# Stability with Crack-Resistance in Modern Mixes: Performance-Based Mix Design

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**April 8, 2015**

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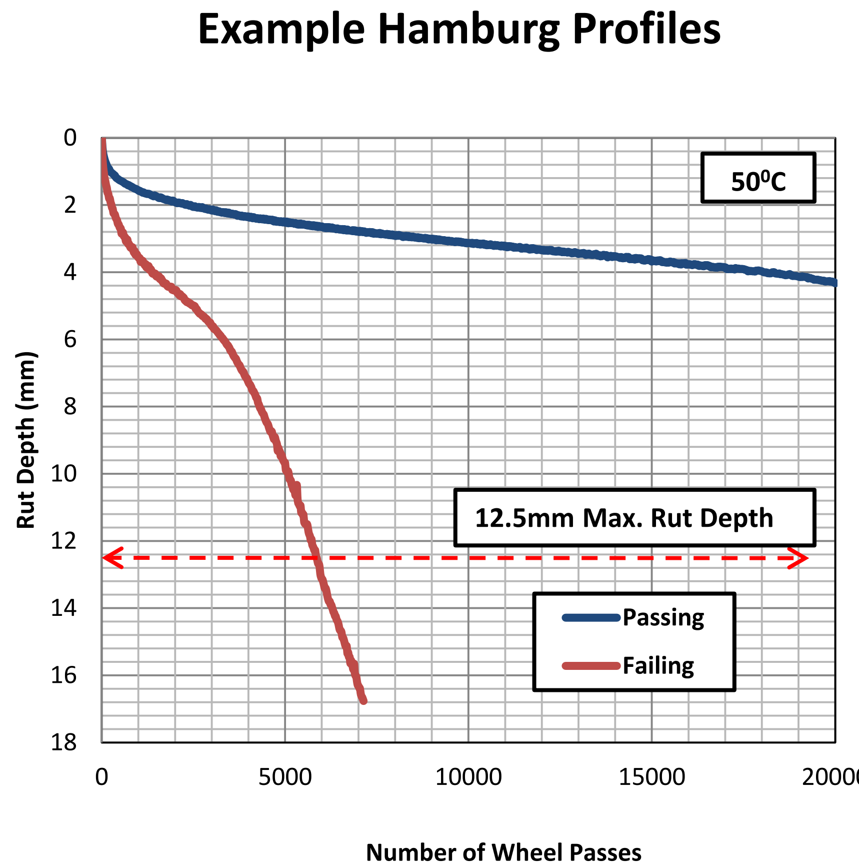
# Rutting – Under Control w/ Hamburg Rut Test ......



# ....Cracking....not so much.....

- If its not durable, it's probably not sustainable

# Low-Temperature Test Evolution

Manual (Eyeball) Tests, Difficult Temperature Control

Penetration/Frass Binder Tests
(1880's-)
[PEN Grading]

→

Shell, Canadian Research, Mix Stiffness (1950's-1980's)
[AC, AR Visc. Grading, PI, VTS]

Basic Electronics and Mechanical Tests, Better Temperature Control to Low Temps

↓

Digital DAQ, Precise Low-Temp Control, Advanced Field Instrumentation, 3D Linear FEM (Adv. Mix tests costly)

Superpave PG Binder Tests and Spec., IDT Creep, Strength, TCMODEL, MEPDG, MnRoad Field Obs. (1990's)
[Superpave Binders, Polymers]

→

NSF GOALI RC Study, APT RC Study, DC(T), SCB, Pooled Fund LTC Study, ASTM D7313, RILEM CAP and MCD (2000's)
[RAP, WMA]

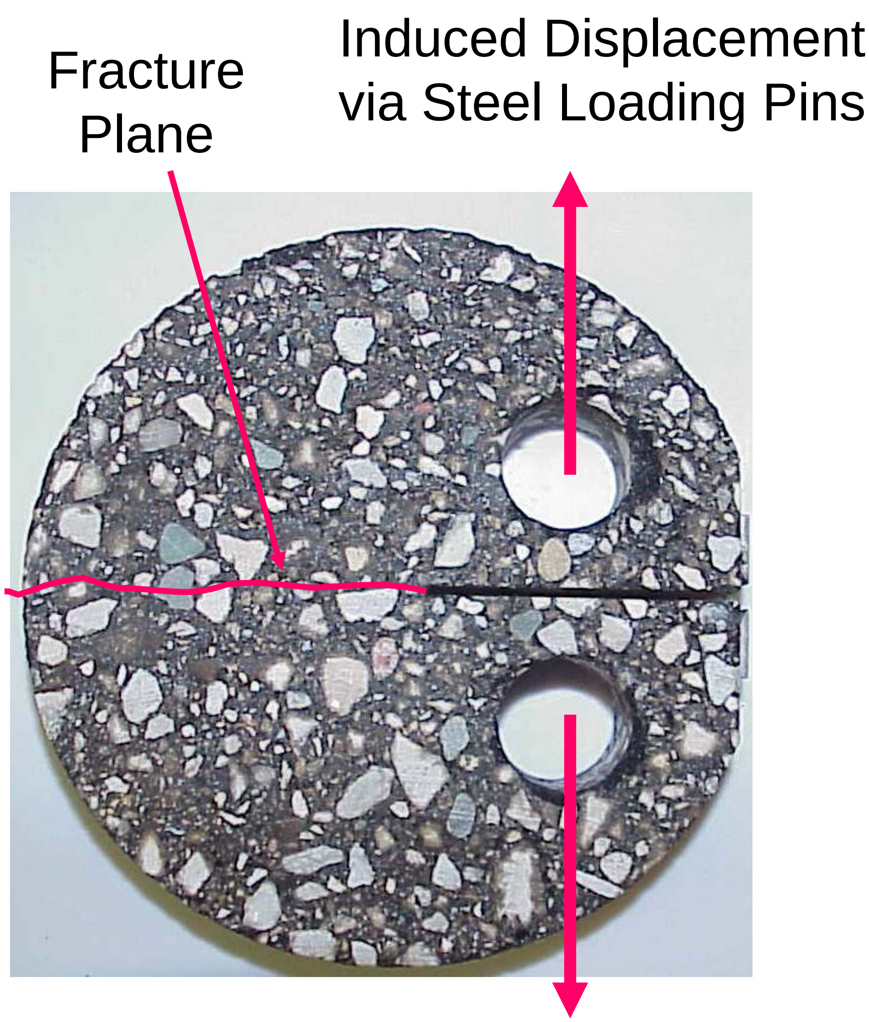
Advanced Mixture Tests Common Worldwide (prices under $100k), 3D NLIM FE, Applicable fracture tests and models for quasi-brittle materials

↓

Past 5 years:
DC(T) Specifications (MN, IA, WI, CDOT, ORD …), Commercial DC(T), Performance-Bracketing
[RAS, High ABR, Rejuvenators]

Accurate, Repeatable, Portable, Affordable Low Temperature Fracture Test Available, Important Tool for Modern Mixes

# Disk-Shaped Compact Tension - DC(T)



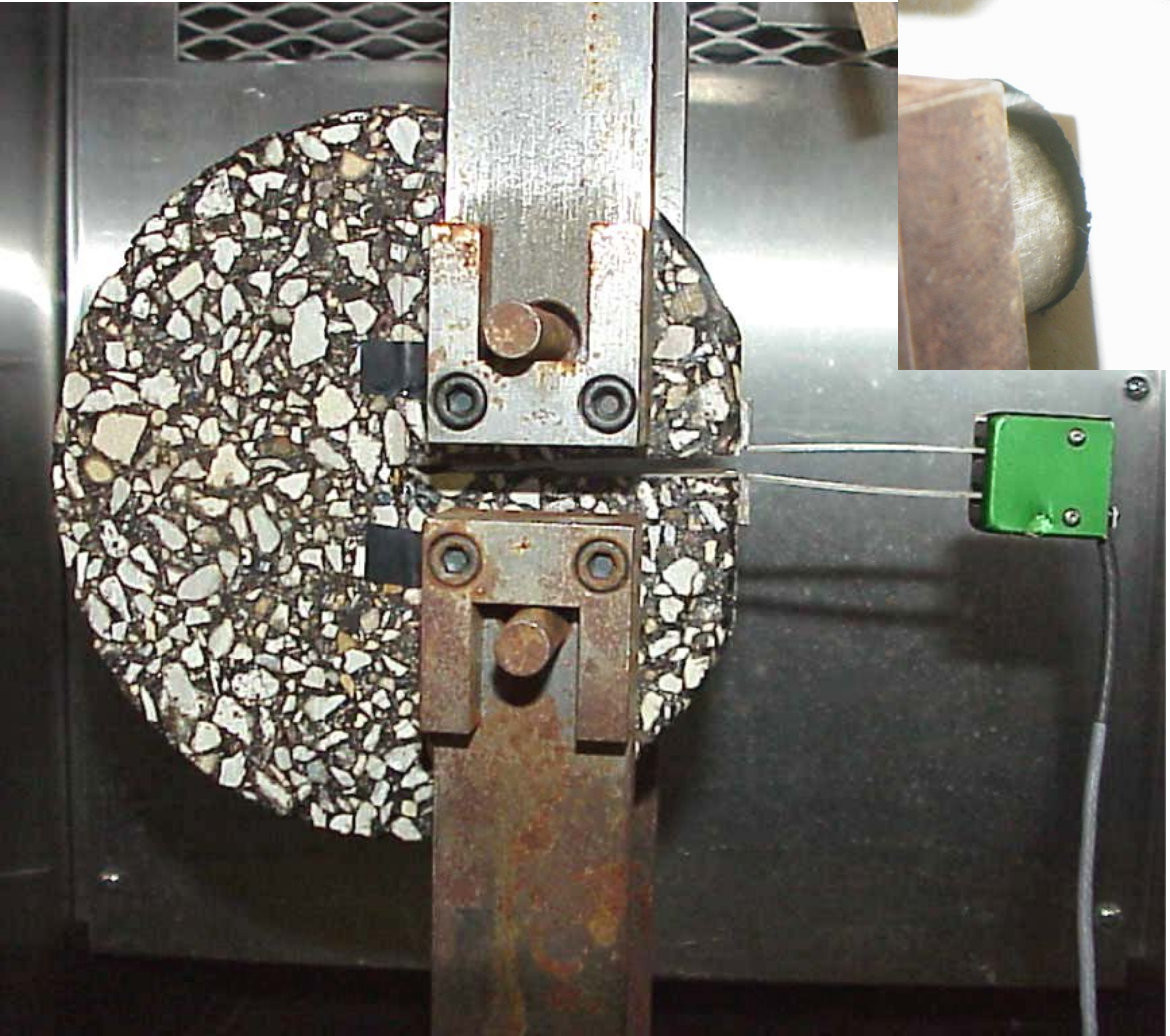

Motivation – measure fracture energy, use cylindrical specimens, maximize repeatability, use true fracture test

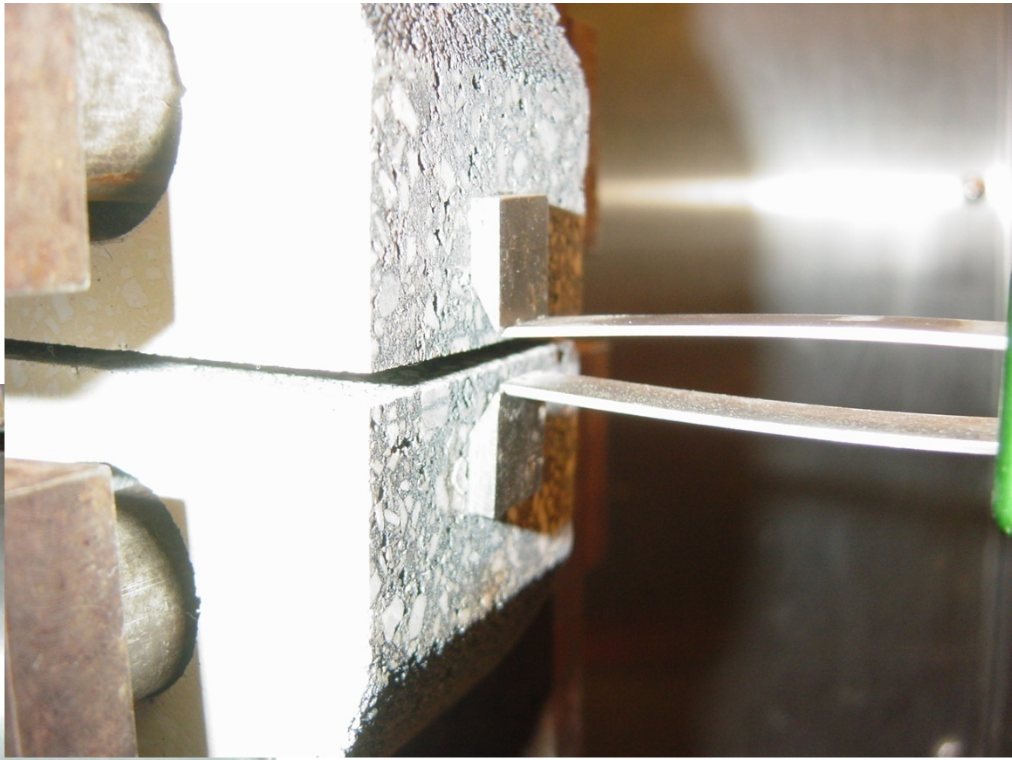
Based on ASTM E399 – Geometry slightly modified to account for differences in the fracture behavior of steel and asphalt concrete

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 circa 2006

ASTM INTERNATIONAL

Designation: D 7313 – 06

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



### 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/meter² (J/m²) [inch-pound/inch² (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).

# Specimen Prep




Total technician time per specimen for prep:

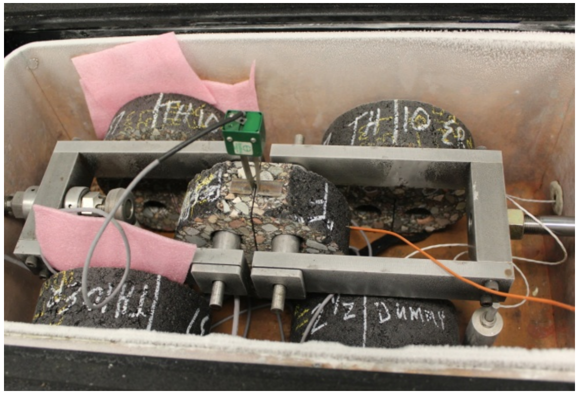
- 10 minutes (large # samples)
- 30 minutes (small # samples)

Reason for complex geometry:

- -Create standard, accepted fracture test
- -Compact tension: no-glue, rotating platens with crack moving away from platens, compact, efficient tension test (it's worth it!)

# Testing

- The easy part!
- Less than 10 minutes
- Load specimen, then turn-key operation
- ~ $49k device
- 110V wall outlet



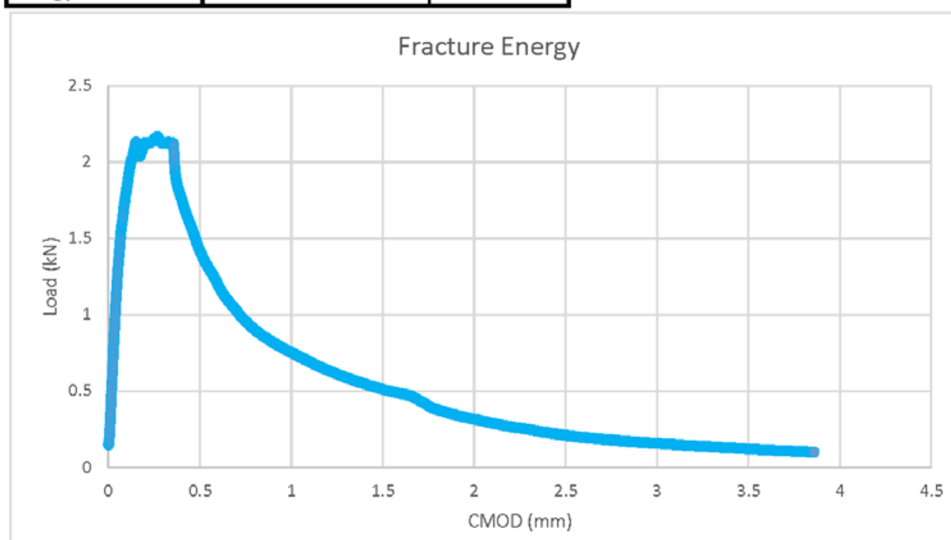
Test Quip DC(T) (acknowledgement: Tom Brovold)

# 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** | **$J/m^2$** | |

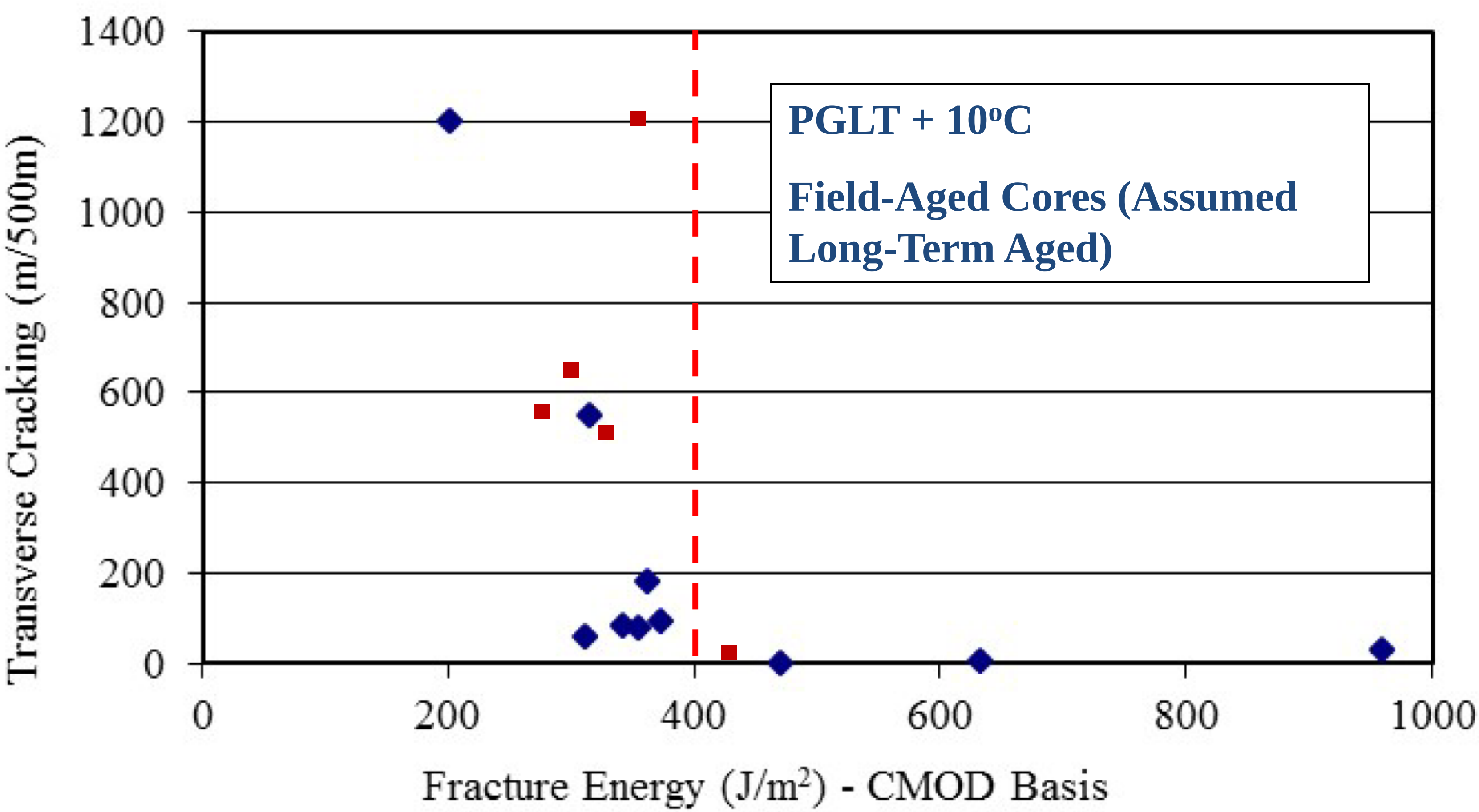


# Typical COV Data/Trends

| 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%
- In general:
  - Better temperature control, lower COV
  - Smaller NMAS, lower COV
  - Lower temperature, lower COV

# DC(T) Results from Pooled Fund Study




SCB also evaluated, but found by Univ. of MN to have high COV and poor correlation to field cracking in blind study

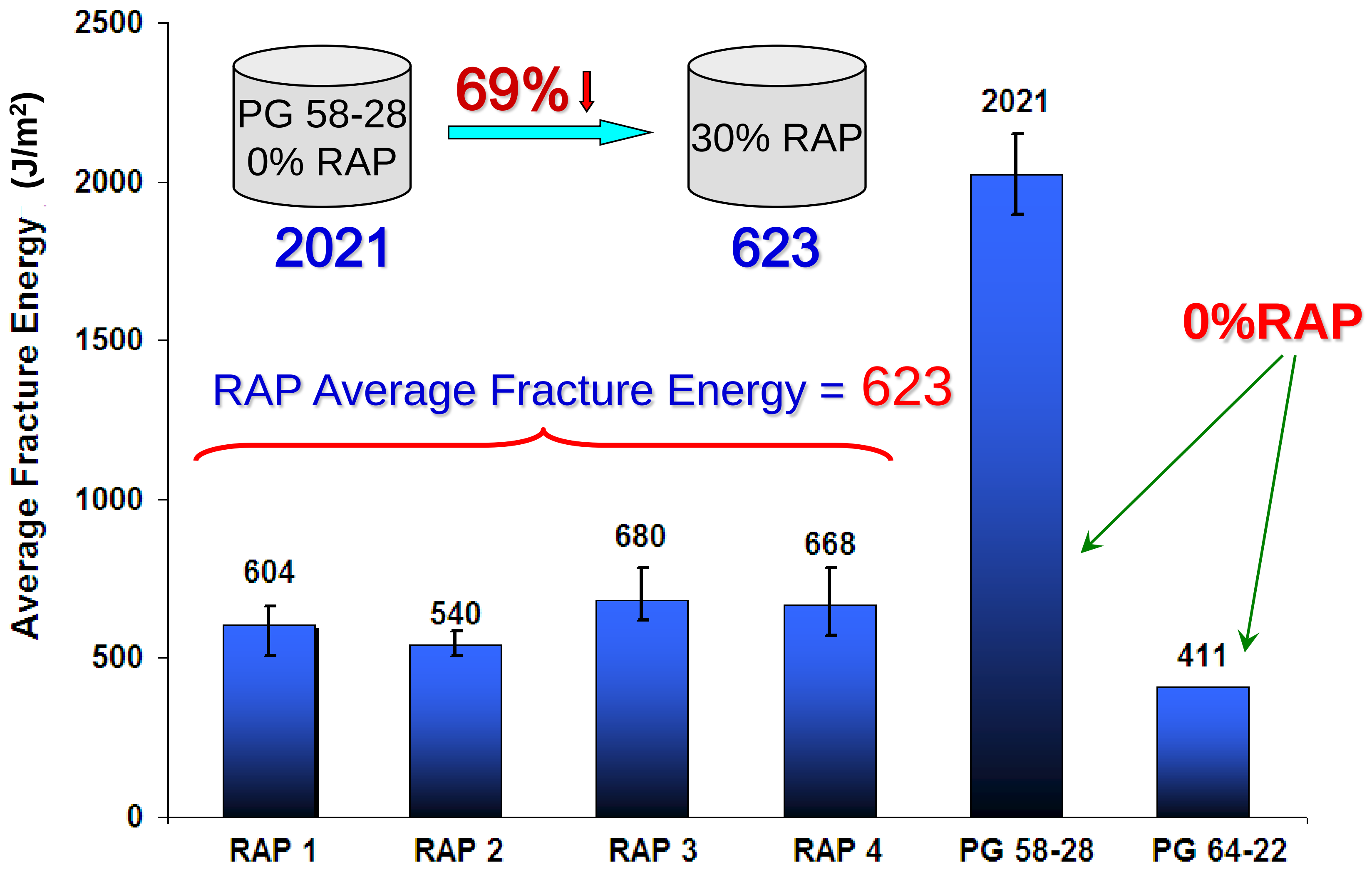
# New DC(T) Based Thermal Cracking Spec

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

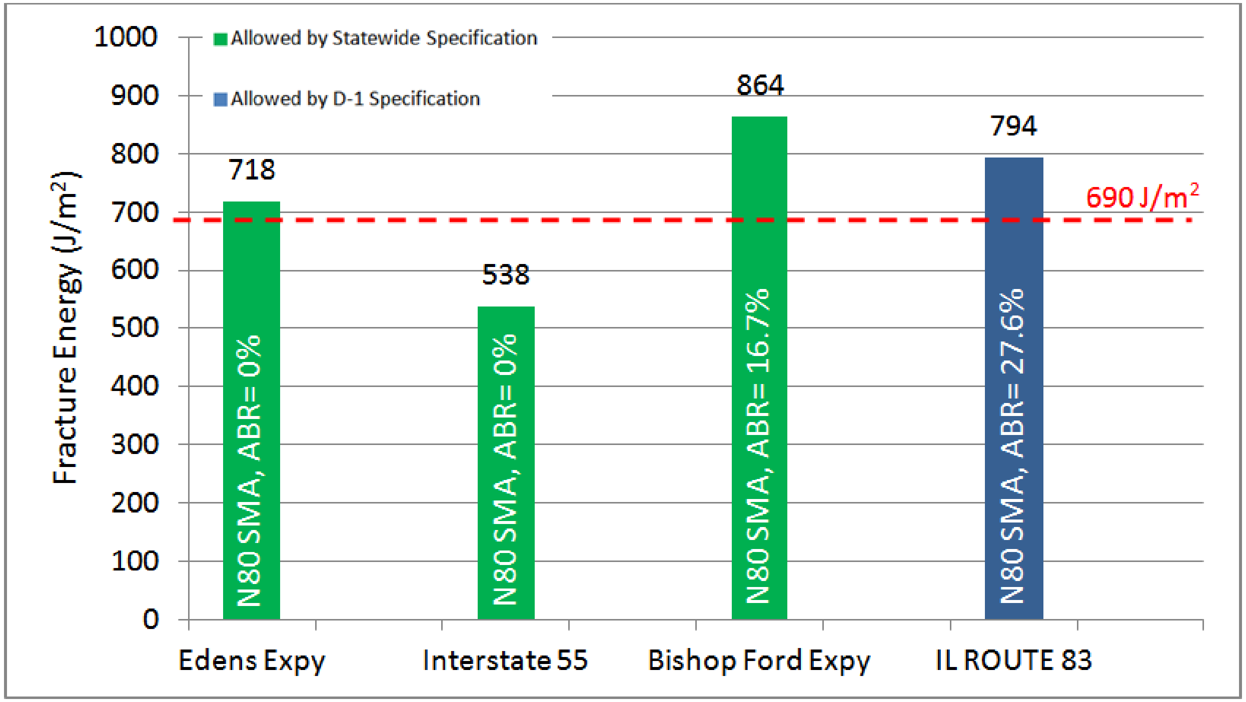
| Contents | Project Criticality/ Traffic Level | | |
|---|---|---|---|
| | High<br>>30M ESALS | Moderate<br>10-30M ESALS | Low<br><10M ESALS |
| Fracture Energy, minimum (J/m$^2$), PGLT + 10oC | 690 | 460 | 400 |
| Predicted Thermal Cracking using ILLI-TC(m/km) | < 4 | < 64 | Not required |

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

# Example DC(T) for RAP* Mix Validation
## (*Recycled Asphalt Pavement)



# Chicagoland Forensic Investigation (Fall 2014) (Report, Video, Road & Bridges – Feb., 2015)

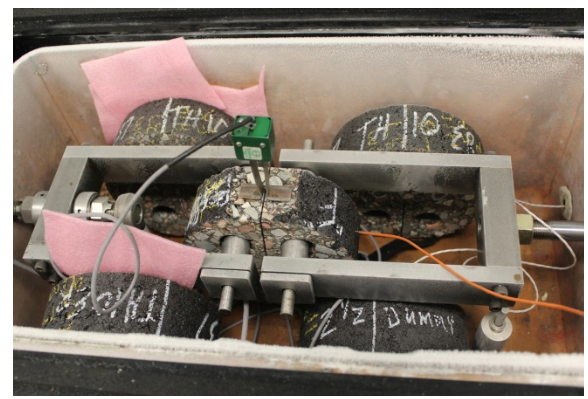



Showed that higher ABR mixes (SMAs in this example) could meet the most stringent standards when designed correctly, identified reflective cracking as major source of surface cracking in Chicagoland, highlighted leading-edge high ABR and SMA designs in Chicago, some w/ RAS.

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

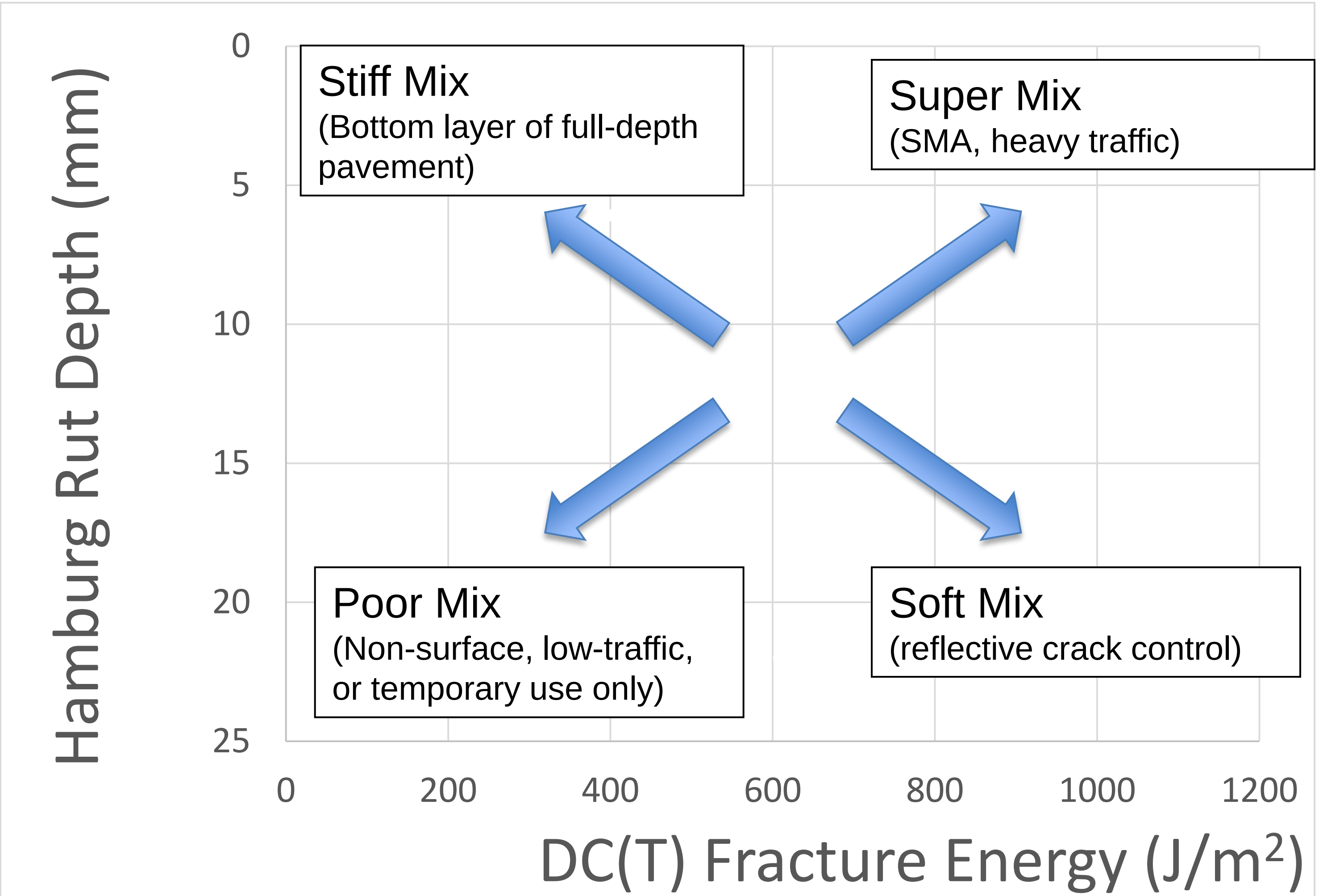
Hamburg

+

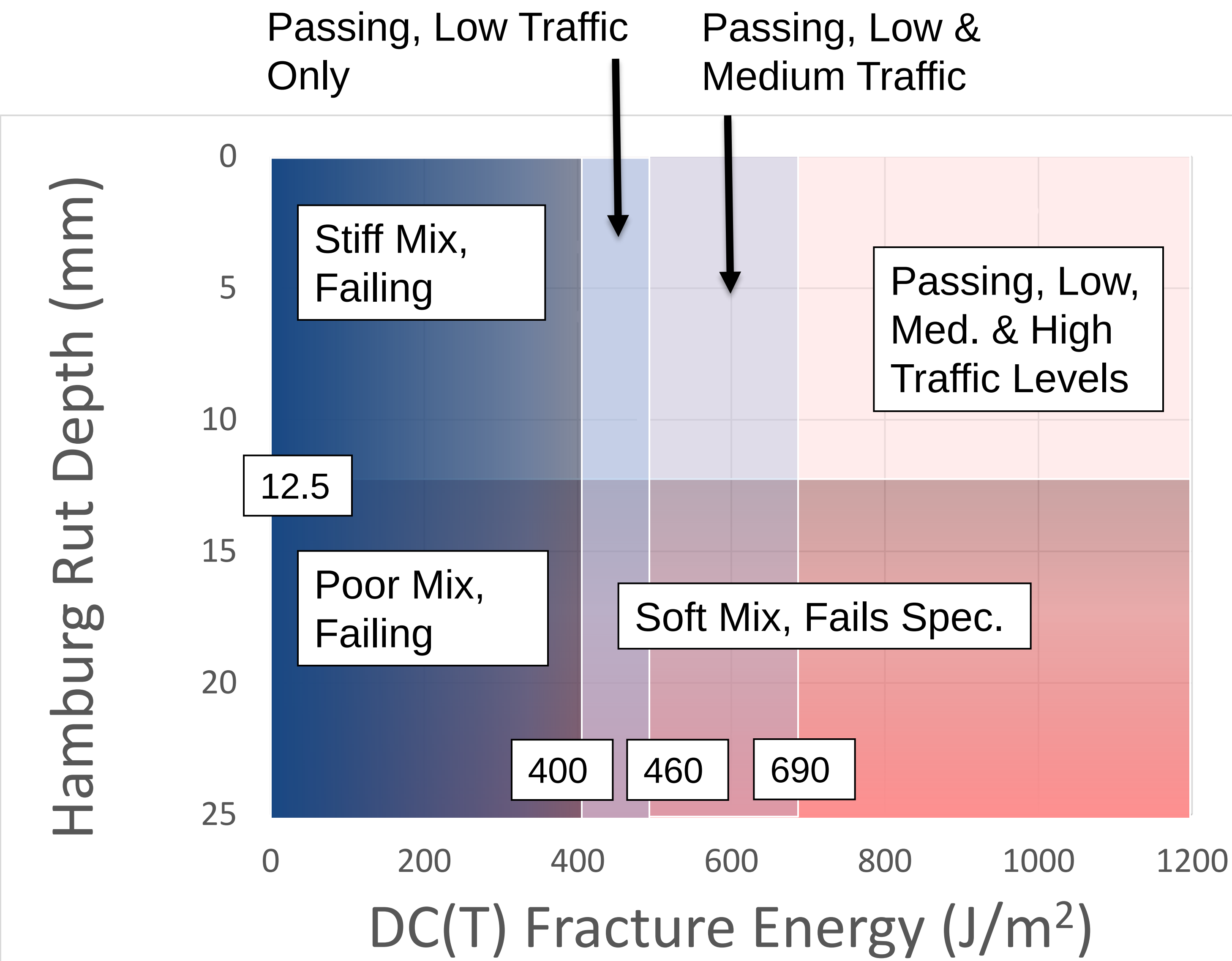


DC(T)

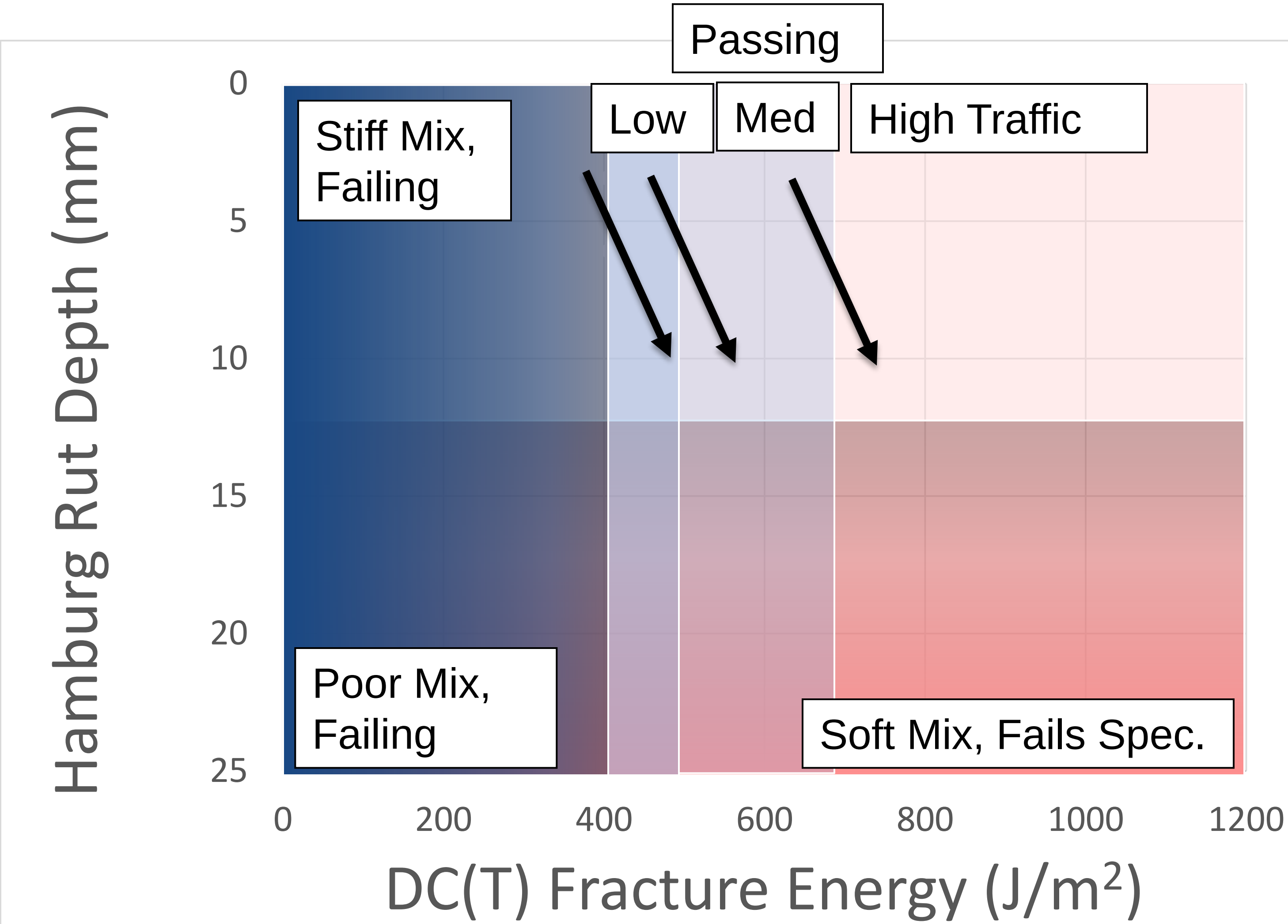
# “Performance-Space” Diagram



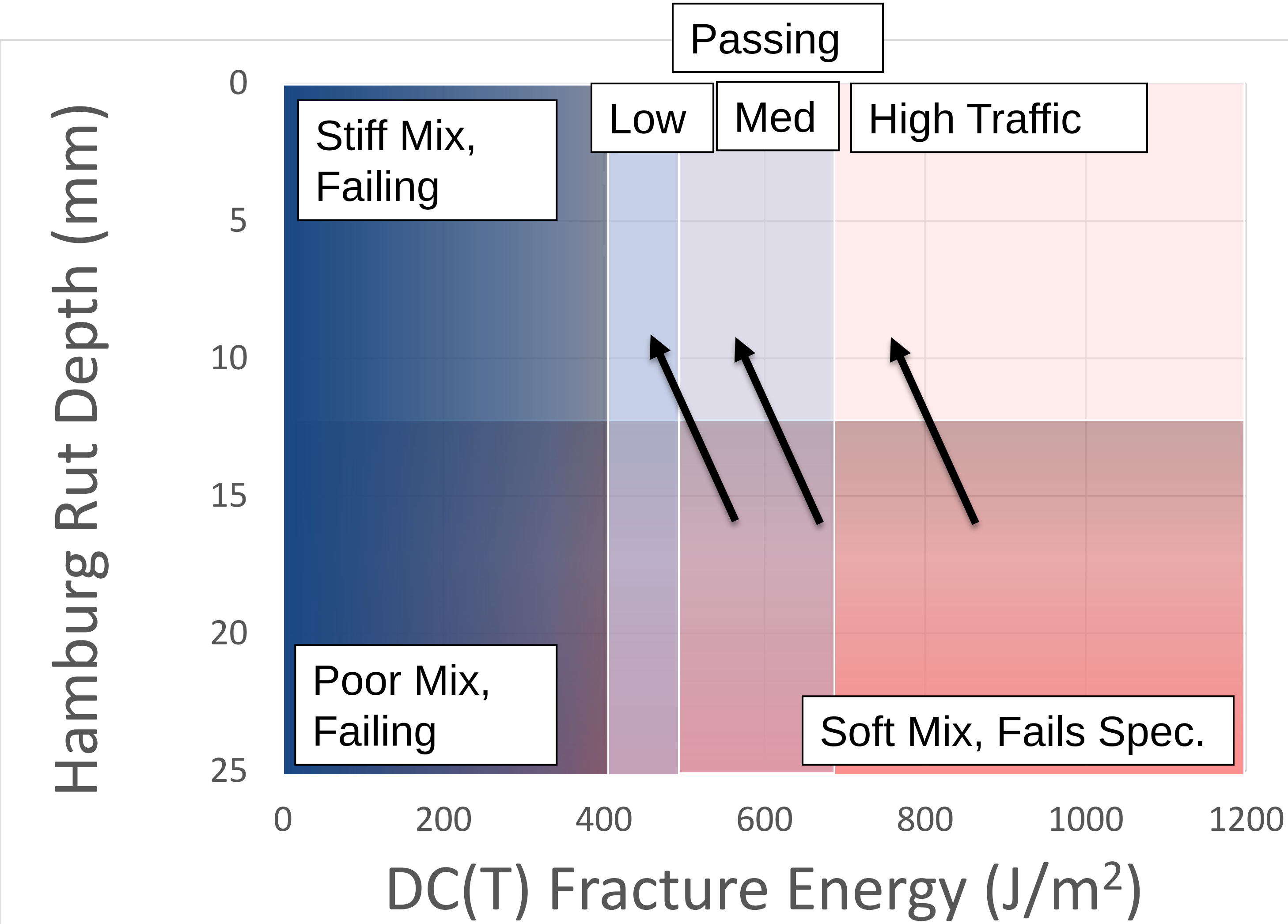
# Performance-Space Diagram: Zones



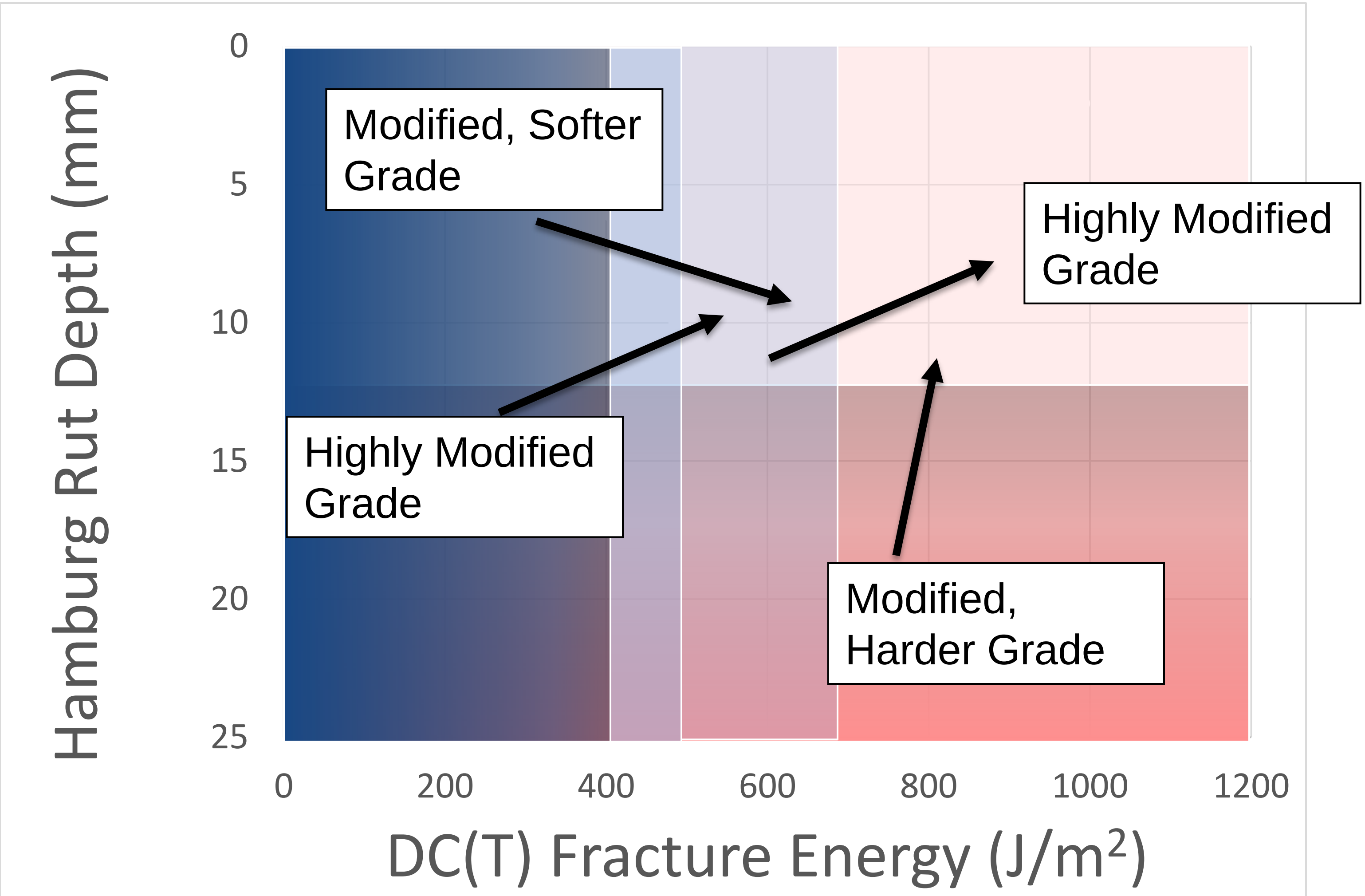
# Mix Adjustment: Softer Binder



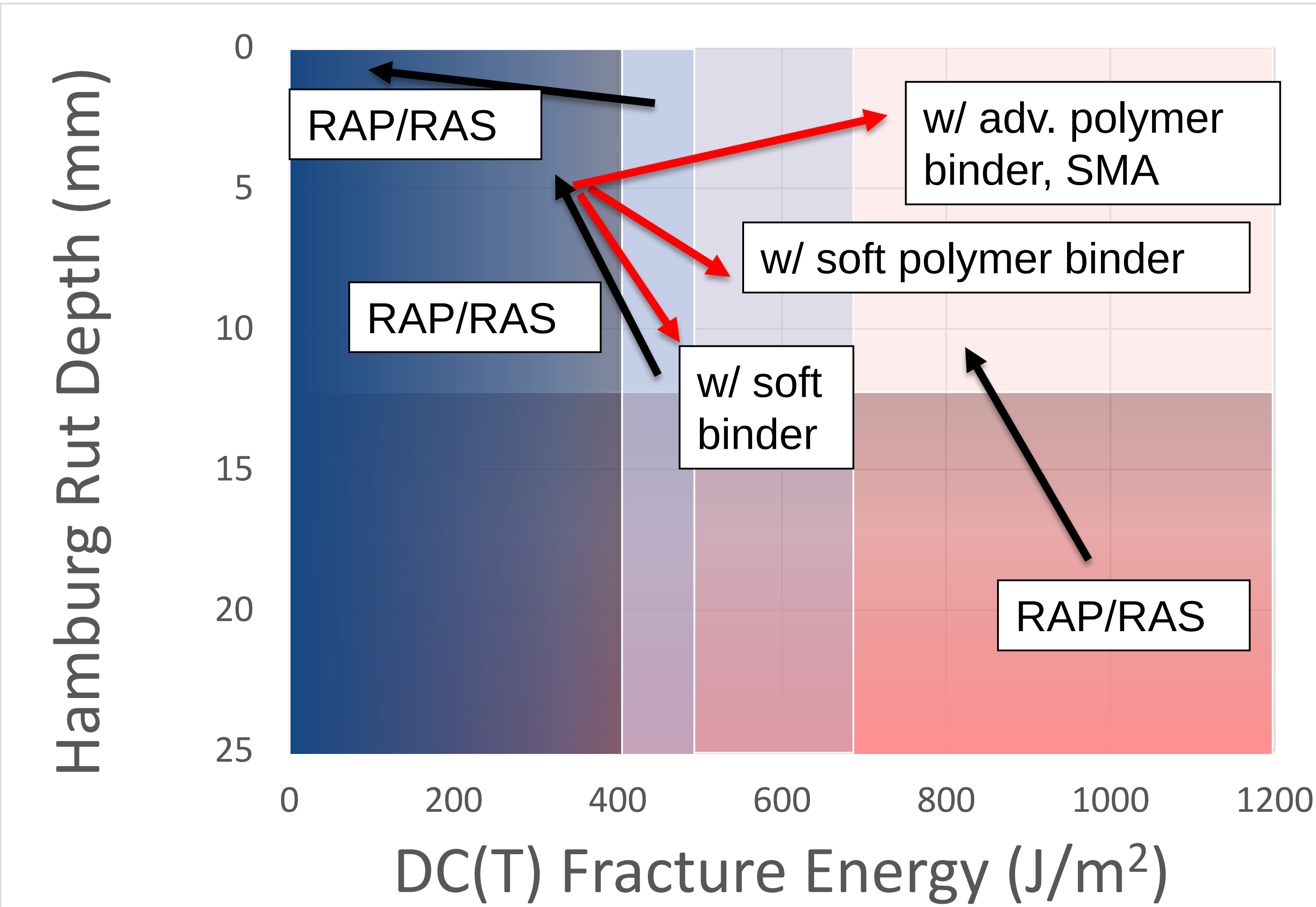
# Mix Adjustment: Stiffer Binder



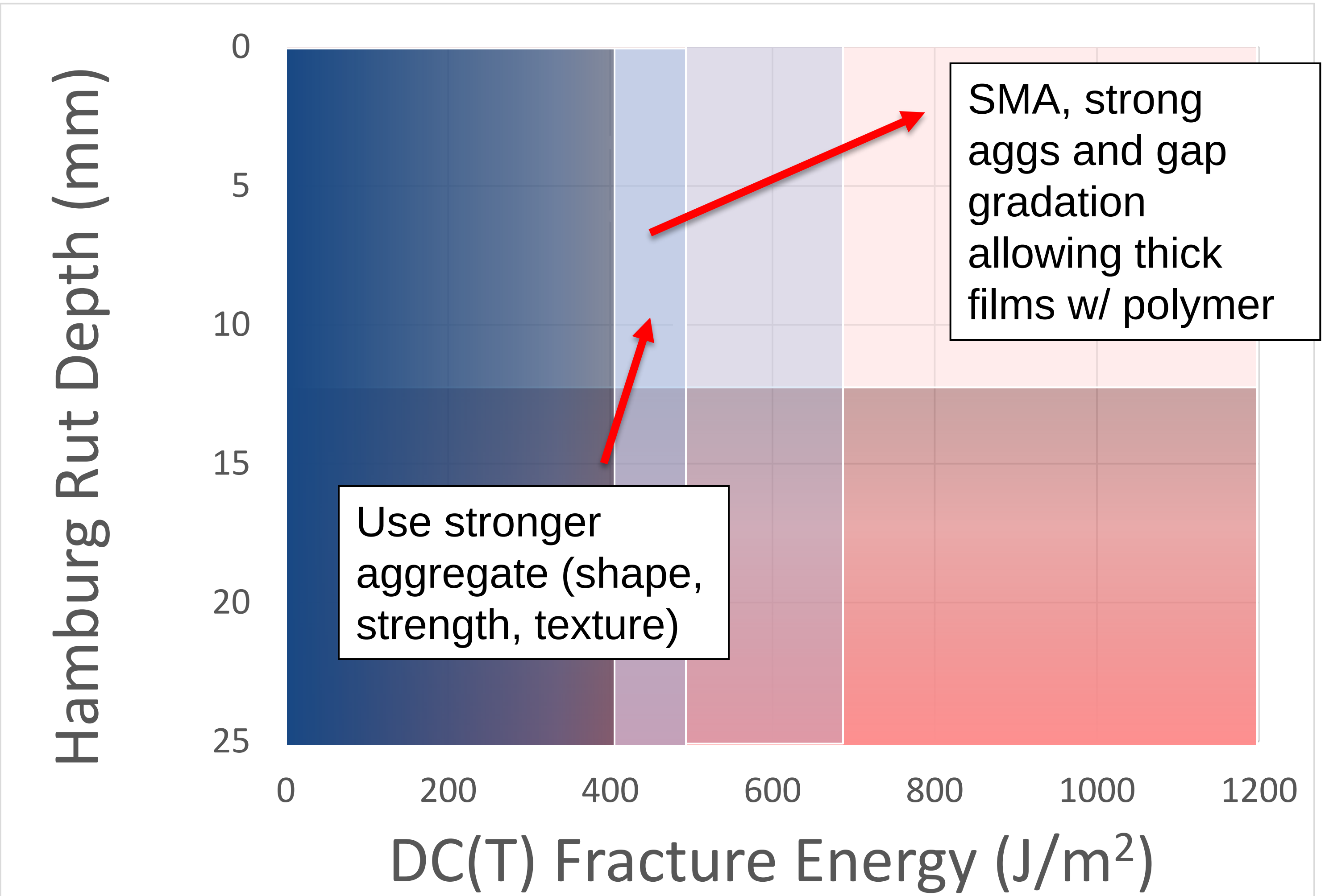
# Mix Adjustment:
# Binder Modification



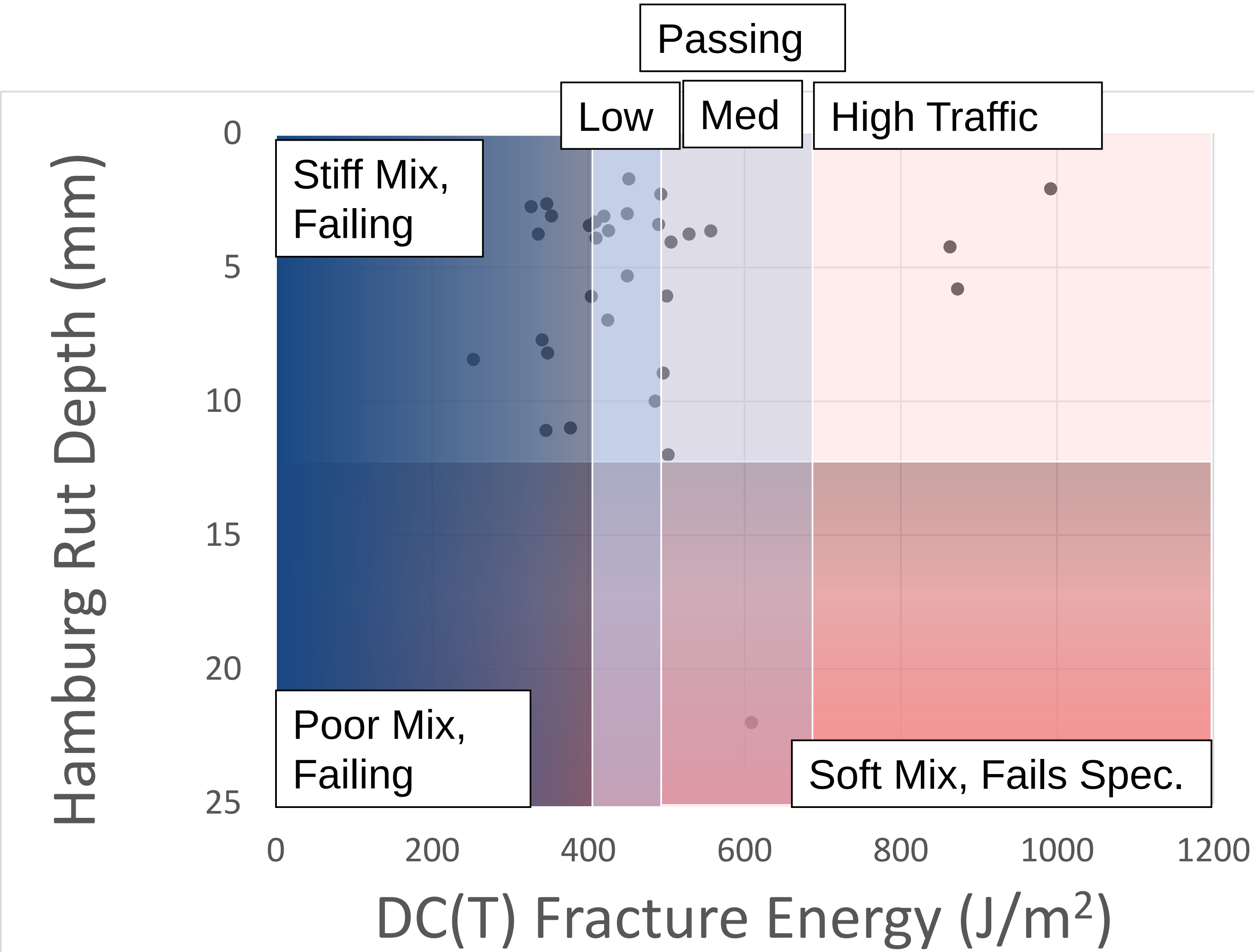
# Mix Affects: Recycling



# Mix Effects:
# Stronger Aggregate, Skeleton

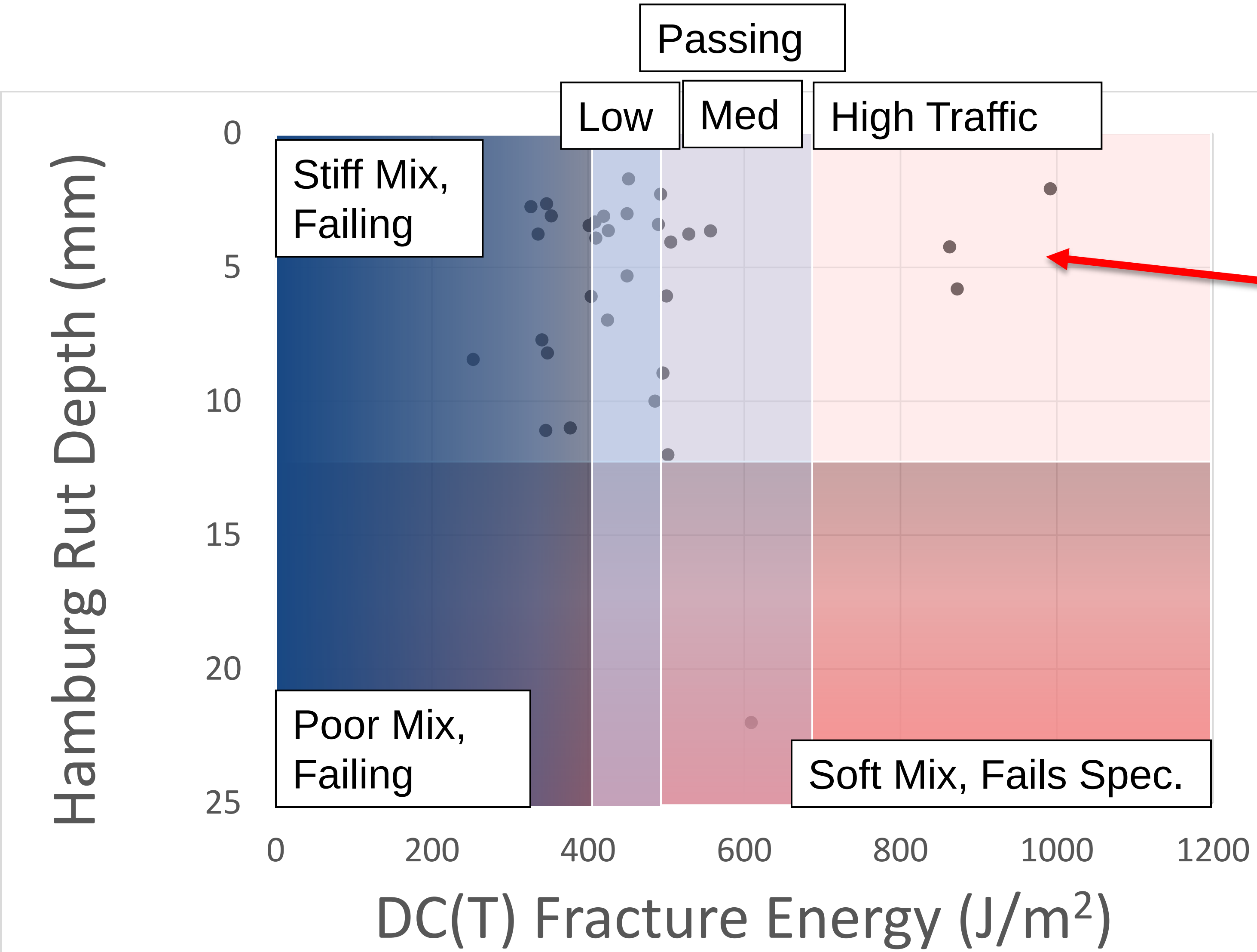


# Early Performance-Space Data for Illinois: How are we Doing?



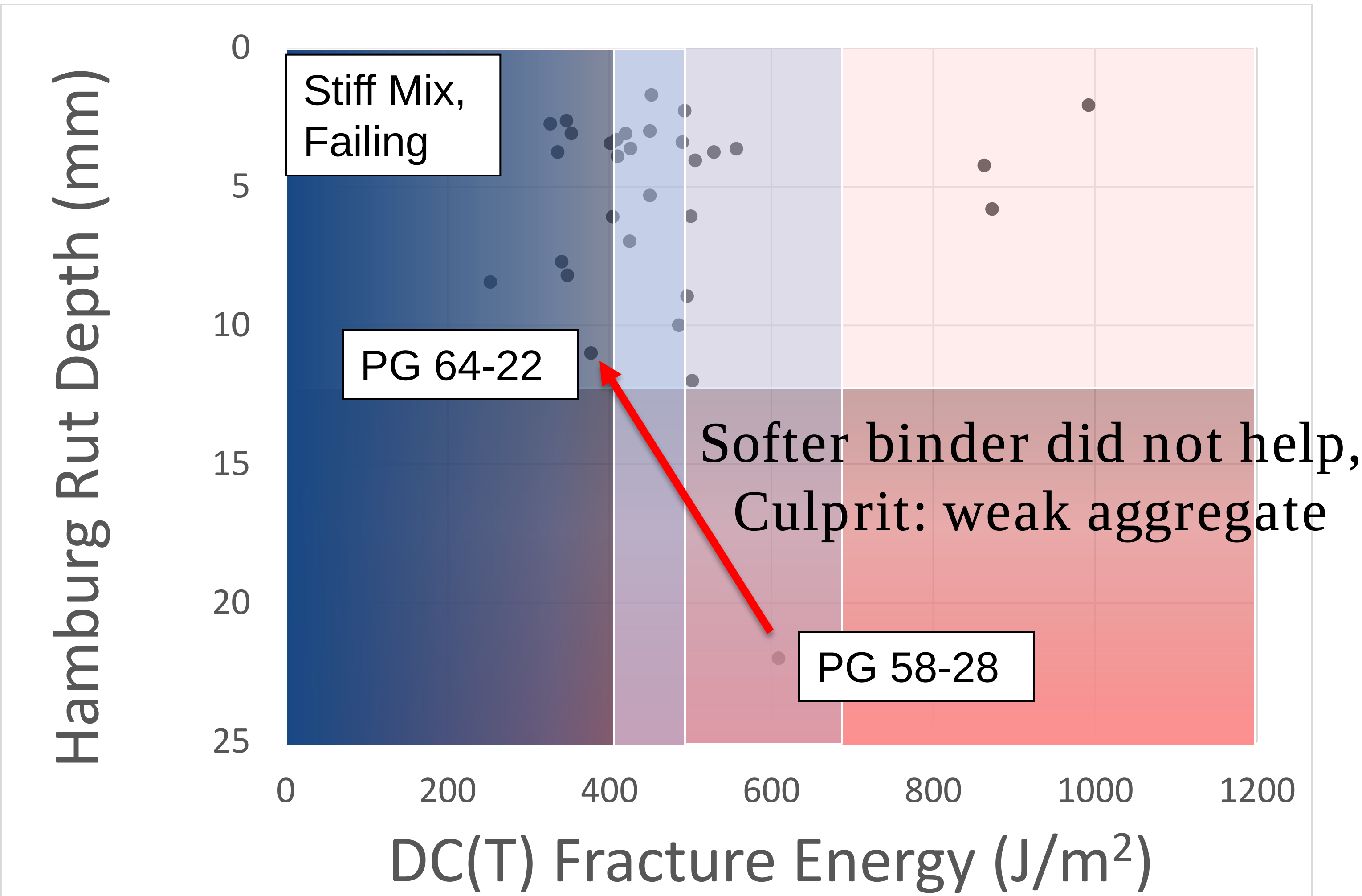

Not surprisingly, tendency towards stiff mixes

# SMA's

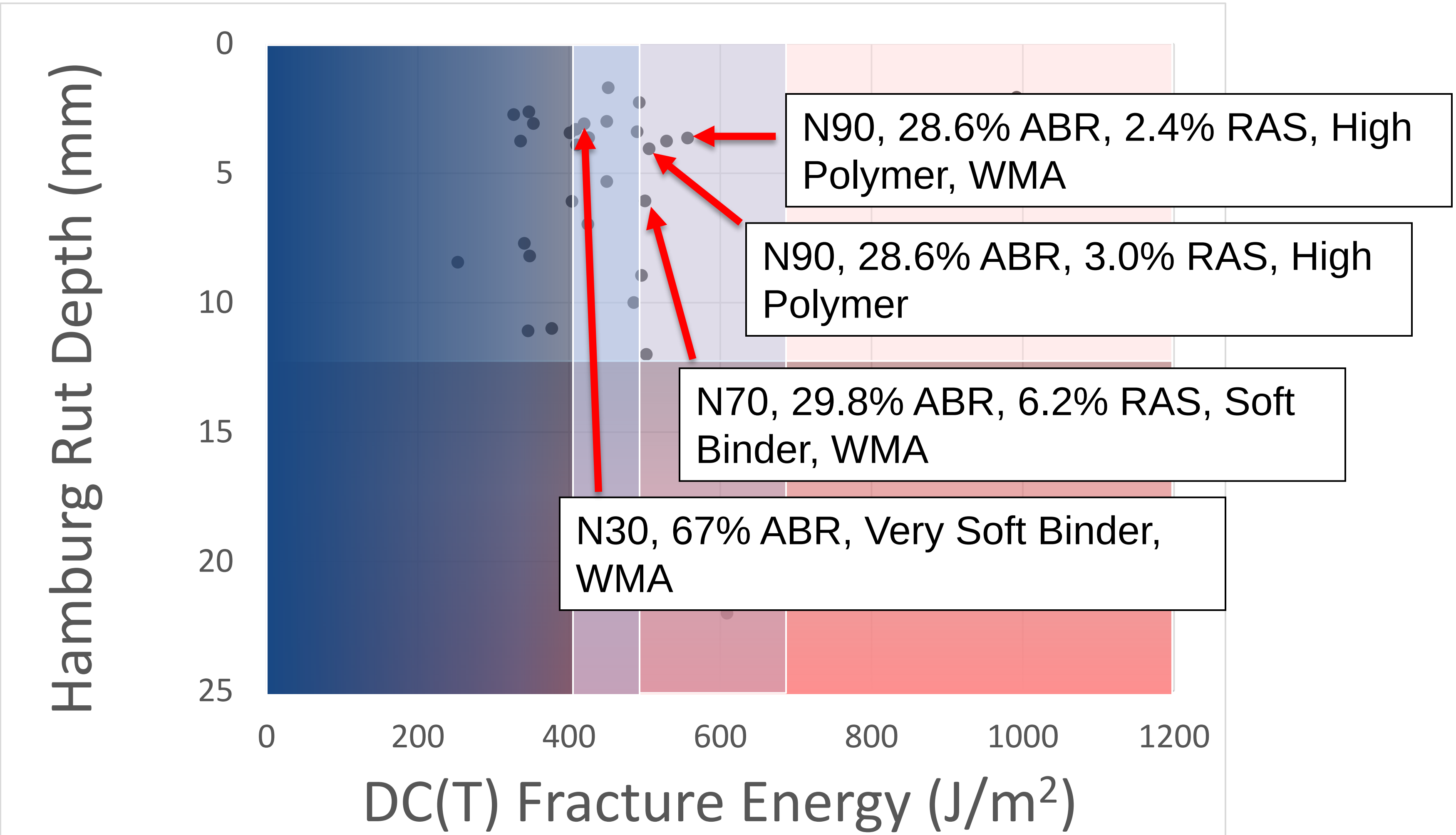



These three mixes are SMA's

# Softer Binder, No Polymer



# High ABR Mixes



# 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 |

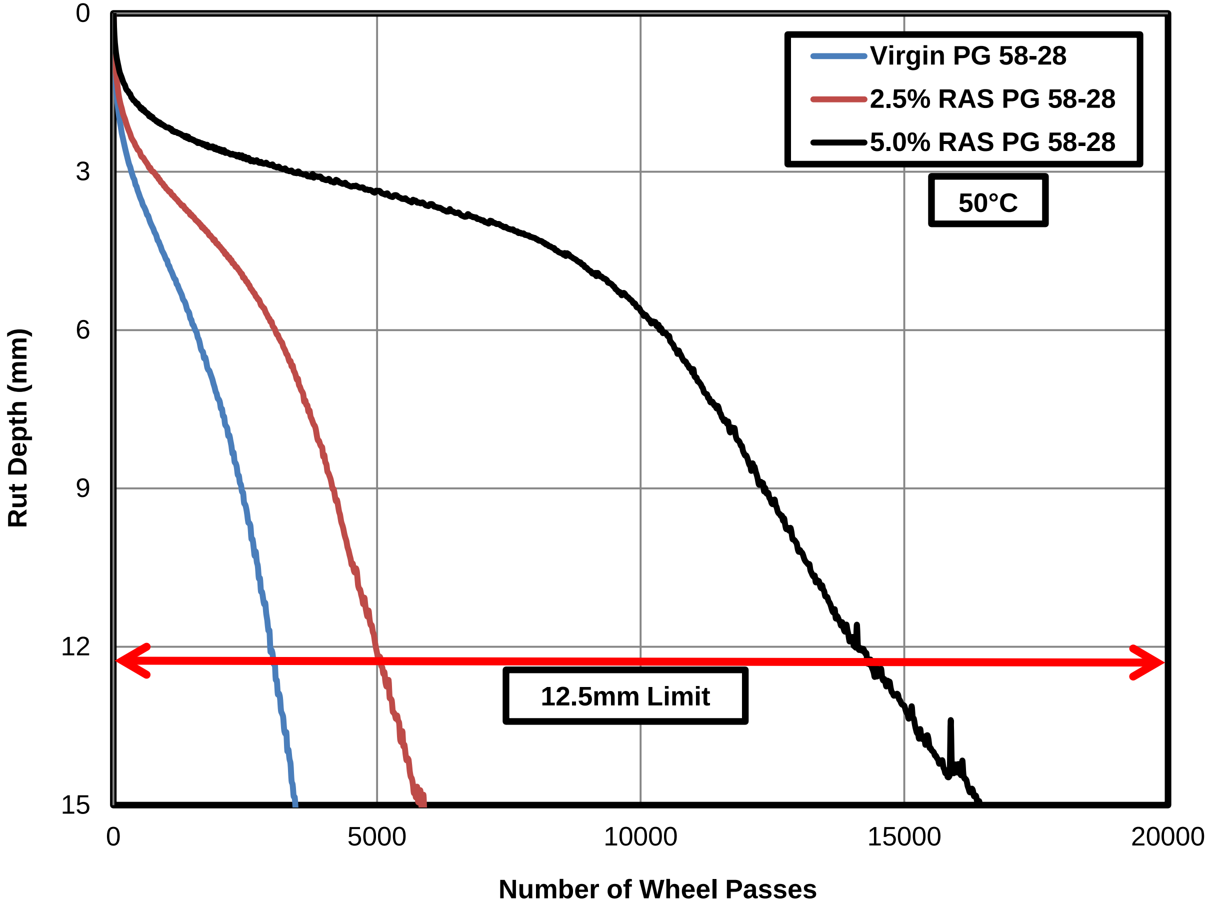
# Designs – Assuming 70% Available

| 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** |

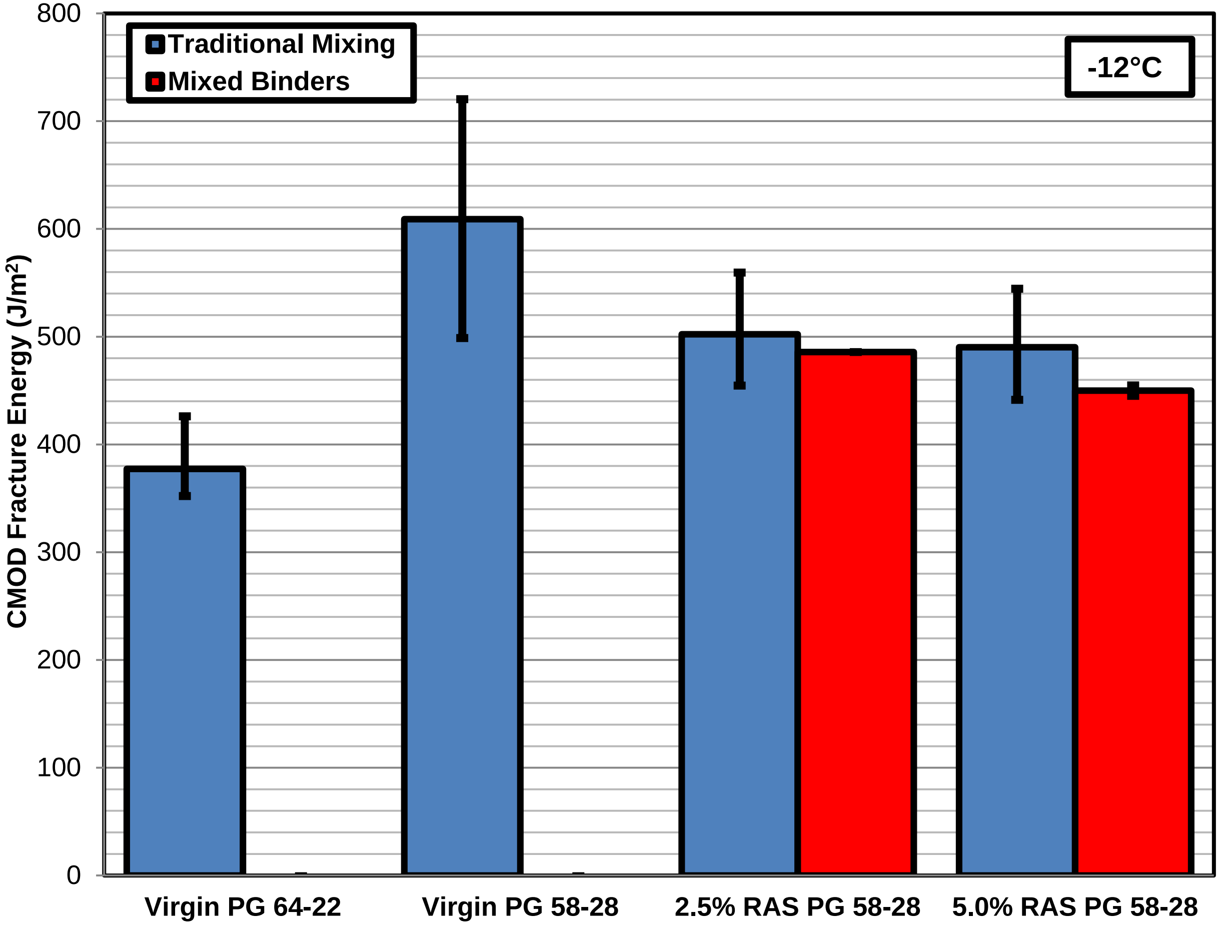
# Hamburg Results



# DC(T) Results

| **Specimen ID** | **Avg. Peak Load (kN)** | **Avg. CMOD $G_f$ ($J/m^2$)** | **CMOD $G_f$ COV (%)** |
|---|---|---|---|
| ***Virgin PG 64-22*** | **3.179** | **377.3** | **9.3%** |
| ***Virgin PG 58-28*** | **3.069** | **609.1** | **18.2%** |
| ***2.5% RAS PG 58-28*** | **3.197** | **502.3** | **8.9%** |
| ***5.0% RAS PG 58-28*** | **3.191** | **490.2** | **8.6%** |
| ***2.5% RAS Manual Mixing PG 58-28*** | **3.223** | **485.7** | **0.2%** |
| ***5.0% RAS Manual Mixing PG 58-28*** | **3.249** | **450.0** | **1.7%** |

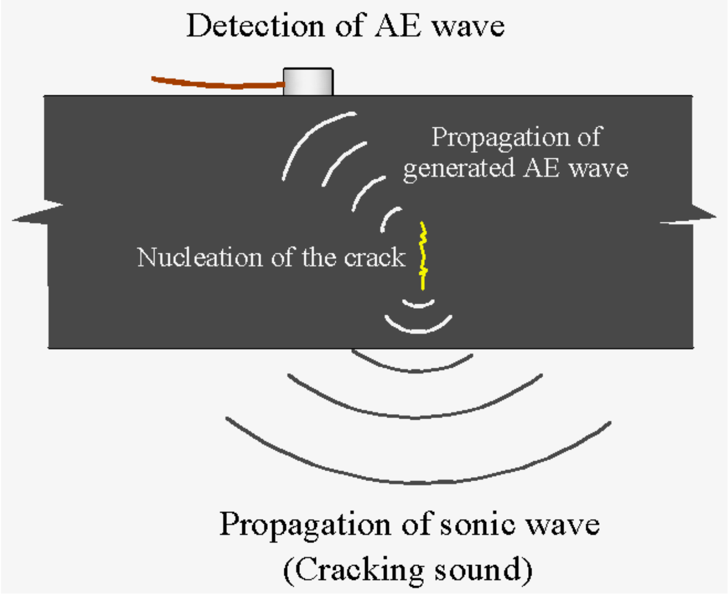
# DC(T) Results

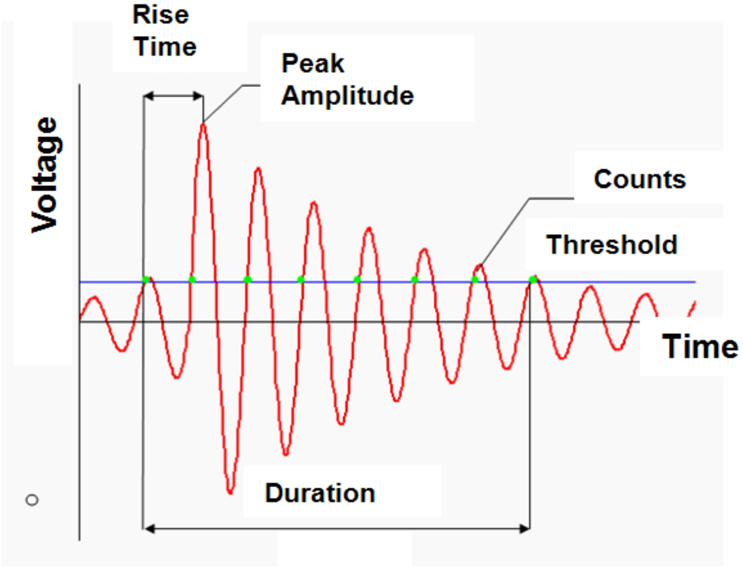


Traditional Mixing
Mixed Binders
-12°C
CMOD Fracture Energy (J/m²)
800
700
600
500
400
300
200
100
0
Virgin PG 64-22
Virgin PG 58-28
2.5% RAS PG 58-28
5.0% RAS PG 58-28

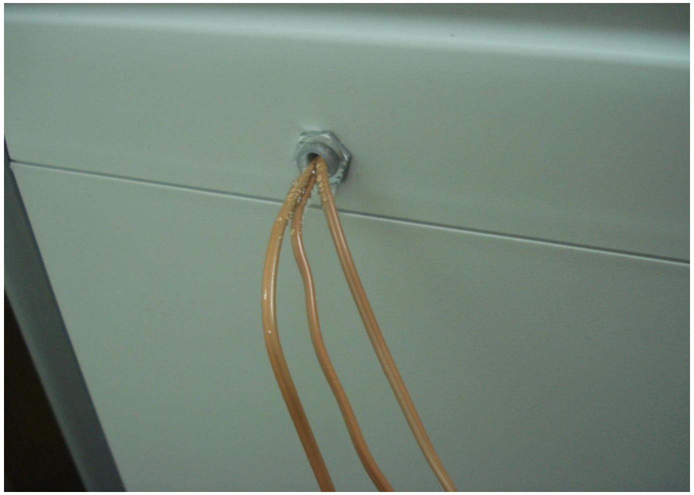
# Acoustic Emission (AE) Testing

- Recognized nondestructive test (NDT) method
- Used commonly to detect and locate defects in materials under stress
- Defined as the spontaneous release of localized strain energy in loaded materials in terms of transient stress waves



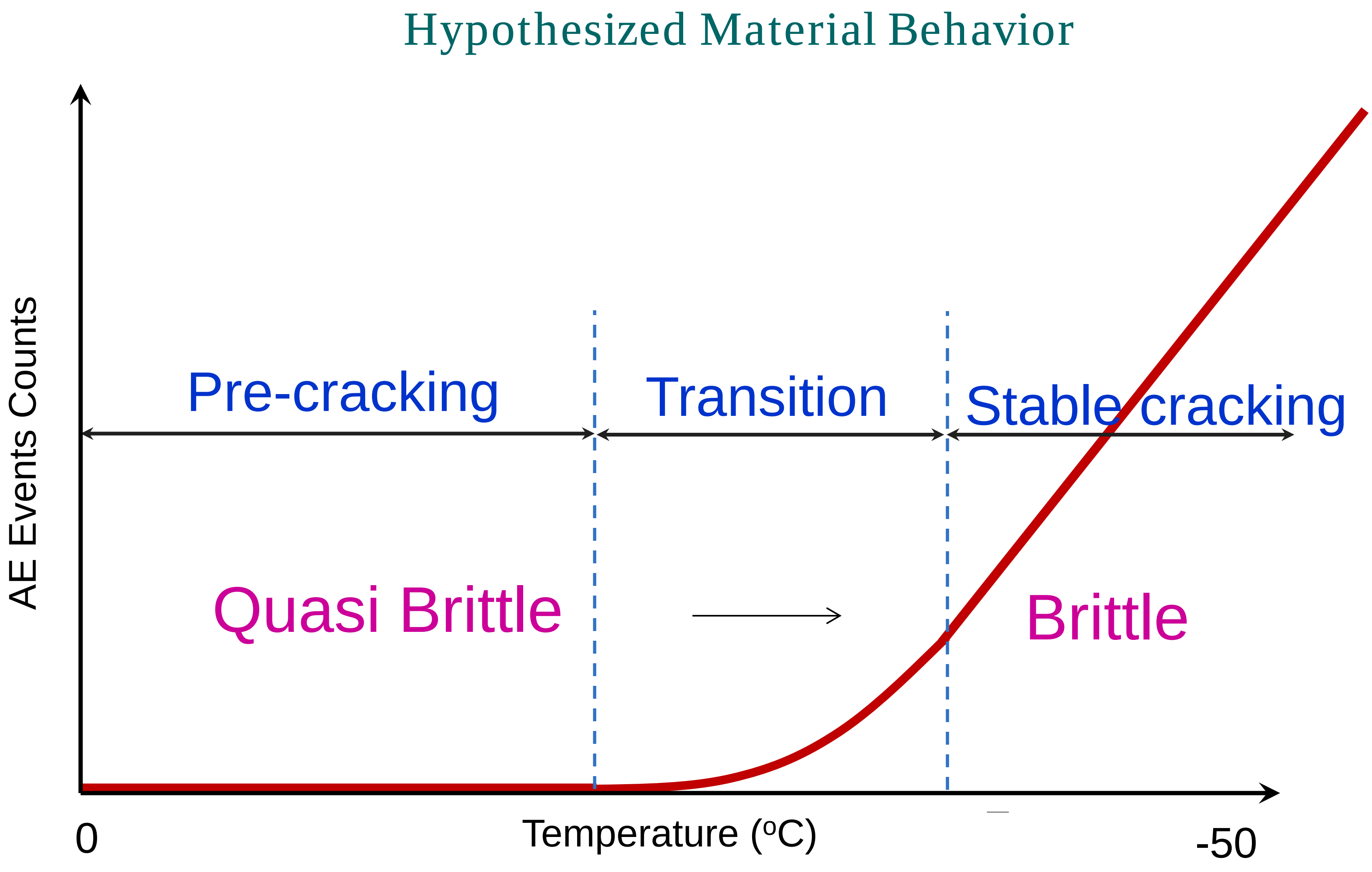



# Shuttle Ultra-cold Portable Freezer



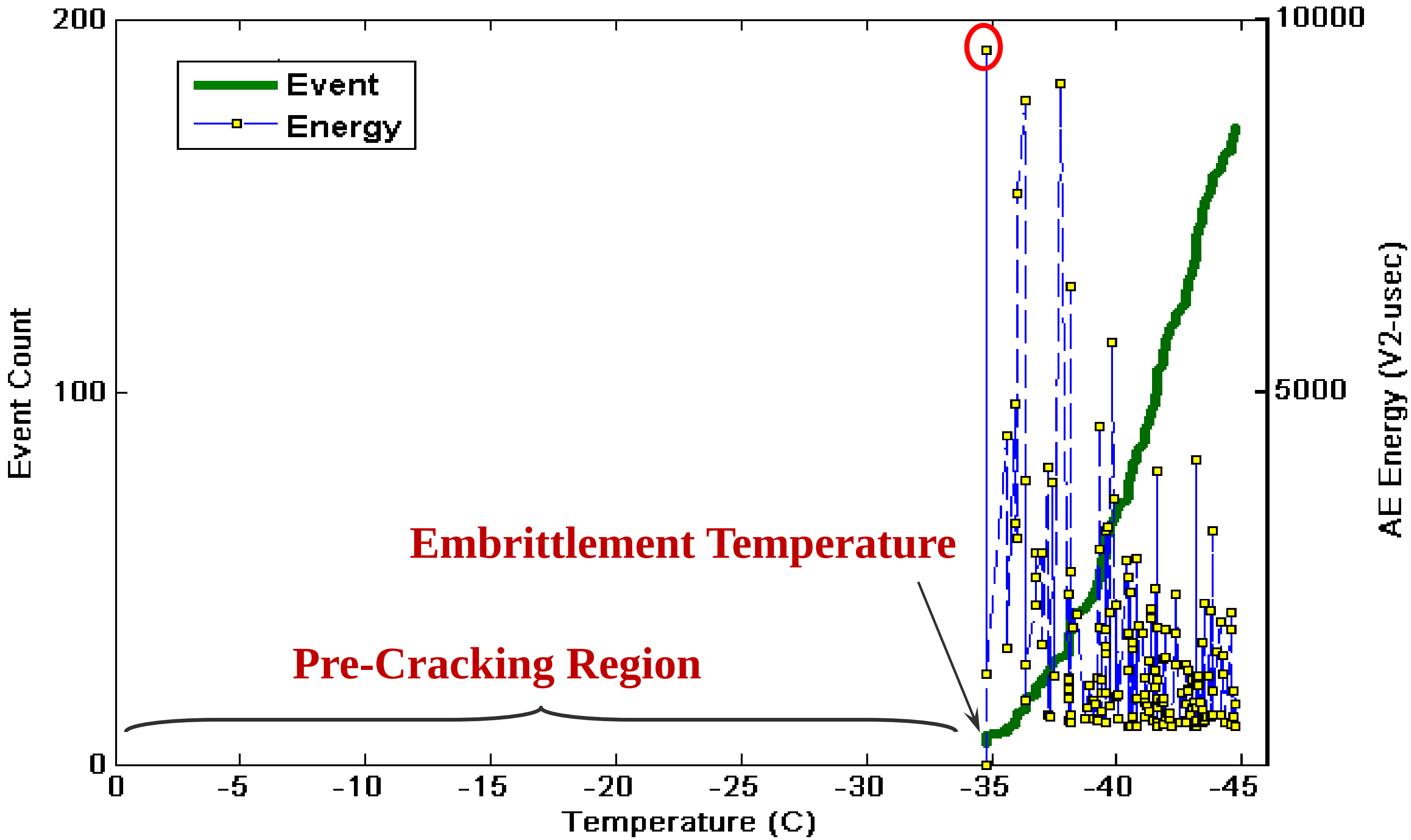
Pass-thru port, 0.25" (6.3mm)

# *Analysis of Acoustic Emission Results*

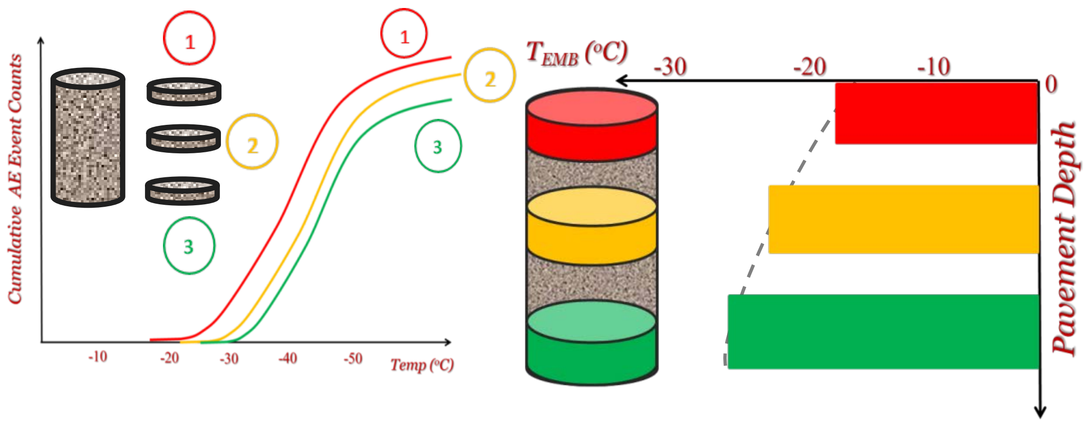


# *Analysis of Acoustic Emission Results*

## Embrittlement Temperature ($T_{EMB}$)

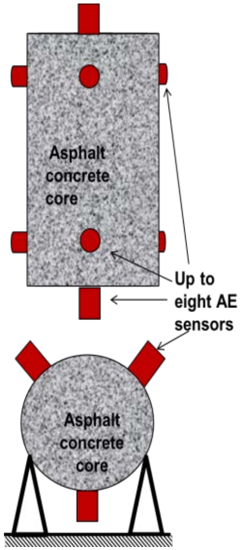


# New NCHRP IDEA Project: Concepts

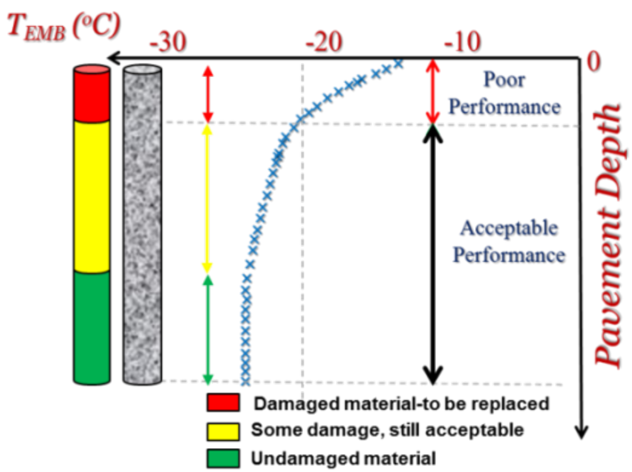



Discrete $T_{EMB}$ Characterization

Small Dia. Core

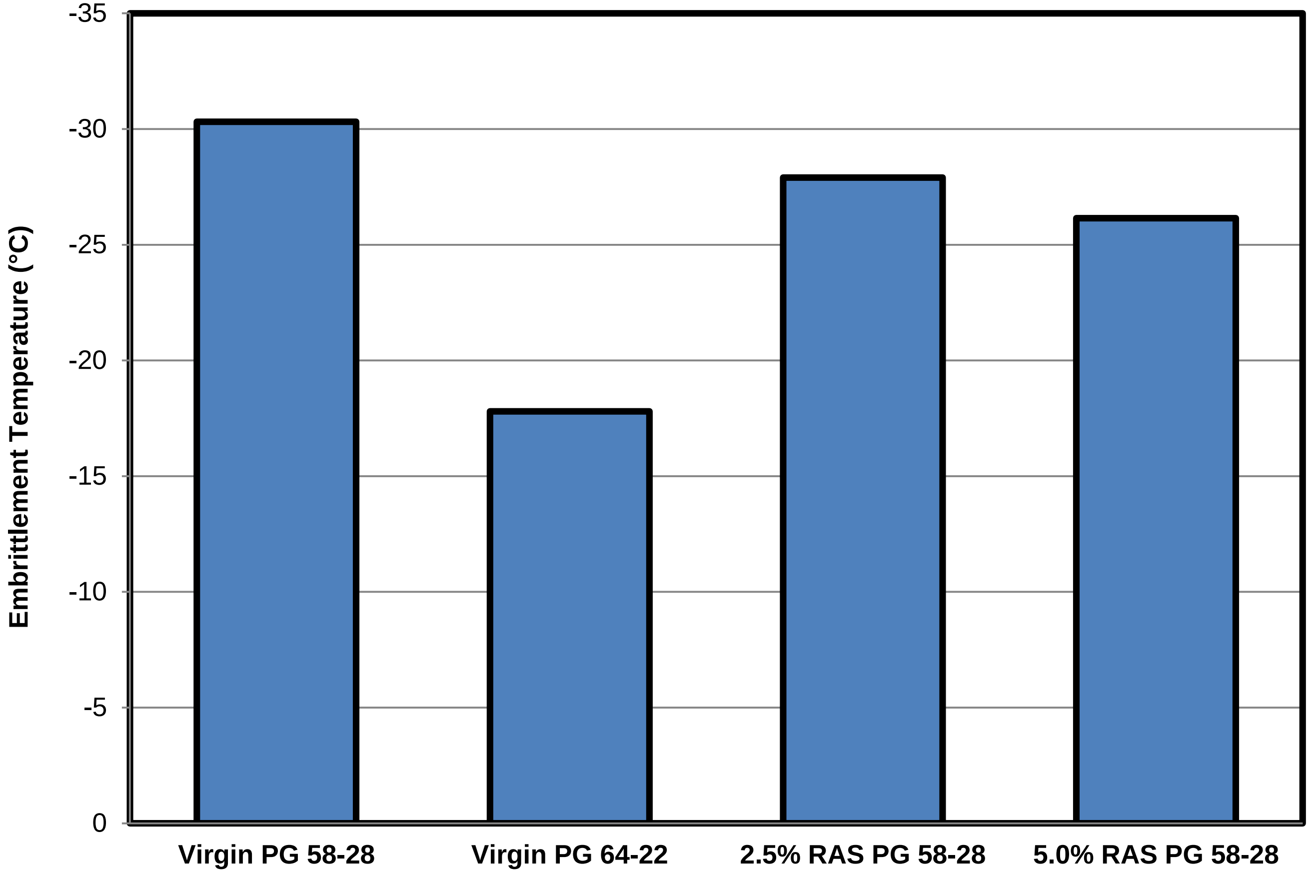



AE Source Location



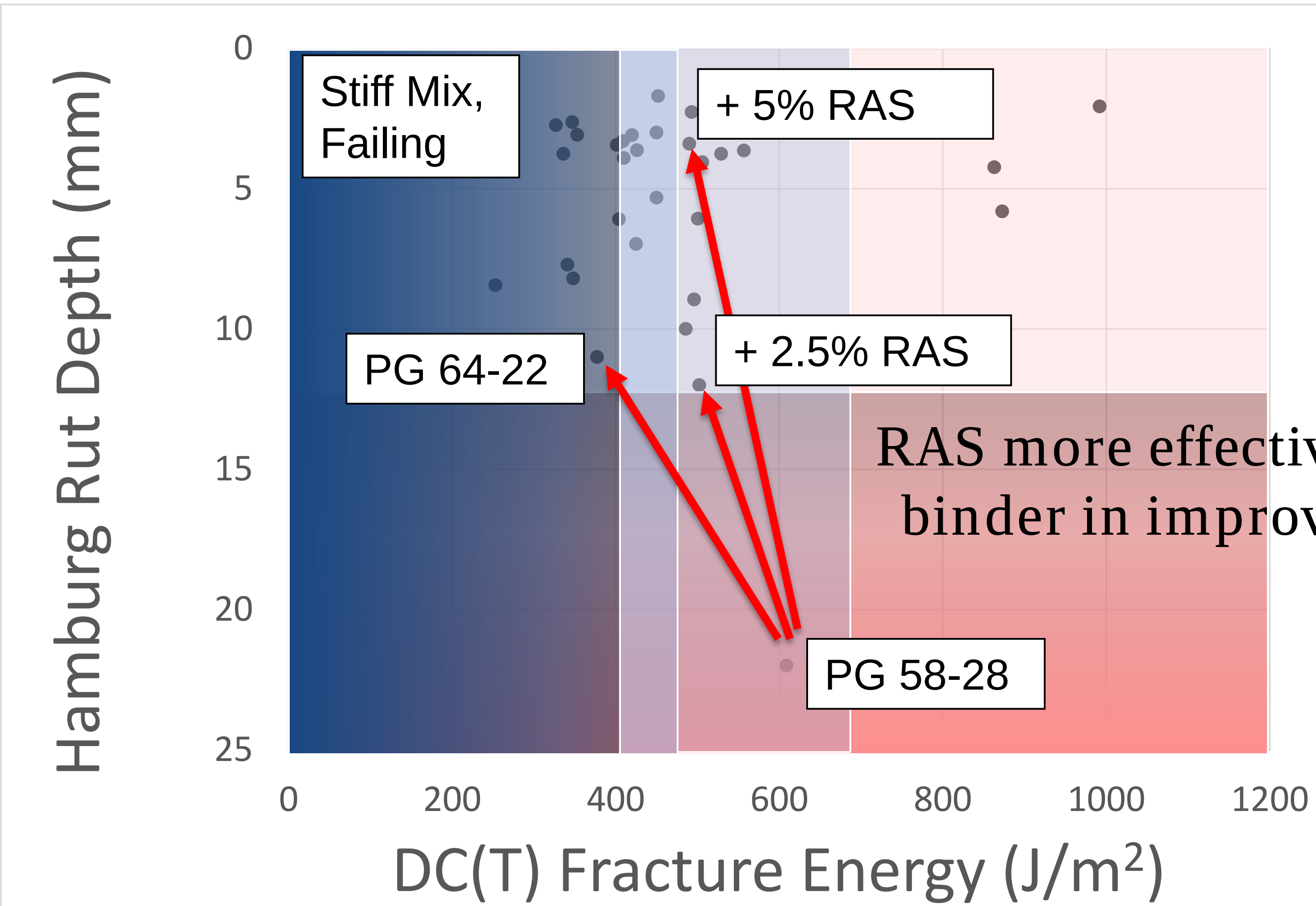

Continuous $T_{EMB}$ Characterization

# AE Results



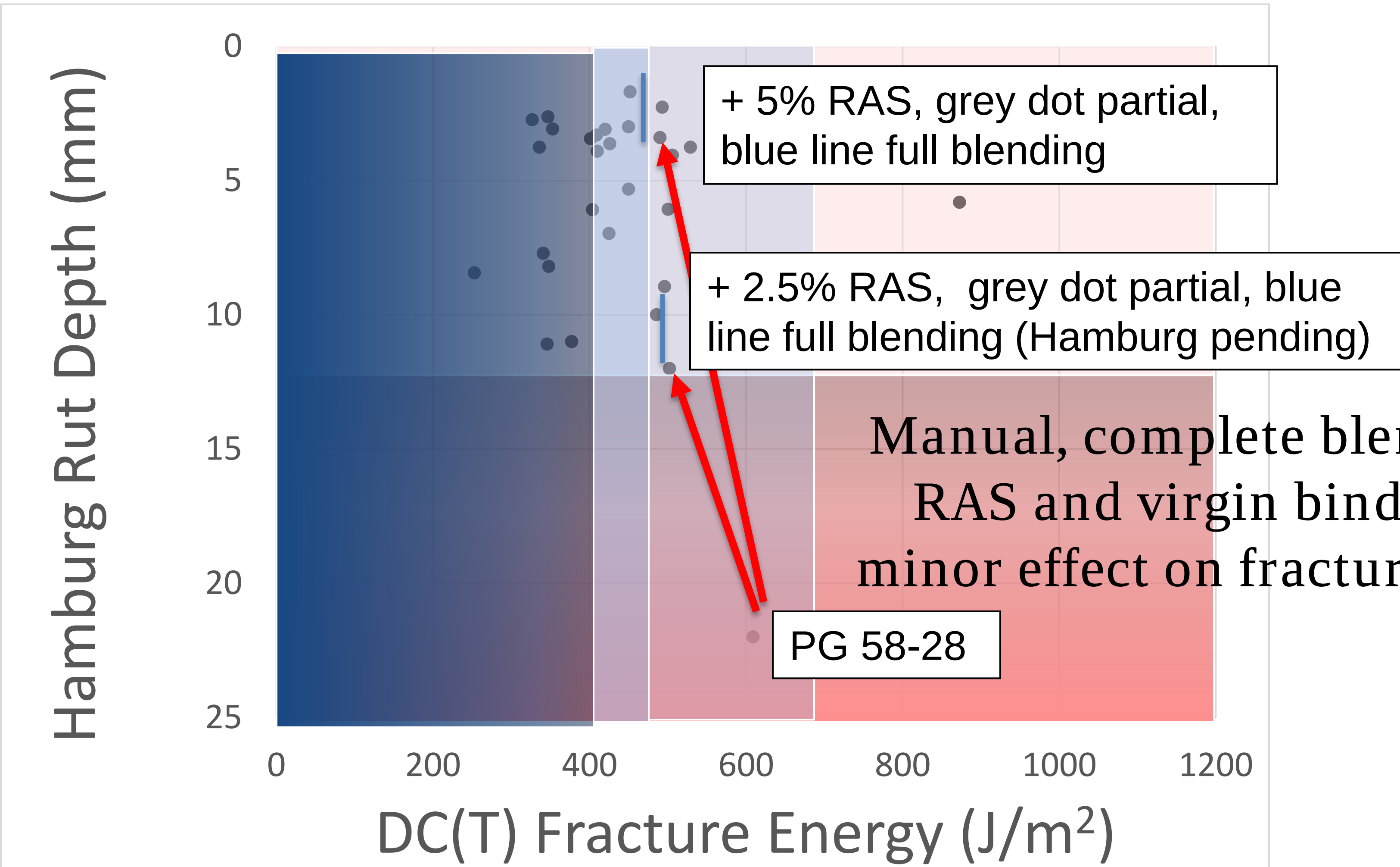
-35
-30
-25
-20
-15
-10
-5
0
Embrittlement Temperature (°C)
Virgin PG 58-28
Virgin PG 64-22
2.5% RAS PG 58-28
5.0% RAS PG 58-28

# +RAS vs. Harder Binder




RAS more effective than stiffer binder in improving this mix

# Partial vs. Manual Complete Blending



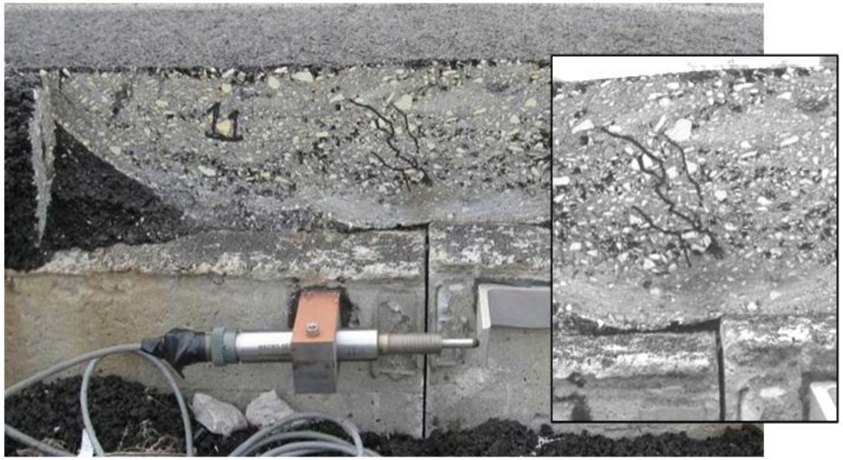

Manual, complete blending of RAS and virgin binder has minor effect on fracture energy

# 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.

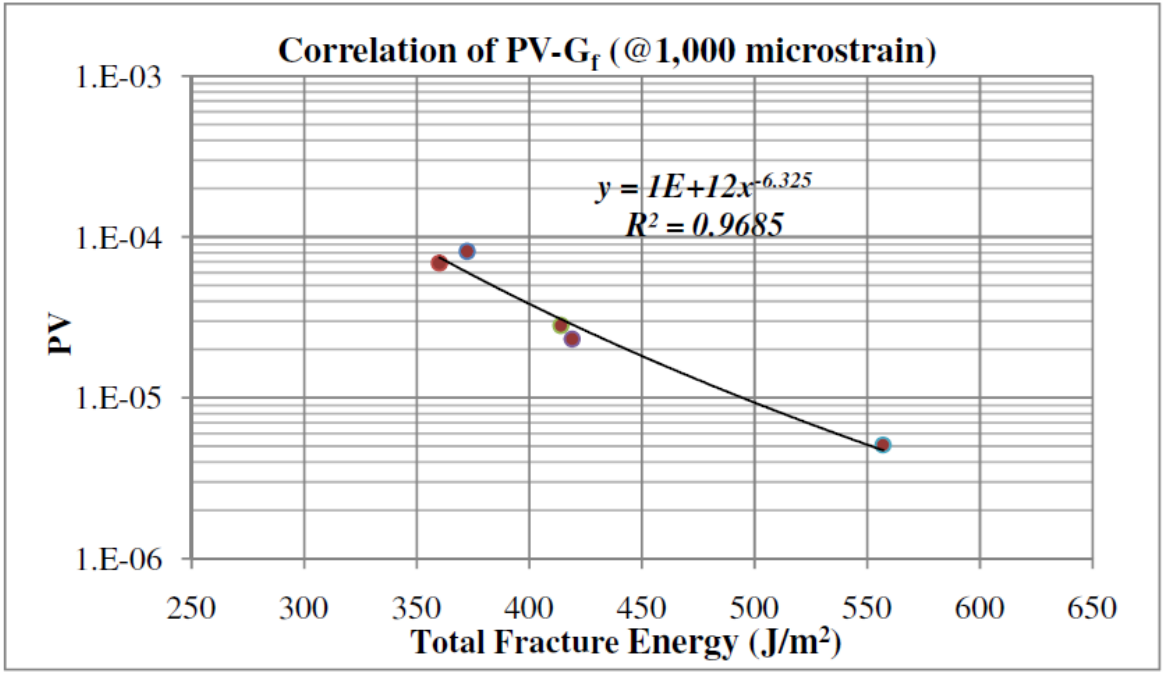
# Ultra-high Fracture Energy Mixes for Reflective Crack Control: ORD 9R Project

Accelerated Pavement Study (ATLAS)



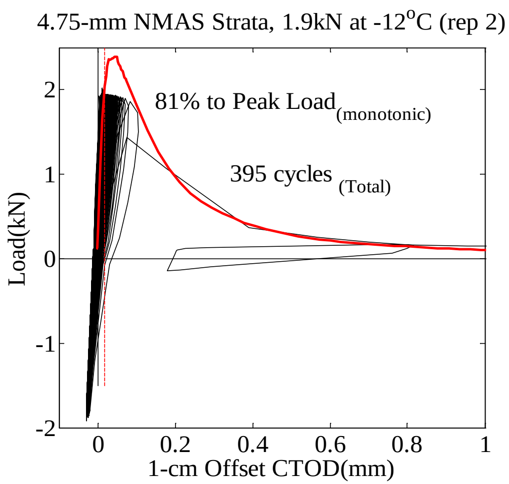

ORD Solution: Ultra-high fracture energy mixtures, 850 - 1,300 J/$m^2$

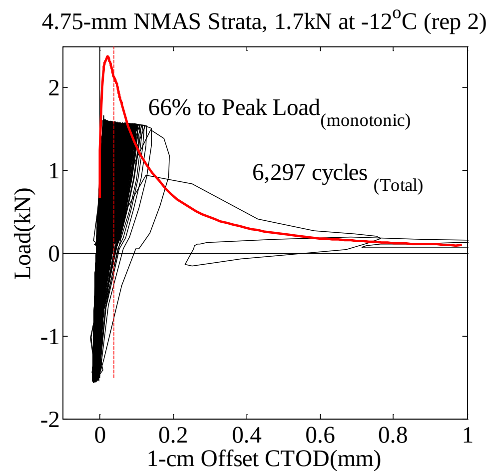
# DC(T) Fracture Energy (Monotonic) vs. 4-pt Flexural Fatigue (Plateau Value)

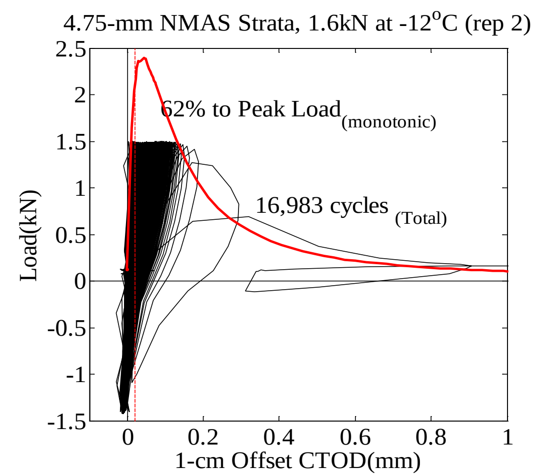


# Cyclic DC(T): Load-Offset CTOD (-12$^o$C)

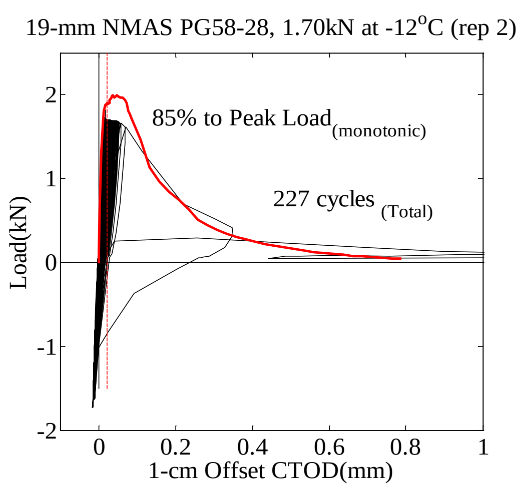
Aged 4.75mm Mix

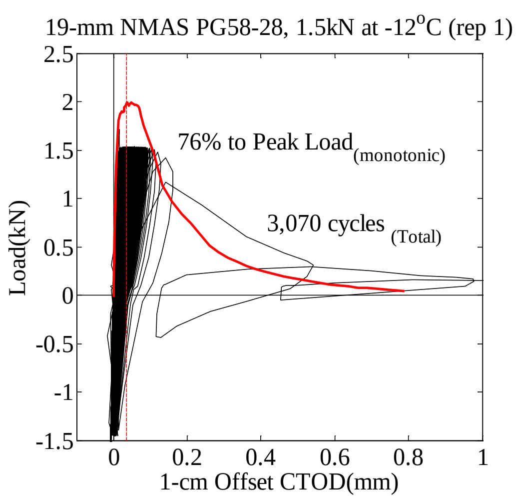


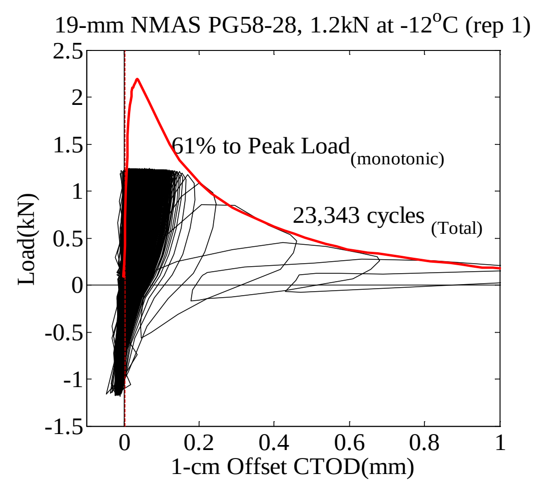



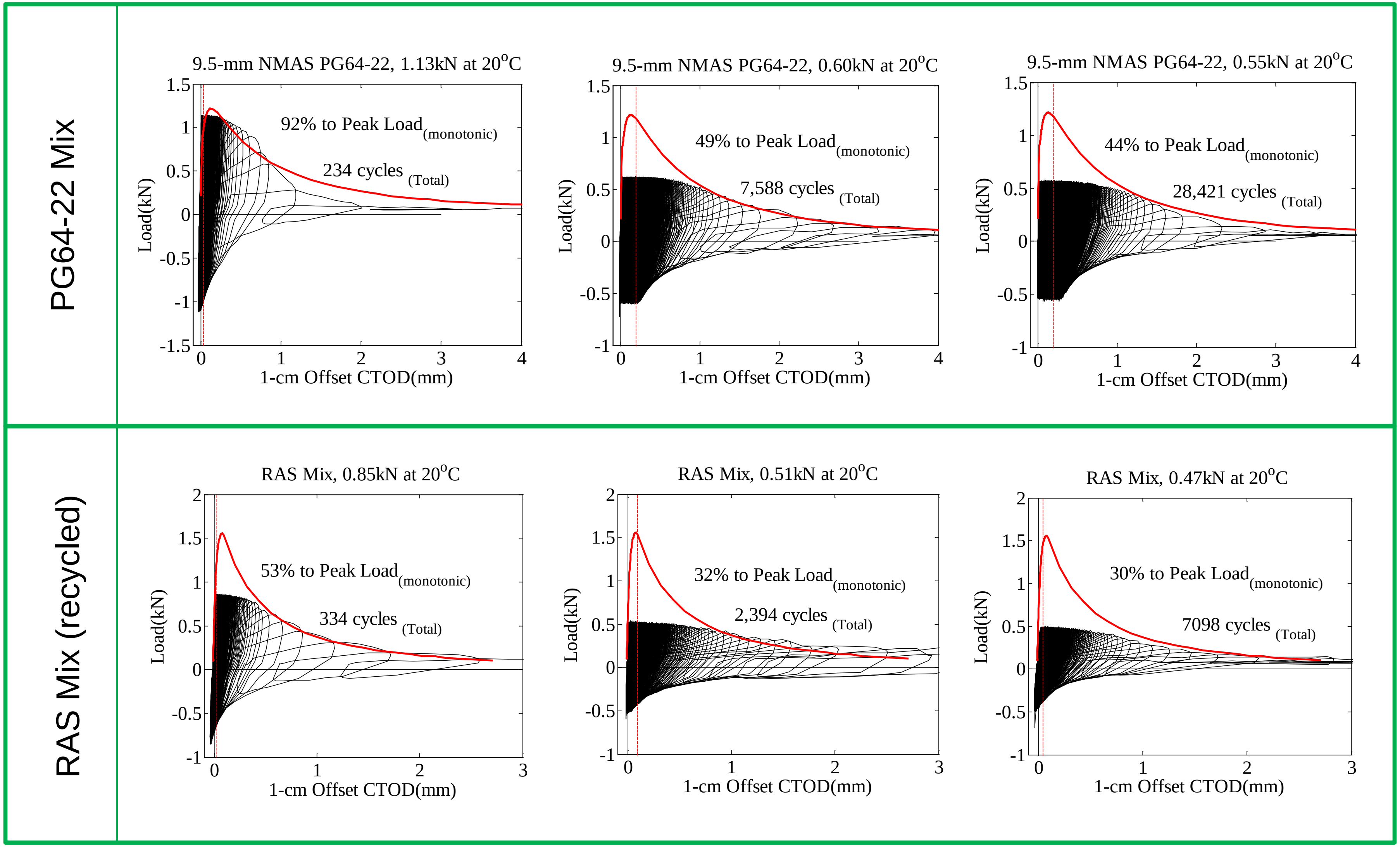

PG58-28 Mix



# Cyclic DC(T): Load-Offset CTOD (20$^o$C)



# 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.

# Acknowledgments

- Road Science LLC, Tulsa, OK
- STATE Testing, LLC
- Test Quip LLC
- IDOT/Illinois Center for Transportation
- Open Road Asphalt LLC, Fairmont, IL
- Emulsicoat Inc, Urbana, IL
- US RAS Association, Midwest

# Thank you for your attention!

Questions/Comments