8	8.6	3
Mix 22	0	1060.0	152.2	14.4	3
Mix 13	-10	1238.7	96.7	7.8	3
Mix 34	0	1319.4	169.6	12.9	3
Mix 31	0	1338.3	11.8	0.9	3
Mix 9	-10	1441.1	133.3	9.2	2

- Most surface mixes tested at low temperatures: COV <=10%
- If mix variability is high, then COV will be higher (field cores, segregated mix)

- ❑ Motivation for Development of DC(T) Test
- ❑ Development of DC(T) and ASTM D7313 Spec
- ❑ **Pooled-Fund Study and Thermal Cracking Spec**
- ❑ Sa
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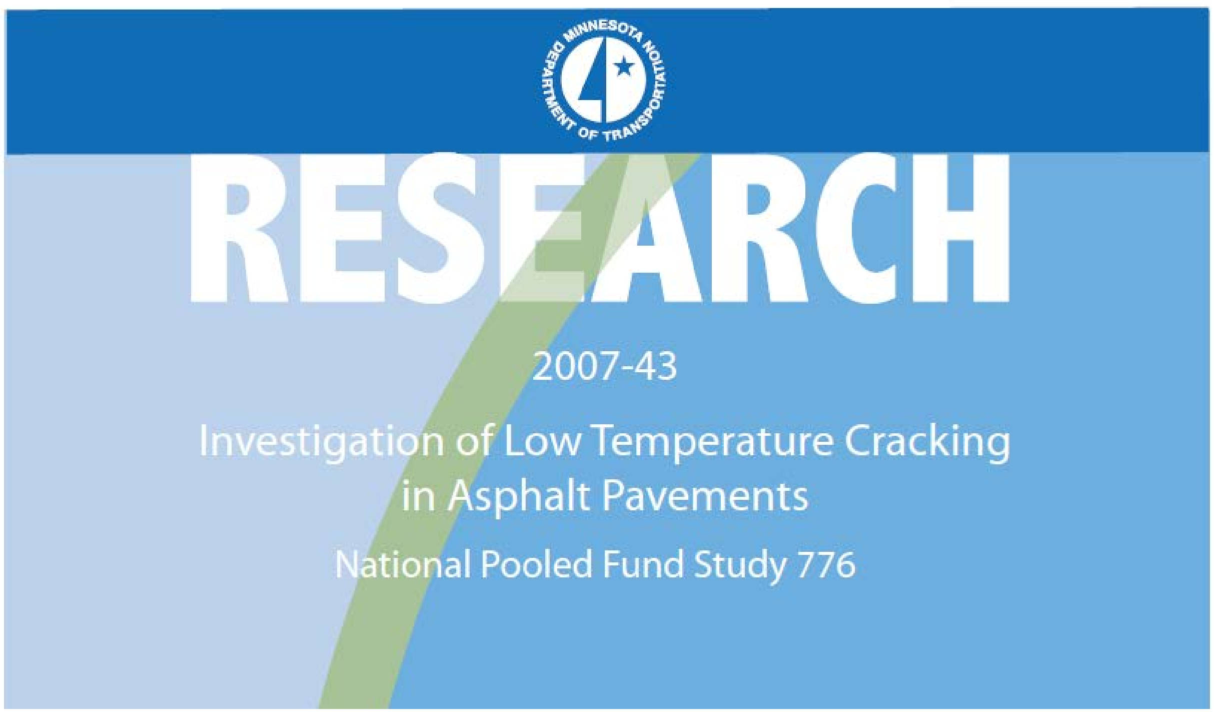
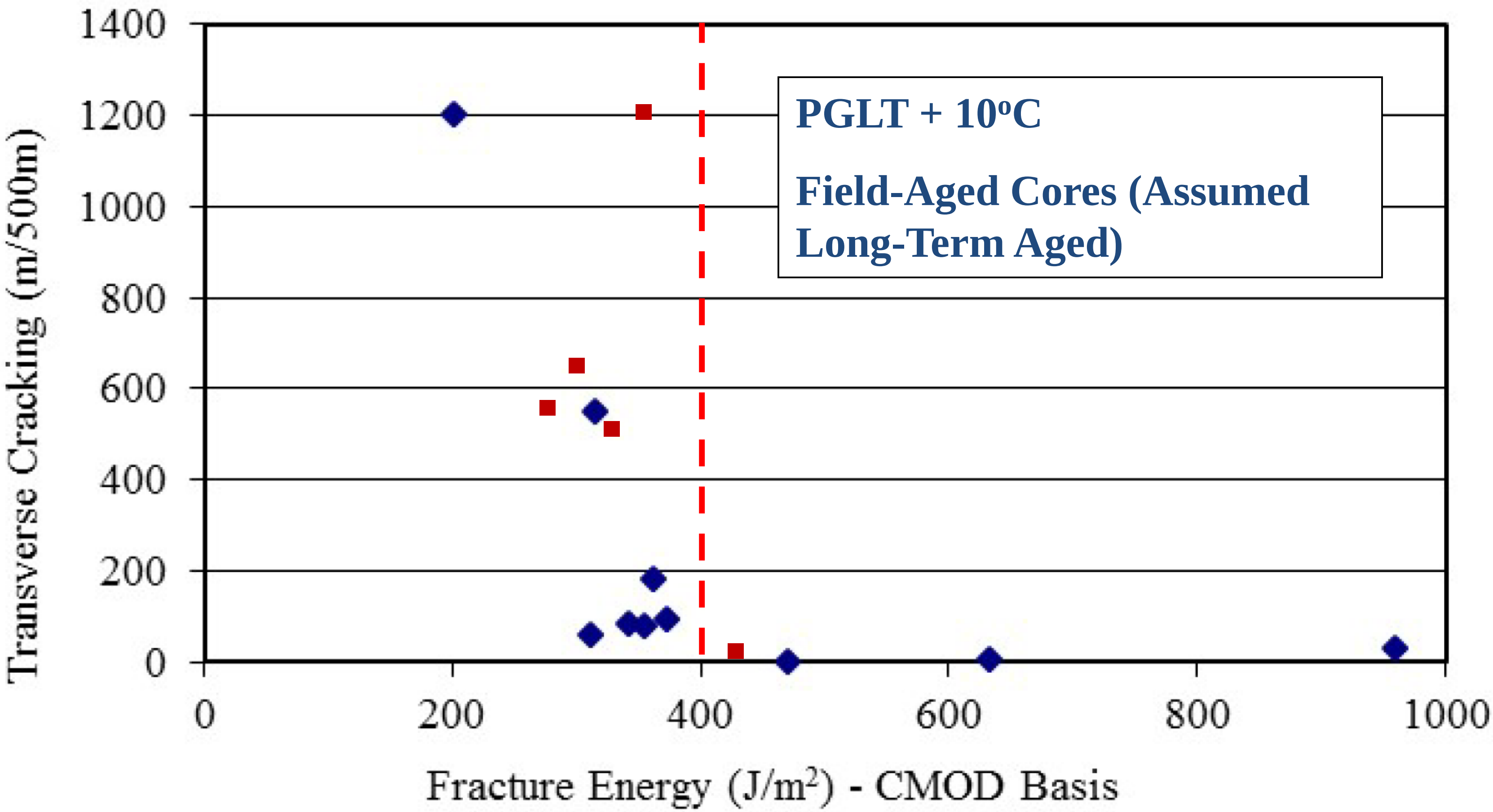


DC(T) Results from Pooled Fund Study



1) Fracture Energy is Enough to characterize and control cracking
2) SCB also evaluated, but found by Univ. of MN to have high COV and poor correlation to field cracking in blind study

New DC(T) Based Thermal Cracking Spec

Table 4.2: Recommended Low-Temperature Cracking Specification for Loose Mix

Contents	Project Criticality/ Traffic Level		
	High >30M ESALS	Moderate 10-30M ESALS	Low <10M ESALS
Fracture Energy, minimum (J/m^2), PGLT + 10oC	690	460	400
Predicted Thermal Cracking using ILLI-TC(m/km)	< 4	< 64	Not required

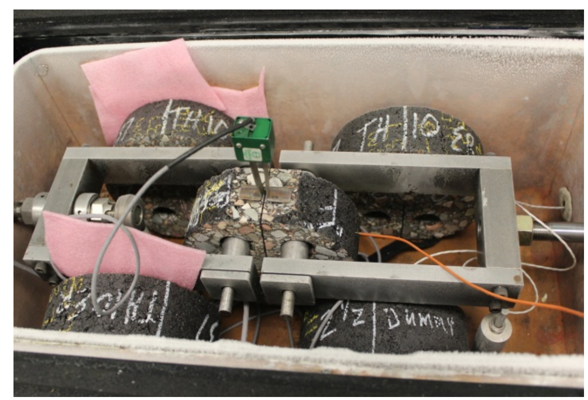
From: http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=2178

Implementation: Minnesota, Iowa, Wisconsin, Chicago DOT, O'Hare, Asphalt Institute

Stability with Crack-Resistance: Two-Dimensional View of Performance

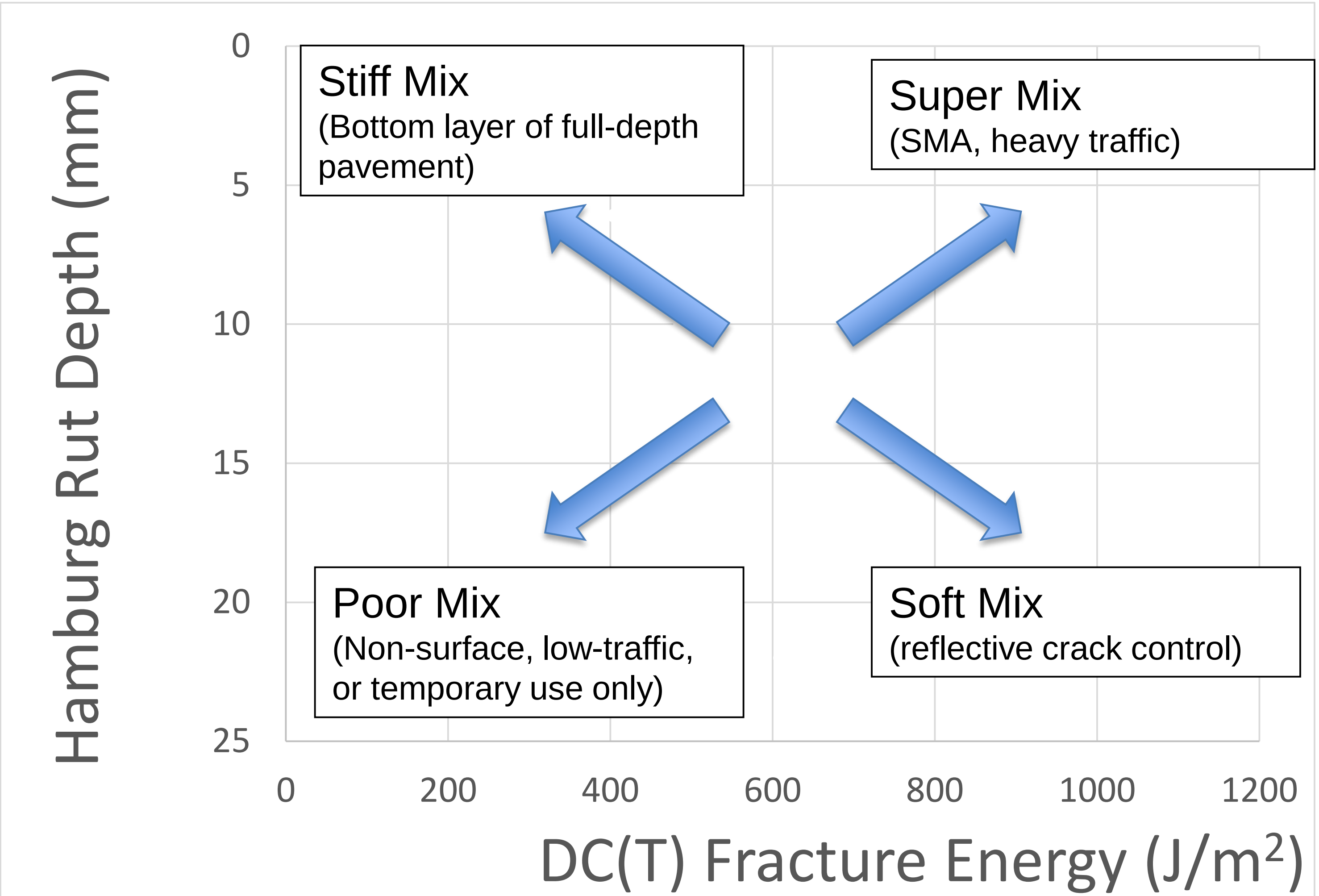
Hamburg

+

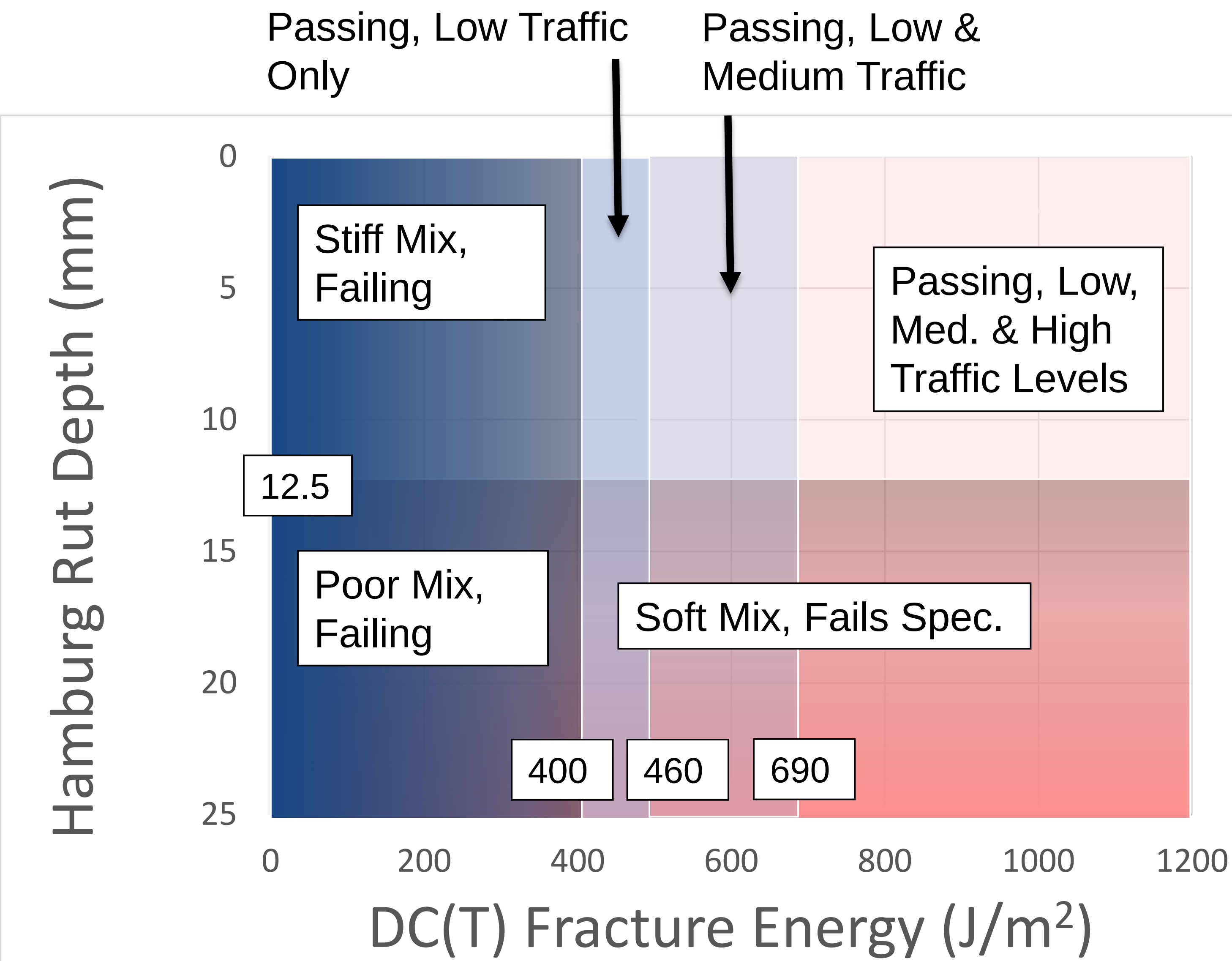


DC(T)

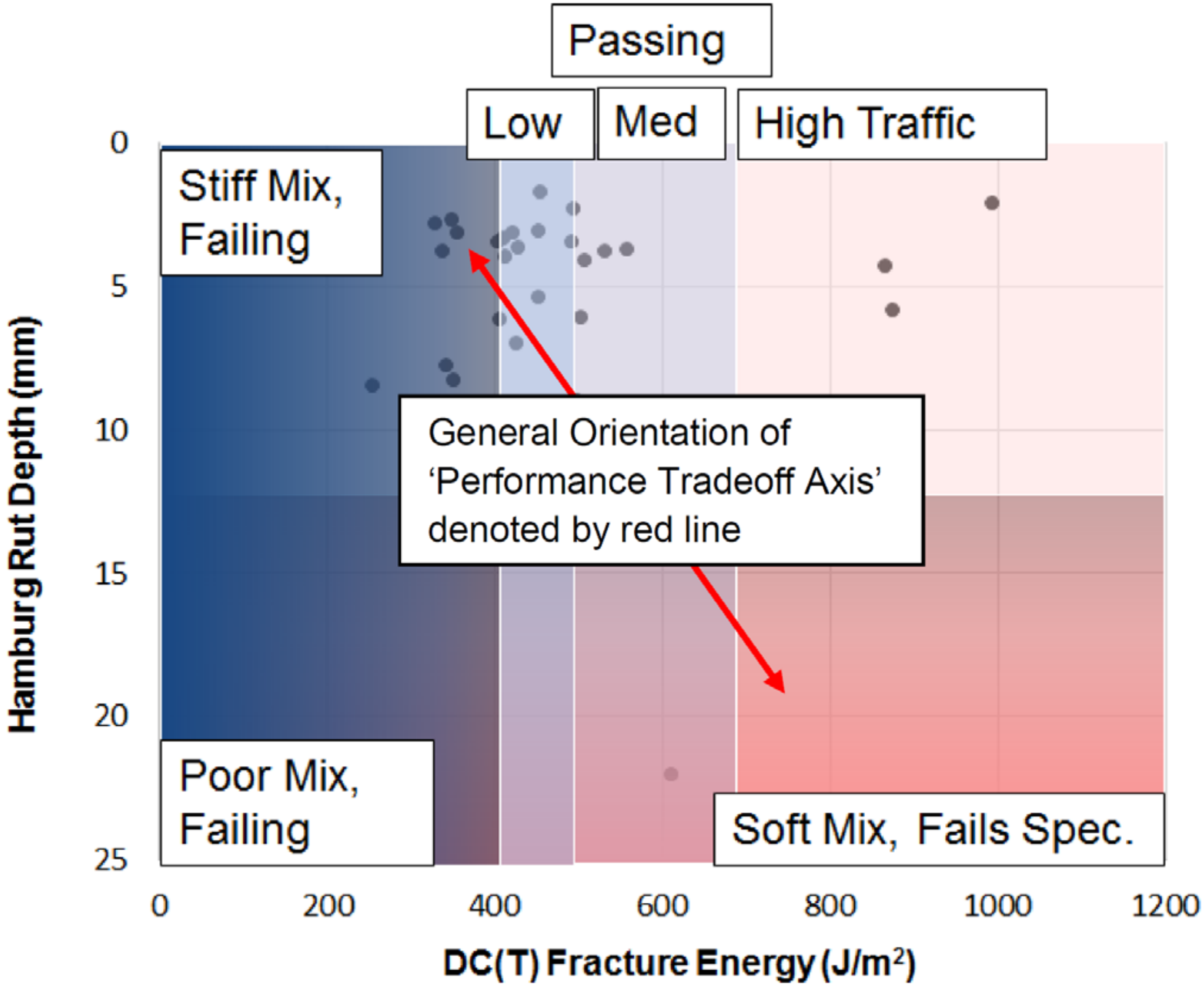
“Performance-Space” Diagram



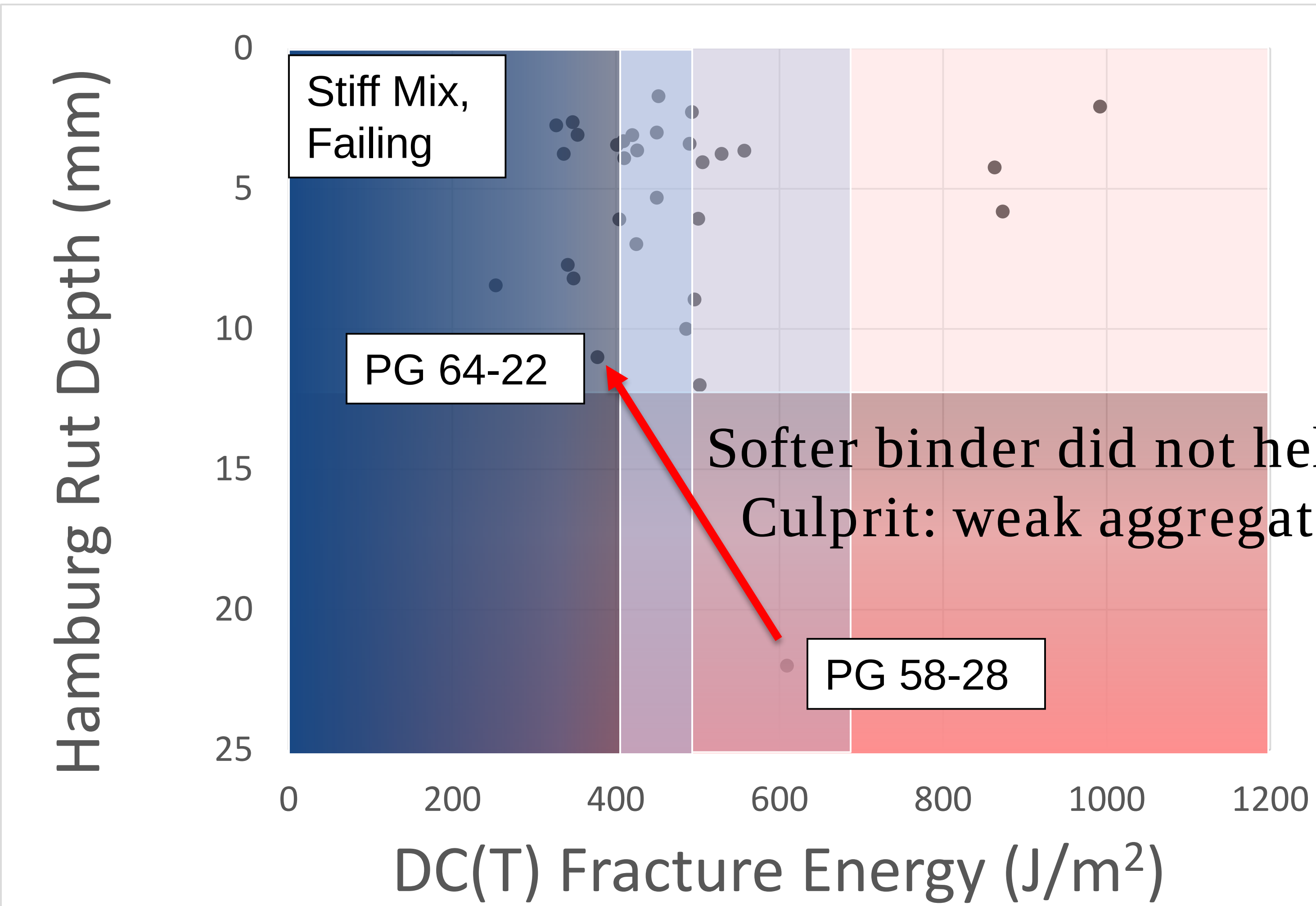
Performance-Space Diagram: Zones



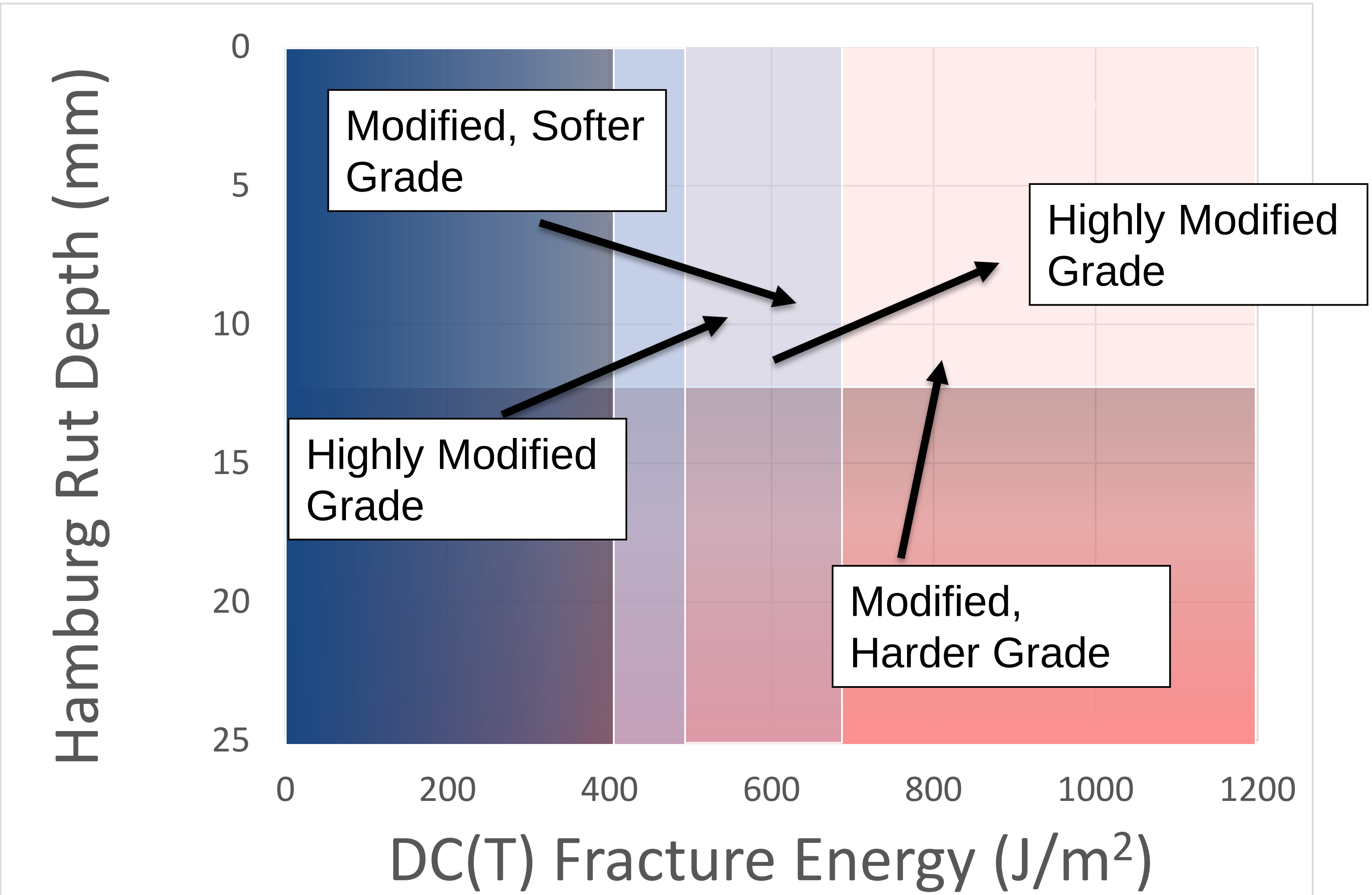
Performance Tradeoff Axis Concept



Softer Binder, No Polymer



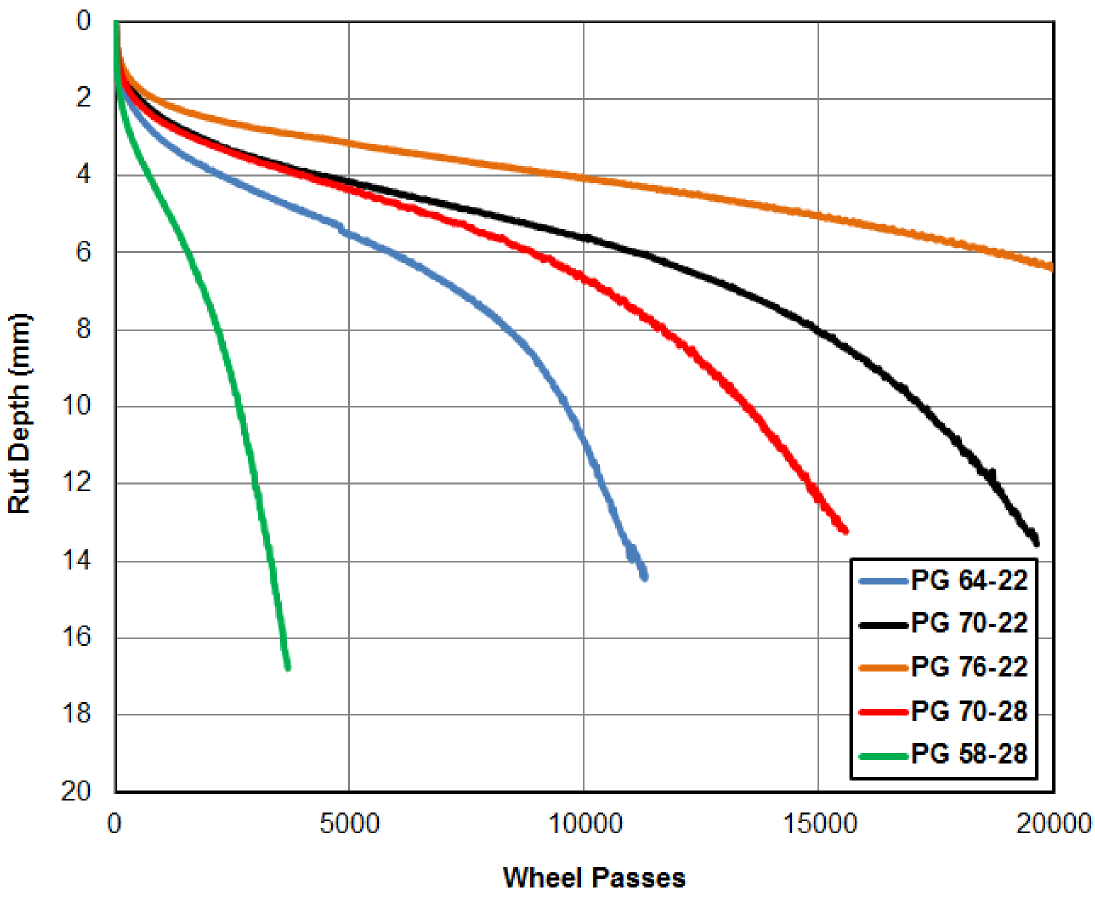
Mix Adjustment: Binder Modification Hypothesized



Binder Modification Mixture Design

Volumetric Properties	
Total Asphalt Content (%)	6.6
ABR (%)	0.0
Air Voids (%)	4.0
VMA (%)	15.2
VFA (%)	74.0
Effective Asphalt Content (%)	4.9
Dust/Effective AC	1.1

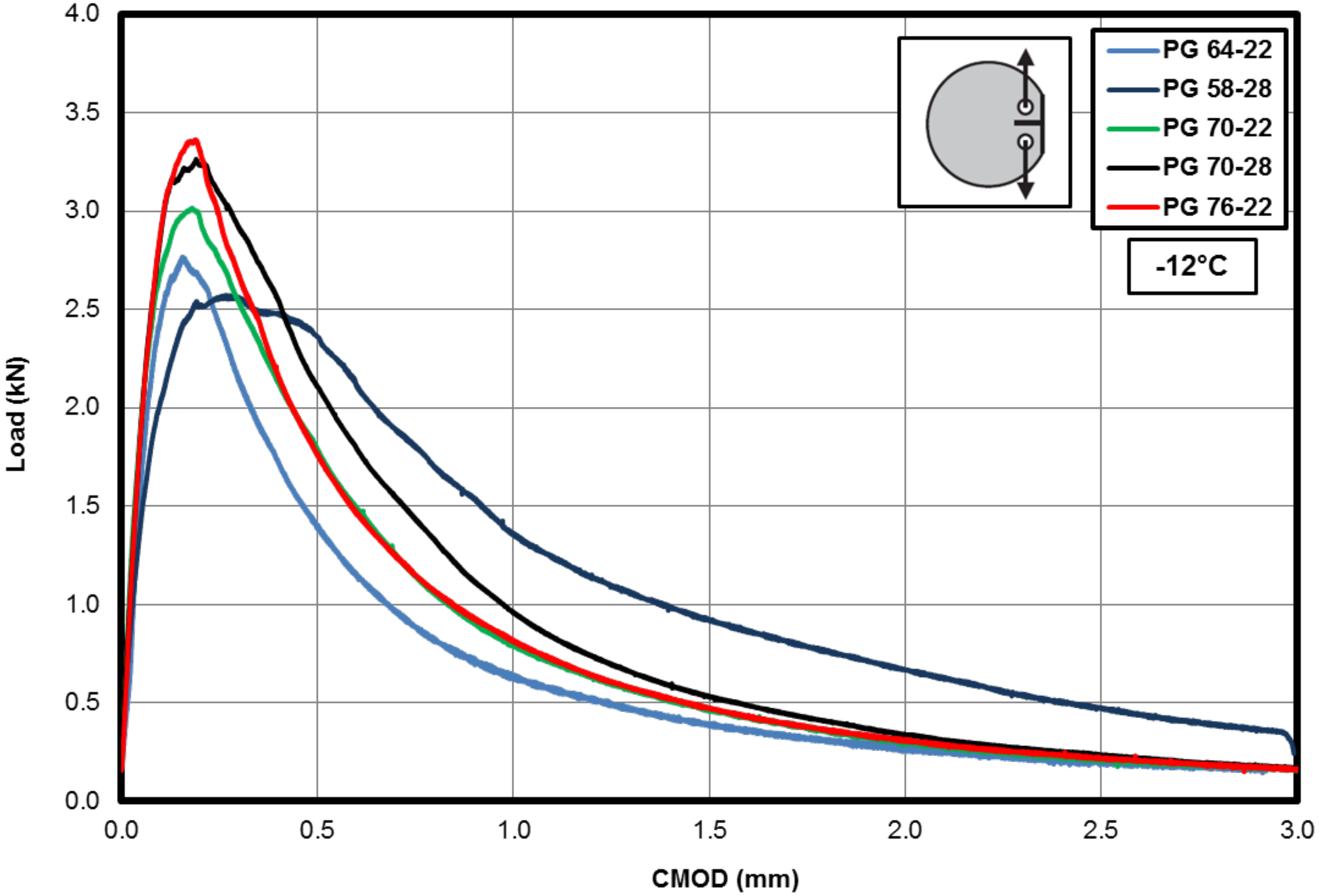
Hamburg Results



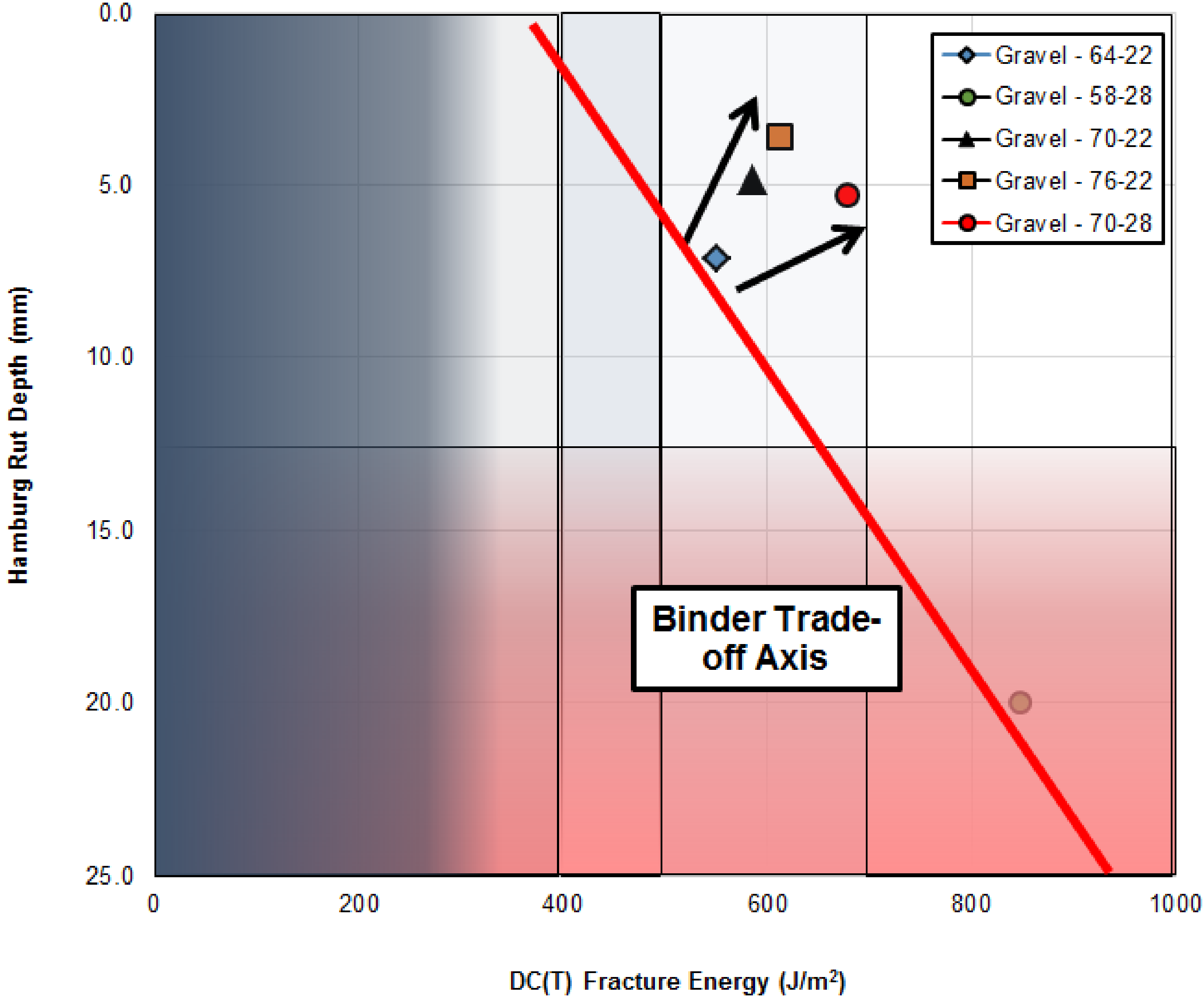
DC(T) and SCB Results (-12C)

DC(T) Results		
Binder Grade	Avg. Peak Load (kN)	Avg. CMOD G_f (J/m^2)
PG 64-22	3.209	551
PG 58-28	2.592	848
PG 70-22	3.209	585
PG 70-28	3.291	679
PG 76-22	3.586	615
SCB Results		
PG 64-22	4.679	1055
PG 70-22	5.201	1064
PG 70-28	4.680	1117
PG 76-22	5.364	1290

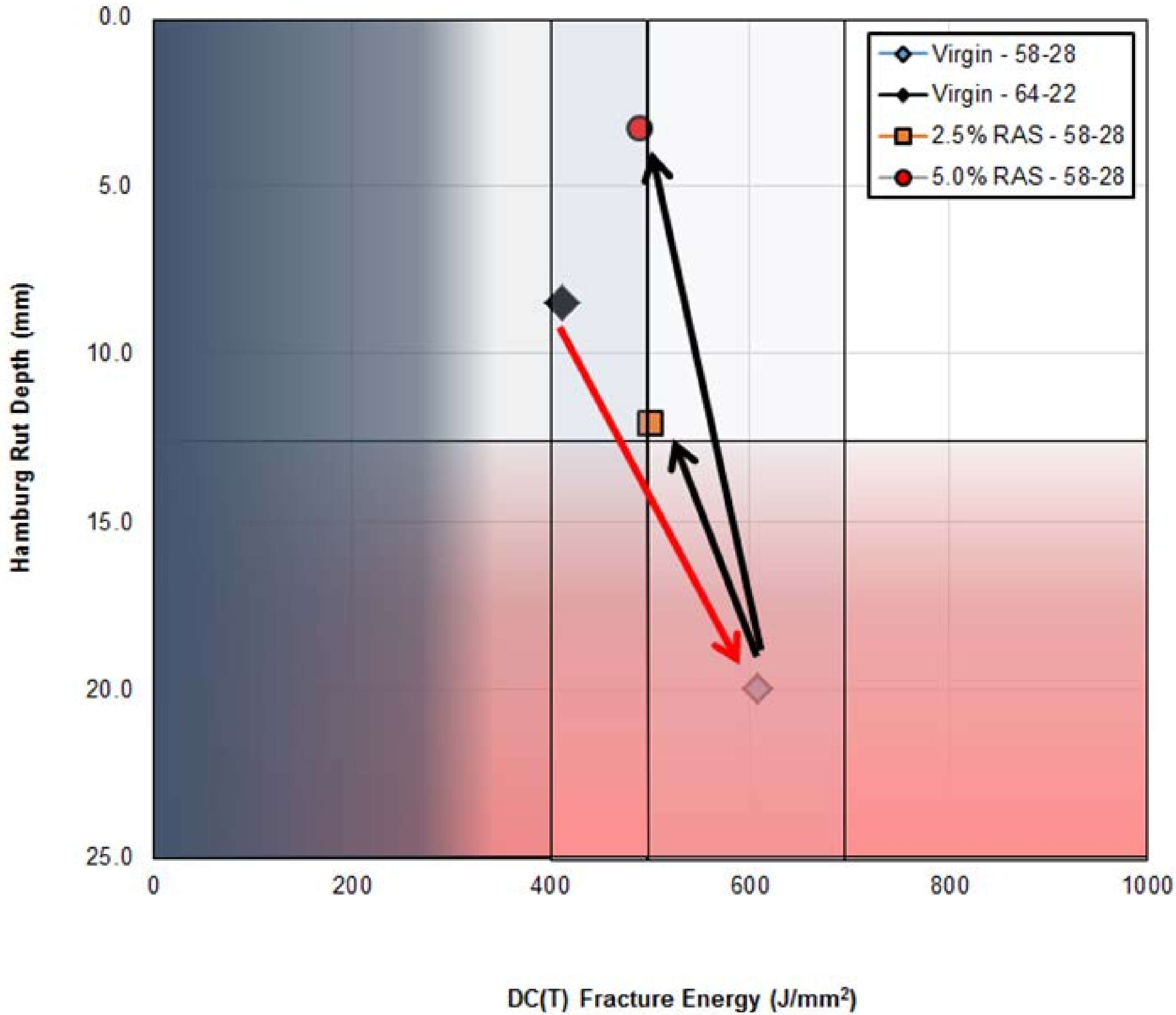
DC(T) Load-CMOD Curves



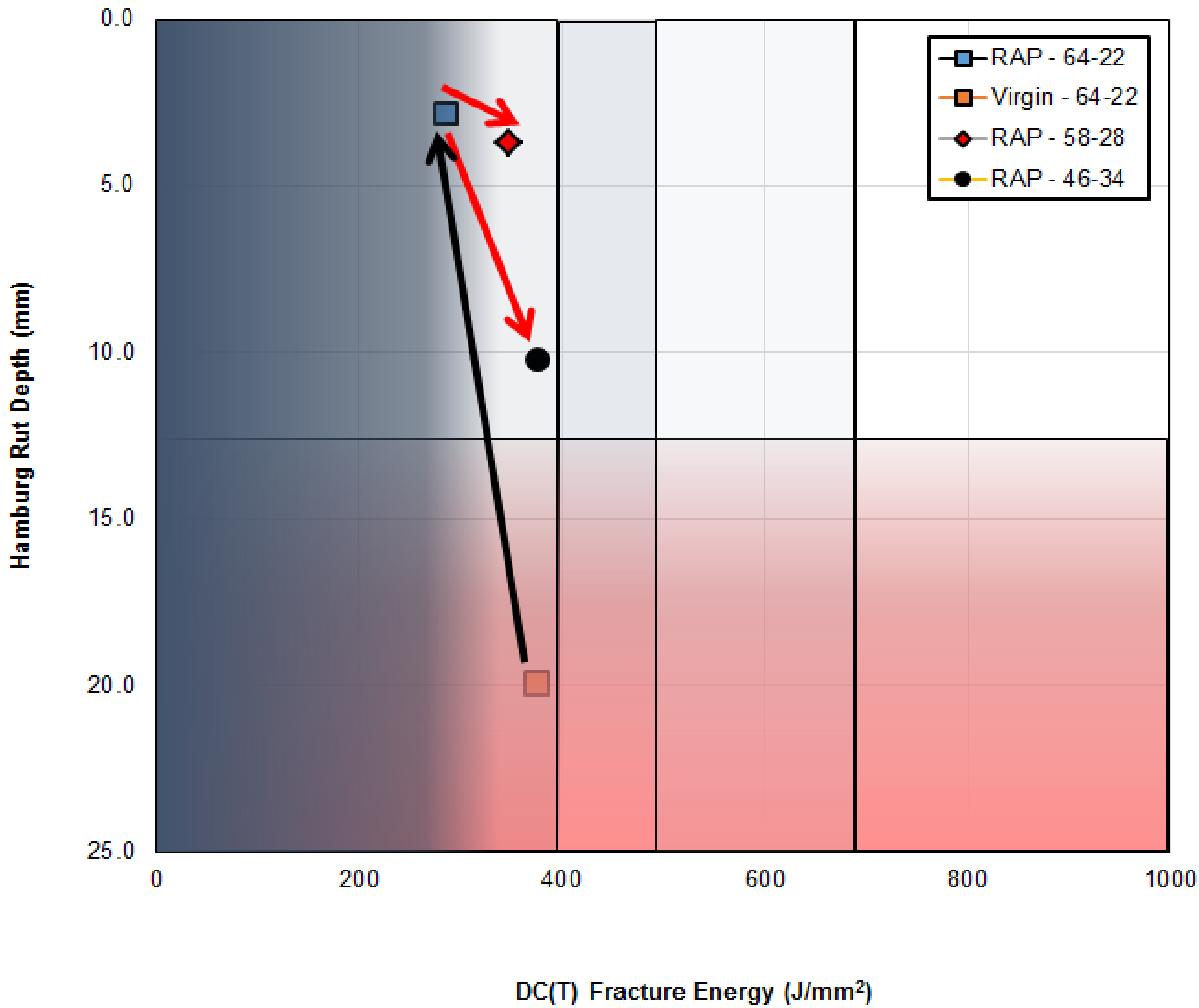
Hamburg-DC(T) Space



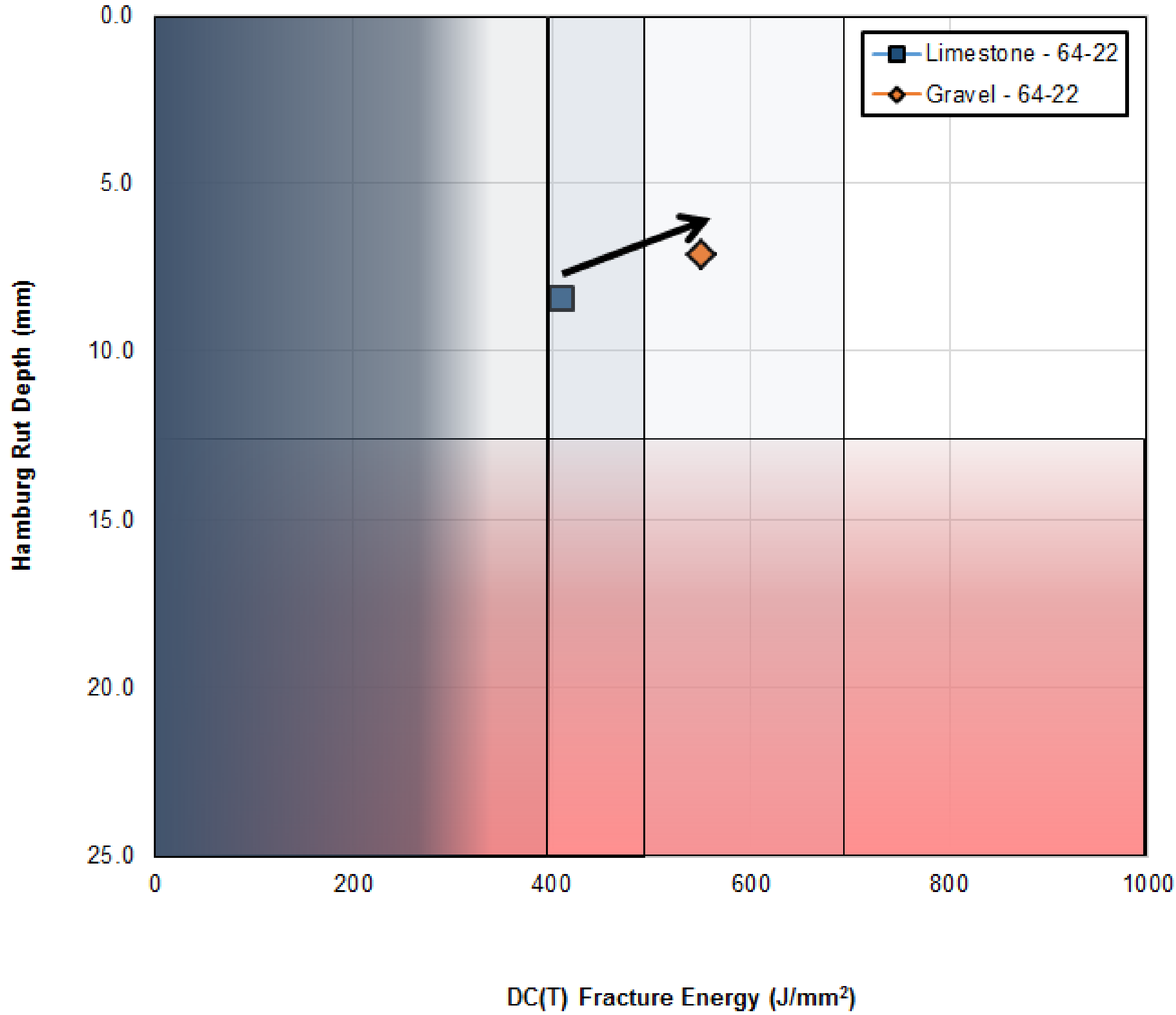
Mix Affects: RAS/Recycling



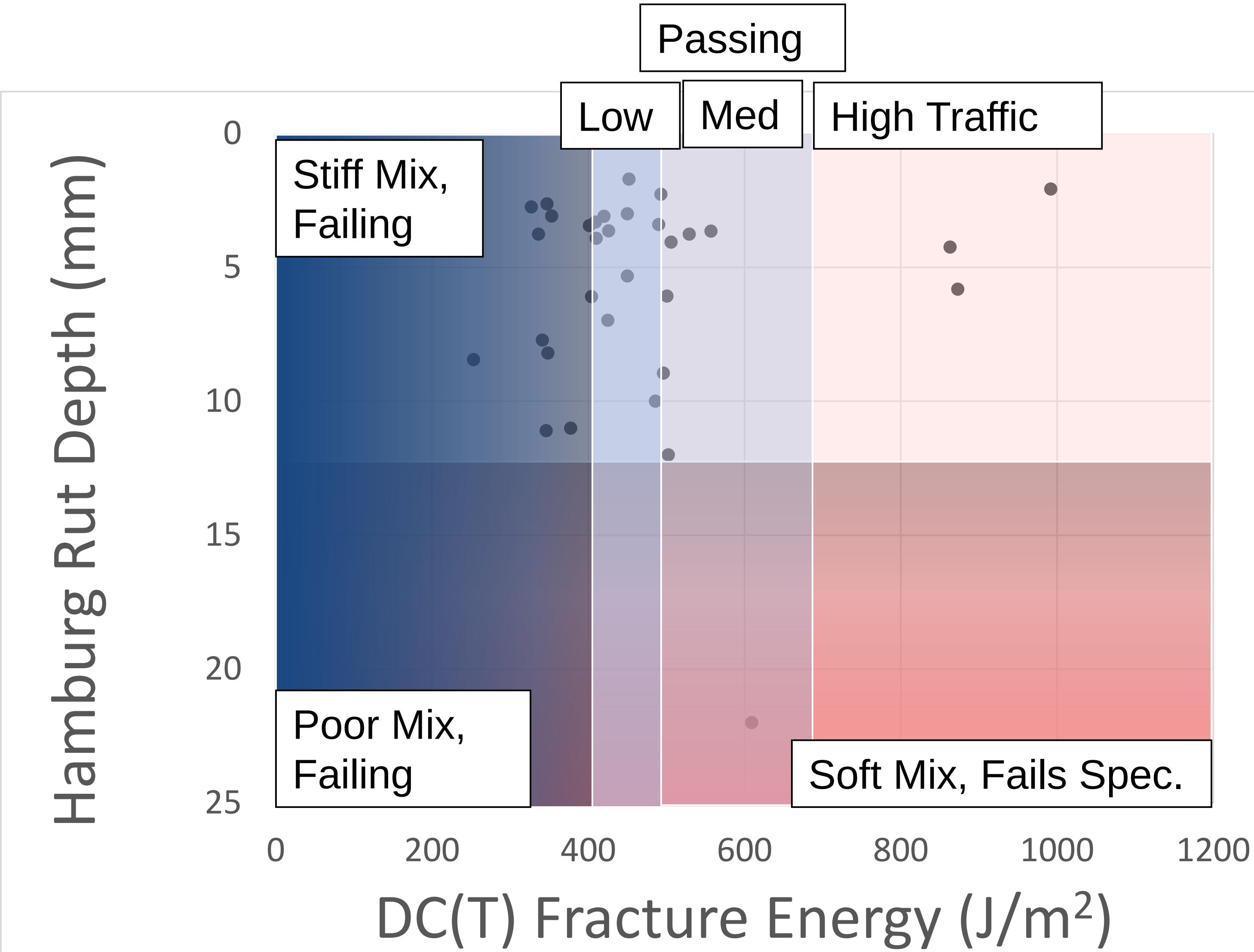
Mix Affects:
RAP/Recycling (45% RAS mixes)



Mix Effects: Stronger Aggregate

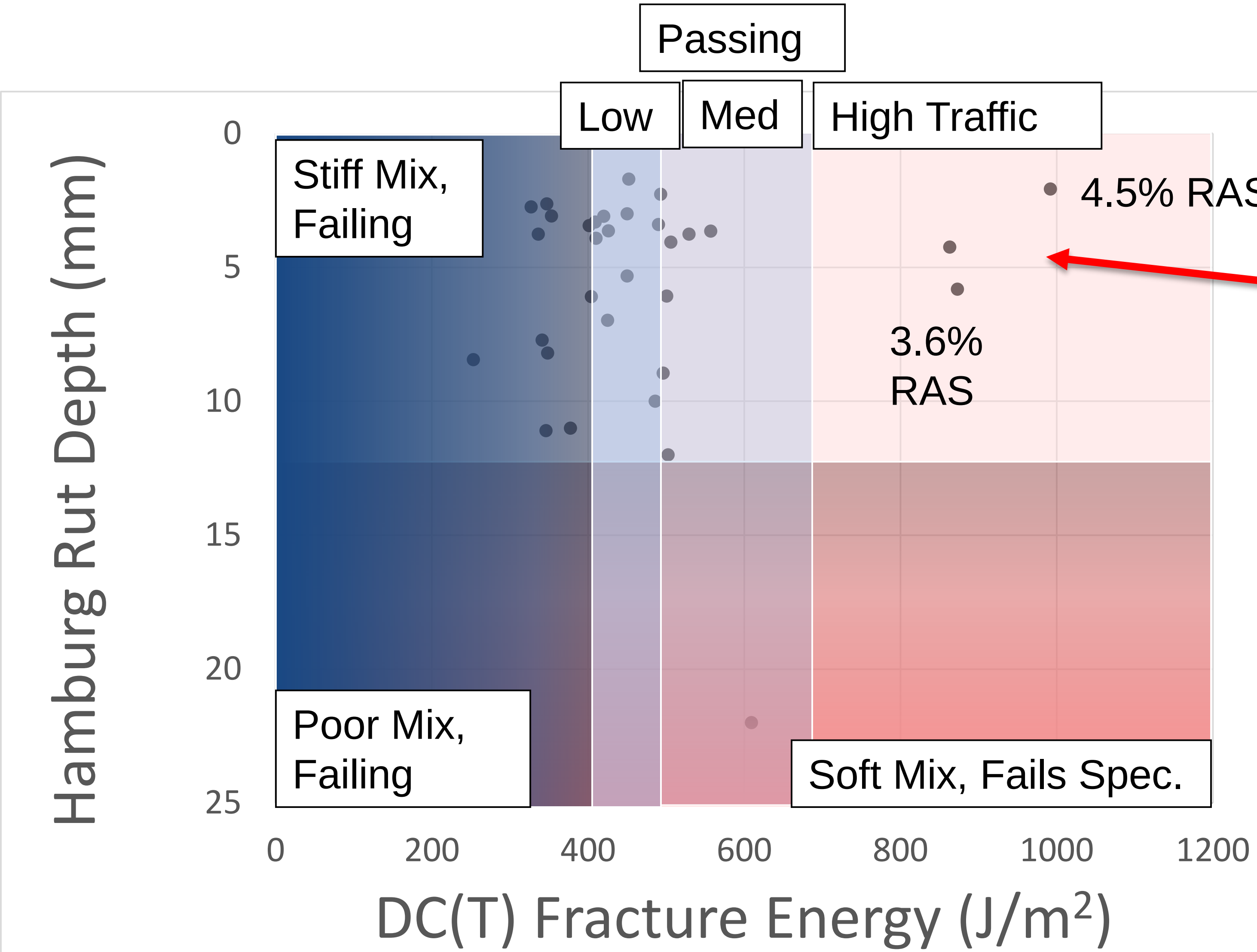


Early Performance-Space Data for Illinois: How are we Doing?



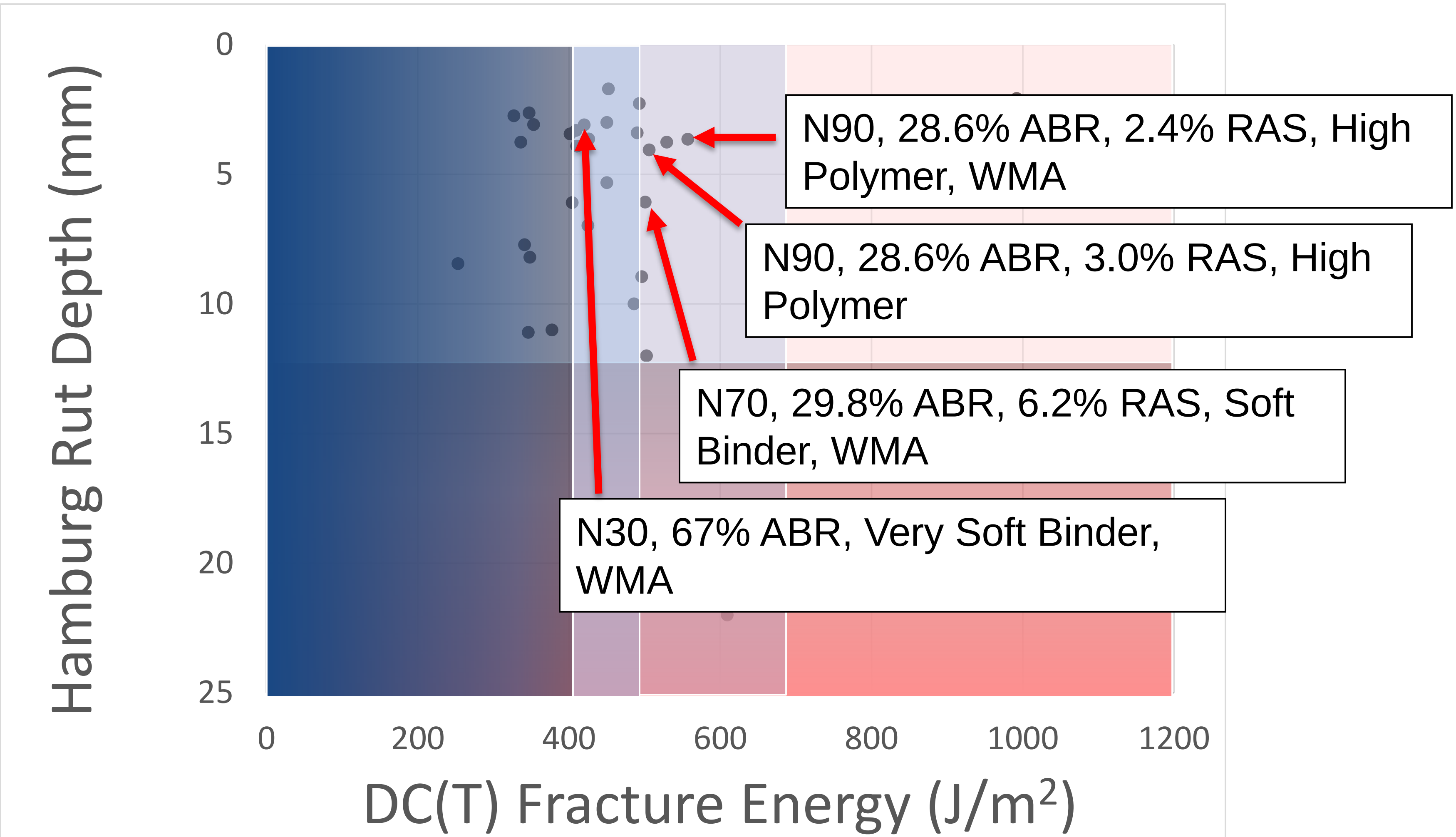
Not surprisingly, tendency towards stiff mixes

SMA's

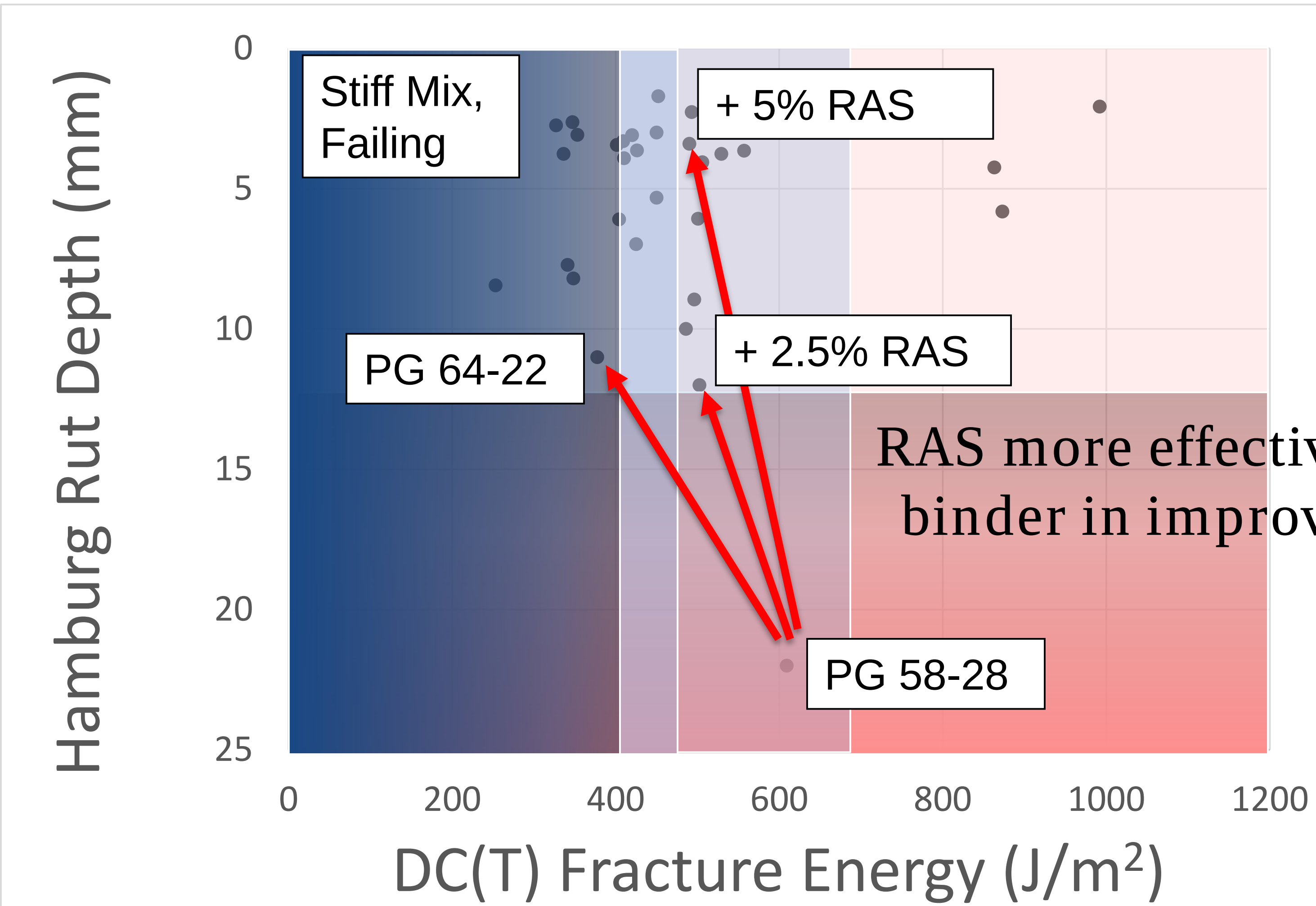


These three mixes are SMA's

High ABR Mixes



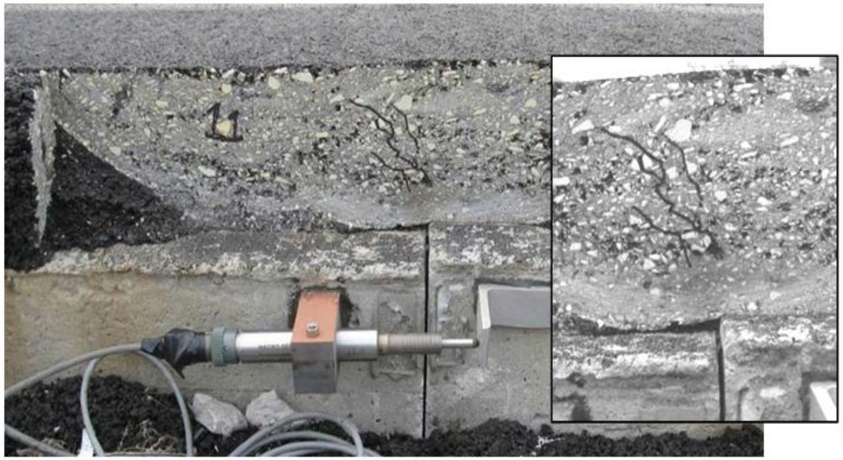
+RAS vs. Harder Binder



RAS more effective than stiffer binder in improving this mix

Ultra-high Fracture Energy Mixes for Reflective Crack Control: ORD 9R Project

Accelerated Pavement Study (ATLAS)



ORD Solution: Ultra-high fracture energy mixtures, 850 - 1,300 J/m^2

Advantages of a Hi – Low Based Spec?

- Asphalt transitions from ductile to quasi-brittle when the binder passes glass transition temperature
  - Usually around PGLT +10C
  - This is why BBR and DC(T) were set at this temperature
  - Easier than PGLT, but captures condition where cracks advance
  - Testing at 25C is in a <u>different response regime</u>
- Depending upon design objective, it may not be necessary to introduce another performance test at intermediate temperatures
  - Reflective cracking, fatigue cracking specs can be developed using DC(T)
  - However, may not be necessary
    - High fracture energy mixes at low temperature correlate to crack resistant mixes at intermediate temperatures
    - Florida study showed top-down cracking controlled by fracture energy
    - Not all pavements will experience traditional fatigue cracking
    - Not all designs should attempt to control reflective cracking

A Means to Relaxing Over-constrained Specs?

- After Bookend Performance Tests are Implemented, Design and Construction Specifications Should be Revisited/Relaxed
- Over-specification can unnecessarily constrain design and innovation space
- With Hamburg + DC(T), the following can be removed/relaxed:
  - Dust-to-Asphalt Ratio, P200 range, sand blend requirements
  - TSR Requirement
  - Design Air Void Target
  - ABR limits

Summary Thoughts

- DC(T) Test has > 10 yrs. in development, validation
  - Developed in 2004, ASTM specified in 2006
  - Fracture Energy is sensitive to many variables: binder type, temperature, specimen size, RAP, RAS, mix type, aggregate strength, air voids
  - Selected in National Pooled Fund Study, strongly correlated to thermal cracking (SCB was not), specification developed
  - Specimen fabrication is well worth the effort: repeatable, meaningful test
  - Other options have drawbacks: beams = cumbersome; other geometries - small fracture area, less repeatable, some only work at higher temps
  - Used in Chicagoland, neighbor states, and supported by Asphalt Institute
- Bracketing performance at high and low temperatures is essential
  - Follows binder specification philosophy
  - Hamburg and DC(T) track one another – simplifies design and innovation
  - Thermal and block cracking - very damaging, time to start mitigating, requires testing <u>mix</u> at <u>low temperature</u>

Recommendations

- The DC(T) is well developed and vetted as a low temperature test – recommended for ‘other bookend’
- Like binder specification, additional tests can be added for intermediate temperature property and performance control, if deemed needed
  - DC(T) device has application in reflective crack control, fatigue and bonding, usually requires different test temperature and rate, and sometimes a modified test mode/geometry
  - Other tests have merit, but <u>must be repeatable and correlated</u>, otherwise their best use is for research
- Once performance is bracketed, some mix design and control parameters can be relaxed to simplify and to avoid over-constraint (dust, voids, ABR)

Thank you for your attention!

Questions?

Acknowledgments

- Road Science LLC, Tulsa, OK
- S.T.A.T.E. Testing, LLC
- Test Quip LLC
- IDOT/Illinois Center for Transportation
- Open Road Asphalt LLC, Fairmont, IL
- Emulsicoat Inc, Urbana, IL
- US RAS Association, Midwest
- Marathon Petroleum Corp.

RAS Binder Availability - Comments

- Performance-based approach for recycled mix design
  - Use standard mix design principles w/ performance testing as alternative to AASHTO PP78-14 (Hamburg + DC(T))
  - What other mix design parameters can be relaxed in light of performance tests?
- RAS binder is stiff, but it is still binder and not aggregate. Facilitates compaction, physically resides in ‘V’ part of VMA; savvy designers use to boost performance. Ditto for RAP.
- Mix performance tests present best chance for effects of partial blending (PB) – don’t assume PB is detrimental, after all, advanced composites draw strength from diversity of material properties!
- Standard (uncompromised) volumetric techniques, including 100% available binder for calculations, plus performance tests should be permitted for RAP/RAS mix designs.

Summary

- DC(T) has evolved over past 11 years as a simple, repeatable, standardized, commercially-available, scientifically-vetted, low-temperature cracking test linked to cracking performance
- Hamburg + DC(T) = Stability + Crack Resistance
  - Combined use is the ticket towards higher sustainability without sacrificing quality
  - Already in use in Minnesota, Iowa, Wisconsin, Chicagoland, and elsewhere
  - Performance-Space Diagram gives mix designers and binder formulators considerable insight and adjustment capability; a powerful tool critically needed for modern mixes, performance-based mix designs
- Standard (uncompromised) volumetric techniques, including 100% available binder for calculations, plus performance tests should be permitted for RAP/RAS mix designs. Relaxing other parameters in light of performance specs should be considered to allow innovation, cost savings and enhanced sustainability.

RAS and Performance Testing

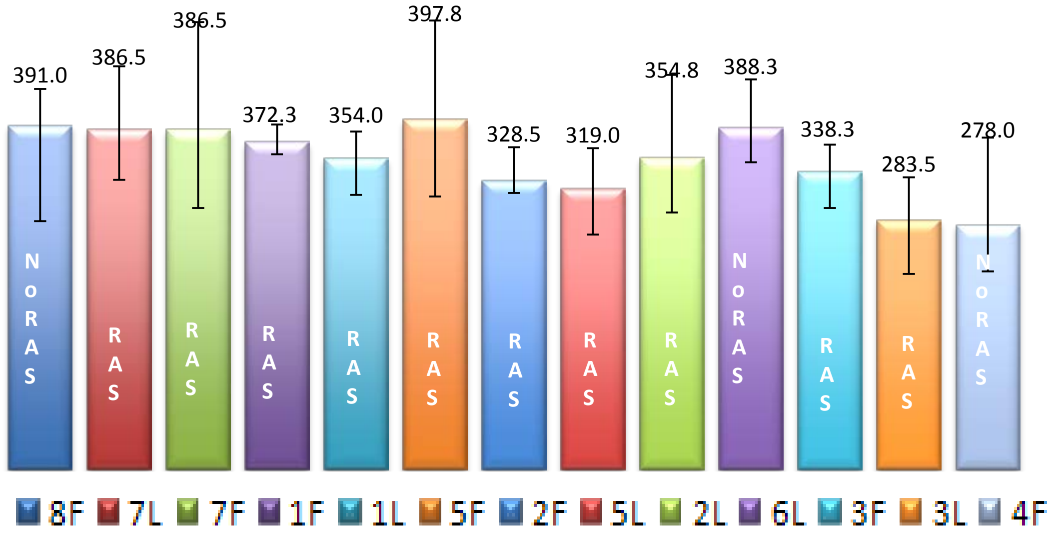
Investigation of Tollway Shoulder Mixes (AAPT 2011)

Table 7. DC(T) Results

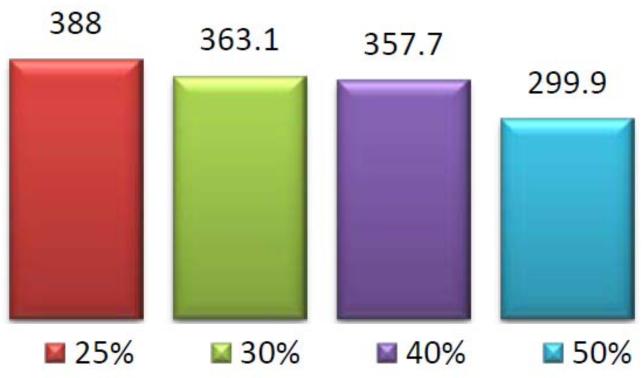
Specimen	*RAP %*	*RAS %*	*Peak Load (kN)*	*CMOD G_f*	*COV CMOD G_f*	*Delta 25 G_f*	*COV Delta 25 G_f*
4 Field	50	0	3.001	278.0	24.7%	180.5	21.9%
3 Lab	45	5	3.178	283.5	16.1%	177.0	16.4%
5 Lab	35	5	2.790	319.0	13.1%	215.3	20.0%
2 Field	35	5	3.240	328.5	7.6%	209.0	7.3%
3 Field	45	5	3.268	338.3	9.6%	220.1	9.0%
1 Lab	25	5	2.995	354.0	8.5%	227.4	10.2%
2 Lab	35	5	3.009	354.8	20.4%	237.3	21.3%
1 Field	25	5	2.905	372.3	4.0%	242.6	3.4%
7 Lab	20	5	2.887	386.5	14.8%	247.6	14.6%
7 Field	20	5	2.746	386.5	25.1%	222.3	18.0%
6 Lab	40	0	3.030	388.3	11.8%	244.4	11.6%
8 Field	25	0	2.477	391.0	18.6%	252.3	23.3%
5 Field	35	5	3.012	397.8	20.9%	251.5	20.5%

Virgin PG Binder Grade of PG 58-22 Used on All Sections

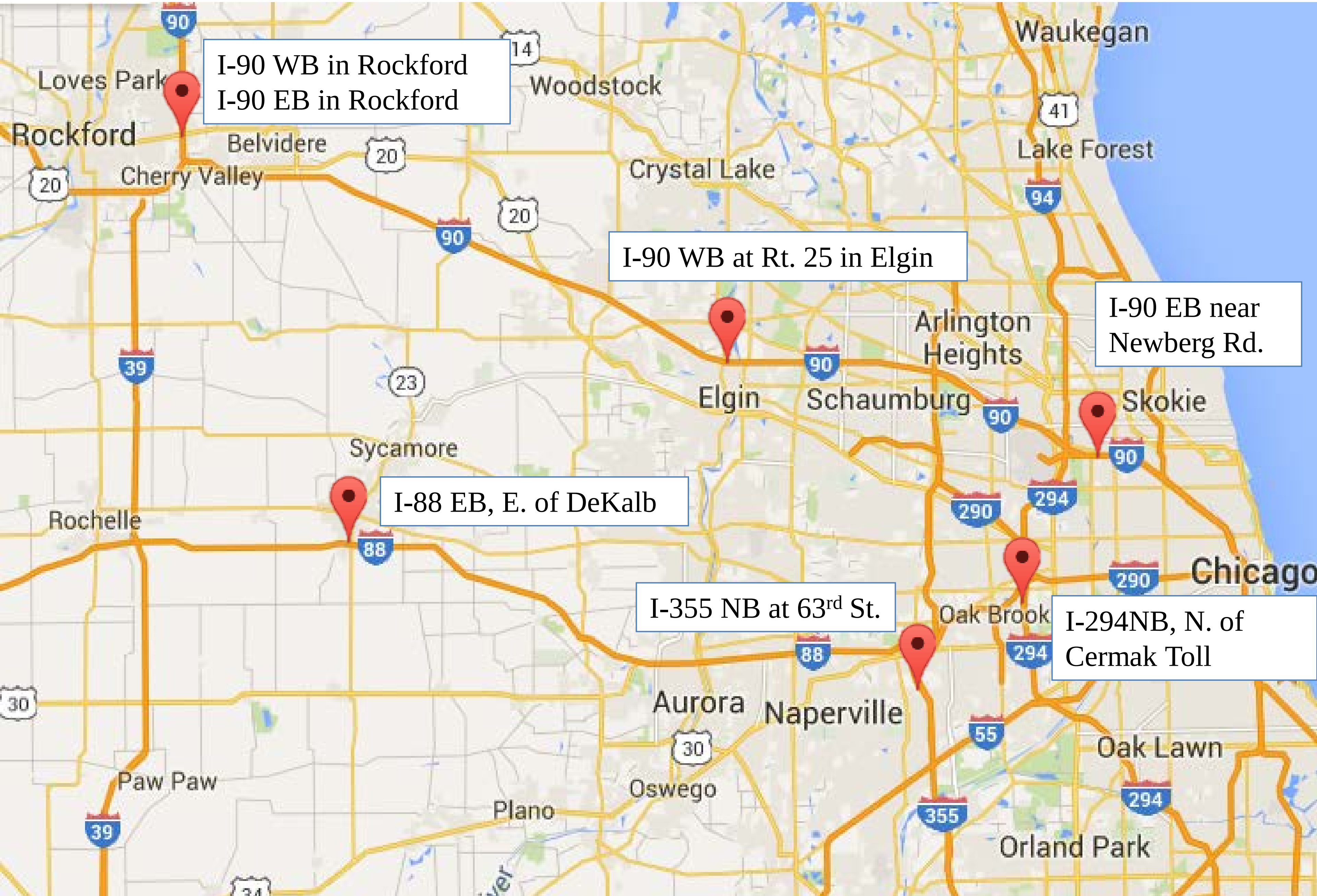
Investigation of Tollway Shoulder Mixes (AAPT 2011)



Averaged Results, by Asphalt Binder Replacement (ABR)

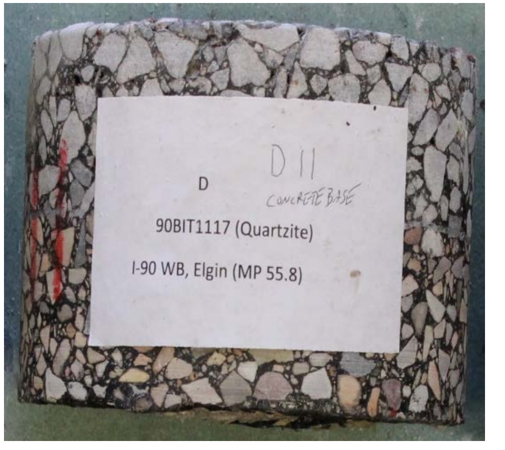


Illinois Tollway High ABR Performance Testing

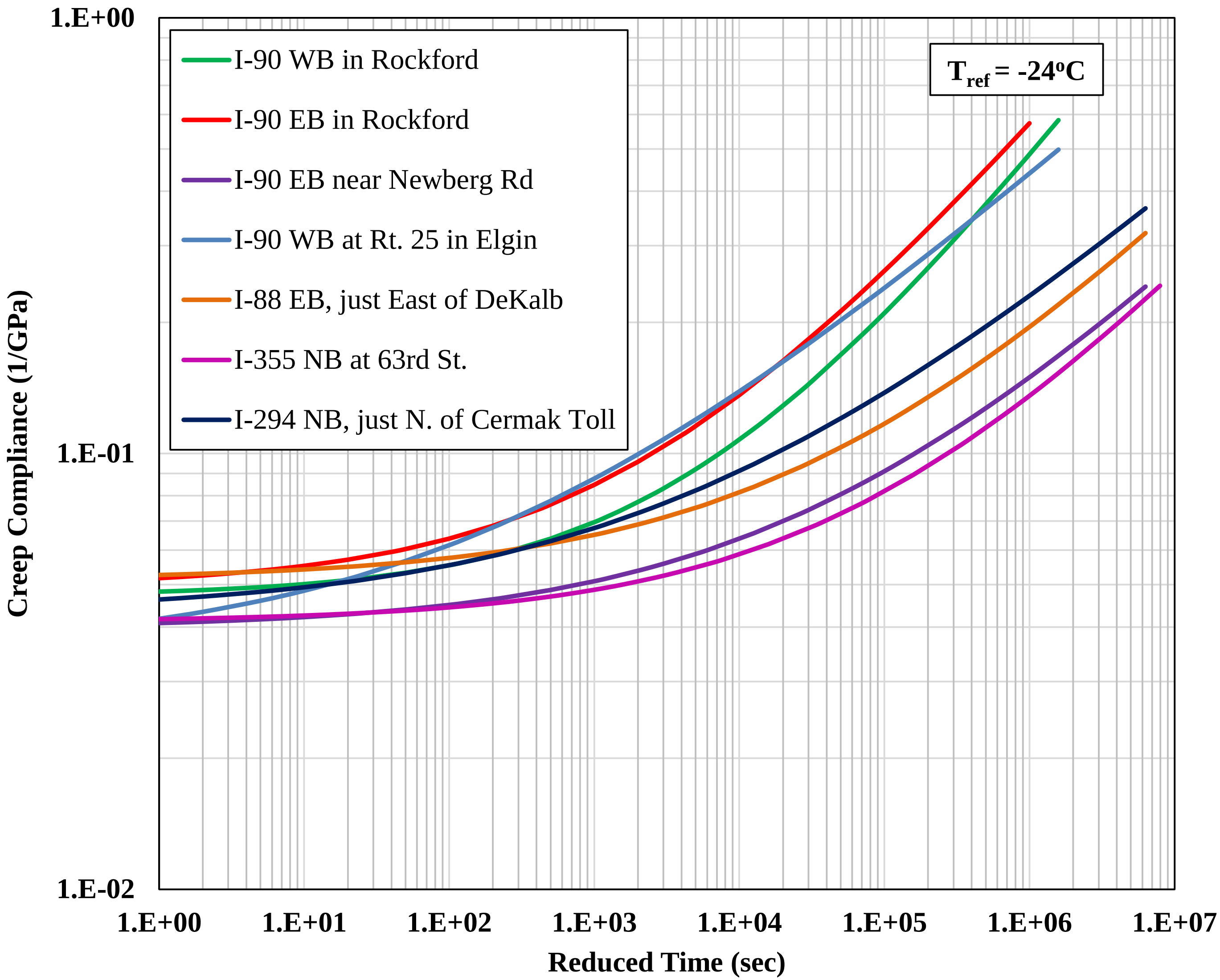


RAS Section - 2011

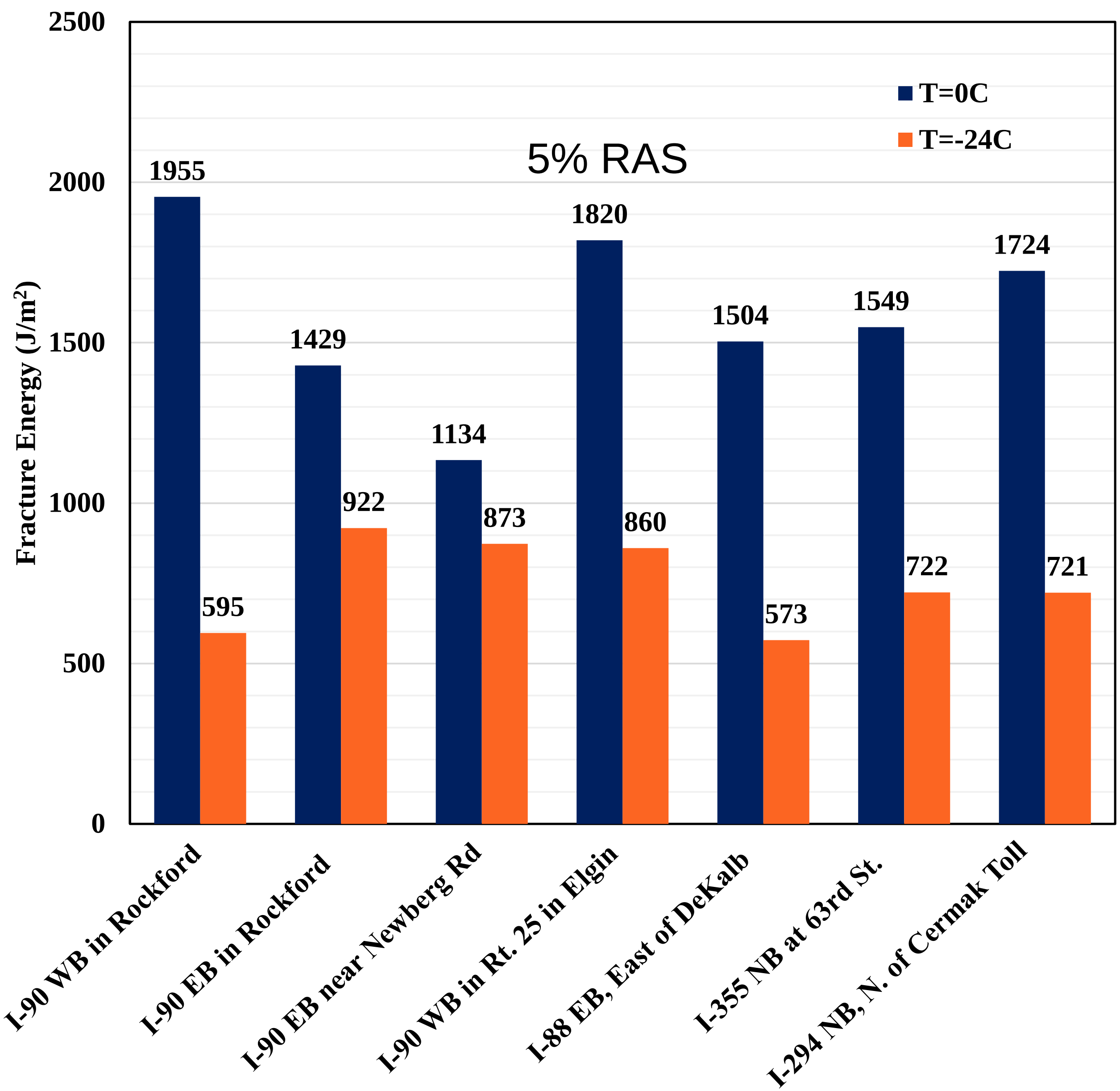
- Section D
  - Location: I-90 WB Elgin
  - Year Placed: 2011
  - Asphalt Binder: PG 70-28 SBS
  - ABR: 33% (5% RAS)
  - Aggregate: Quartzite



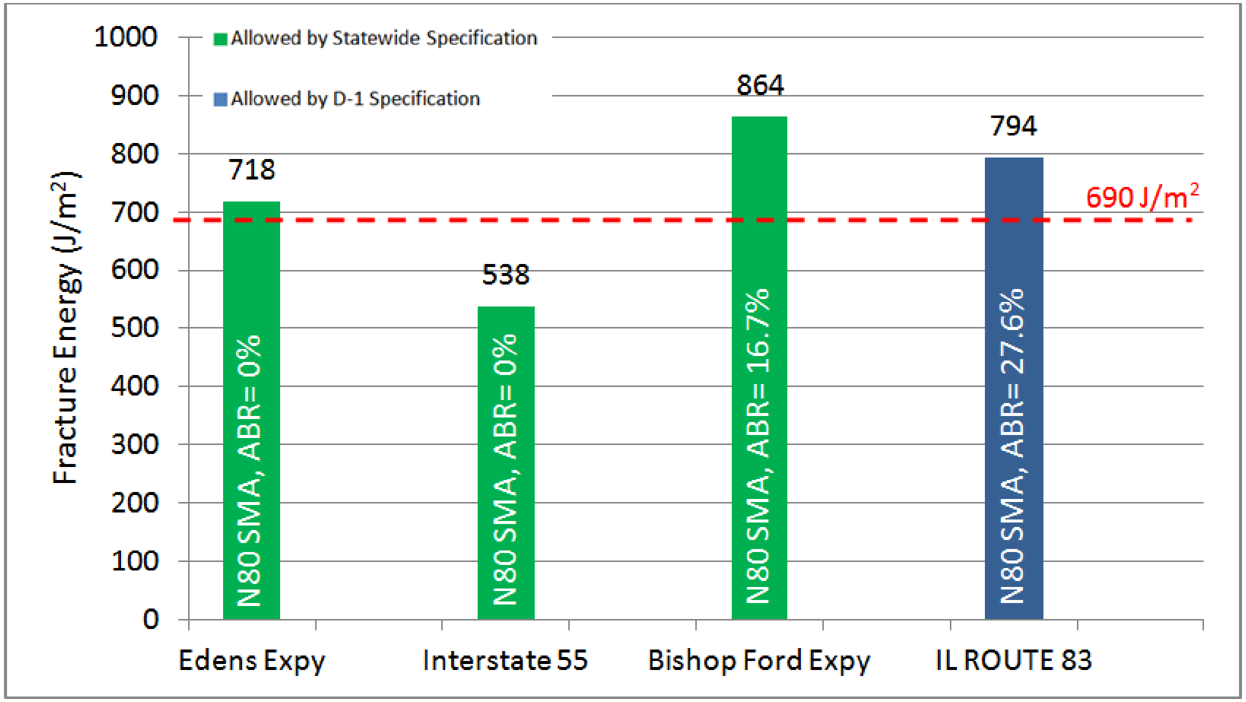
Creep Compliance (Higher = Better)
RAS Section = I-90 WB (Light Blue)



Fracture Energy Results (Non-Standard Test Temps)



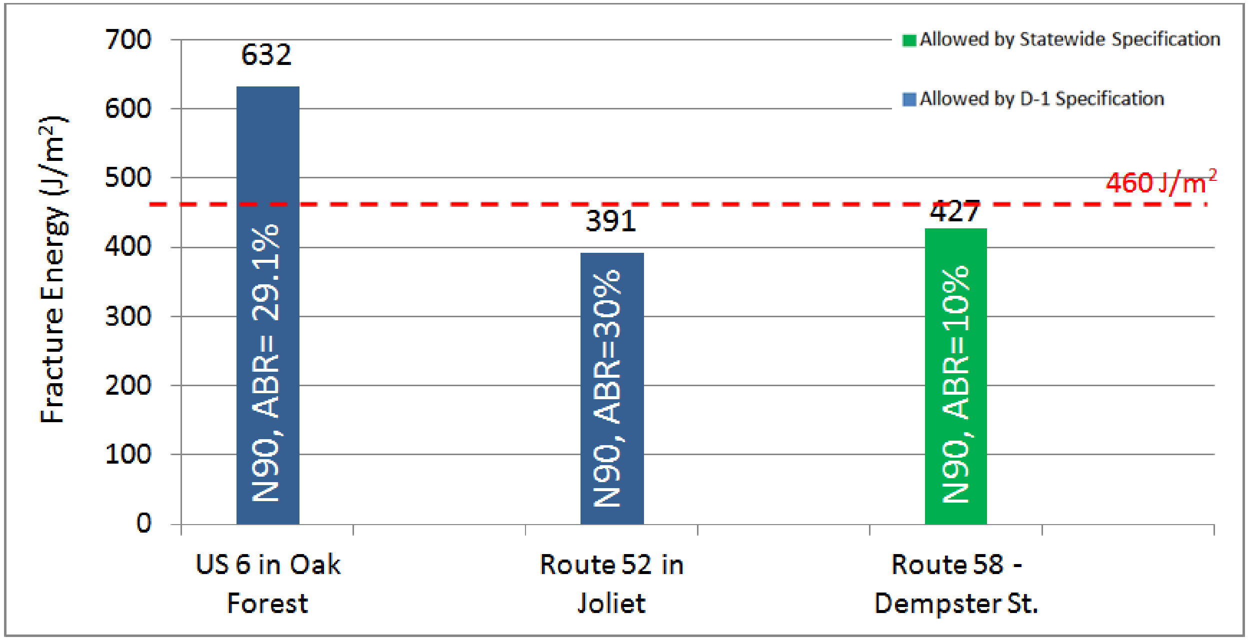
Chicagoland High ABR Forensic Investigation SMA Mixes



0% RAS 0% RAS 5% RAS 3.1% RAS

SMAs can meet the most stringent standards when designed correctly

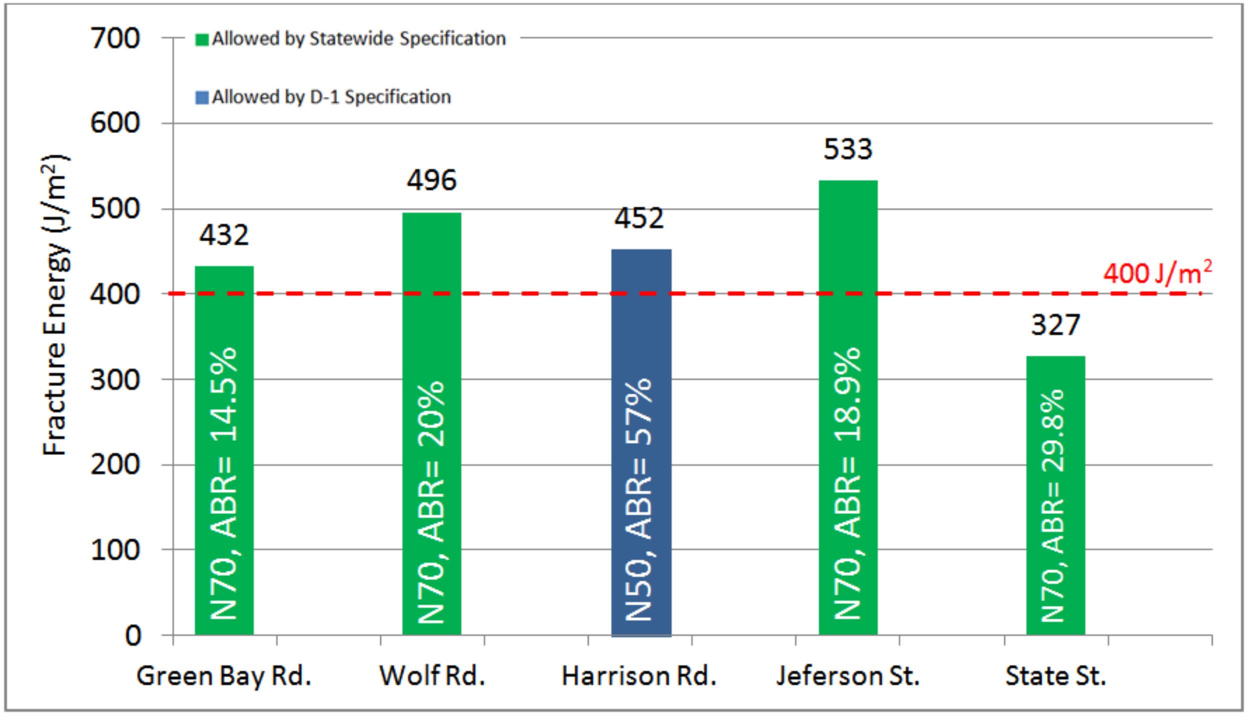
Chicagoland High ABR Forensic Investigation N90 Mixes



5% RAS 2.4% RAS 0% RAS

Highest Fracture Energy in this Category was a Higher ABR Mix

Chicagoland High ABR Forensic Investigation N50/N70 Mixes

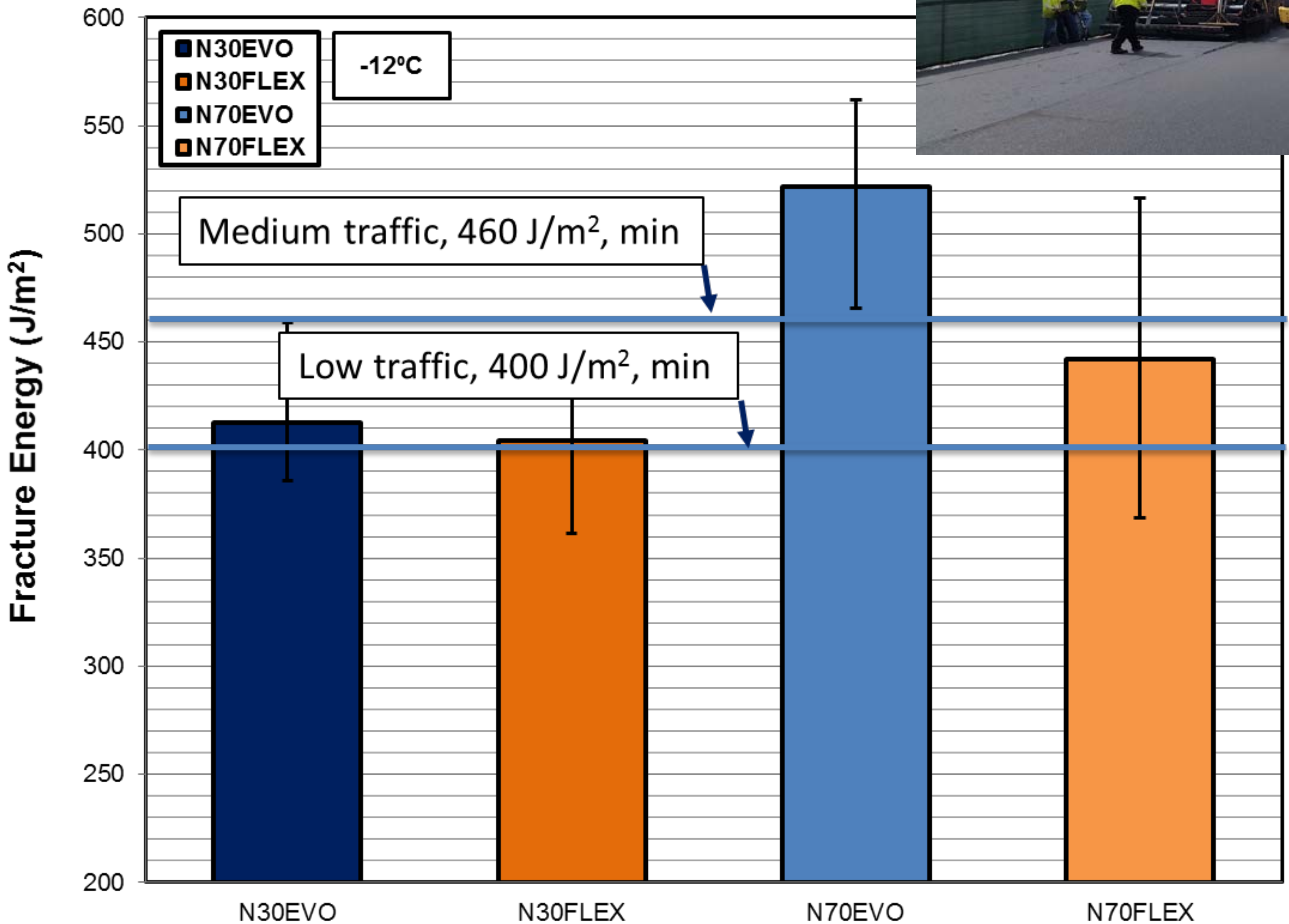


0% RAS 0% RAS 5% RAS 0% RAS 2.5% RAS

The Highest ABR Mix Met the Fracture Energy Recommended Level

Overall:3-of-4 Mixes Using the D1 Specification Met DC(T) Criteria

Grand Ave Study
Spring 2015



66.5% ABR (7.5% RAS)
3% Design Voids

50% ABR (5.0% RAS)
3.5% Design Voids

What about Other Cracking Tests?

- IDT Creep, Strength – from SHRP - research tool ($, complex)
- TX OLT – Highly variable – research tool
- 4-PT Bend – from 1960's – variable, complex – research tool
- SCB – since 1980's – simple, small fracture area – variable?

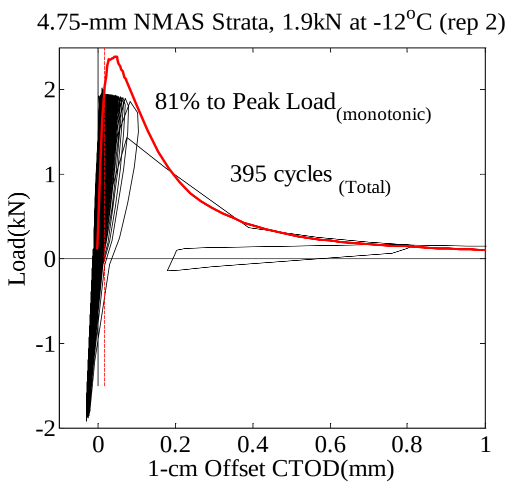
Grand Ave Study (2015)

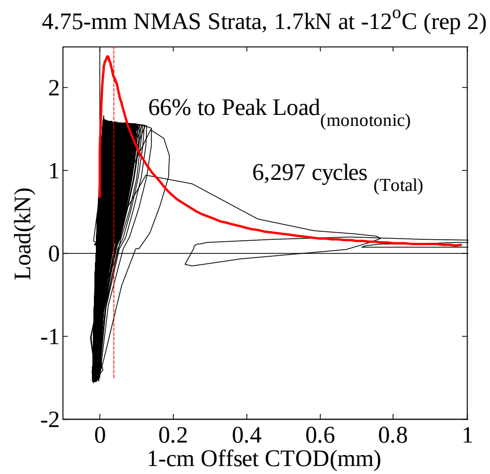
Specimen ID	DC(T) Results (-12C)			SCB Results (25C)		
	CMOD G_f (J/m^2)	Avg. CMOD G_f (J/m^2)	CMOD G_f COV (%)	Flexibility Index	Avg. FI	FI COV (%)
N30EVO	385.6	412.8	9.8	4.6	3.4	29.7
	393.6			2.7		
	459.1			3.0		
N30FLEX	361.5	404.1	9.1	1.4	1.2	56.4
	427.0			1.7		
	423.9			0.4		
N70EVO	538.3	521.8	9.6	6.4	6.2	4.3
	561.8			6.2		
	465.4			5.9		
N70FLEX	368.6	442.2	16.7	2.9	2.8	14.9
	516.3			3.2		
	441.7			2.4		
		Average	11.8		Average	26.3

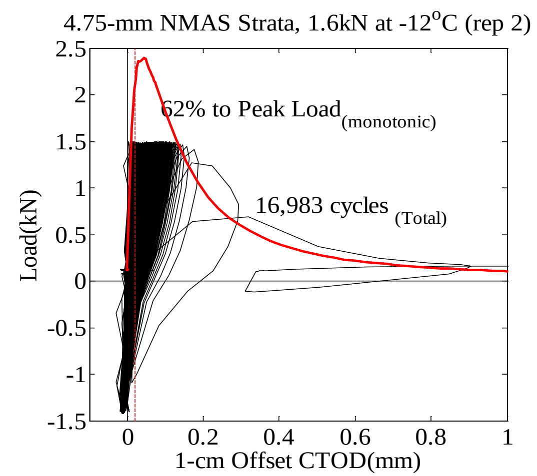
Cyclic DC(T): (-12°C)

Cyclic cracking related to DC(T) Fracture Energy

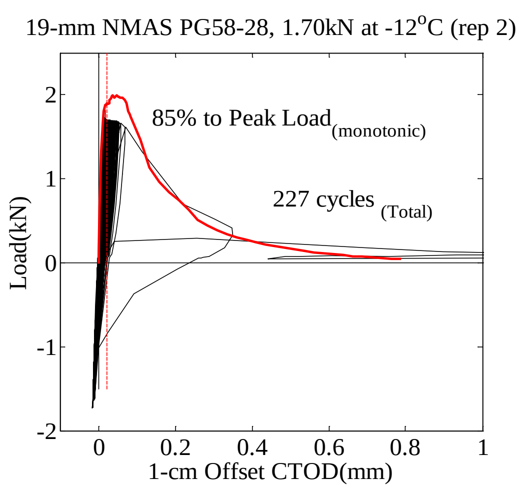
Aged 4.75mm Mix

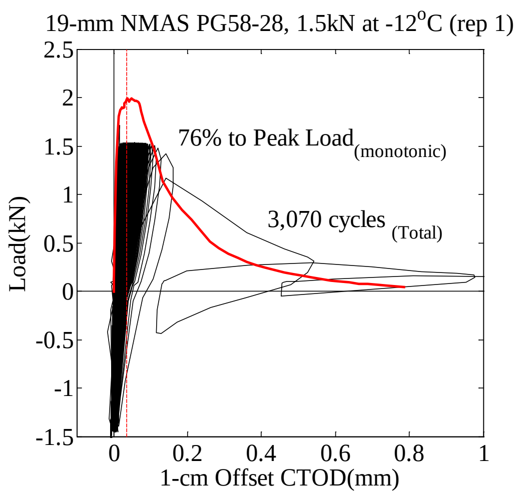


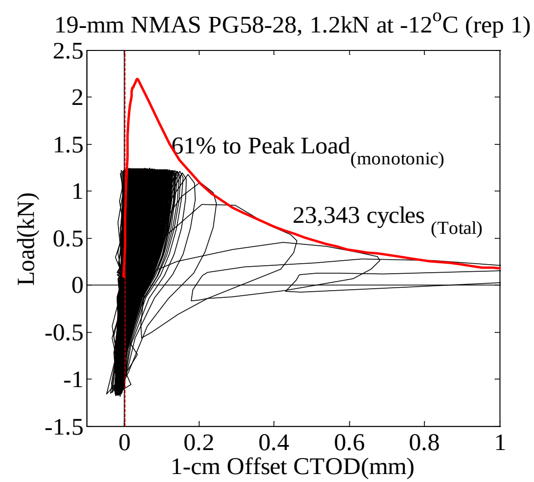




PG58-28 Mix







RAS Binder Availability Study

- Hold volumetrics constant for fair comparison
- Evaluate partial vs. full binder blending effects
- Evaluate RAS effects on performance-space diagram
- Explore performance-based approach for recycled mix design
  - Use of standard mix design principles w/ performance testing as alternative to AASHTO PP78-14

Mixture Designs

Volumetric Property	Mixture		
	Virgin	2.5% RAS	5.0% RAS
Total Asphalt Content (%)	6.6	6.6	6.6
ABR (%)	0.0	10.6	21.2
Air Voids (%)	4.0	4.0	4.0
VMA (%)	15.2	15.3	15.2
VFA (%)	74.0	73.8	73.7
Effective Asphalt Content (%)	4.9	4.9	4.9
Dust/Total AC	0.8	1.0	1.3
Dust/Effective AC	1.1	1.3	1.7

Designs – Assuming 85% Available

Volumetrics (85% Availability)	Mixture		
	Virgin	2.5% RAS	5.0% RAS
Total Asphalt Content (%)	6.6	6.5	6.4
ABR (%)	0.0	9.2	18.4
Air Voids (%)	4.0	4.0	4.0
VMA (%)	15.2	15.2	15.0
VFA (%)	74.0	73.7	73.3
Effective Asphalt Content (%)	4.9	4.9	4.7
Dust/Total AC	0.8	1.0	1.3
Dust/Effective AC	1.1	1.3	1.8

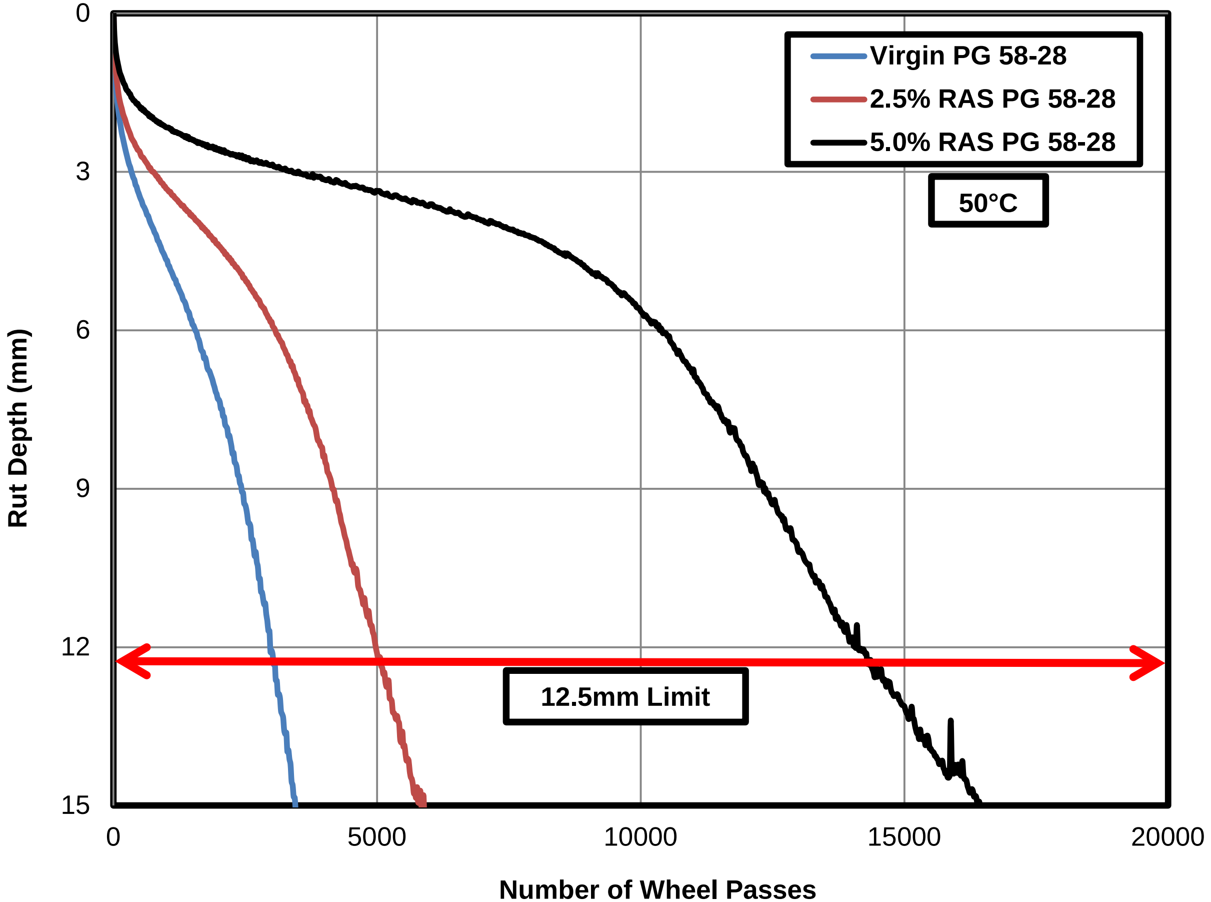
Designs – Assuming 70% Available

Volumetrics (70% Availability)	Mixture		
	Virgin	**2.5% RAS**	**5.0% RAS**
Total Asphalt Content (%)	**6.6**	**6.4**	**6.2**
ABR (%)	**0.0**	**7.6**	**15.2**
Air Voids (%)	**4.0**	**4.0**	**4.0**
VMA (%)	**15.2**	**15.1**	**14.8**
VFA (%)	**74.0**	**73.5**	**73.0**
Effective Asphalt Content (%)	**4.9**	**4.9**	**4.5**
Dust/Total AC	**0.8**	**1.0**	**1.4**
Dust/Effective AC	**1.1**	**1.3**	**1.9**

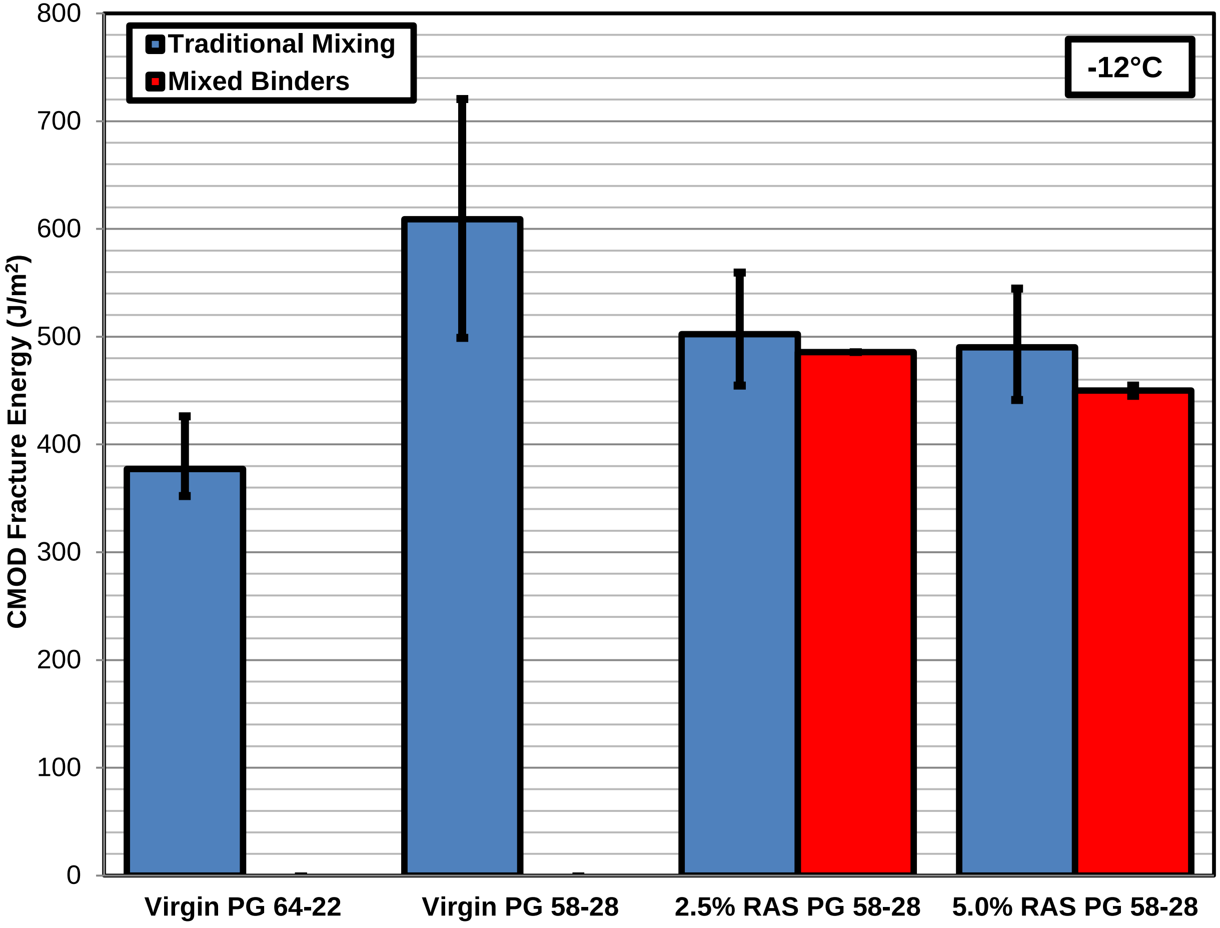
Hamburg Results

Mixture	No. of Passes to Failure (12.5mm)	Required No. of Passes	Pass/Fail
Virgin PG 58-28	3030	5000	**Fail**
Virgin PG 64-22	5860	7500	**Fail**
2.5% RAS PG 58-28	5110	5000	**Pass**
5.0% RAS PG 58-28	14430	7500	**Pass**

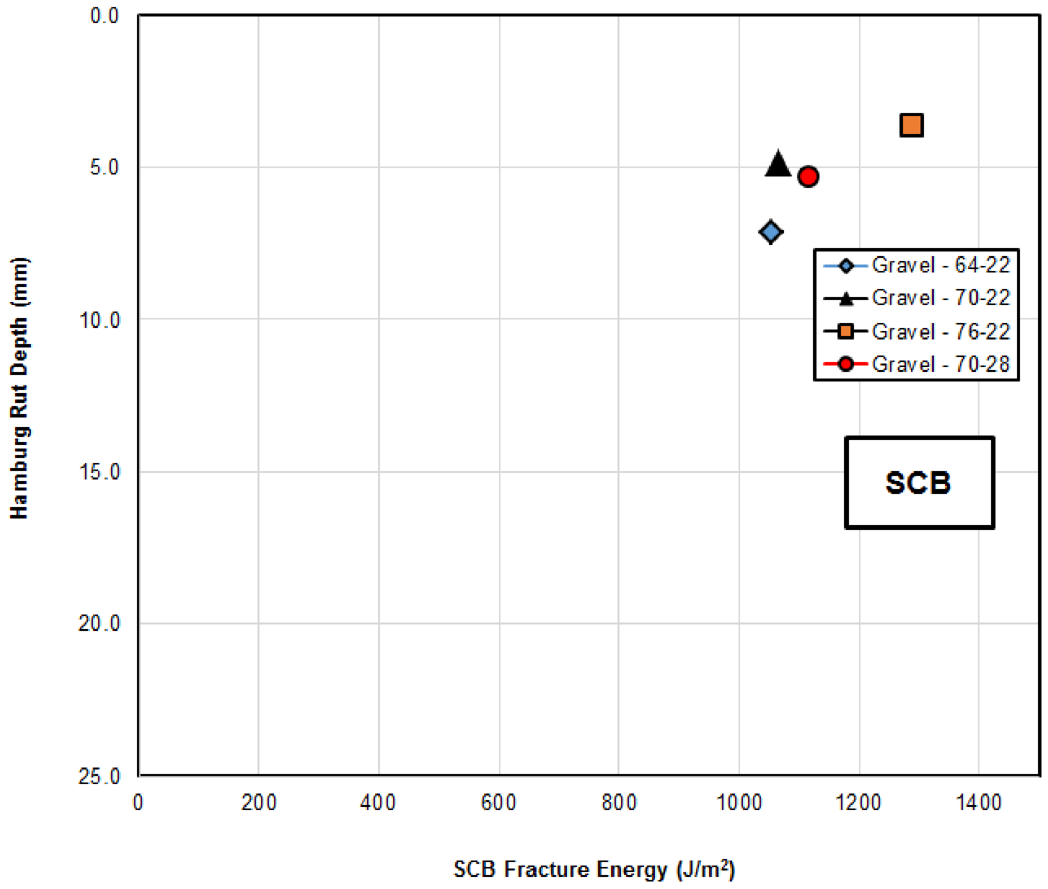
Hamburg Results



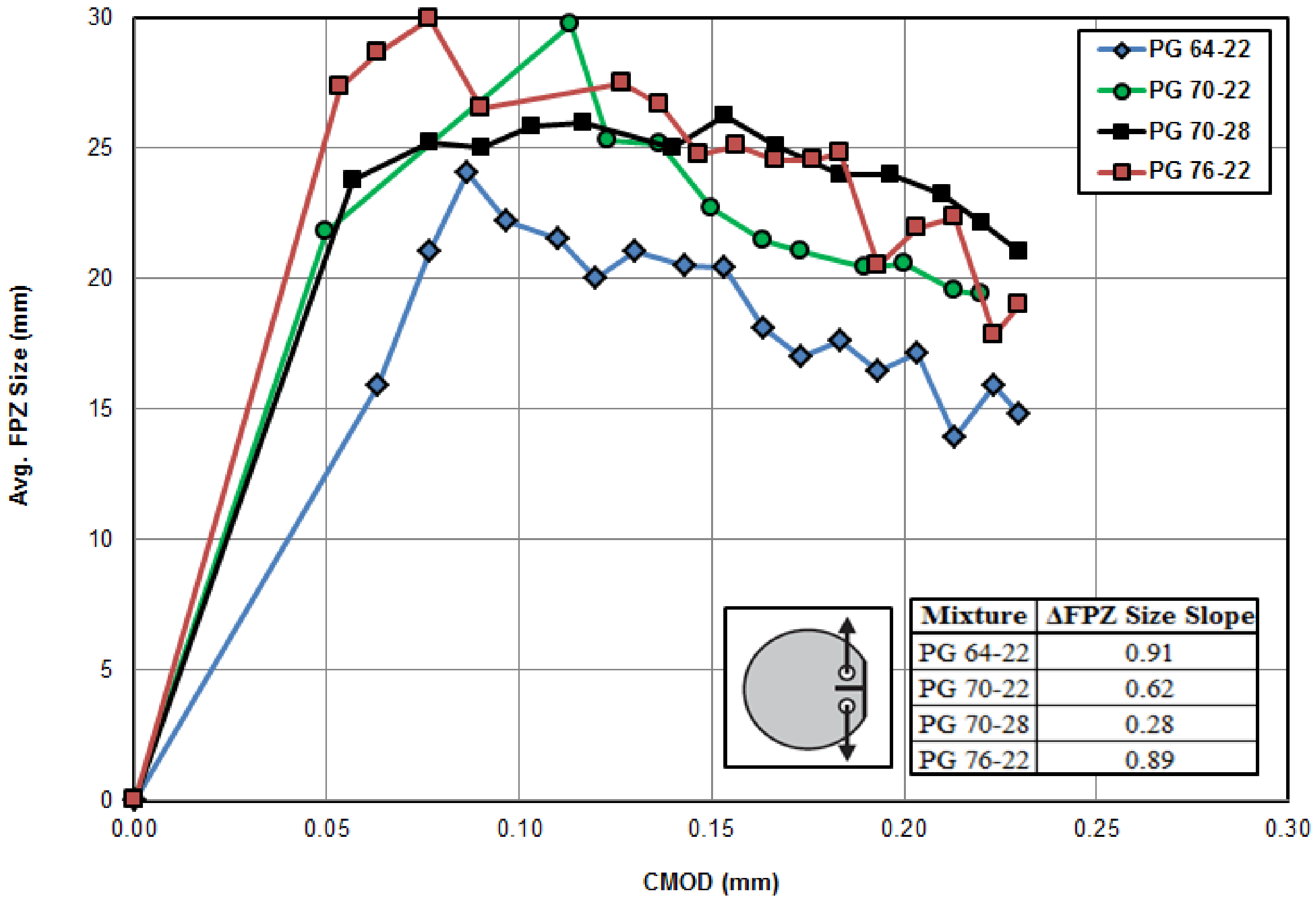
DC(T) Results


Traditional Mixing
Mixed Binders
-12°C
CMOD Fracture Energy (J/m²)
0
100
200
300
400
500
600
700
800
Virgin PG 64-22
Virgin PG 58-28
2.5% RAS PG 58-28
5.0% RAS PG 58-28

Hamburg-SCB (-12C) Plot



FPZ Size Evaluation



Mixture	ΔFPZ Size Slope
PG 64-22	0.91
PG 70-22	0.62
PG 70-28	0.28
PG 76-22	0.89

FPZ Size Evaluation