ISAP- International Workshop on Asphalt Binders and Mastics

Overview of the Use of Fracture Mechanics for Binders and Mastics Characterization

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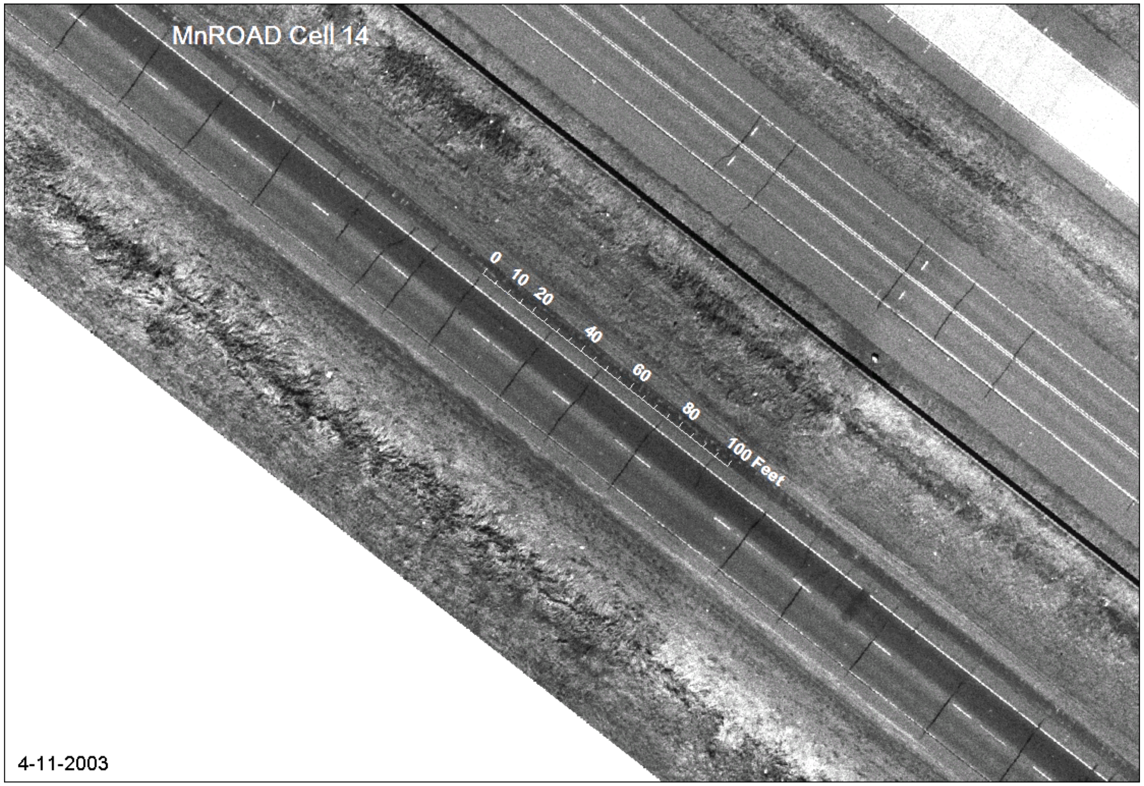
Madison-Wisconsin

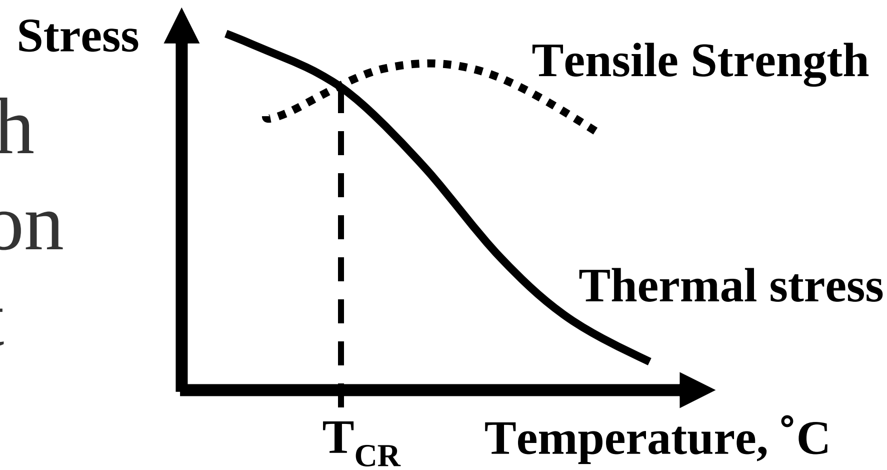
Motivation



***From Marasteanu class lectures**

Motivation

Thermal cracking is addressed based on strength and creep tests performed on asphalt binders and asphalt mixtures



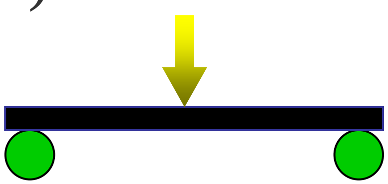
Two simple laboratory tests were developed by SHRP:

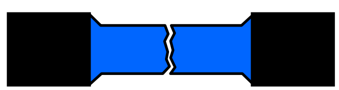
(1) Bending Beam Rheometer Test (**BBR**)

(2) Direct Tension Test (**DTT**)

$$\sigma_{ij}(t) = \int_0^t E_{ijkl}(t-\xi)\frac{\partial \varepsilon_{kl}(\xi)}{\partial \xi}d\xi$$

$$\varepsilon_{ij}(t) = \int_0^t D_{ijkl}(t-\xi)\frac{\partial \sigma_{kl}(\xi)}{\partial \xi}d\xi$$





Motivation

Mitigation of thermal cracking requires an understanding of relevant parameters that describe how cracks initiate and propagate

- Most widely used binder test method to address low temperature cracking is **BBR**
- **BBR** characterizes material in linear viscoelastic domain at small strain levels and therefore could be limited in its ability to provide a complete picture of thermal cracking phenomenon
- More appropriate approach is to use test methods based on fracture mechanics principles => such as Single-Edge Notch Beam test (**SENB**)

Background

- Various pavement distresses are related to fracture properties of asphalt layer
  - Longitudinal, thermal, and reflective cracking
- Fracture resistance of asphalt materials significantly influences service life of pavements
- Most powerful tool to study fracture properties of engineering materials is fracture mechanics
  - Earliest attempts to investigate mechanism of fracture in asphalt was performed by Moavenzadeh (1967)
  - It took more than two decades to incorporate fracture mechanics tools in asphalt materials characterization

Background

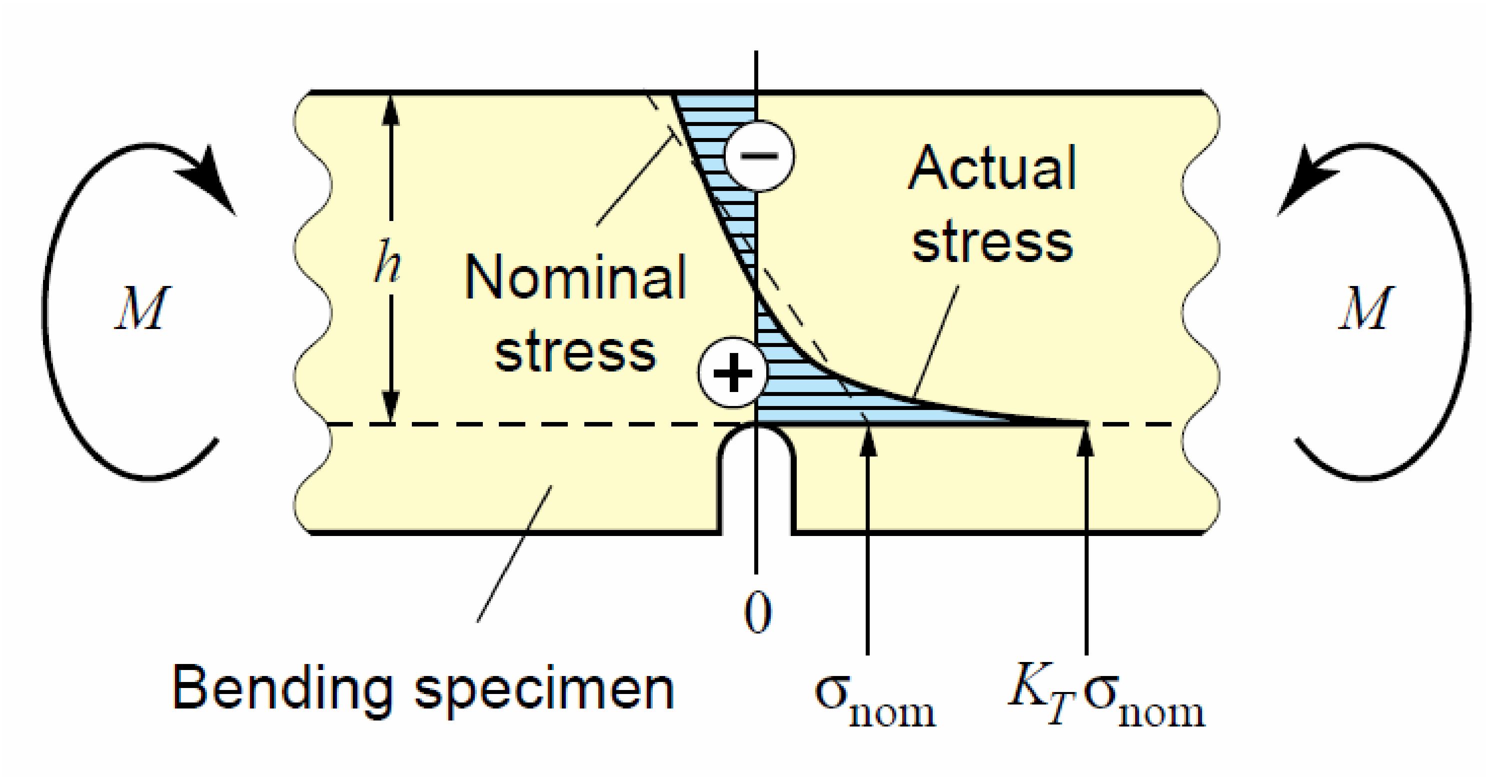
Fracture strength is function of cohesive forces holding atoms together

Theoretical cohesive strength of brittle and elastic material is ~ E/10 => Experimentally E/100 to E/10,000

Griffith (1920s) proposed that difference is due to microscopic flaws amplifying local stress and producing stress concentration

Background

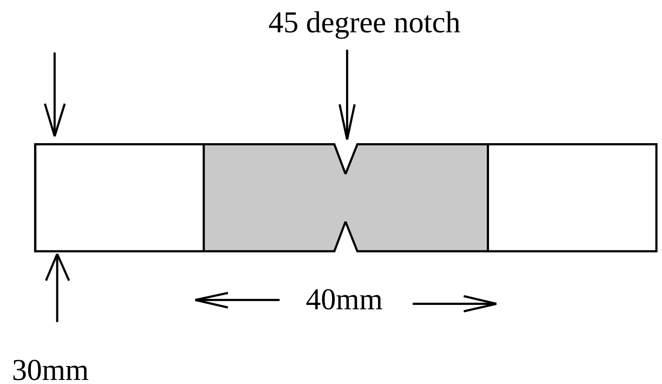
Stress-Concentration Effect of Notch in Bending



Double Edge Notch Tension Test (DENT)

Andriescu and **Hesp** (2004) tested binders at 20°C and fracture energy (**G_f**) was measured to predict fatigue cracking

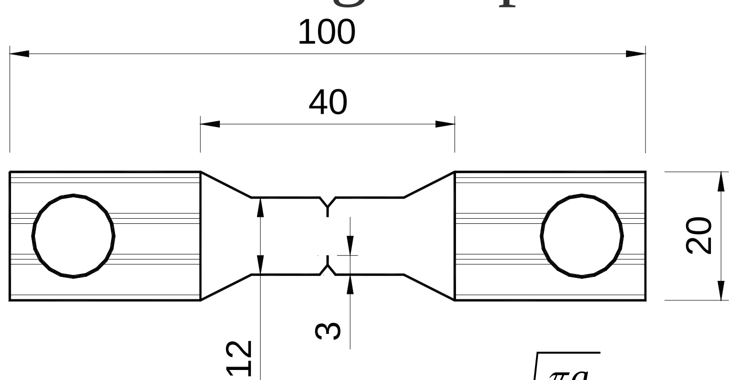
- Essential work of fracture (**EWF**) method was used to estimate fracture resistance of binders by dividing strain energy into essential work of fracture (w_e) and plastic work of fracture (w_p)

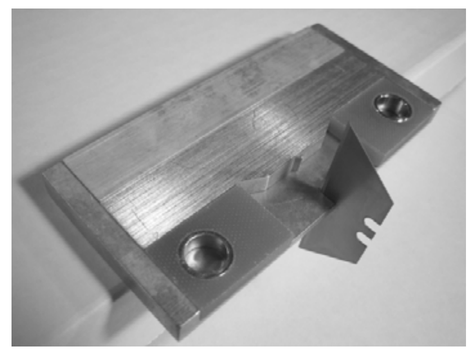


Double Edge Notch Tension Test (DENT)

Zofka and **Marasteanu** (2007) compared **DENT** and **DT** for nine different binders

-Results showed that **DENT** produces better repeatability than **DT** and it can be used to estimate critical cracking temperatures of binders





$$K_{IC} = \frac{P}{B\sqrt{W}} \frac{\sqrt{\frac{\pi a}{2W}}}{\sqrt{1-\frac{a}{W}}} \left[1.122 - 0.561\left(\frac{a}{W}\right) - 0.205\left(\frac{a}{W}\right)^2 + 0.471\left(\frac{a}{W}\right)^3 + 0.190\left(\frac{a}{W}\right)^4 \right]$$

Single-Edge Notched Beam (SENB)

Lee and Hesp (1994) were among first to use **SENB** geometry to measure fracture properties of asphalt binders

Anderson et al. (2001) used SE(B) or SENB test to measure fracture toughness of fourteen types of asphalt binders: one plain binder and its thirteen modified ones

- They checked effectiveness of characterization of low-temperature cracking resistance with different grading methods
- Fourteen asphalt binders were much better discriminated based on fracture toughness than PG criteria

Single-Edge Notched Beam (SENB)

- **SENB** results by **Olard and Di Benedetto** (2004) indicated that fracture toughness was less dependent on temperature and loading rate than fracture energy
- Data showed probable existence of lower bound for fracture energy of asphalt binders => reached in glassy and brittle state of asphalt binders
  - Asymptotic value for fracture energy of asphalt mixtures was also reported by **Li and Marasteanu** (2004)

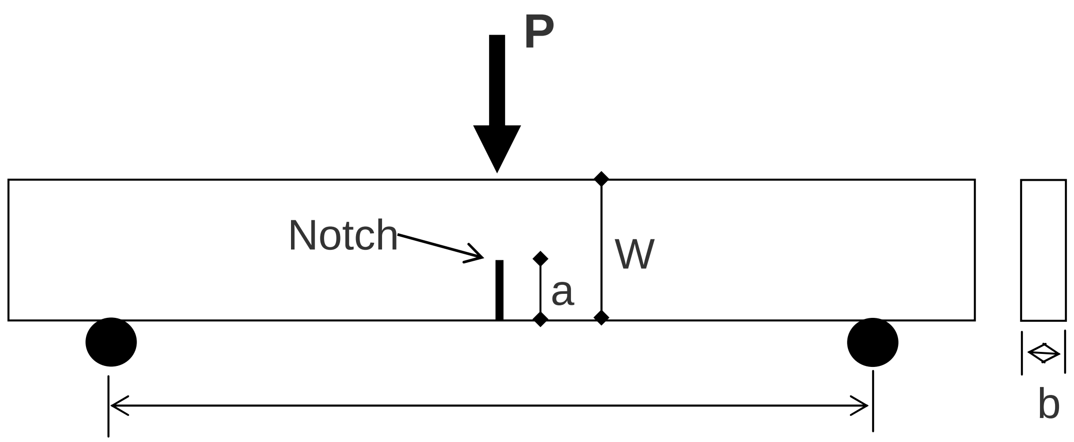
Single-Edge Notched Beam (SENB)

Research by **Hoare and Hesp** 2000, **Hesp** 2003, **Chailleux and Mouillet** 2006, **Chailleux et al**. 2007 have also used SENB to obtain fracture properties of asphalt binders at low temperatures

=> They succeeded in grading a broad range of materials with different levels of modification

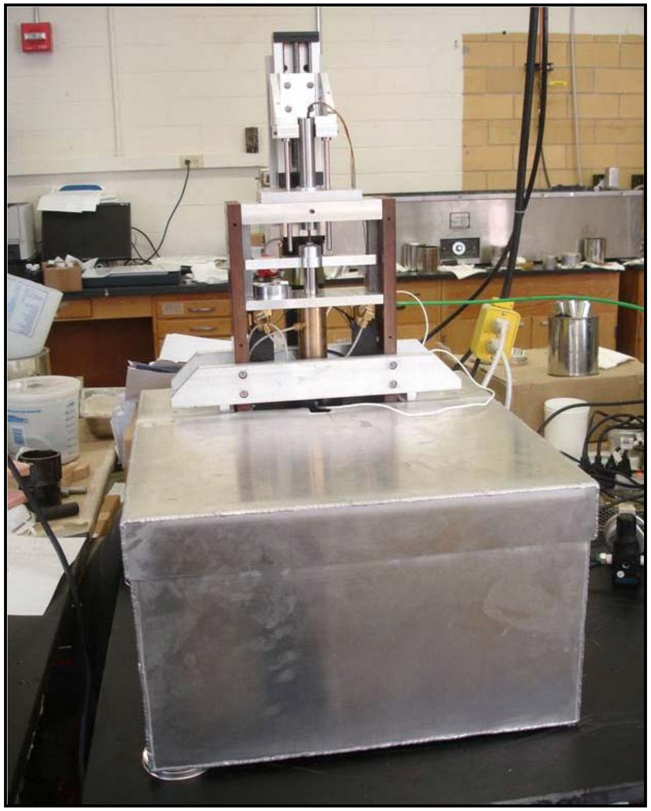
Single-Edge Notched Beam (SENB)

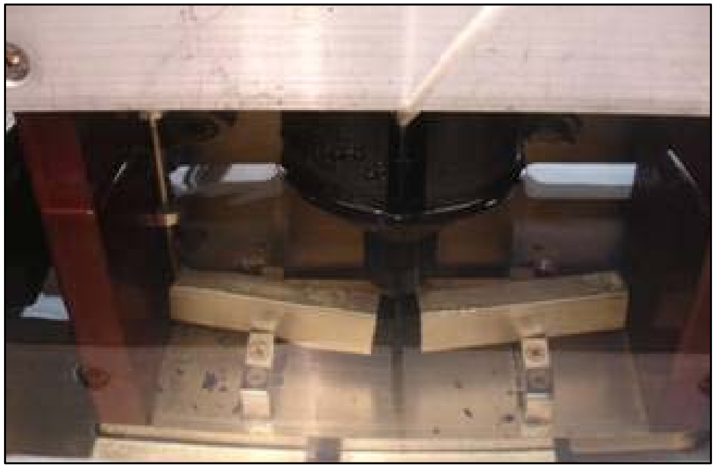
Follows ASTM E399 and assumes linear elastic fracture mechanics (LEFM) conditions are true



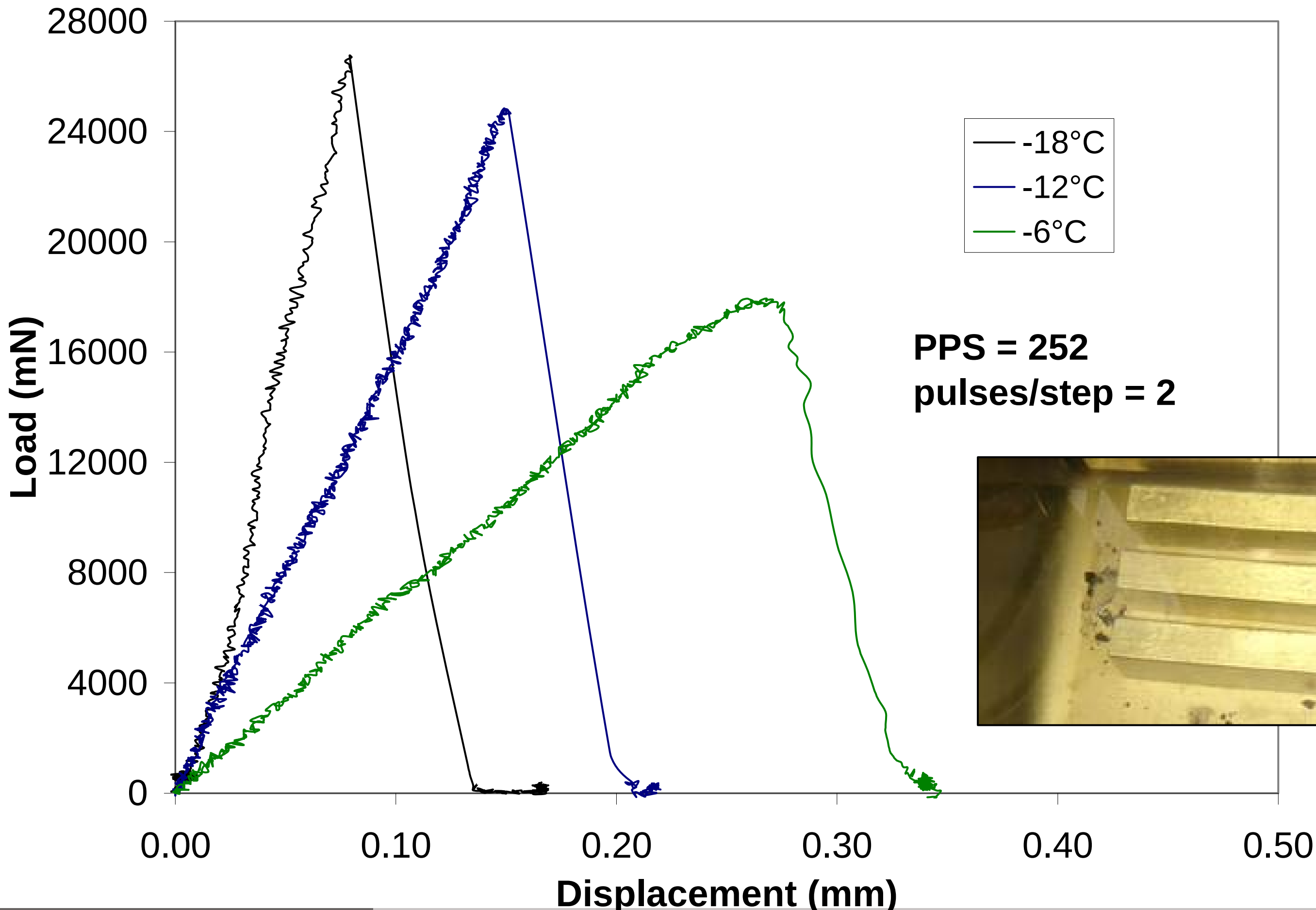
$$K_{\mathrm{I}} = \frac{P \cdot S}{BW^{\frac{3}{2}}} f\left(\frac{a}{W}\right) \longrightarrow f\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^{\frac{1}{2}}\left[1.99 - \frac{a}{W}\left(1 - \frac{a}{W}\right)\left(2.15 - 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)^{2}\right)\right]}{2\left(1 + 2\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}}$$

BBR-SENB system





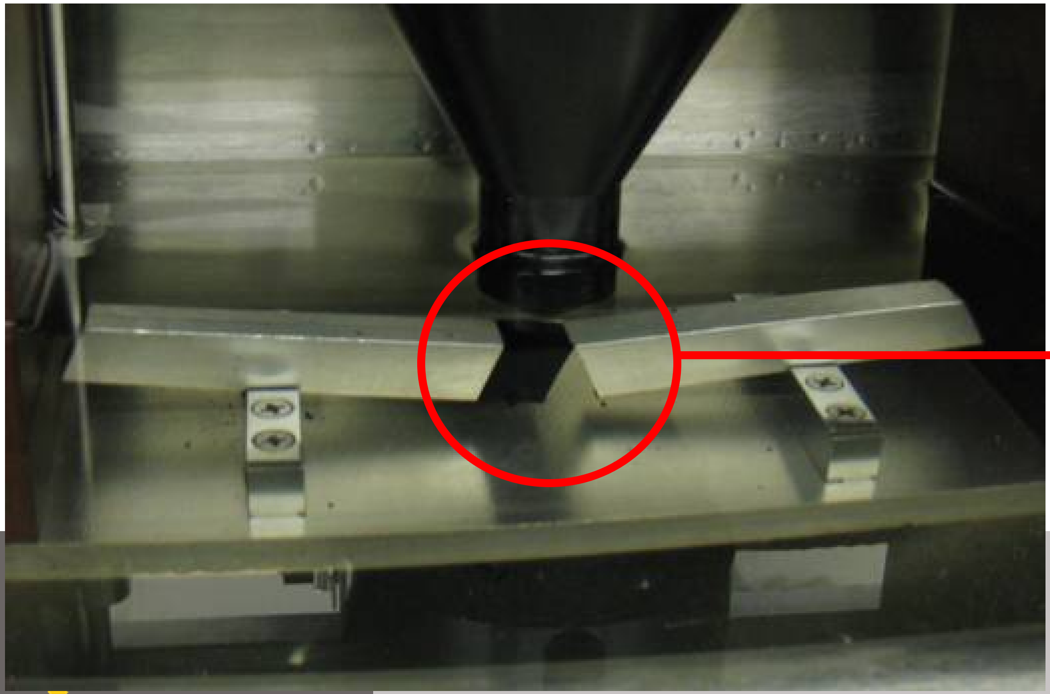
BBR-SENB: Typical Results Binders



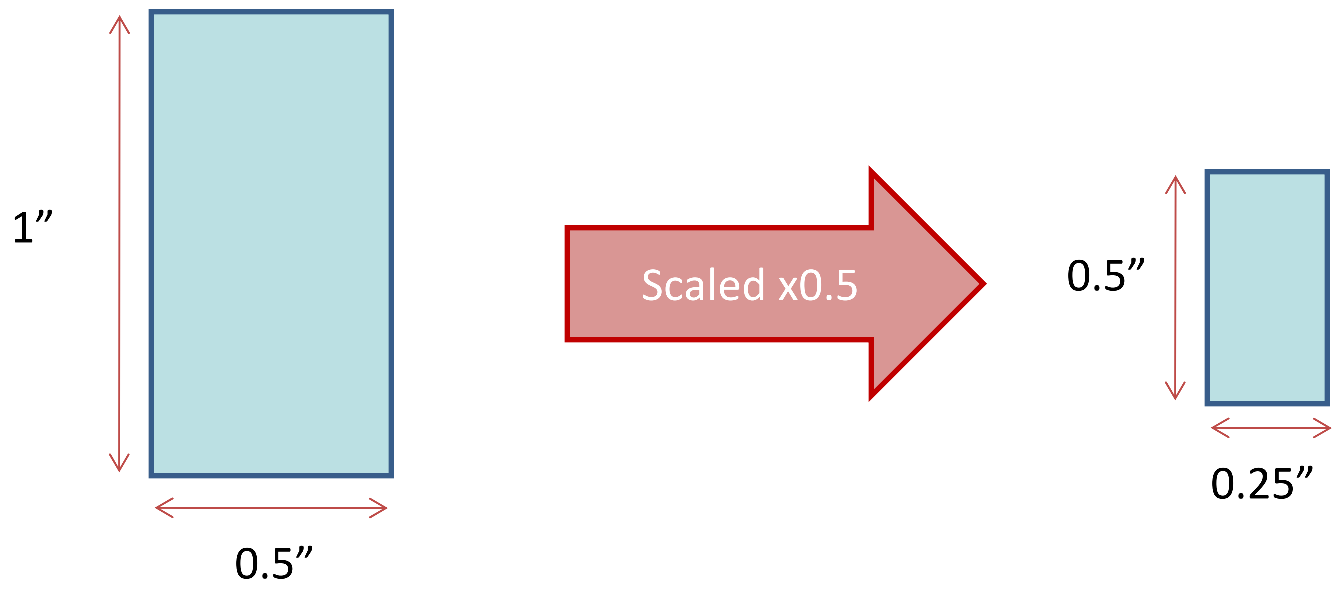
PG 64-22

Issues with current SENB Geometry

- Sample preparation is time consuming and difficult
- Adhesion problems
- Samples are delicate and premature failure at metal-binder interface usually occurs when manipulating beams before testing



Proposed Change in Geometry

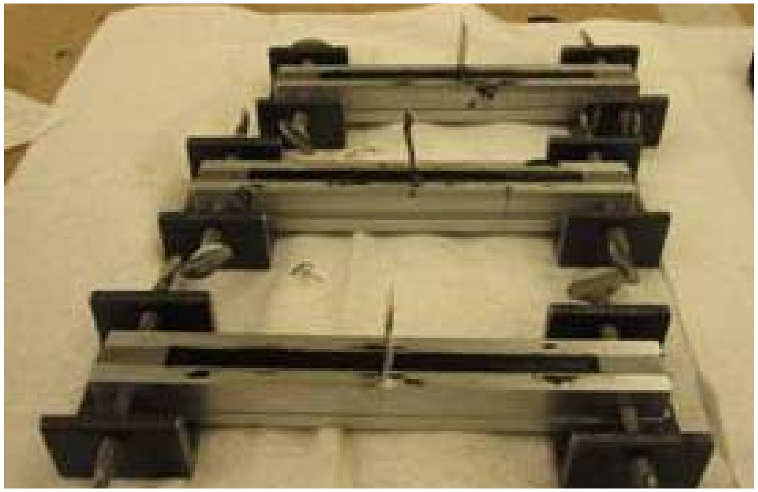


Original Size

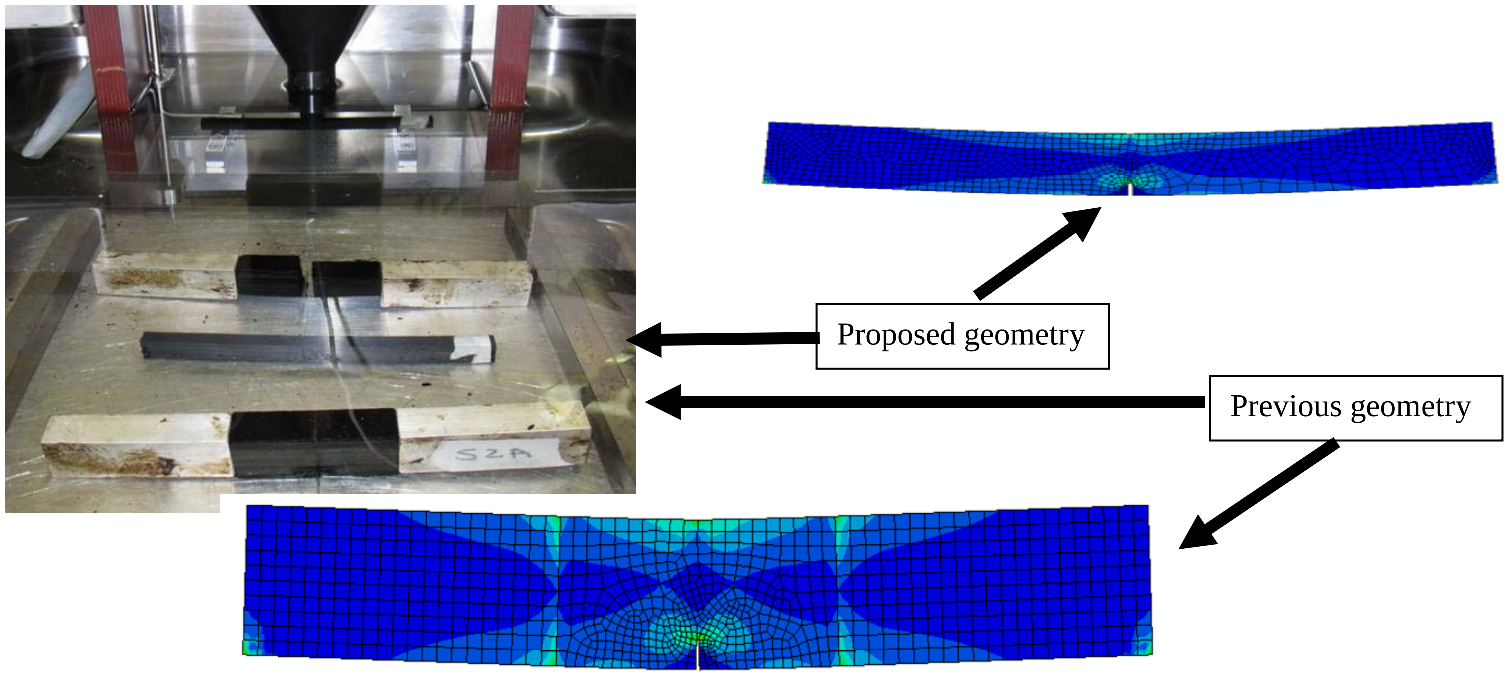
New Size (BBR)

BBR-SENB system

Modification of basic **BBR** testing device was carried out to allow for **controlled deformation rate** and a new SENB sample geometry => **BBR** beam with a notch was used to provide a more homogeneous specimen

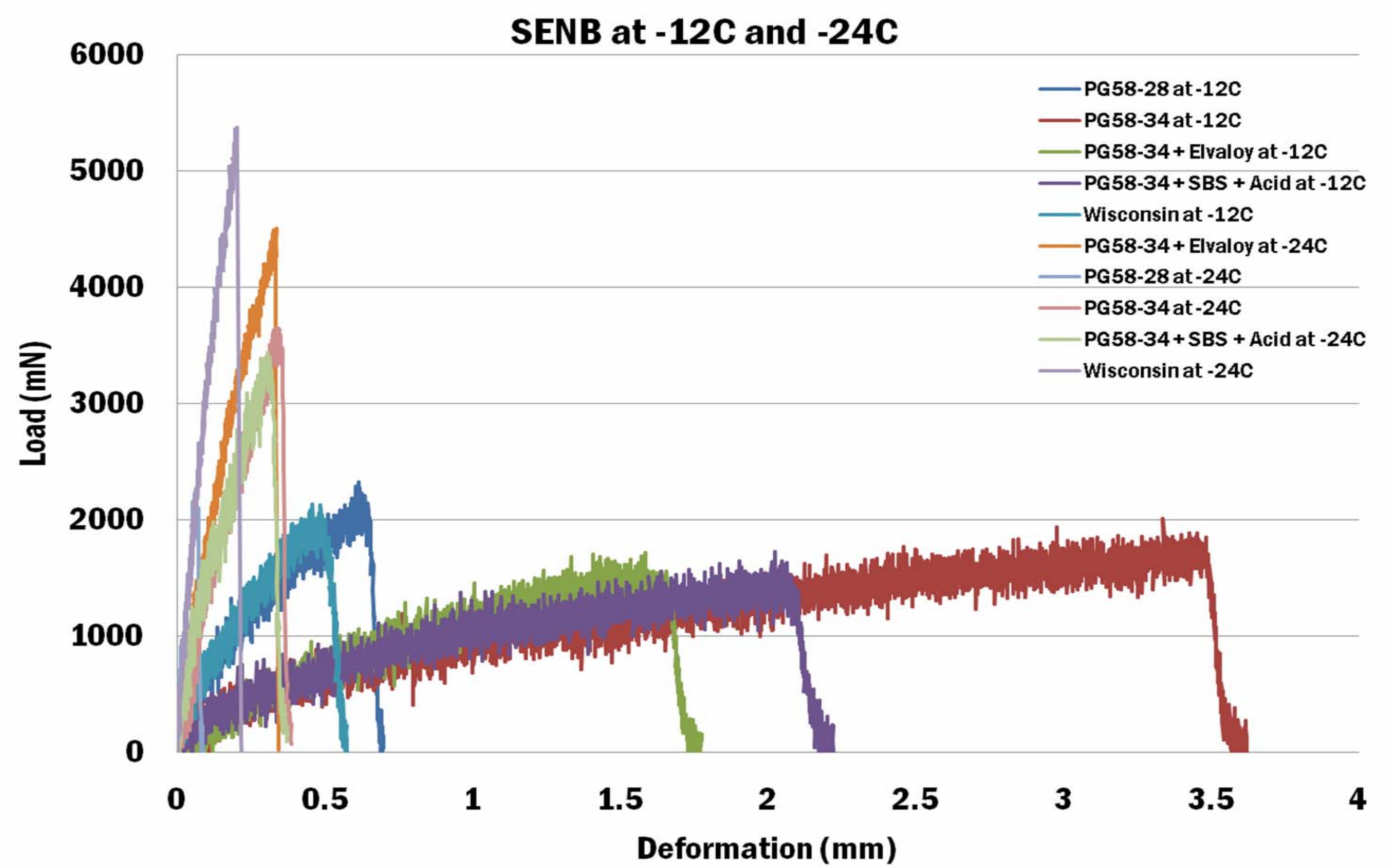


Previous and New Geometry

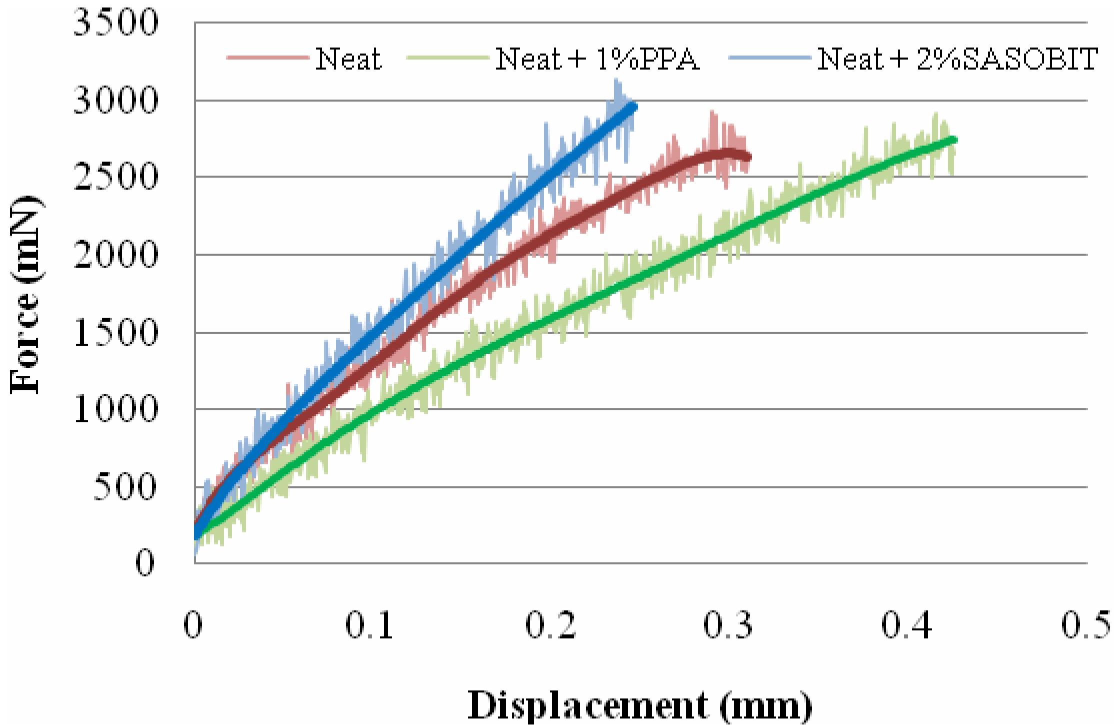


No stress discontinuities are observed proposed geometry. Adhesion problem between binder and metal bars is avoided

BBR-SENB: Typical Results

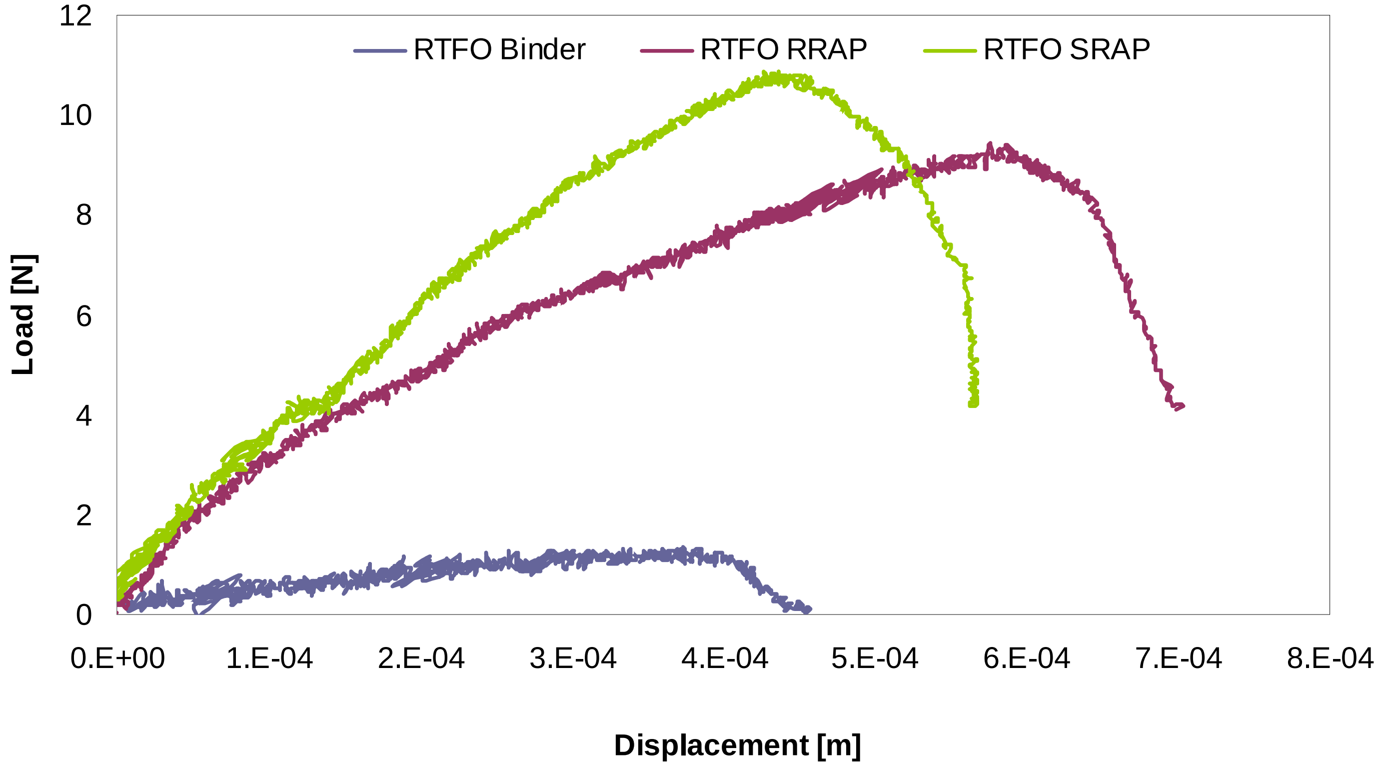


BBR-SENB: Typical Results



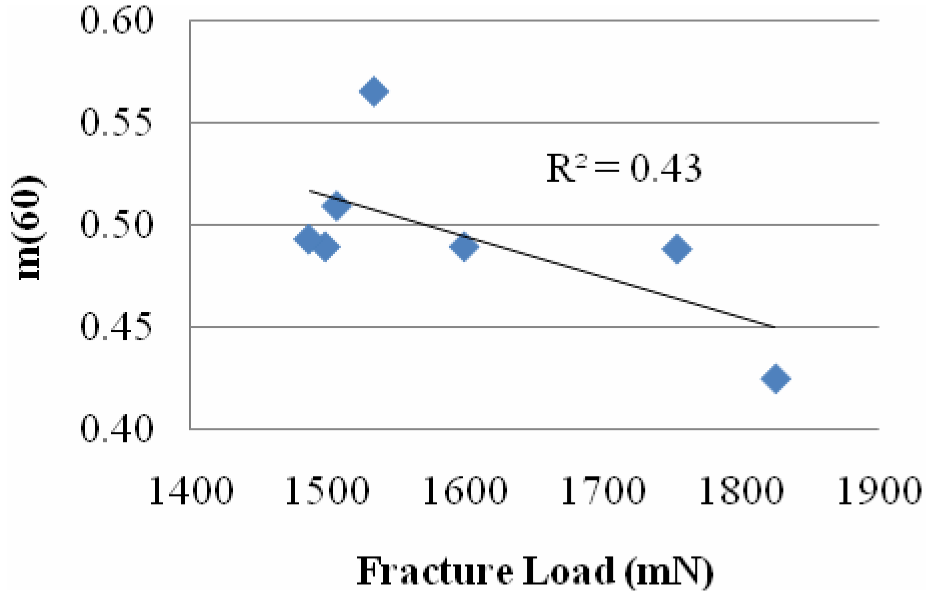
Force-displacement graph for PG 64-22 binder plus modification at -12° C

BBR-SENB: Mastics

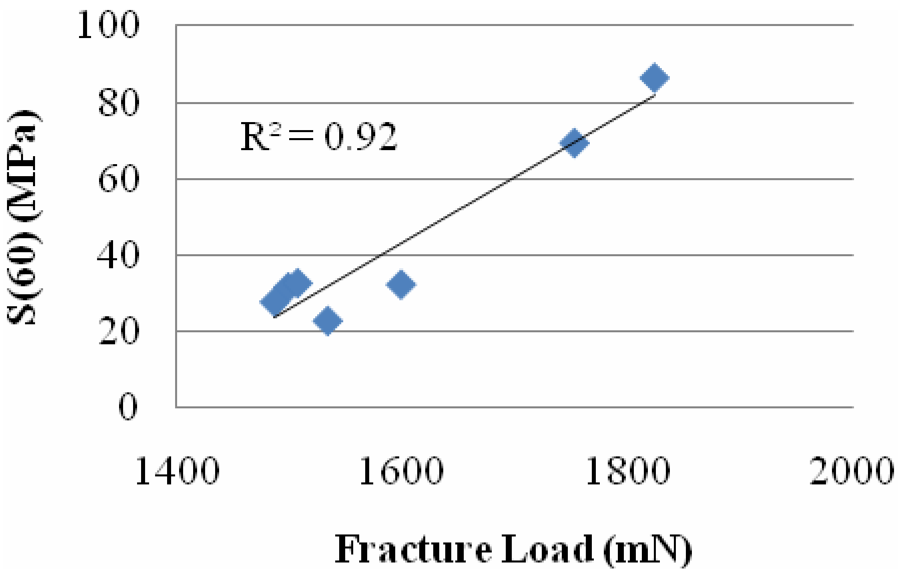


System is capable of differentiating fracture properties of RAP materials

SENB and BBR

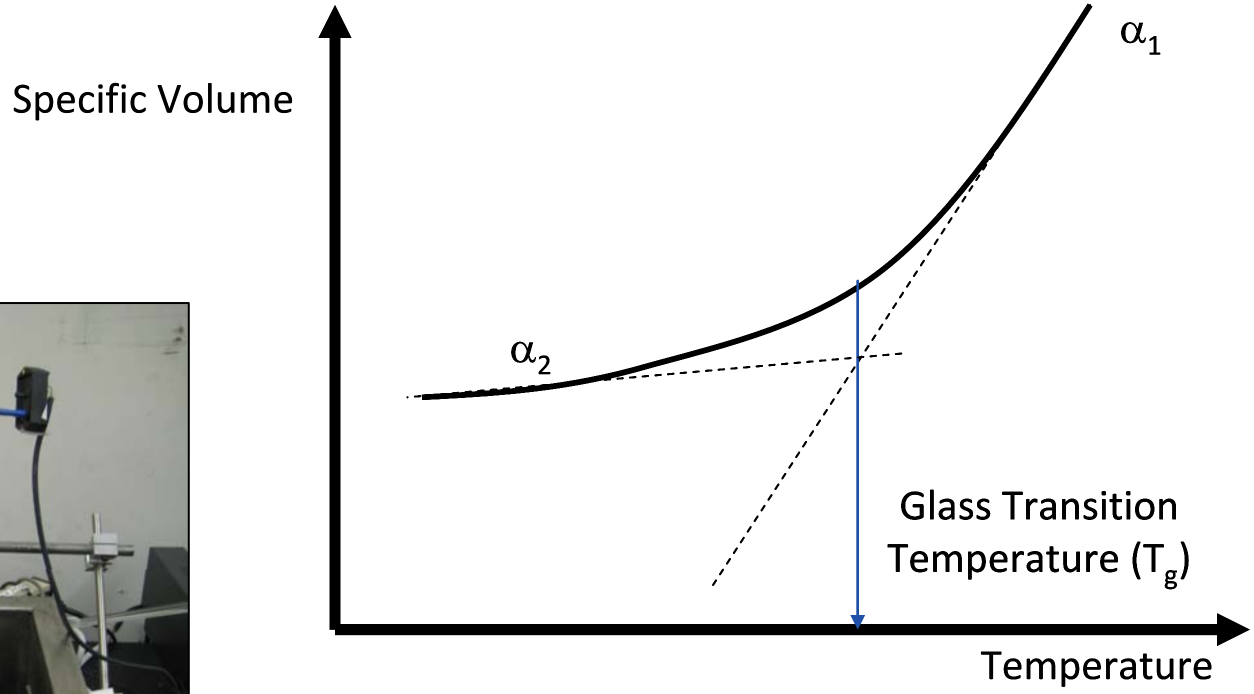


0.60
0.55
0.50
0.45
0.40
m(60)
$R^2 = 0.43$
1400 1500 1600 1700 1800 1900
Fracture Load (mN)

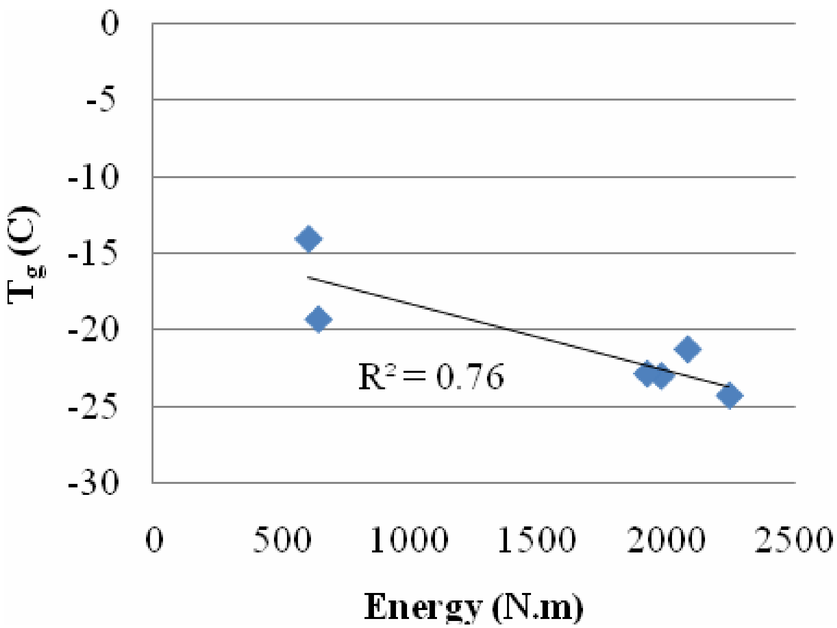


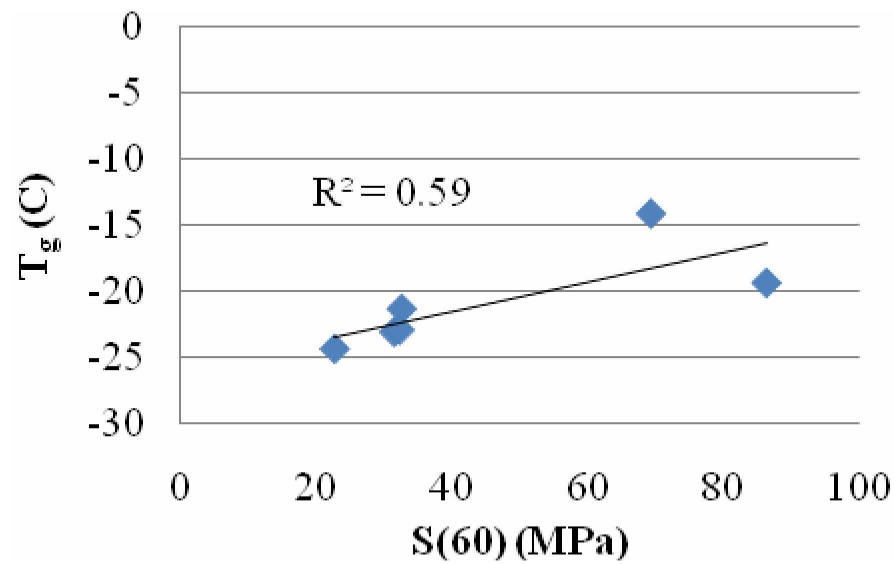
100
80
60
40
20
0
S(60) (MPa)
$R^2 = 0.92$
1400 1600 1800 2000
Fracture Load (mN)

Glass Transition T_g



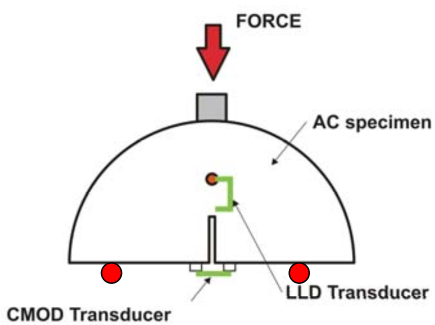
T_g and SENB, BBR



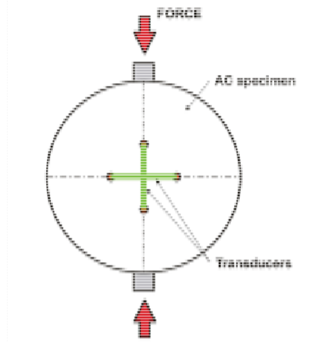


Why use fracture mechanics for low temp cracking?

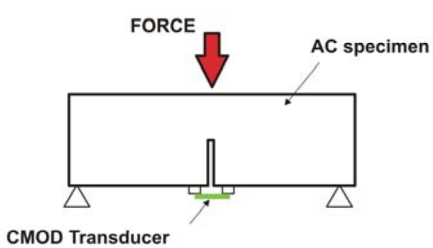
Test Methods in Mixtures



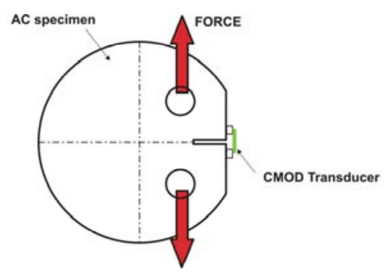
SCB



IDT



SENB



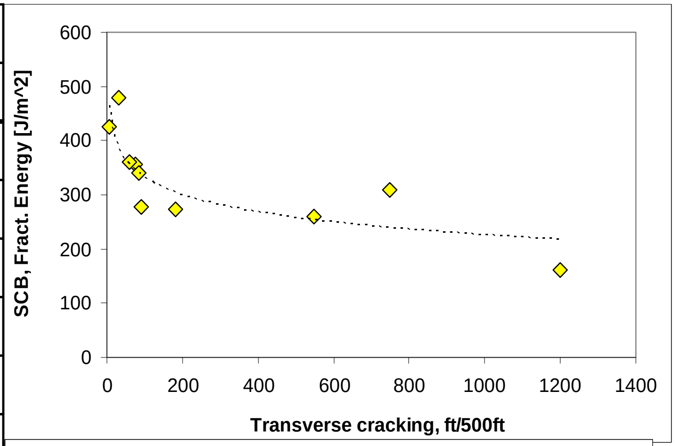
DCT

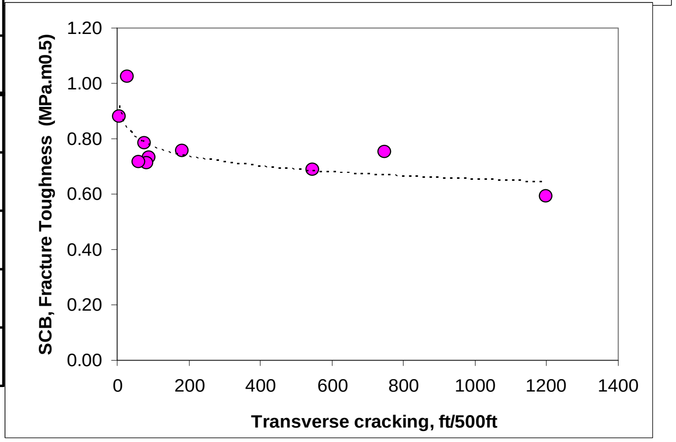
ID	State	Asphalt binder
IL I74	IL	AC-20
MN75 2	MN	PG 58-28
MN75 4	MN	PG 58-34
MnROAD 03	MN	PG 58-28
MnROAD 19	MN	PG 64-22
MnROAD 33	MN	PG 58-28
MnROAD 34	MN	PG 58-34
MnROAD 35	MN	PG 58-40
US20 6	IL	AC-10
US20 7	IL	AC-20
WI STH 73	WI	PG 58-28

*** Marasteanu *et al*. (2007) "Pooled Fund Study on Low Temperature Cracking Phase I"**

Why use fracture mechanics for low temp cracking?

Laboratory parameters		Correlation coefficients	
		Pearson	**Spearman**
Mixture parameters	SCB, fracture energy	-0.708	**-0.718**
	IDT, S(60sec)	-0.713	-0.405
	IDT S(500sec)	-0.590	-0.071
	SCB,Fracture Toughness	-0.639	**-0.736**
	IDT, strength	-0.325	**-0.571**
	DCT, fracture energy	-0.265	**-0.500**
	SEB energy	-0.291	**-0.500**
Binder parameters	BBR S @ 60sec	0.105	0.248
	m-value S @ 60sec	-0.252	0.152
	DT strain at 3%	-0.694	**-0.673**
	DENT Stress at failure	-0.045	0.217
	DENT Strain at failure	-0.239	-0.250





*** Marasteanu *et al*. (2007) "Pooled Fund Study on Low Temperature Cracking Phase I"**

Final Remarks

- **BBR-SENB** test is able to capture ductile-brittle transition =>a good indicator of glass transition of binder
- In contrast to **BBR**, it is believed that **BBR-SENB** test can capture effects of non-linear viscoelastic or damage resistance behavior of binders at low temperatures => a potentially ideal performance characterization test

Final Remarks

- Based on LTC phase I experiments
  - Simple descriptive statistics show that all **fracture parameters** are significant with respect to measured cracking occurrence
  - **Fracture toughness** and **fracture energy** have highest correlations to field performance

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Thank you!