Statens vegvesen

Workshop on Hot Mix Asphalt Thermal Cracking
13. august 2006 (oppsummering)

RAPPORT Teknologiavdelingen Nr. 2470

Veg- og trafikkfaglig senter
Dato: 2006-09-25

TEKNOLOGIRAPPORT nr. 2470

Statens vegvesen

Vegdirektoratet
Teknologiavdelingen

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Tittel

Workshop on Hot Mix Asphalt Thermal Cracking 13. august 2006 (oppsummering)

Utarbeidet av

SINTEF Byggforsk på oppdrag fra Vegdirektoratet Tek-T

Dato:	Saksbehandler	Prosjektnr:
2006-09-25	Joralf Aurstad	601336
	Kontrollert av	**Antall sider og vedlegg:**
	Leif Bakløkk	42

Sammendrag

I forbindelse med 10th International Conference on Asphalt Pavements i Quebec City, Canada i august 2006 ble det arrangert et eget fagseminar (workshop) innenfor temaet lavtemperaturskader/ lavtemperaturegenskaper for asfaltdekker.

Denne rapporten gir en oppsummering av fagseminaret.

Summary

This report gives a summary of the "Workshop on Hot Mix Asphalt (HMA) Thermal Cracking" in Quebec City, Canada 13 August 2006.

The workshop was organised in connection to the 10th International Conference on Asphalt Pavements (ICAP 2006).

Emneord:

Asfalt, klima, skader, lavtemperatur, oppsprekking

SINTEF	NOTAT				
	GJELDER **Oppsummering av workshop med tittel *"Workshop on Hot Mix Asphalt (HMA) Thermal Cracking"* under ISAP 2006**	BEHANDLING	UTTALELSE	ORIENTERING	ETTER AVTALE
SINTEF Byggforsk AS Veg- og jernbaneteknikk Postadresse: 7465 Trondheim Besøk: Høgskoleringen 7A Telefon: 73 59 46 10 Telefaks: 73 59 14 78 Foretaksregisteret: NO 989 015 540 MVA	GÅR TIL Statens vegvesen Vegdirektoratet, TEK-T v/Joralf Aurstad				X
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PROSJEKTNR.	DATO	SAKSBEARBEIDER/FORFATTER	ANTALL SIDER
503524	2006-08-21	Bjørn Ove Lerfald	6 + 3 vedlegg

Oppsummering

Dette notatet gir en oppsummering av en workshop med tittelen; *"Workshop on Hot Mix Asphalt (HMA) Thermal Cracking"*. Workshopen ble avholdt under ISAP 2006 i Quèbec City i Canada. Dette notatet gir en oversikt over programmet for workshopen og et kort sammendrag av de foredrag som ble holdt.

INNHOLDSFORTEGNELSE

1 Bakgrunn

I forbindelse med ISAP-konferansen i Quèbec City den 12. – 17. august 2006 ble det avholdt en workshop med tittelen; *"Workshop on Hot Mix Asphalt (HMA) Thermal Cracking"*. Til å holde innlegg ved denne workshopen var det invitert personer fra Japan, USA, Canada, sentral Europa og fra Skandinavia. SINTEF ble oppfordret til å presentere nyere forskning som har blitt utført i Skandinavia med fokus på lavtemperaturoppsprekking. SINTEF ble samtidig bedt om å skrive en kort oppsummering fra workshopen. Dette notatet gjengir programmet fra workshopen og gir samtidig en kort oppsummering av de innlegg som ble holdt. Presentasjoner som var tilgjengelig er lagt som vedlegg til notatet.

2 Program

Programmet for workshopen var som følger:

8.30 – 8.40	Welcoming speech – Michel Paradis, MTQ
8.40 – 9.00	*Study on Thermal Cracking and Thermal Fatigue of HMA.* Dr. Alan Carter, École de Technologie de Supériure, Canada
9.00 – 9.20	*Thermal Cracking of Asphalt Pavements and Preventive Measures in Japan.* Dr. Jun Takou, Civil Engineering Research Institute of Hokkaido, Japan
9.20 – 9.40	*Research on thermal cracking in asphalt pavements in the Nordic countries.* Bjørn Ove Lerfald, SINTEF Veg- og jernbaneteknikk
9.40 – 10.00	*Low Temperature Cracking Pooled Fund Study.* Dr. William (Bill) Buttlar, University of Illinois, USA
10.00 – 10.30	Coffee break
10.30 – 10.50	*Prediction of low temperature crack spacing of asphalt pavements using TSRST results and mechanistic prediction model.* Dr. Hannele Zubeck, Chair, Arctic Engineering Program School of Engineering, University of Alaska Anchorage, USA.
10.50 – 11.10	*Modelling Developments in FHWA Pooled Fund Study on Low Temperature Cracking.* Dr. William (Bill) Buttlar, University of Illinois, USA.
11.10 – 11.30	*Influence of bitumen cohesion on hot mix thermal cracking.* Dr Chantal de la Roch, LCPC, France.
11.30 – 12.00	Plenary
1200	End of the session

3 Sammendrag

I det etterfølgende gis det et kort sammendrag av innholdet i presentasjonene.

Study on Thermal Cracking and Thermal Fatigue of HMA.
Dr. Alan Carter, École de Technologie de Supériure, Canada

Det ble presentert en oversikt over et pågående prosjekt med fokus på lavtemperaturoppsprekking og utmatting av varmprodusert asfalt (HMA). Bruk av Thermal Stress Restrained Specimen Test (TSRST) var en hovedaktivitet i forskningsarbeidet. I prosjektet skal det foretas en vurdering av prøvens størrelse for resultatene. Videre skal det foretas en vurdering av vann og avisningsvæske samt aldringens betydning for resultatene. Det er også planlagt en å utvikle en prosedyre hvor asfaltprøver utsettes for gjentatte fryse-/tinesykler for å vurdere reduksjon i motstand mot lavtemperaturoppsprekking som følge av "temperaturutmatting".

Thermal Cracking of Asphalt Pavements and Preventive Measures in Japan.
Dr. Jun Takou, Civil Engineering Research Institute of Hokkaido, Japan

Presentasjonen inneholdt en oversikt over pågående forskning på termal oppsprekking av asfaltdekker i Japan.
Det var fokusert både på termisk spenninger som opptrer i dekket og lavtemperaturegenskapene til dekkene, samt selve mekanismen for lavtemperaturoppsprekking og tiltak for å forhindre at oppsprekking skjer. Lengden av veger i kalde regioner har økt i Japan og det har blitt viktigere å utbedre sprekkeskader som skyldes lave temperaturer. Følgende hovedpunkter ble belyst:

1. Termiske sprekkeskader i vegdekker er hyppig registrert i Hokkaido, som er en kald region i Japan. I enkelte regioner overskrider fryseindeksen 1000 (°C * dager). Det er også store forskjeller mellom maks og minimumstemperatur. Minimumstemperaturen kan bli under 30 °C.
2. Tiltak mot lavtemperaturoppsprekking er i hovedsak bruk av myke bindemidler i asfaltdekkene og bruk av varmproduserte asfaltmasser i bærelag.
3. For å få bedre forståelse av lavtemperaturegenskapene til asfaltdekkene og de termiske spenninger som oppstår er det gjennomført undersøkelser hvor det er benyttet SHRP indirekte strekk test og måling av akustisk emisjon. Fra denne studien forelå følgende resultater:
   a. Resultater feltmålinger viser at dess større temperaturgradienten i dekket er jo større blir spenningene i dekket. Det registreres høye strekkspenninger i overflaten mens det lenger ned i dekkekonstruksjonene registreres trykkspenninger.
   b. Ved bruk av målinger fra akustisk emisjon blir lyder fra sprekker og sprekkutvikling målt. Resultatene viser at ved lave temperaturer skjer det for asfaltmaterialer en overgang fra visko-elastisk til elastisk oppførsel. Ved senkning av temperaturen oppstår mikrosprekker og til sist oppstår gjennomgående sprekker. Det er også funnet at mikrosprekker oppstår ved lavere temperaturer i dekker med modifiserte bindemidler enn med "ren bitumen". Temperaturforskjellen fra mikrosprekker oppstår og til gjennomgående sprekker oppstår er også større for masser med modifiserte bindemidler.
   c. Det er gjennomført forsøk med SHRP indirekte strekkforsøk. Resultatene fra disse viser at det er sammenheng mellom S-verdien fra bindemiddeltestingen og "deformasjonsmodulen" for asfaltmassen. Det kan være mulig å estimere

deformasjonsegenskapene til asfaltmassen ut fra volumandel steinmaterialer og S-verdien av bindemiddelet.

d. Det er utviklet en ny metode for rehabilitering av dekker med lavtemperatursprekker. Denne går ut på å benytte en elastisk fugemasse i sprekkene. Så legges et spenningsrelakserende lag før et drenerende asfaltdekke med modifisert bindemiddel legges på toppen. Oppfølging av denne metoden i felt viser at oppsprekkingen er redusert.

Research on thermal cracking in asphalt pavements in the Nordic countries.
<u>Bjørn Ove Lerfald, SINTEF Veg- og jernbaneteknikk</u>

Det ble presentert resultater fra prosjektet *"Ny asfaltteknologi"* som ble gjennomført i perioden 1994 – 98. I dette prosjektet ble det tatt i bruk utstyr som ble benyttet i det nye bindemiddelklassifiseringssystemet som ble utviklet i det amerikanske forskningsprosjektet SHRP. I *" Ny asfaltteknologi"* ble de mest vanlige norske bindemidler testet. Det ble også gjennomført feltundersøkelser for å se hvordan spesifikasjonene i SHRP passet for norske forhold. Det ble videre presentert resultater fra oppfølging av norske flyplasser over flere år. Resultatene som ble presentert var en verifisering av kriteriene for vurdering av bindemidlenes lavtemperaturegenskaper basert på S- og m-verdi etter BBR-undersøkelser.
Det ble også presentert noen utdrag fra en dr-ing. undersøkelse fra Sverige. Presentasjonen er lagt i vedlegg 1 og det vises til dette for detaljer.

Low Temperature Cracking Pooled Fund Study.
<u>Dr. William (Bill) Buttlar, University of Illinois, USA</u>

I 2004 startet et prosjekt I USA for å studere lavtemperaturegenskapene til asfaltdekker. Fire universiteter deltar i dette arbeidet (University of Minnesota, University of Wisconsin (Madison), Iowa State University og University of Illinois at Urbana Champaign). En viktig målsetting med arbeidet er å vurdere motstand mot lavtemperaturoppsprekking for ulike dekkekonstruksjoner hvor det var benyttet både modifiserte og umodifiserte bindemidler.
Andre viktige målsettinger er:

- Utvikle testmetoder for vurdering av lavtemperaturegenskaper.
- Validere modellen MEPDG for lavtemp.
- Etablere retningslinjer for MnROAD (felt verifisering))

Et omfattende forskningsprogram ble presentert. En rekke ulike testmetoder er planlagt gjennomført. Det ble også presentert en del resultater av arbeidet så langt, samt noen planer om videre arbeid i prosjektet.
Det vises til vedlegg 2 hvor presentasjonen er lagt ved for detaljer.

Prediction of low temperature crack spacing of asphalt pavements using TSRST results and mechanistic prediction model.
<u>Dr. Hannele Zubeck, Chair, Arctic Engineering Program School of Engineering, University of Alaska Anchorage, USA.</u>

I presentasjonen ble det redegjort for hvordan sprekkeavstand kan beregnes basert på resultater fra TSRST og bruk av en mekanistisk modell. Avstanden mellom sprekkene er avhengig av bruddspenning og skjærspenning mellom dekke og underliggende ubundne lag.

Modelling Developments in FHWA Pooled Fund Study on Low Temperature Cracking.
Dr. William (Bill) Buttlar, University of Illinois, USA.

Det ble presentert et arbeide med utvikling og validering av en modell for kalkulering av lavtemperaturoppsprekking. Arbeidet er en del av prosjektet presentert tidligere i workshopen med tittel, " *Low Temperature Cracking Pooled Fund Study"*. Det ble presentert bruk av nye testmetoder og nye modeller for lavtemperaturoppsprekking. Disse modellene tar hensyn til ulike parametere som f. eks type bærelag (type lag under asfalterte lag). Det gjenstår imidlertid en del utfordringer. Her nevnes:

- Temperaturen i dekket i felt varierer med tid og lokalisering.
- Oppsprekking som skyldes lave temperaturer og temperaturendringer kan bli påvirket av andre typer sprekker.
- Sprekkegeometrien er kompleks.

For detaljer om de brukte testmetoder og modellutviklingen vises til vedlegg 3.

Influence of bitumen cohesion on hot mix thermal cracking.
Dr Chantal de la Roch, LCPC, France.

I denne presentasjonen er det fokusert på bitumen kohesjon og dens betydning for lavtemperaturoppsprekking. To testmetoder ble omtalt , "3 points bending test" og "local fracture of bitumen". Prinsippet for den siste er å teste bruddstyrke og "healing" av en tynn bitumenfilm (ca 100 µm) mellom to stålkuler som simulerer tilslag. Resultatene fra testen angir sprø og duktil oppførsel til bitumen og kan også fokusere på "selvlegingsegenskaper" ved lave temperaturer så snart en sprekk oppstår inne i bitumenfilmen.
Viktige konklusjoner er:

- For å forstå lavtemperaturoppsprekking er det nødvendig å se på kohesjon i bitumen/mastiken.
- Mikrostrukturen i bindemidlet påvirker oppsprekkingsforløpet.
- Må også se på hvordan den totale massen oppfører seg ved lave temperaturer (samvirke mellom bindemiddel/mastik og steinmaterialet) for å forstå lavtemperaturoppsprekking.

Research on thermal cracking in asphalt pavements in the Nordic countries

Bjørn Ove Lerfald

SINTEF Road and Railway Engineering,

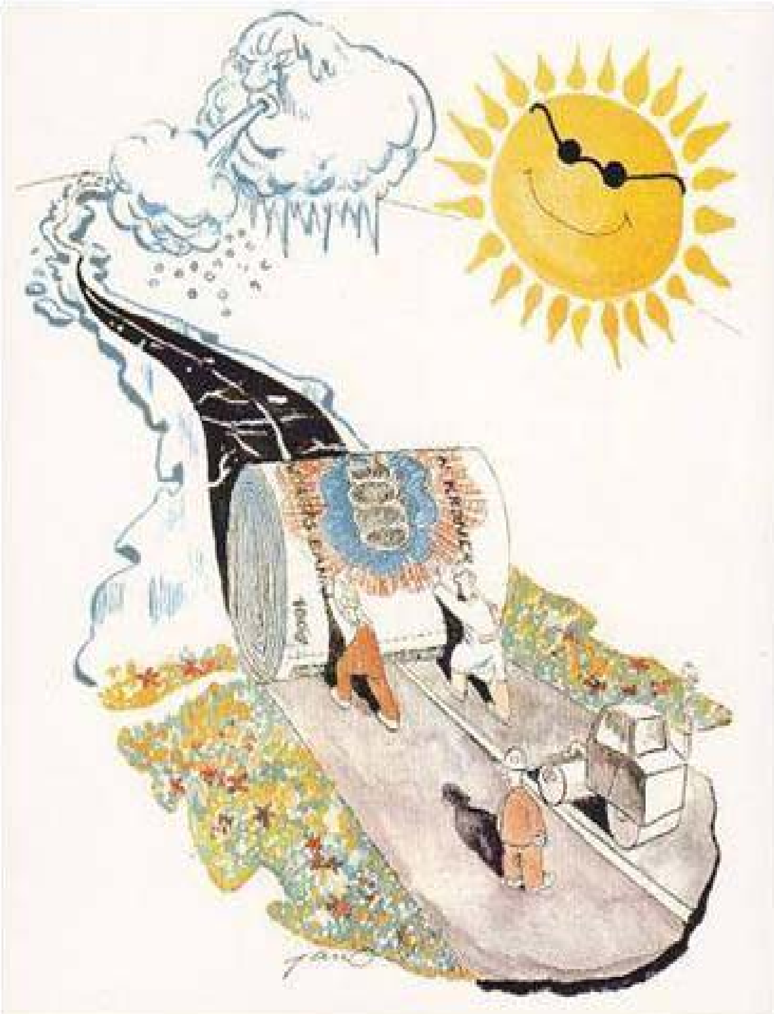
Trondheim, Norway

Contents

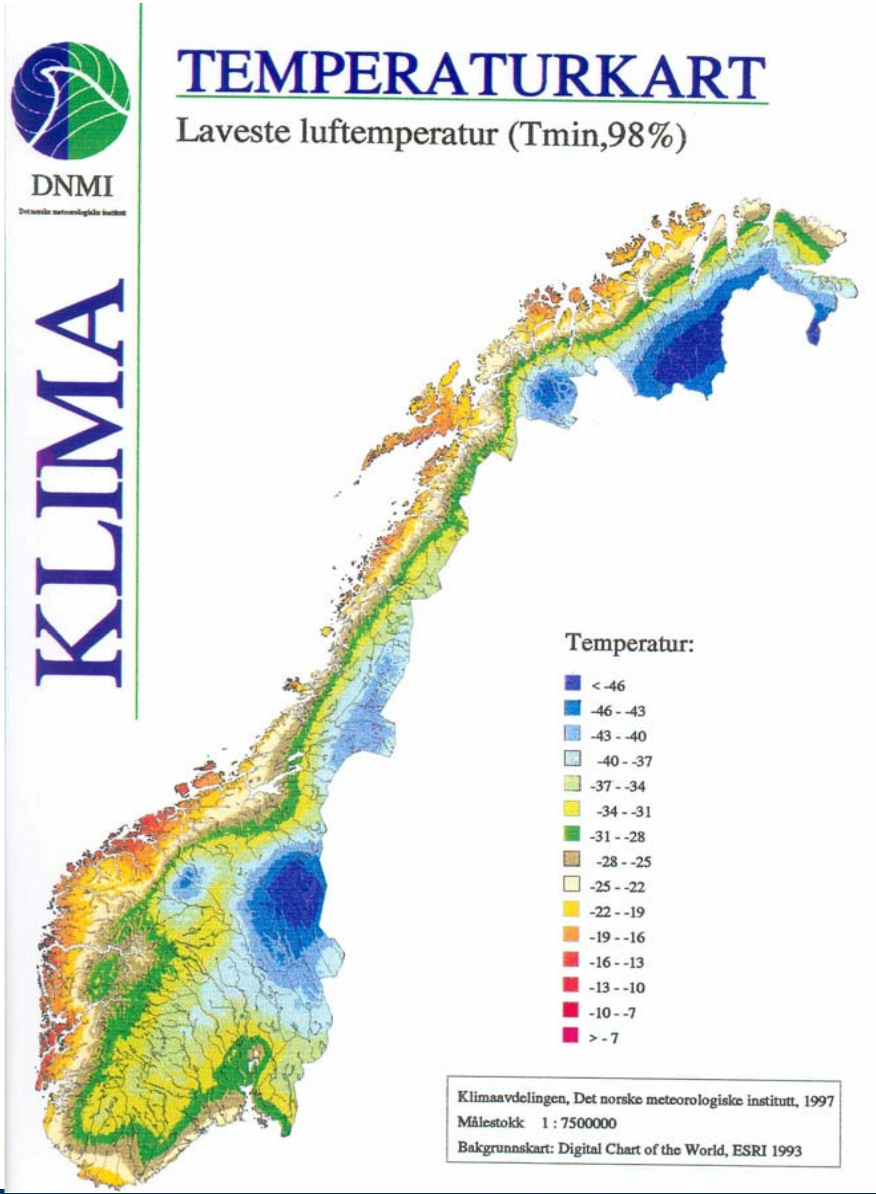
1. Climate conditions in Norway
2. Superpave in Norway
3. Validity of the Superpave BBR Specification Limits for Norwegian Conditions
4. Long Term Pavement Performance on Norwegian Asphalt Runways
5. PhD-thesis from Sweden (H. Zeng, 1995)
6. Conclusions

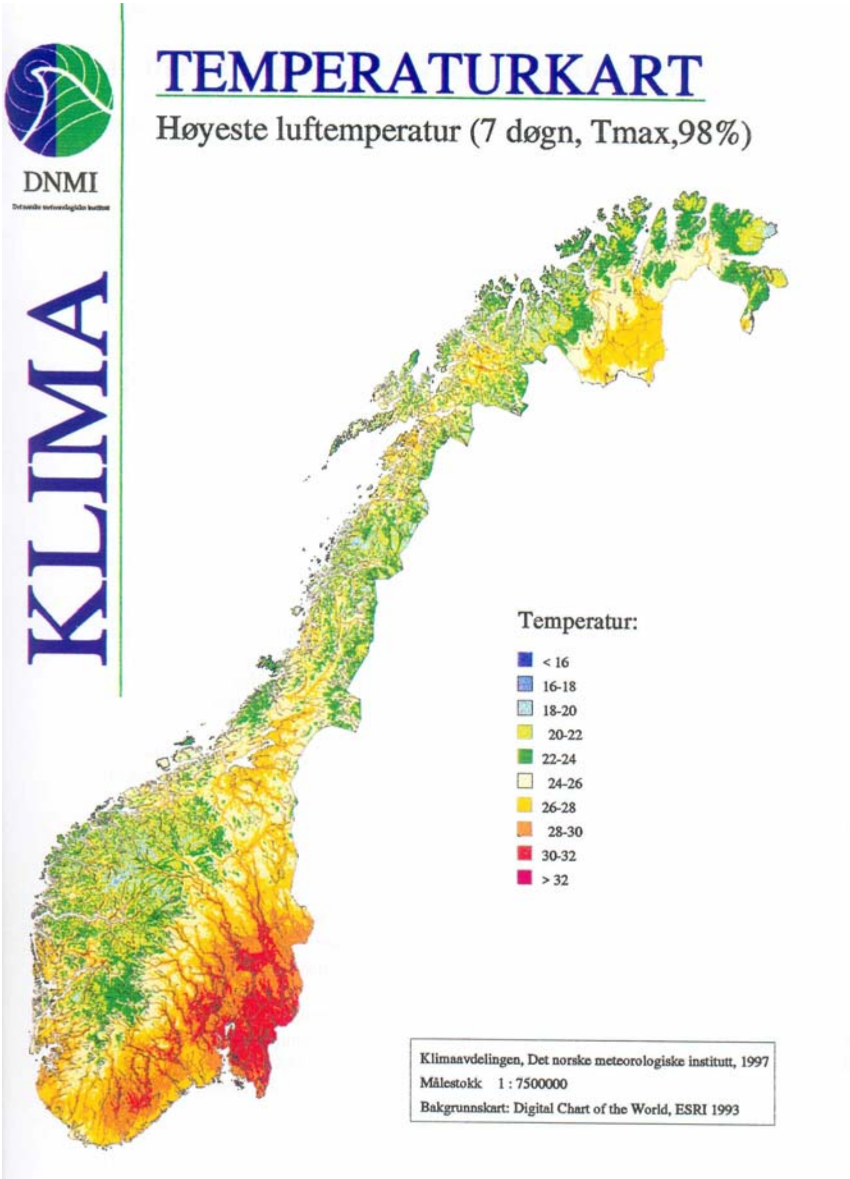
1.0 Climate conditions in Norway

- Large variations in climate
- Mix design is important
  - Temperature
  - Traffic
  - Traffic speed
  - Functional requirements
- Cost savings in the future



1.1 Climate in Norway

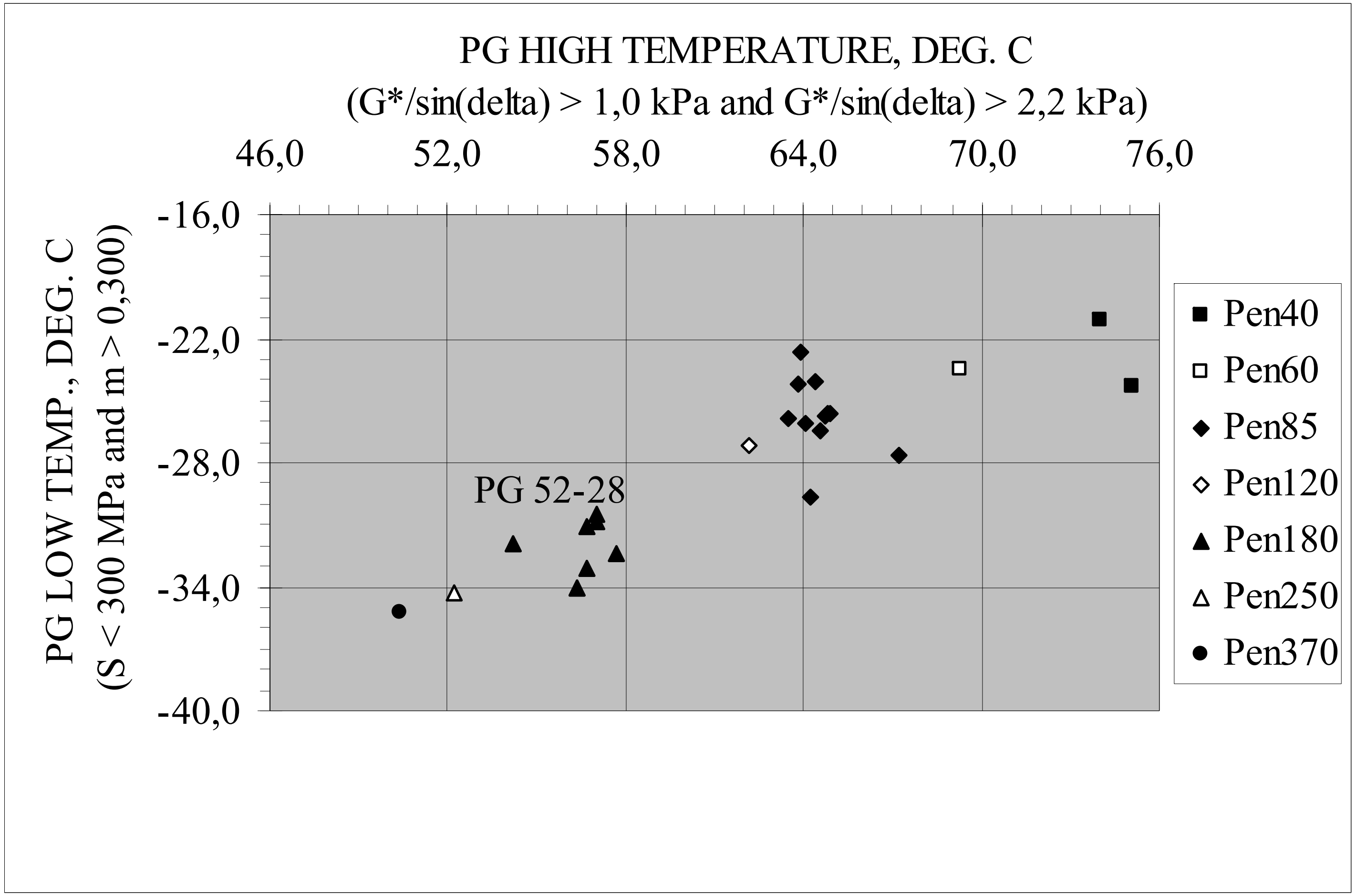




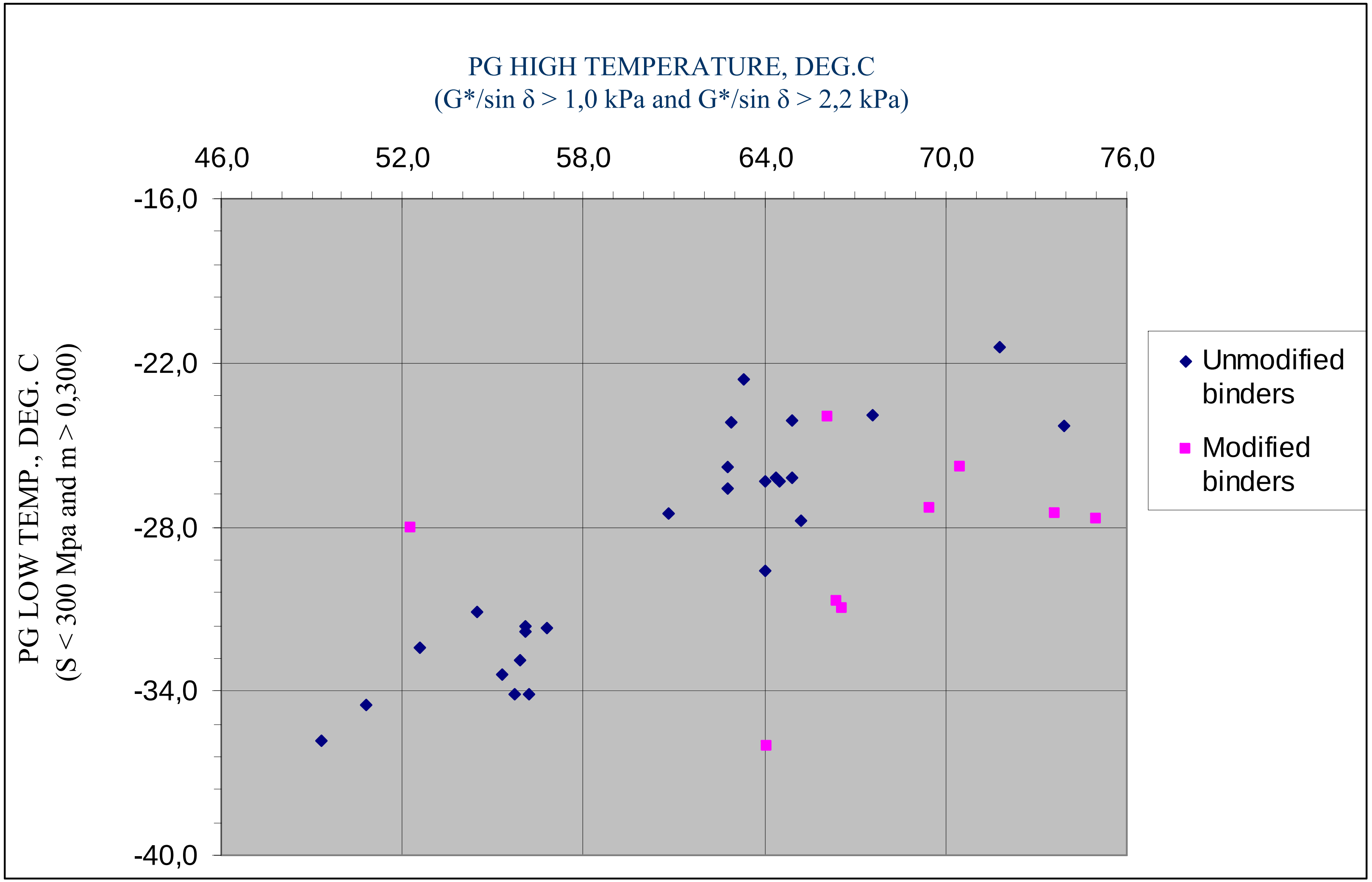
2.0 Superpave binder technology in Norway (Andersen, E., et al.)

- A project aiming to study and evaluate the Superpave binder technology was carried out 1994-1998.
- 40 different binders was tested using both Superpave (DSR, BBR) and traditional methods (penetration, viscosity, softening point).
- Field and laboratory investigations were performed.

2.1 Classification (pure bitumen)



2.2 Classification, modified and unmodified binders



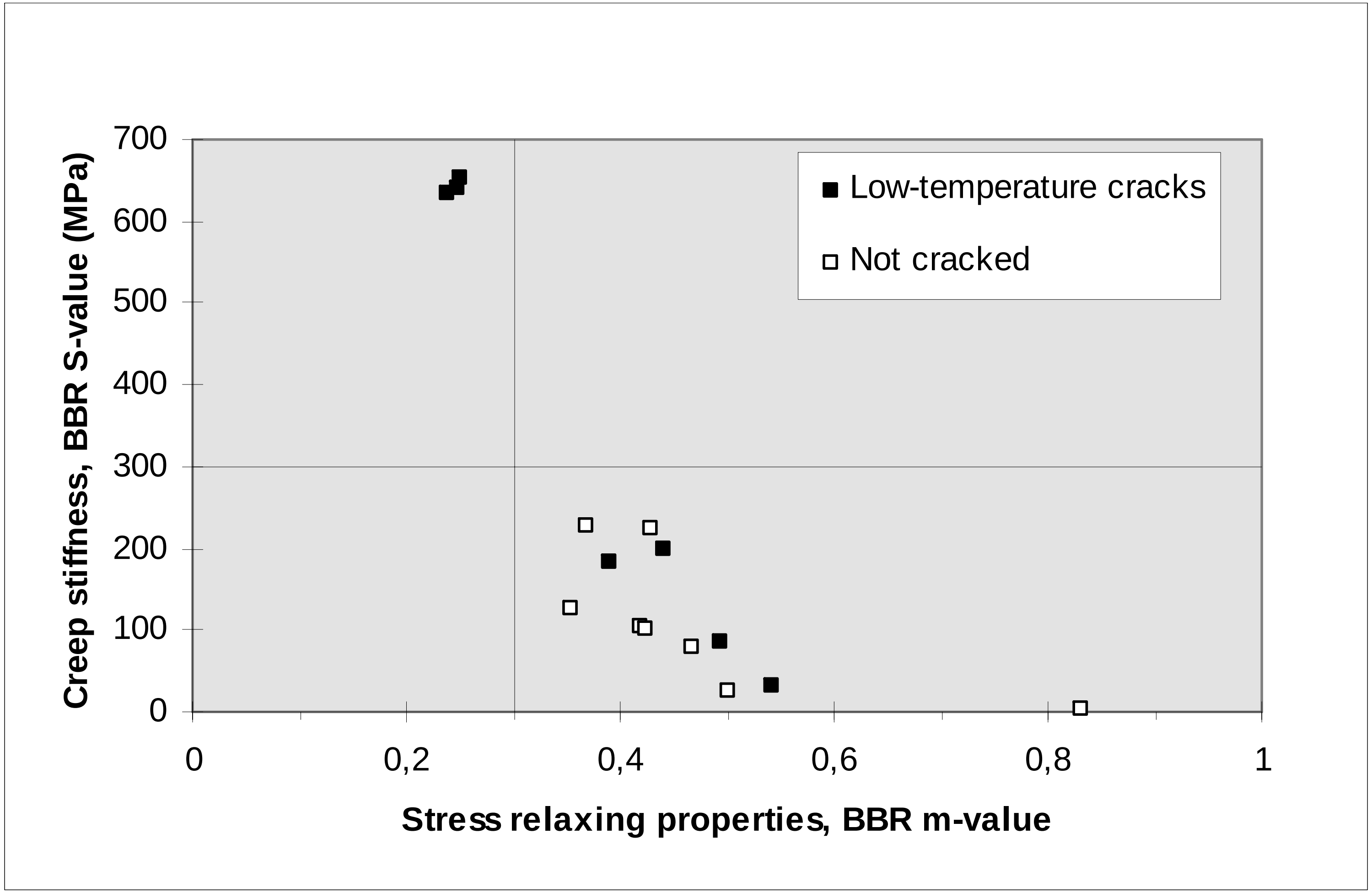
3.0 Validity of the Superpave BBR Specification Limits for Norwegian Conditions (Andersen E., et al)

- Core samples from pavements with and without low-temperature cracks were collected.
- In the laboratory the binders were recovered and tested in the BBR at the assumed critical pavement temperatures.
- Lowest air temperatures were collected from nearby meteorological stations.
- 19 pavements were included in the investigation. Low temperature cracks were reported for 11 of these pavements.

3.1 Summary of results

Pavem. number	Cracked?		Pavement age, yrs.	Critical Pavement Temp. (CPT), °C	BBR at CPT + 10 °C	
	Yes	No			S-value, MPa	m-value
1		X	6	-25,9	103,7	0,420
2		X	3	-25,9	124,9	0,354
3	X		3	-25,9	181,6	0,391
4		X	6	-15,1	25,8	0,501
5		X	11	-10,7	2,2	0,833
6	X		14	-40,0	653,5	0,250
7	X		7	-39,4	197,5	0,440
8		X	6	-25,6	101,8	0,425
9		X	3	-39,4	223,9	0,430
10	X		2	-39,4	640,1	0,247
11	X		2	-39,4	635,3	0,239
12	X		5	-25,5	84,5	0,494
13	X		4	-25,5	30,4	0,542
14		X	5	-27,9	225,6	0,369
15		X	6	-27,9	77,4	0,467

3.2 BBR-values and Superpave-specification limits



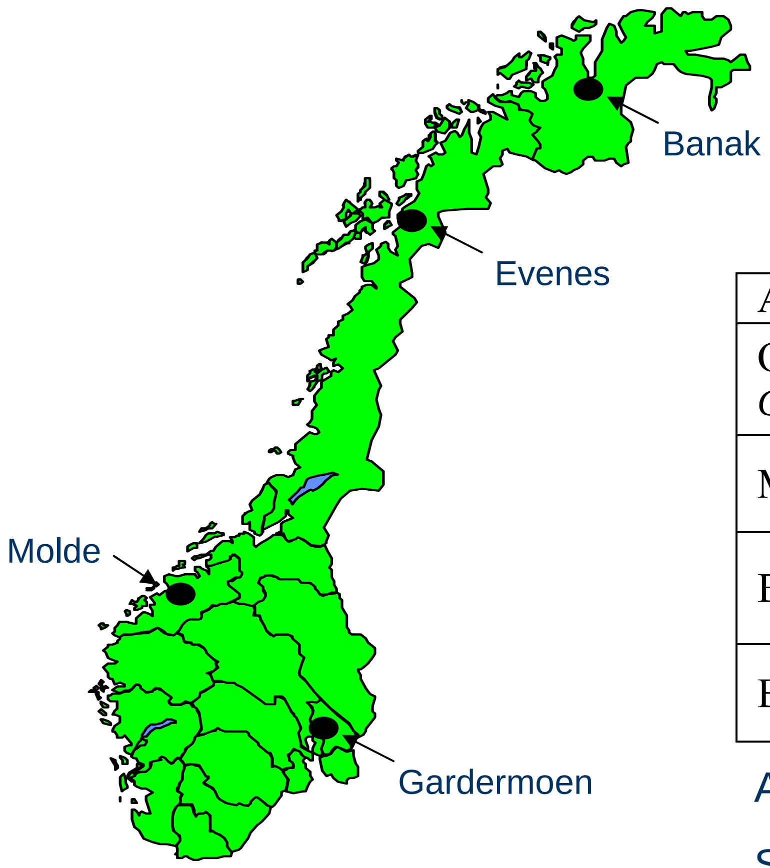
4.0 Long Term Pavement Performance on Norwegian Asphalt Runways (Aurstad et. al.)

- Research and development program started in early 1990`s.
  1. Literature review
  2. Investigations of existing/old pavements
  3. Accelerated laboratory ageing test
  4. Field monitoring of new asphalt pavements
- Main object was to develop more lasting pavements.

4.1 Field monitoring of asphalt pavements

- A number of airfields were reconstructed or repaved.
- Some pavement are closely monitored in more than 10 years:
  - Distress identification
  - Core sampling
  - Changes in functional properties are studied
  - Measured low temperature properties are compared with recorded temperatures.

4.2 Airfields that have been studied closely



Airfield	Age	Pavement
Oslo *Gardermoen*	1989 *old runway*	AC11 mm, 180pen bitumen *grooved surface*
Molde	1993	SMA16 mm, 180pen bitumen
Evenes	1994	SMA16 mm, 180pen bitumen
Banak	1993	SMA11 mm, 110pen PmB (250pen bitumen modified with SBS)

AC = Asphalt Concrete

SMA = Stone Mastic Asphalt

4.3 Field monitoring program

Surface characteristics	Distress mapping and ident. Macro-texture	 *Sand patch method*
Pavement/mix properties	Indirect tensile strength Fatigue resistance Density Void content Binder content	 *3-point beam fatigue test*
Recovered binder properties	Penetration value Softening point Dynamic viscosity Low temperature charact.	 *Brookfield rotational viscometer* *Cannon Bending Beam Rheometer*

4.4 Low temperature cracking

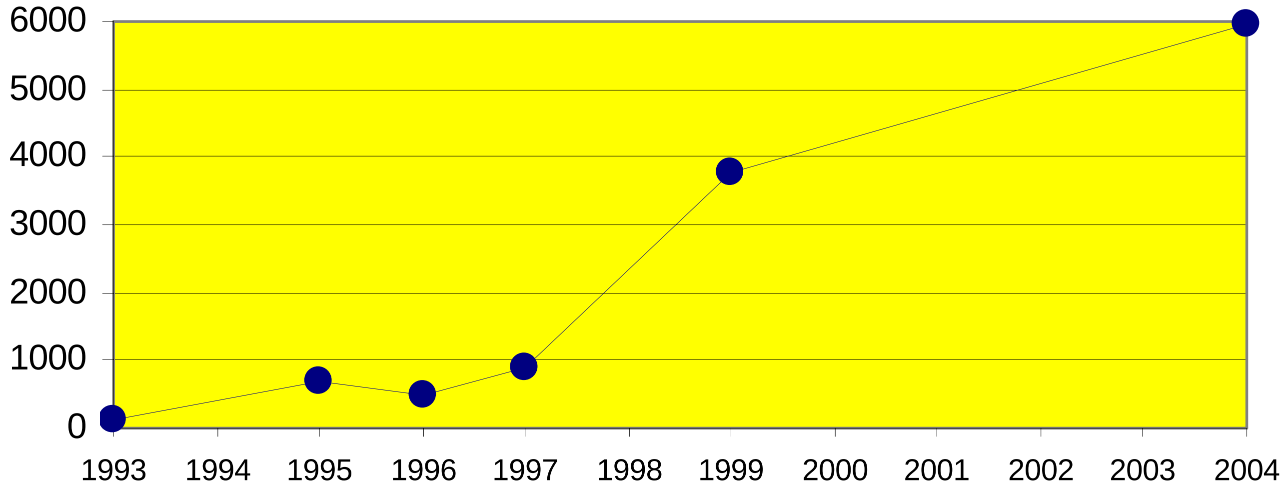
Laboratory estimated critical low temperature (BBR)

	PAV-aged orig. bit.	Top layer (0-10 mm)				Second layer (10-20 mm)		
		1995	1997	1999	2004	1997	1999	2004
Banak	-31,0 °C	-34,7 °C	-35,5 °C	-33,7 °C	-32,2 °C	-	-36,0 °C	-35,9 °C
Evenes	-34,1 °C	-	-34,2°C	-33,5 °C	-34,4 °C	-36,0 °C	-36,0 °C	-35,7 °C
Molde	-	-	-	-31,7 °C	-	-	-33,1 °C	-

Recorded asphalt surface low temperatures in field

	1995	1997	1998	1999	2004
Banak	-	-16,8 °C	-27,5 °C	-34,3 °C	-
Evenes	T_{min} > -28 °C (all years)				
Molde	T_{min} > -22 °C (all years)				

Accumulated transverse and longitudinal cracking (Banak)



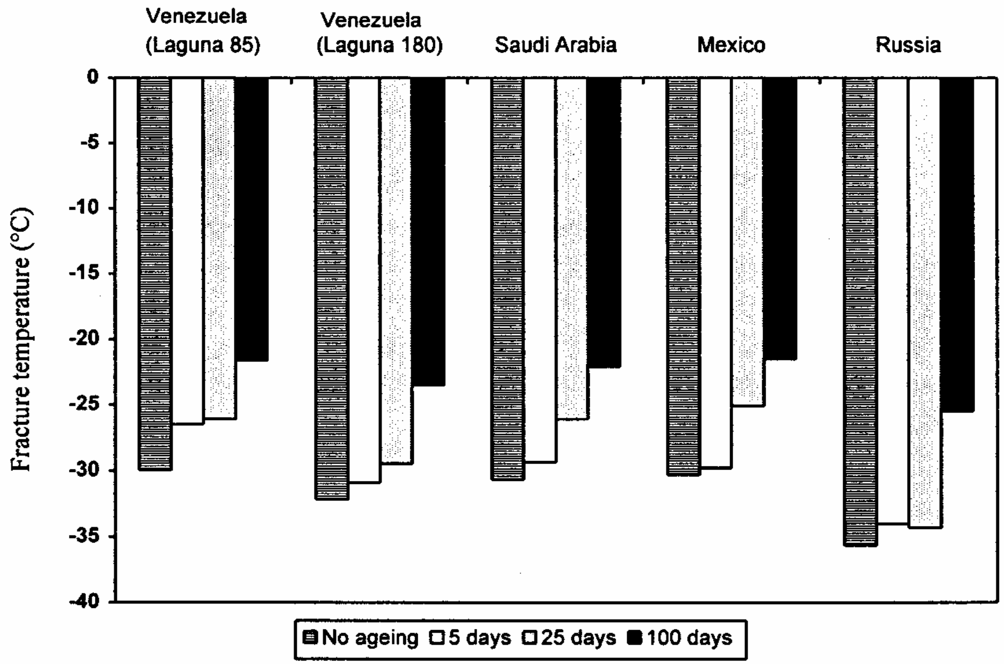
5.0 PhD-thesis from Sweden (H. Zeng, 1995)

“ On the low temperature cracking of asphalt pavements”

- Literature study on low temperature properties of asphalt pavements.
- Laboratory studies on factors influencing the low temperature behavior of asphalt concrete mixtures.
- The ageing process with regard to low temperature cracks
- Development of a test method for determining thermal contraction coefficients of asphalt mixtures.
- The use of Tensile Stress Restrained Specimen Test (TRST) for predicting filed performance at low temperatures.

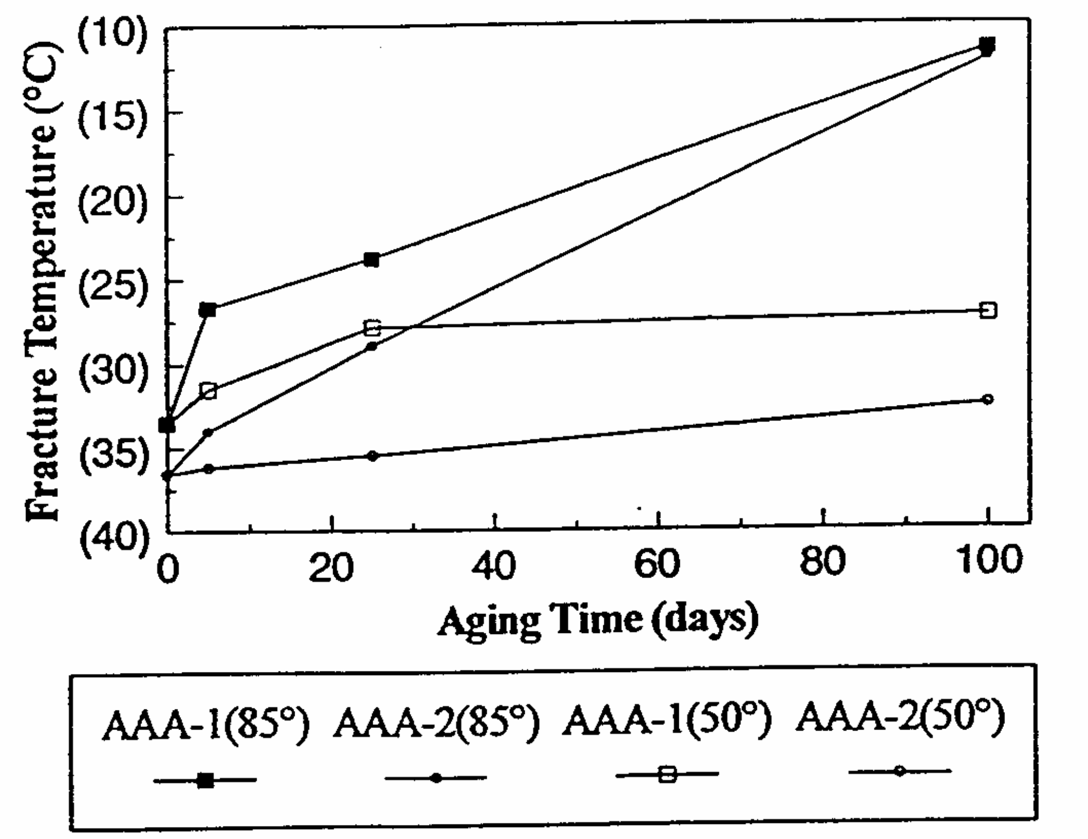
5.1 Influence of binder characteristics

- The effect of five plain bitumens, five polymer modified bitumens and three mixture types are studied.
- The fracture temperature is affected by degree of ageing, as well as by binder source.



5.2 Effect of ageing

- The ageing temperature strongly influences changes in low temperature properties.



5.3 Other conclusions from the thesis are:

- The binder properties are most important with regard to low temperature cracking. Other factors influencing are:
  - The mixture composition
  - Air void content (ageing)
  - Production factors
- Binders with a high proportion of non-polar components are less susceptible to oxidative ageing than other binders, but this property makes this material susceptible to thermal cracking, because of structuring that occurs at low temperatures.
- Tensile Stress Restrained Specimen Test (TSRST) can be used in the prediction of low temperature cracking.

6.0 Conclusions

- The BBR and the Superpave specification limits seems to be successful at controlling low temperature cracking for *unmodified binders.*
- The BBR and Superpave specification limits seems to underestimate the low temperature properties of some modified bitumens.
- A field monitoring program of Norwegian airfields indicate that the Superpave procedures may give reasonable/good predictions of the low temperature properties.

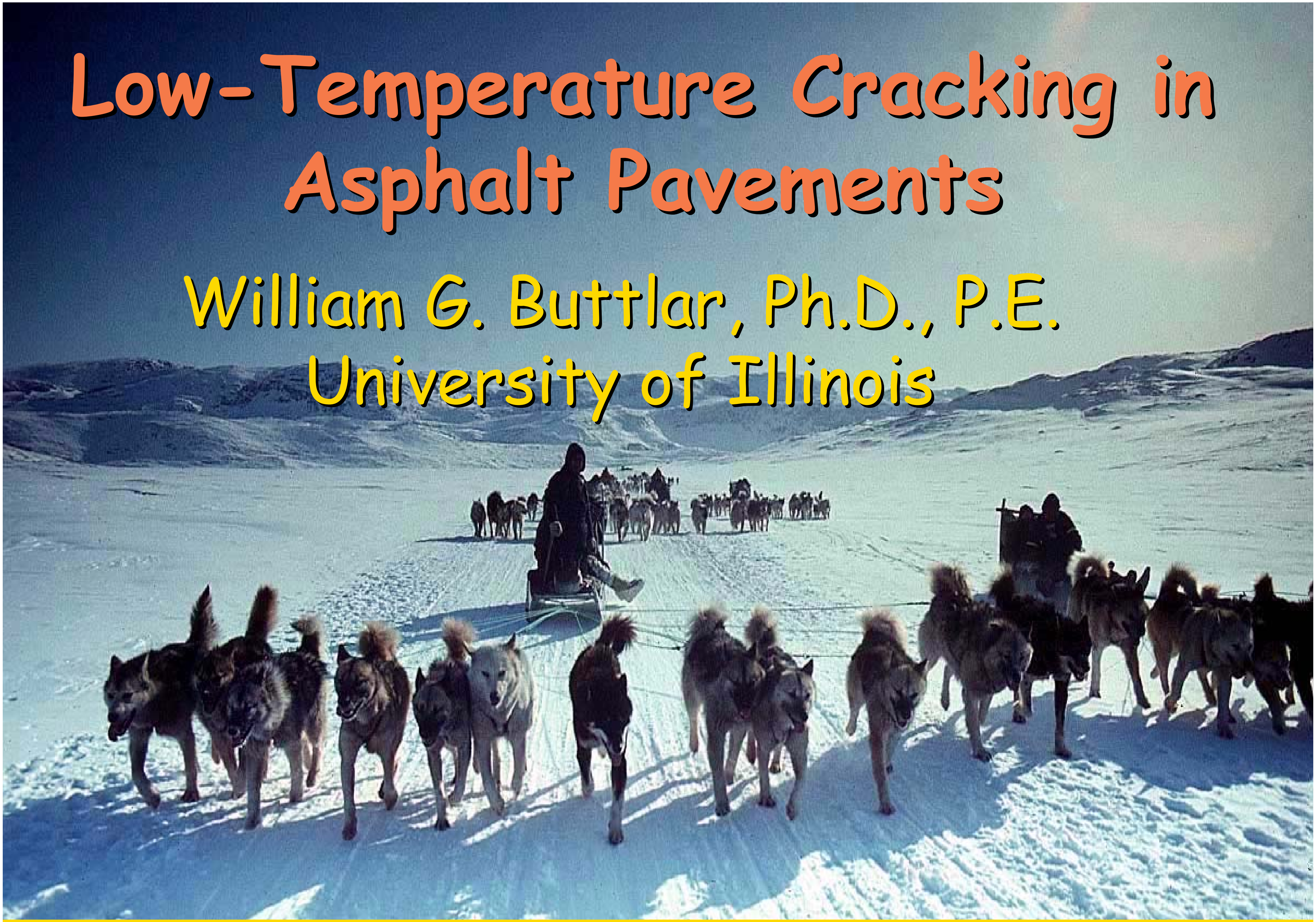
6.0 Conclusions

- Often, new asphalt pavements are overlays over older asphalt pavements. *The potential for reflection cracks should always be examined. If possible, this should be dealt with in mix design or in the construction of the new pavement.*

Thank you for your attention!

Low-Temperature Cracking in Asphalt Pavements

William G. Buttlar, Ph.D., P.E.
University of Illinois



Thermal Cracking Workshop, ICAP, Quebec City, Aug. '06

Acknowledgements

- Mihai Marasteanu – Univ. of Minnesota
- Chris Williams – Iowa State
- Hussain Bahia – Univ. of Wisconsin
- Mn/ROAD Research Group (Ben Worrel, lead)
- UIUC – Prof. G. Paulino, A. Braham, H. Yin

Low-Temperature Cracking

- Adequate fracture resistance essential for asphalt pavements in northern US and in Canada
  - ✓Low-temperature cracking represents the prevalent distress in Minnesota and neighboring states

Thermal Cracking – Open Questions

Mechanisms

- Temperature Related
- Load Related

- Thermo-Mechanical (elements of both)

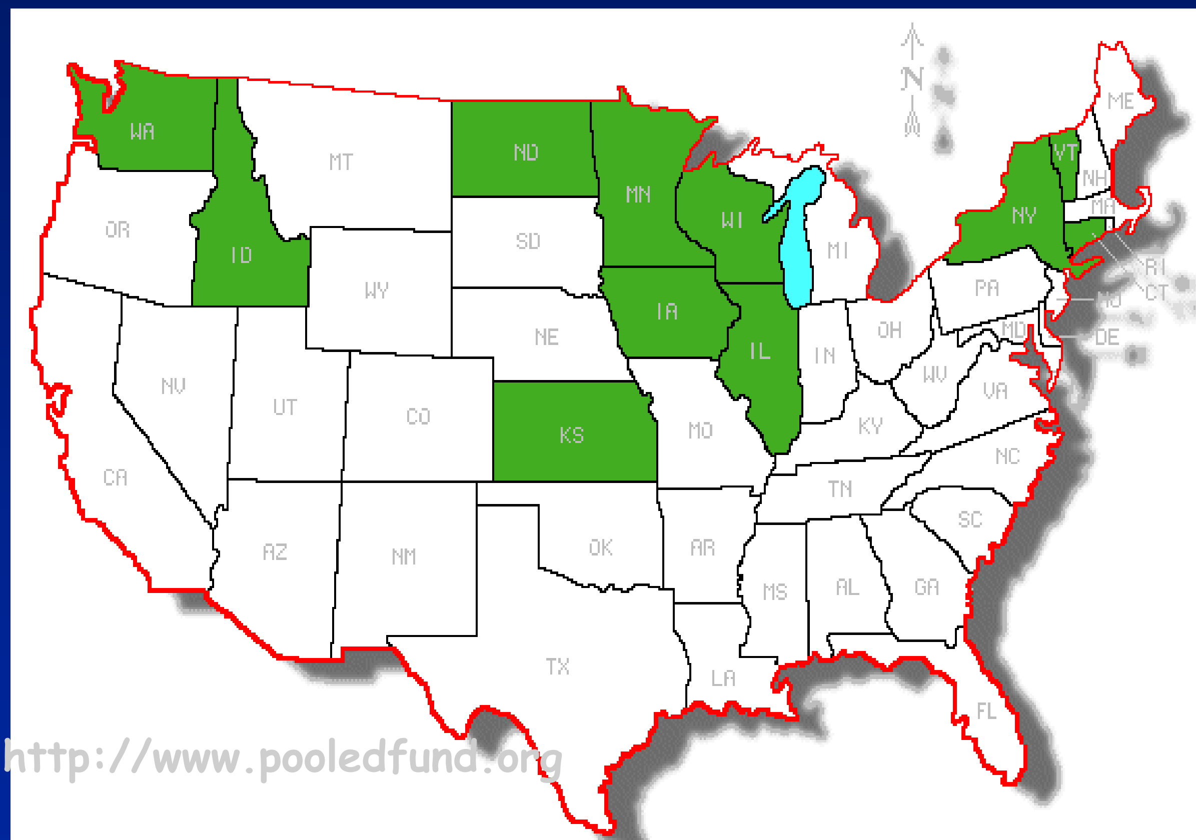
Single Event vs. Thermal 'Fatigue'

Relative Importance of Other Factors: Aging, material layering and gradients, 1D, vs. 2D vs. 3D modeling, strength vs. fracture, etc. Also, binder-to-mixture links revisited in light of new tests and models.

Existing US TC Specs - Limitations

- PG Binder Spec, AASHTO MP1 - Missing critical information about the mixture: aggregate contribution to material creep and fracture behavior, material compatibility, physio-chemical interactions, voids
- Binder AASHTO MP1a – Attempts jump from binder to mixture, but very simplistic
- AASHTO MEPDG - TCMODEL – Addresses these shortcomings with mixture tests and pavement models, but has several key limitations currently

Low Temperature Cracking Pooled Fund State Participation



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FHWA

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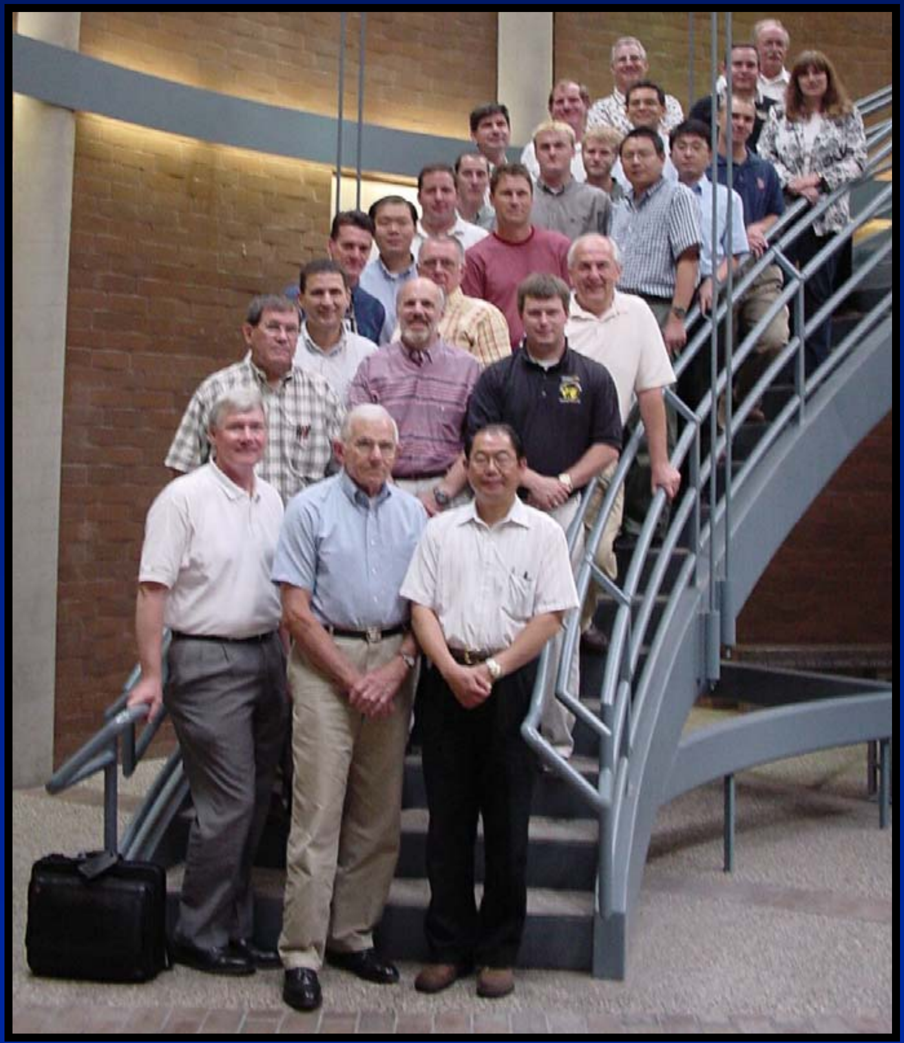
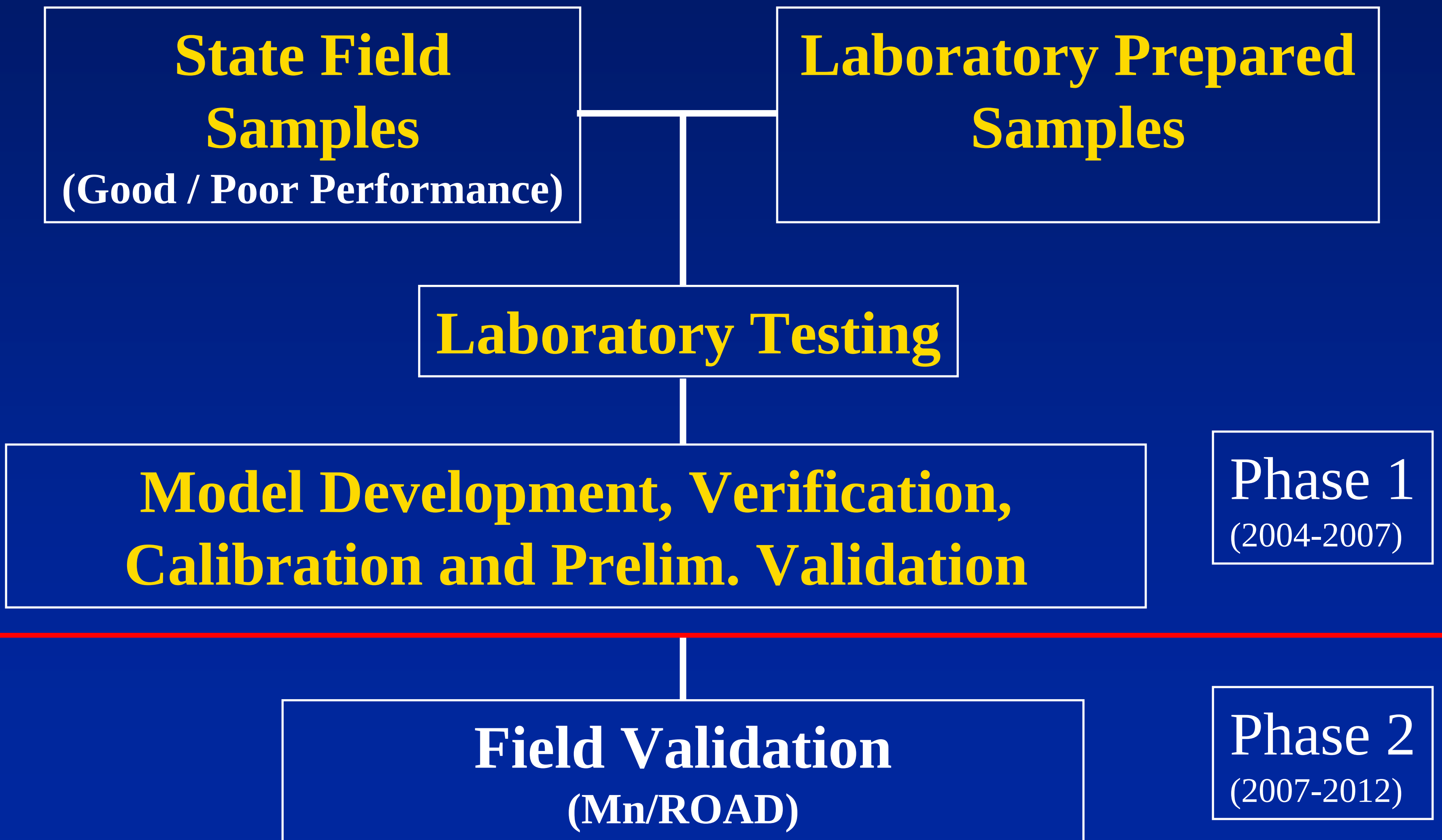


August 2003 Initial Meeting
University of Minnesota

Provides technical insight to the participating states and the four Universities

Low Temperature Cracking Pooled Fund (Overall Plan)



Pooled Fund Study Goals

- Development of test methods / protocols for LTC
  - Fresh look at tests for binders and mixtures
- Validate / refine MEPDG thermal cracking model
- Establish guidelines for MnROAD field validation

Scope of Study

- Eleven States
- Four Universities
- 28 Lab Mixtures
  - ✓ 10 Binders, 2 Aggs, 2 Void Levels, 2 AC Levels
- 8 Field Sections
- 3 Test Temperatures, 2 to 3 Reps
- Mix Tests (8): SCB, DC(T), IDT(3), TSRST, SE(B), Dilatometric
- Binder Tests (4): BBR, DTT, DENT, Dilatometric
- <u>Thousands of Tests!!!</u>
- Fundamental Data Will Enable a Plethora of Analysis

Current status

- Field sites were selected from nominated sites submitted by participating states
  - ✓Coring finished
- Laboratory prepared specimens
  - ✓Iowa State finished preparing gyratory specimens, UIUC will complete slab compaction by August 2006
- Testing at U Mn, UIUC and UW: 80% complete
- Development of models in progress at UIUC: baseline models complete

Laboratory Prepared Specimens

	Air Voids	Design (4%)				As constructed (7%)			
	Aggregate Type	**Aggregate 1 Granite**		**Aggregate 2 Limestone**		**Aggregate 1 Granite**		**Aggregate 2 Limestone**	
	Binder Content	Design	Film thick.	Design	Film thick.	Design	Film thick.	Design	Film thick.
Binder Type (modification)	PG58-40, modifier 1 (Flint Hills Resources)	**X**	**X**	**X**					
	PG58-40, modifier 2	Not available, replaced with 64-22							
	PG58-34, modifier 1 Elvaloy (Murphy)	**X**	**X**	**X**					
	PG58-34, modifier 2 (Flint Hills Resources)	**X**		**X**					
	PG58-28, plain 1 (Seneca)	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
	PG58-28, plain 2 (Payne and Dolan)	**X**		**X**					
	PG64-34, modifier 1 Elvaloy (Murphy)	**X**		**X**					
	PG64-34, modifier 2 (Husky, Black Max)	**X**		**X**					
	PG64-28, plain 1 (Seneca)	**X**		**X**					
	PG64-28, modifier 1 SBS (Seneca)	**X**		**X**					
	PG64-22, plain (Seneca)	**X**		**X**					
	PG70-22, modified SBS (Seneca)	Received but not part of the approved work plan							

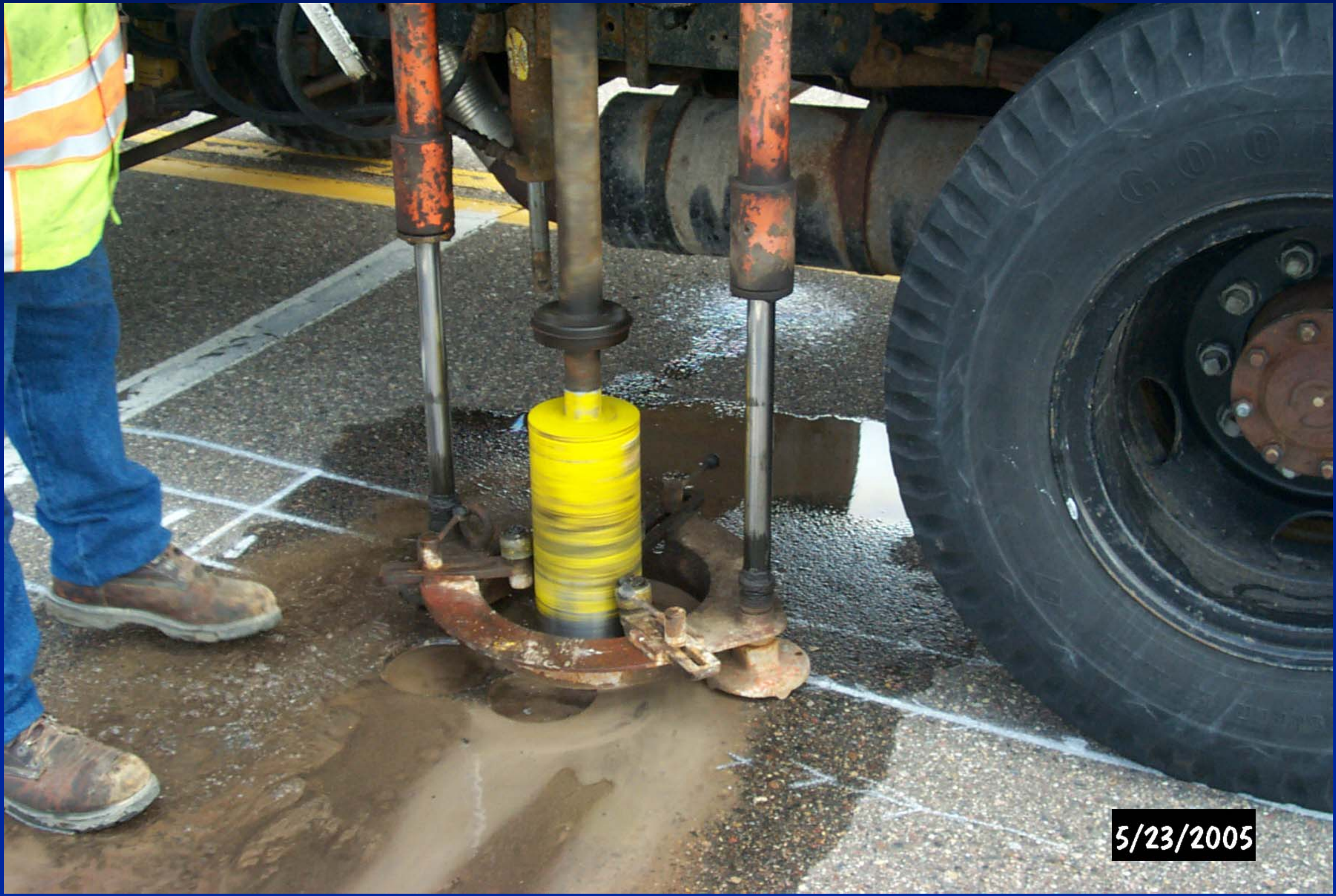
Laboratory Prepared Specimens

		MTU	*UIUC*	*UMN*	*WISC*
	Mixture Indirect Tension Creep and Strength			**X**	
	Mixture Fracture Test Disc Compact Tension		**X**		
	Mixture Fracture Test SE(B)		**X**		
	Mixture Fracture Test SCB			**X**	
	Mixture Thermal Stress Test TSRST	**X**		**X***	
	Binder Low Temperature DSR, BBR and DTT			**X**	**X**
	Binder Fracture Test DENT			**X**	
	Mixture and Binder Dilatometric Measurements				**X**

Mixture and Binder Test Temperatures

- Test at 3 temperatures
  - ✓Match 2 out of 3 temperatures for binders and mixtures
    - -For mixtures 6°C do not lead to big change in properties
- Binders:
  - ✓PG +10°C (for a -28 it will be -18°C), 6°C below it (-24°C) and 12°C below it (-30°C)
- Mixtures:
  - ✓PG +10°C, 12°C below it, 12°C above it.

MnROAD Coring

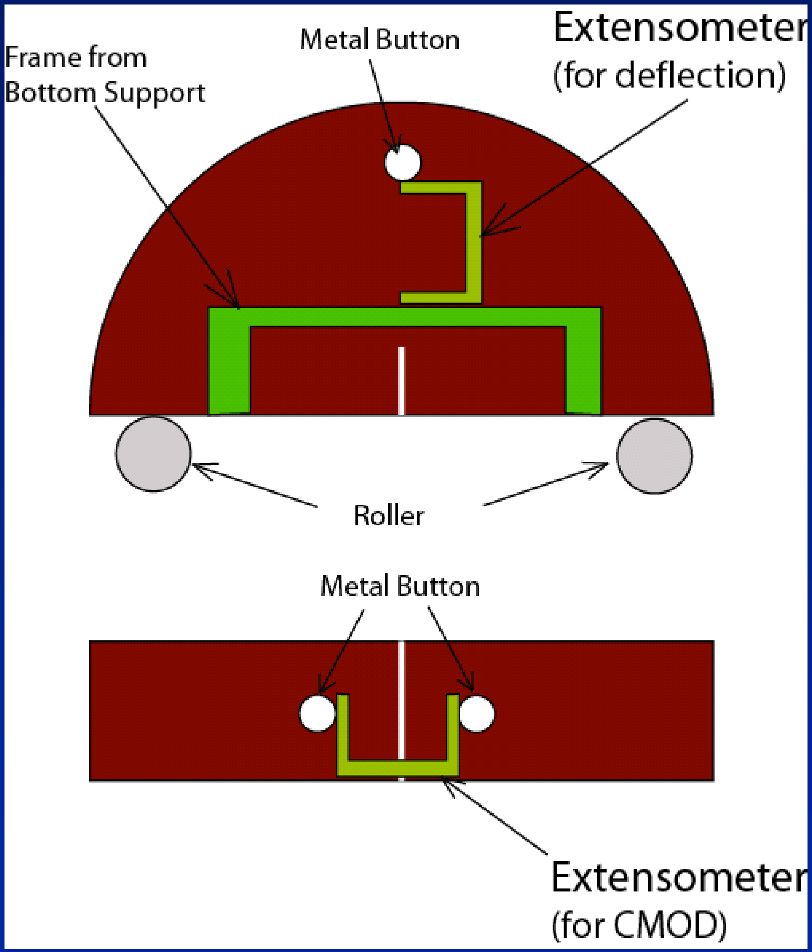


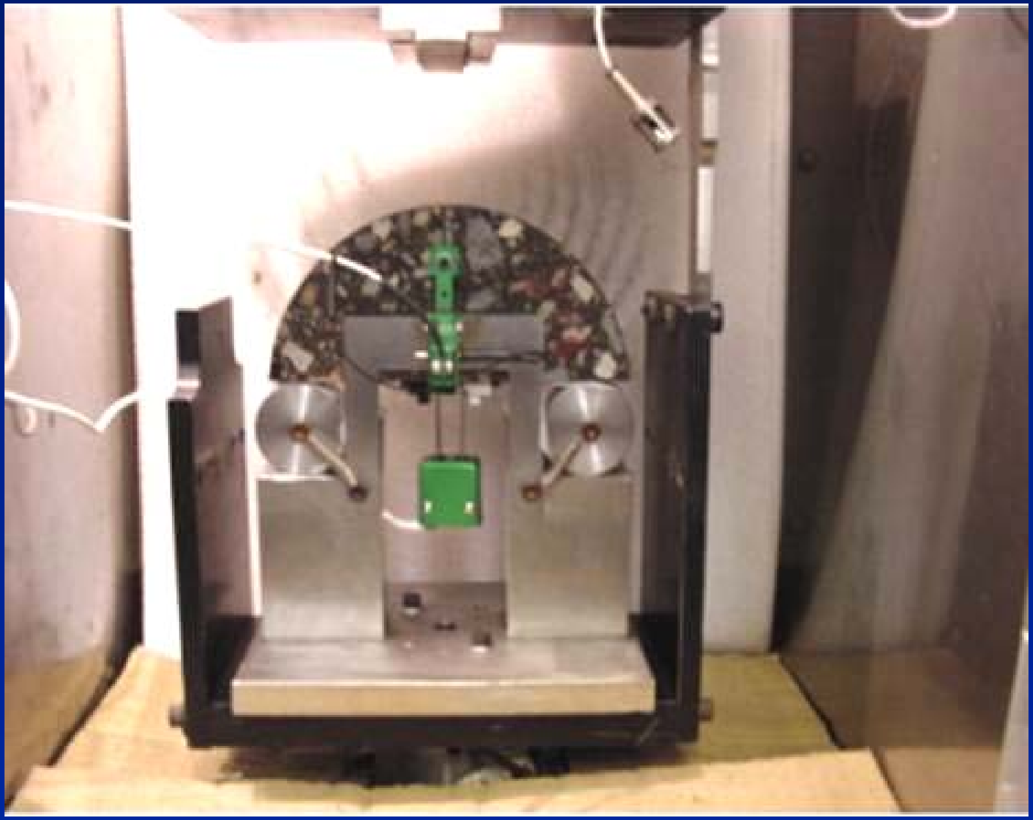
MnROAD Slab Cutting

MnROAD Sample Extraction

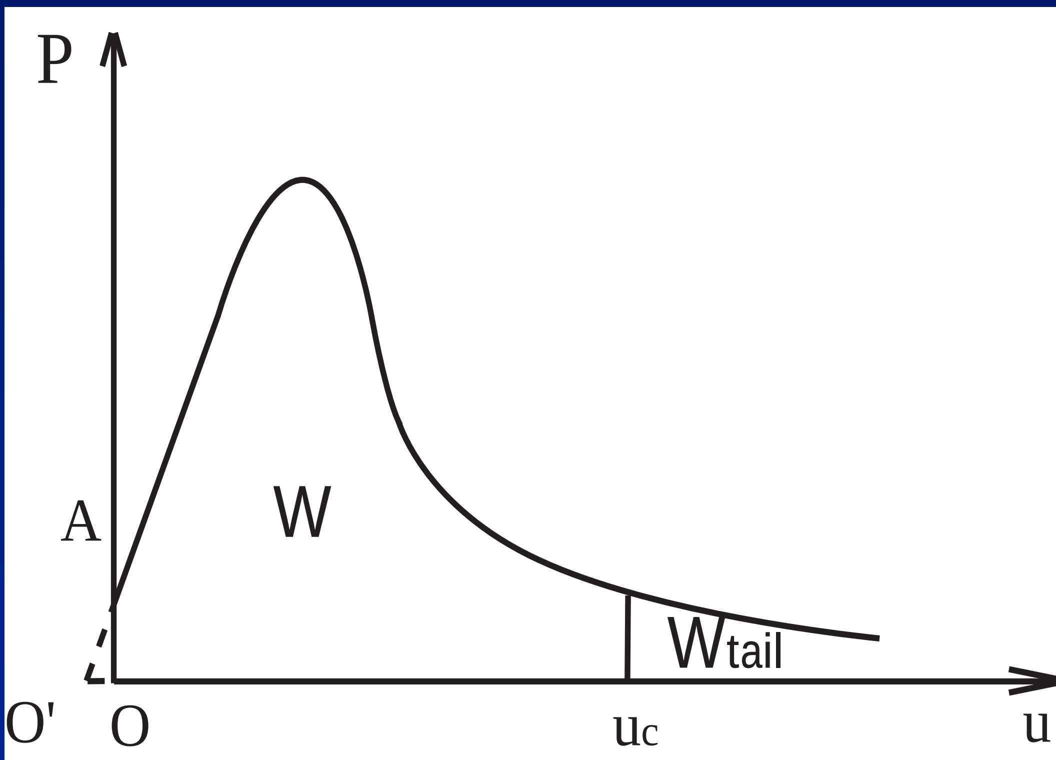
IL US20 Slab Extraction

Semi-Circular Bend Test – SCB @ UMn





Fracture Energy

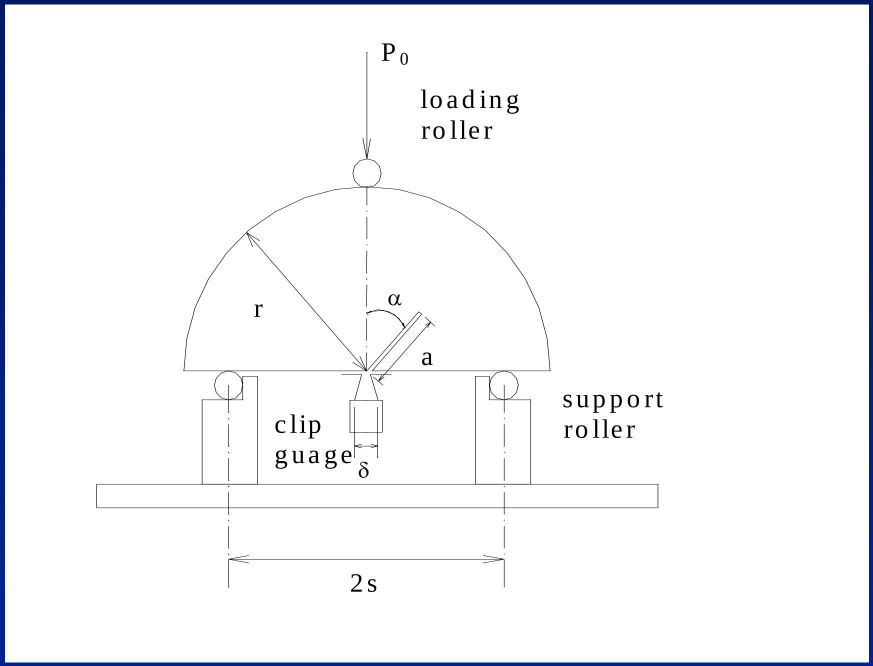


$$W_f = \int P du$$

$$G_f = \frac{W_f}{A_{lig}}$$

W_f: work of fracture
A_{lig}: area of the ligament

Stress Intensity Factor K_I



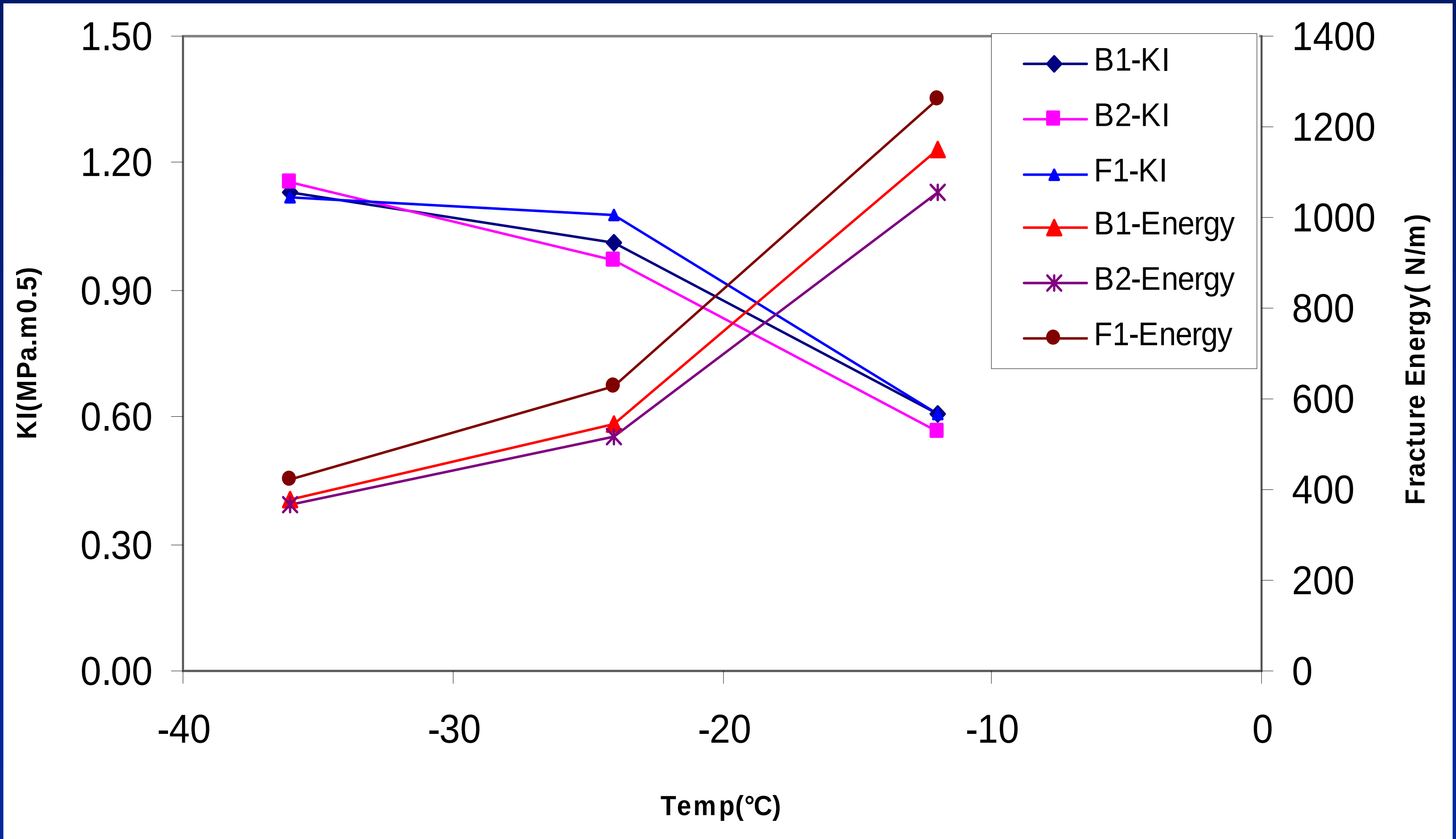
$$K_I = \sigma_0 \sqrt{\pi a} Y_I$$

$$\frac{K_I}{\sigma_0 \sqrt{\pi a}} = Y_{I(s_0/r)} + \frac{\Delta s_0}{r} B$$

$$Y_{I(s_0/r)} = C_1 + C_2 (a/r) + C_3 \exp(C_4 (a/r))$$

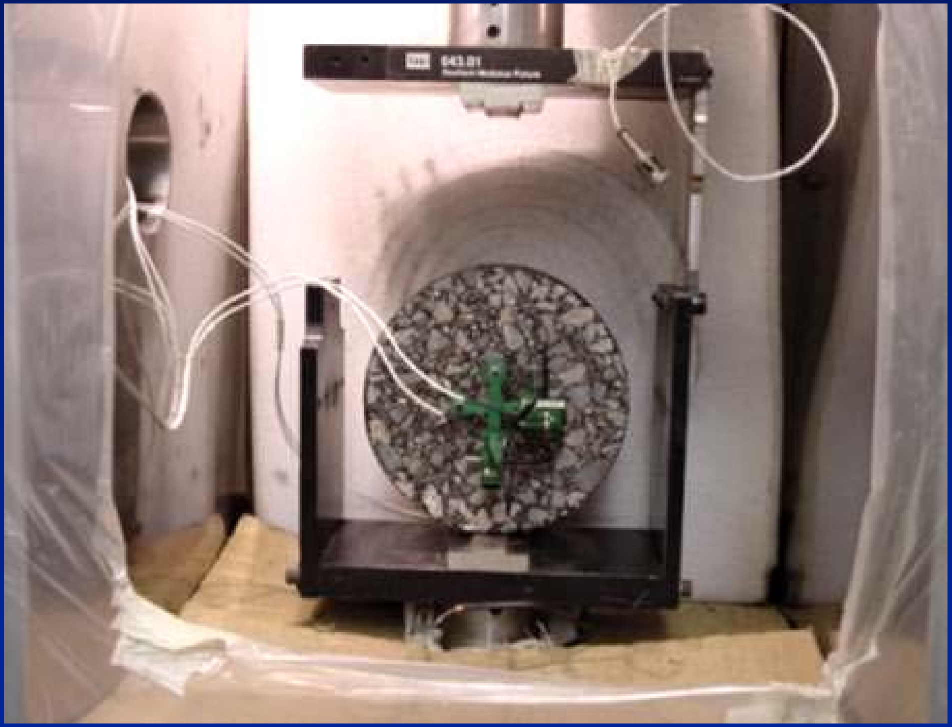
$$B = 6.55676 + 16.64035 (\frac{a}{r})^{2.5} + 27.97042 (\frac{a}{r})^{6.5} + 215.0839 (\frac{a}{r})^{16}$$

SCB - temperature effect on K_{IC} and G_f

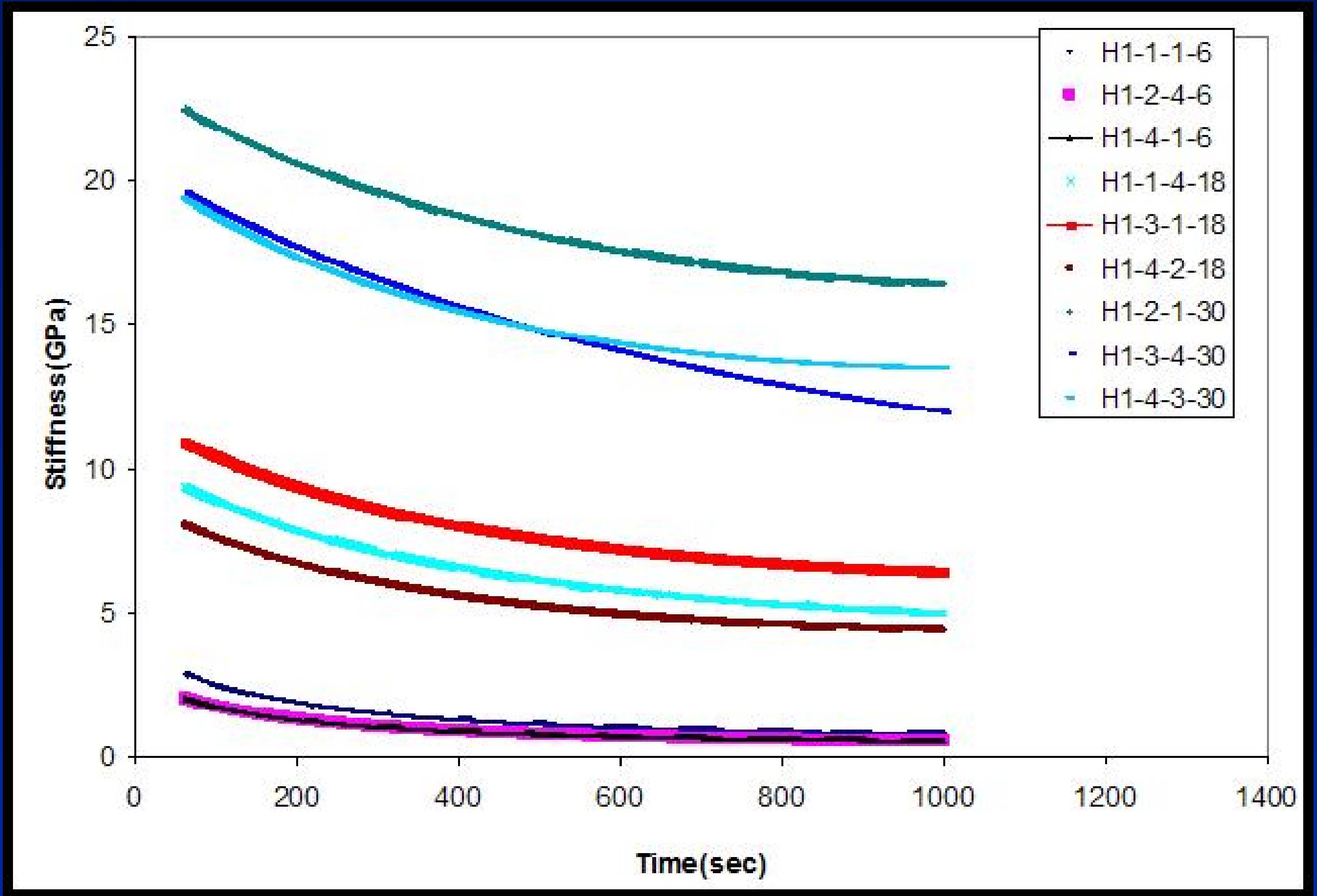


IDT - Creep and Strength

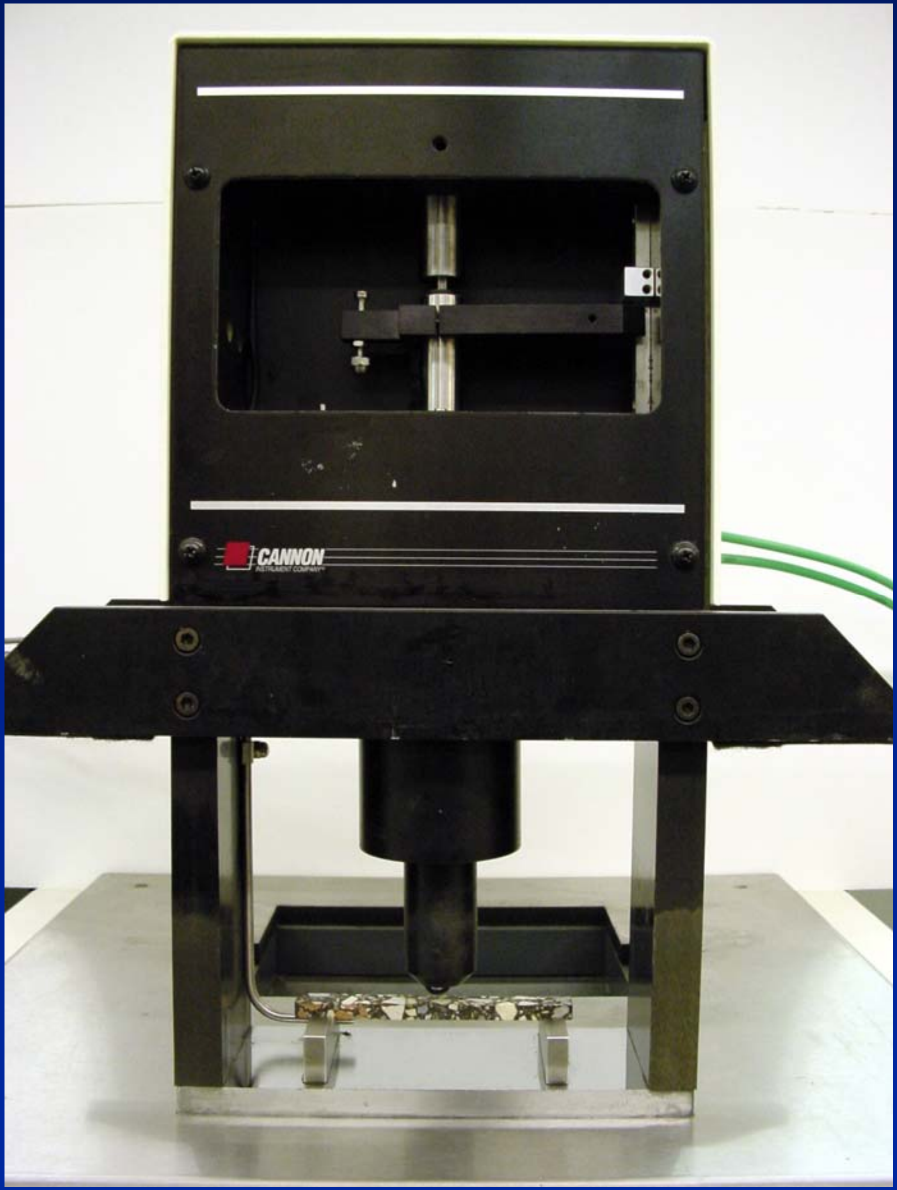
- Specification type tests
- In addition:
  - ✓Limited creep tests at different load levels
  - ✓Limited strength tests at different loading rates

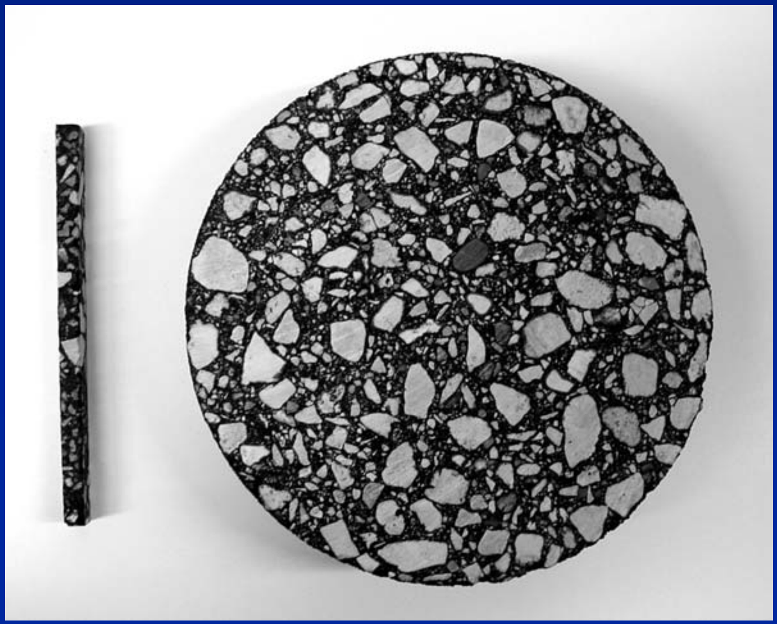


IDT Creep Data

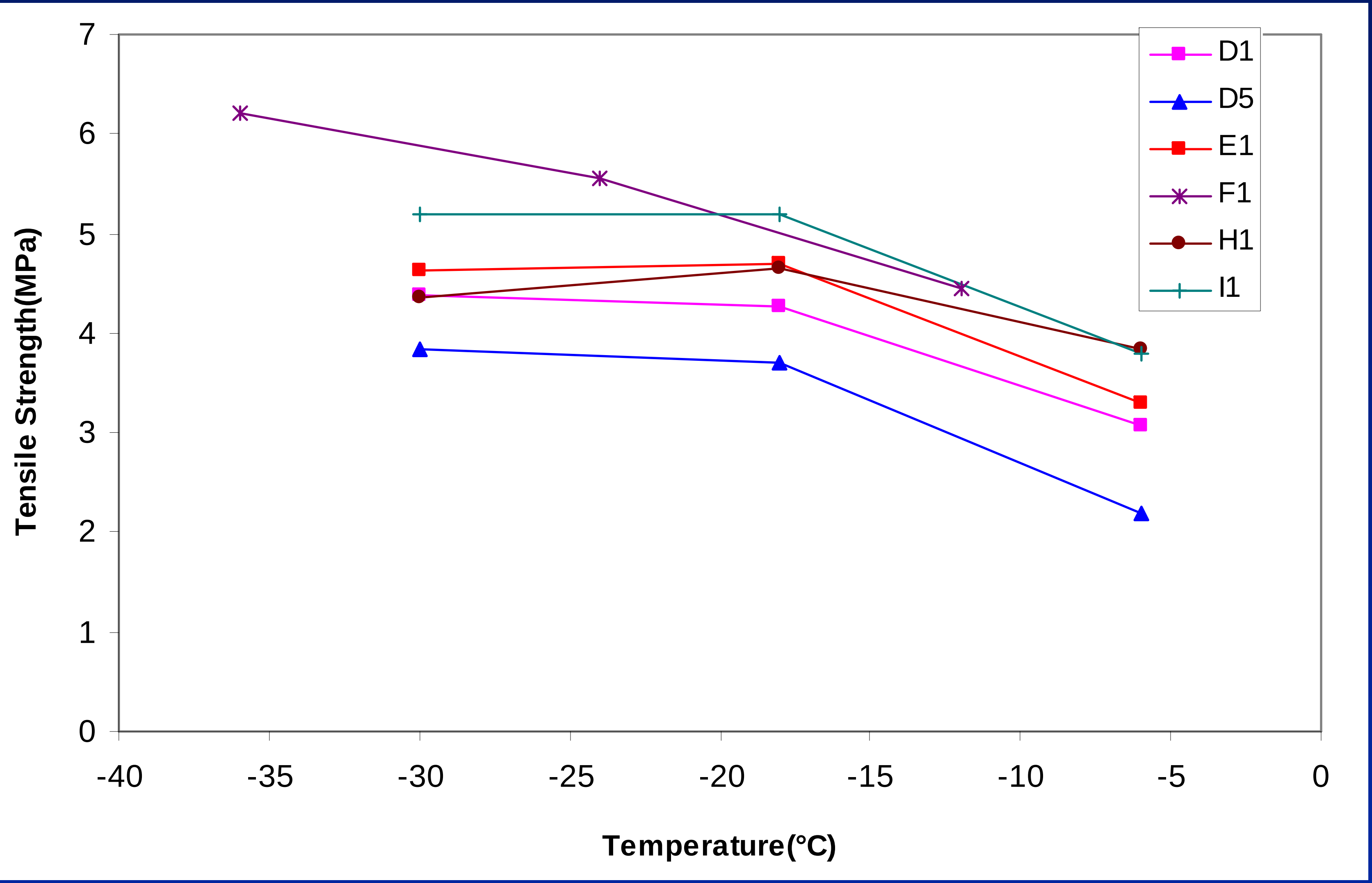


Mix Creep Data via BBR





IDT Strength Data

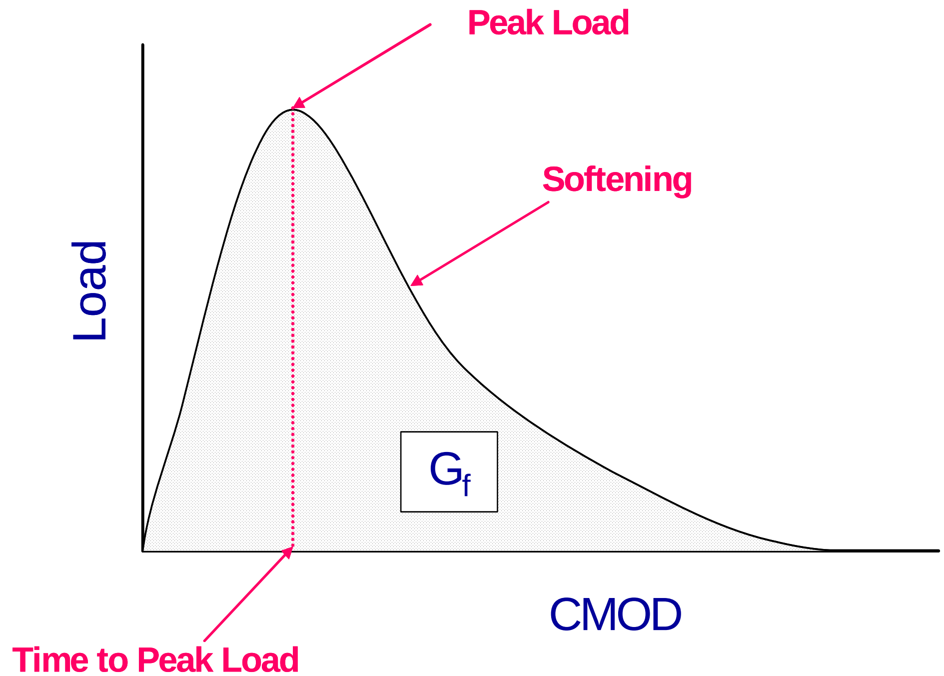


Fracture Testing - UIUC

- Disc Shaped Compact Tension
  - ✓DC(T)
  - ✓1 mm/min CMOD
  - ✓150mm

- Single Edge Notched Beam
  - ✓SE(B)
  - ✓1 mm/min CMOD
  - ✓50x75x375mm

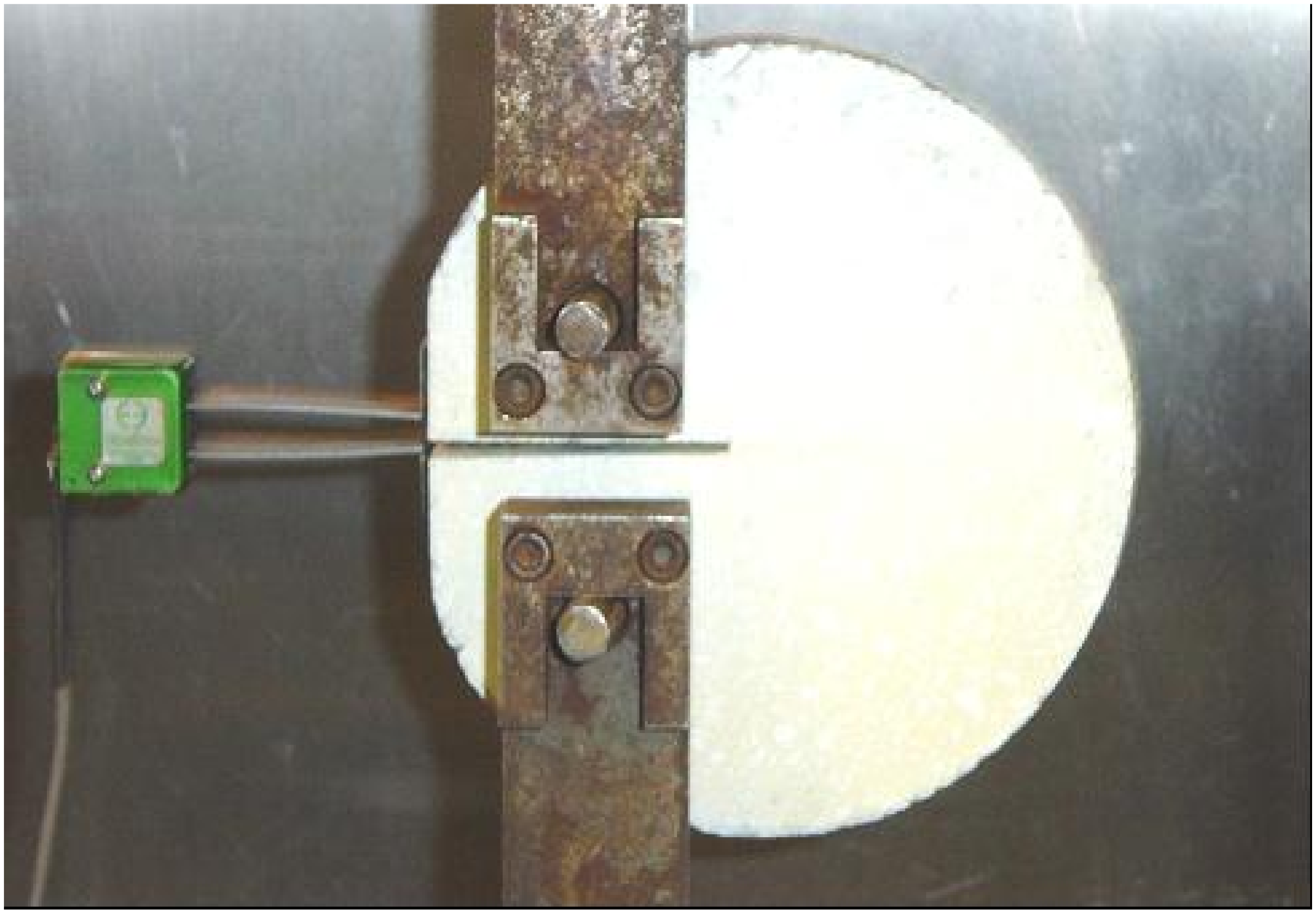
Fracture Energy Analysis Using the Disc-Shaped Compact Tension Test



Andrew Braham
Dr. William Buttlar
Dr. Glaucio Paulino
Dr. Huiming Yin

University of Illinois at Urbana-Champaign

UIUC collected fracture energy using the Disc-Shaped Compact Tension Test for 28 mixtures



A CMOD rate of 1.0 mm/min is used for the DC(T) test

Each mixture was run at three temperatures with three replicates

PGHH-LL

Low temperature → -2°C of LL* (T_{BBR} - 12)

Mid temperature → +10°C of LL* (T_{BBR})

High temperature → +22°C of LL (T_{BBR} + 12)

Example: PG58-28

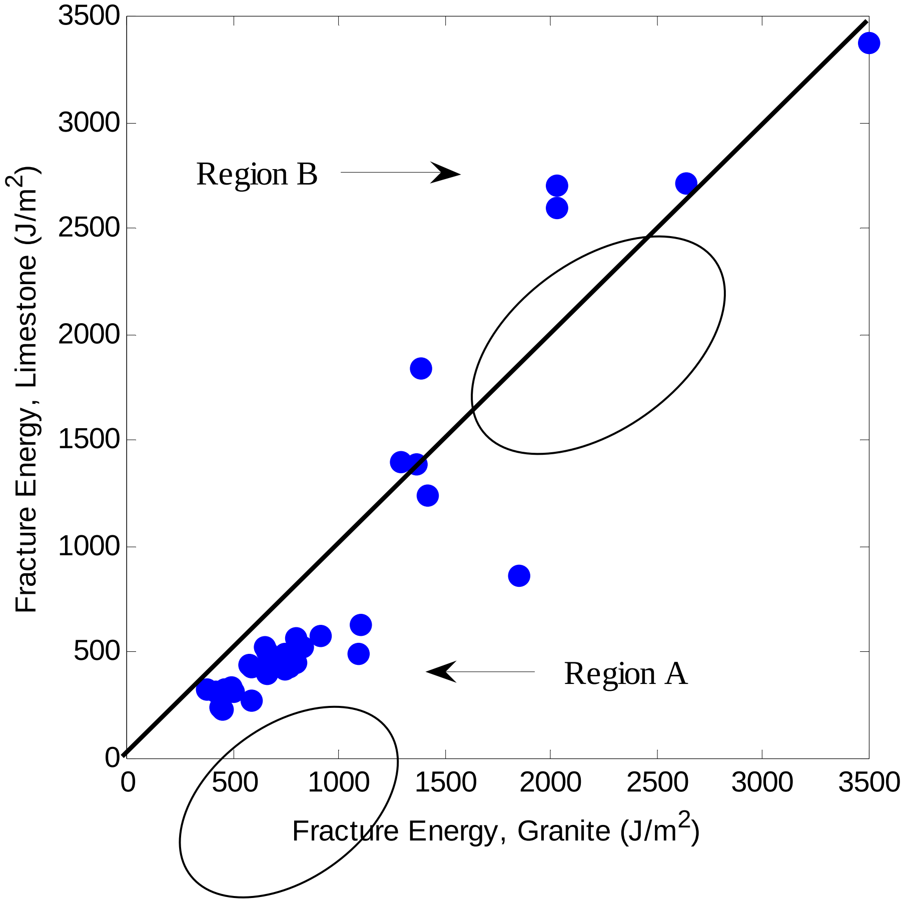
Low temperature → -30°C

Mid temperature → -18°C

High temperature → -6°C

Allowed a wide range of temperature influence and matched asphalt cement testing temperatures (asterisk)

How did the granite and limestone aggregate influence fracture energy?



Granite dominates in Region A while limestone dominates in Region B – Suggests aggr strength is important at very low temperatures, while mastic strength is important at intermed. temps.

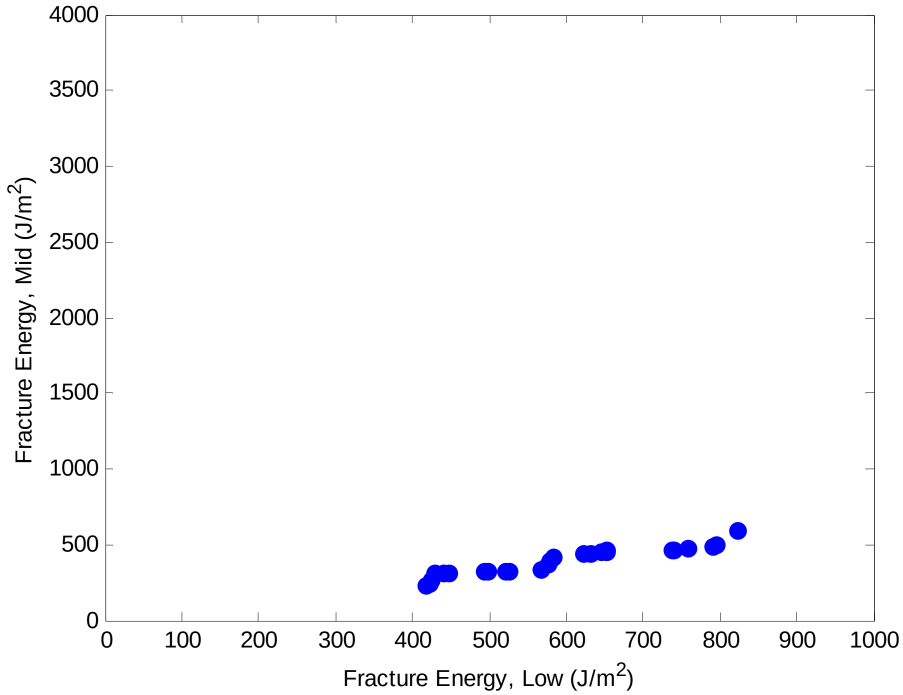
At lower temperatures, limestone aggregate fractures but the granite does not

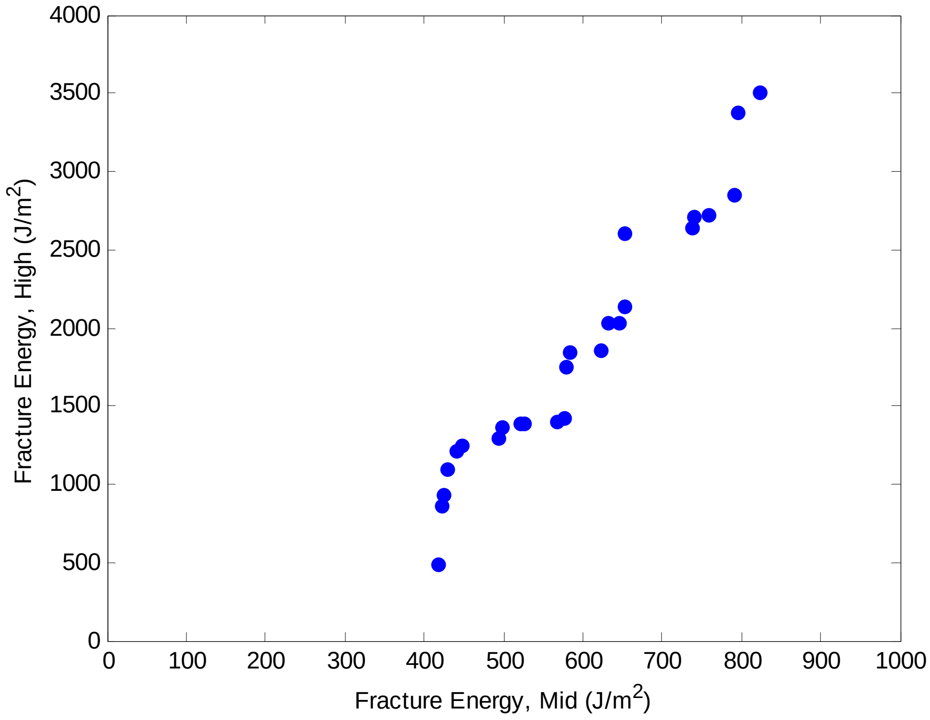
Limestone and granite at low temp

Limestone and granite at high temp

At higher temperatures, neither aggregate fractures

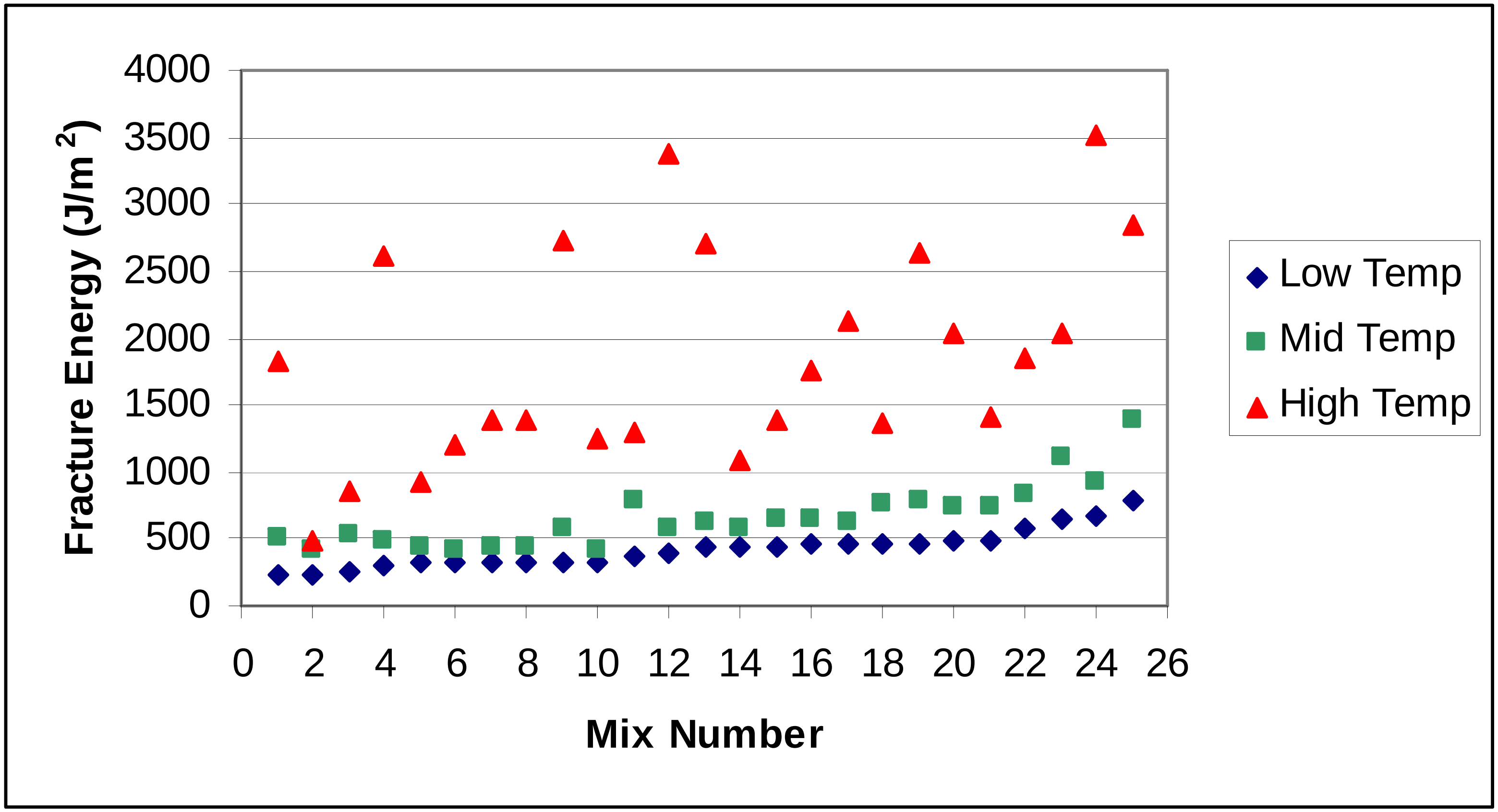
Comparing the two temperature ranges, low-mid and mid-high, shows very different behavior





From low-mid, HMA behaved in a brittle fashion; from mid-high, HMA behaved in a ductile fashion

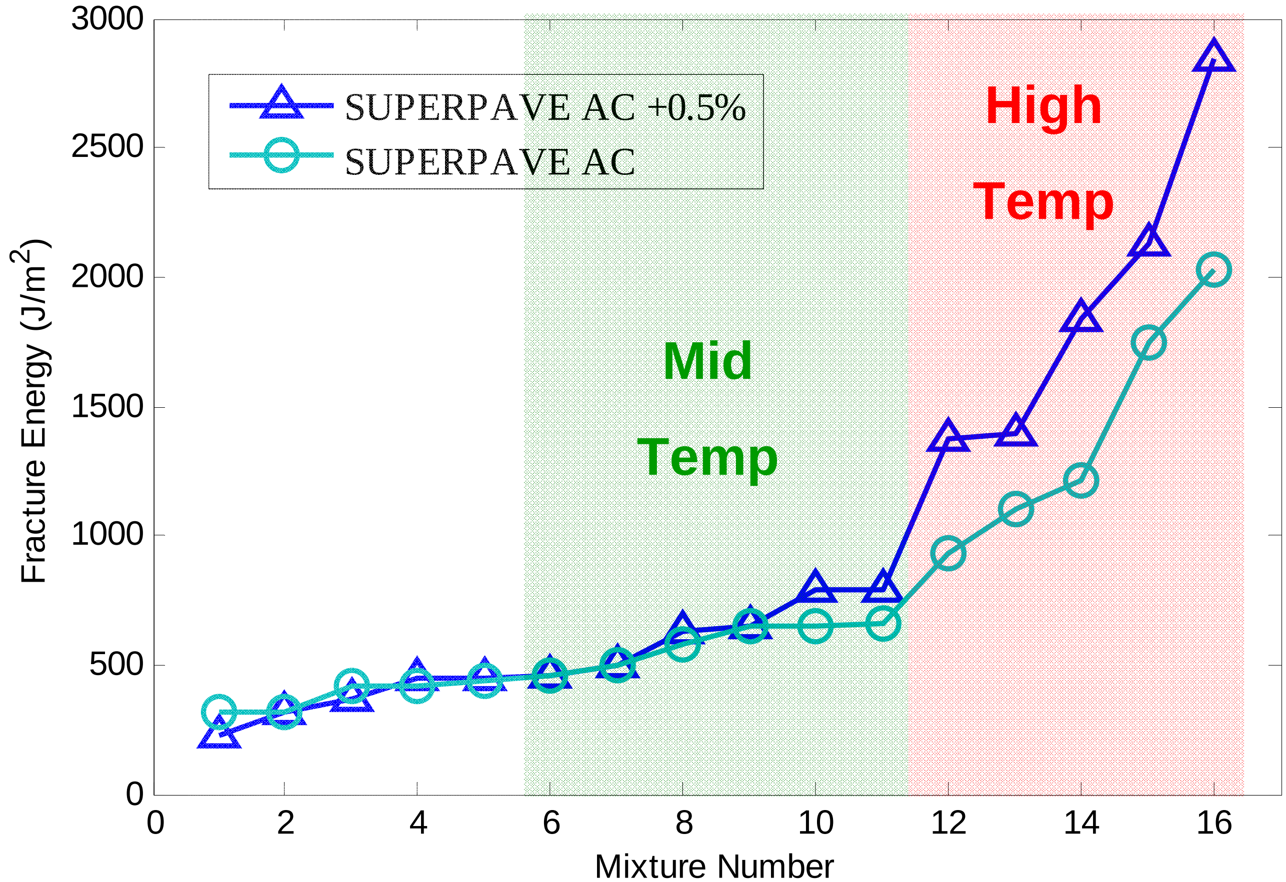
Comparing the two temperature ranges, low-mid and mid-high, shows very different behavior



Effect of Temperature on Fracture Energy Trends

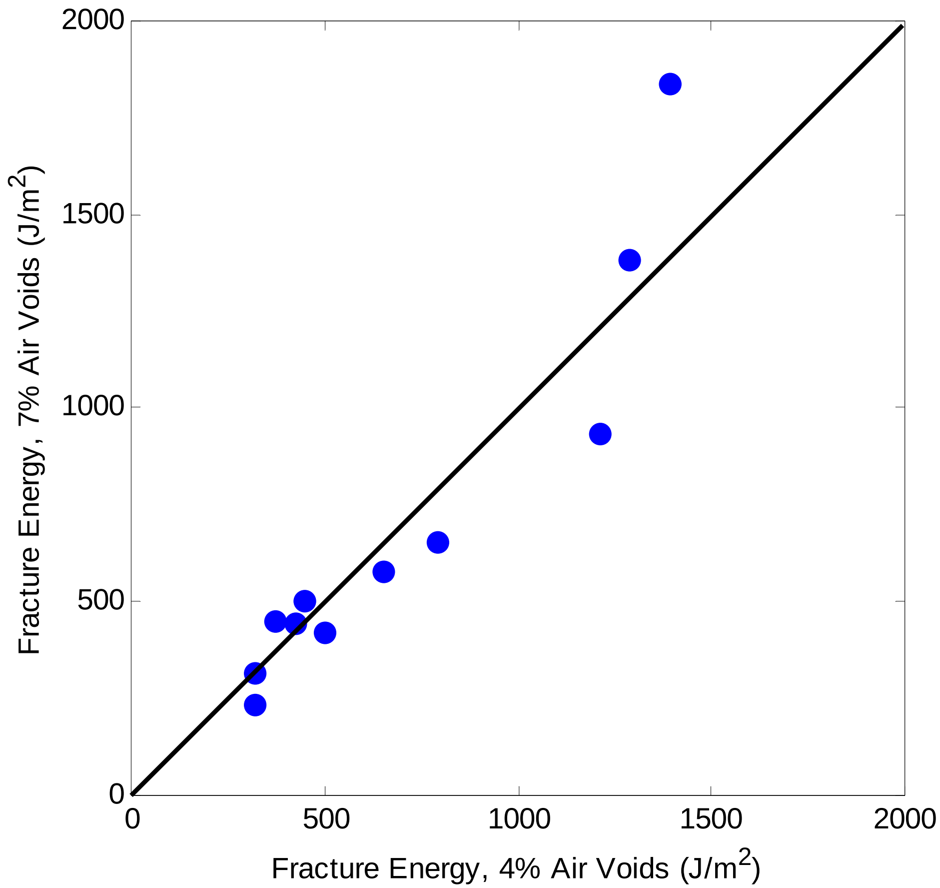
Note: Revised Plot Shown

Asphalt content influence becomes apparent at high temperatures



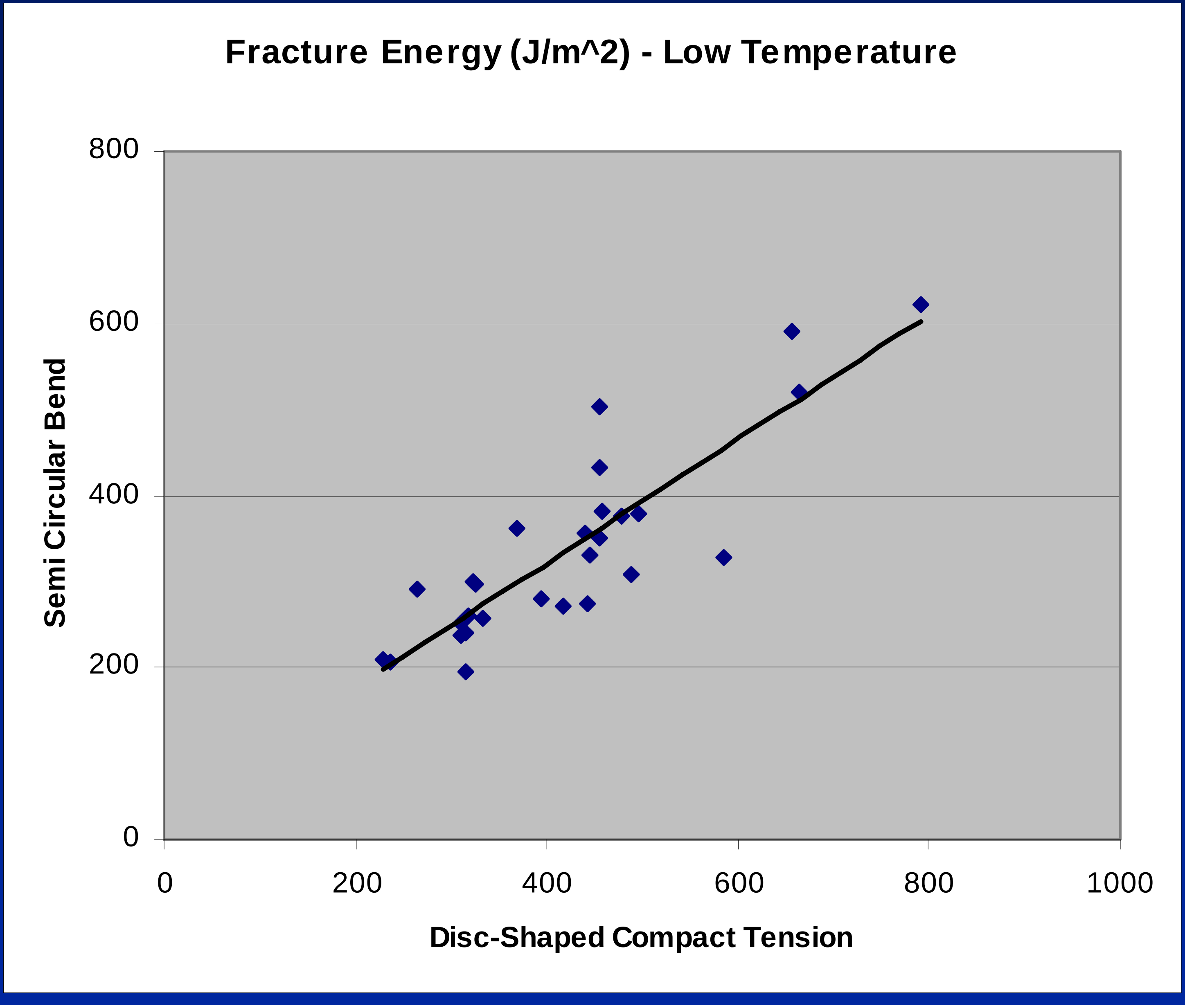
More asphalt cement does not appear to increase fracture energy at low temperatures

The effect of air voids on fracture energy is not conclusive



Three more data points are pending, at will be in high fracture energy range

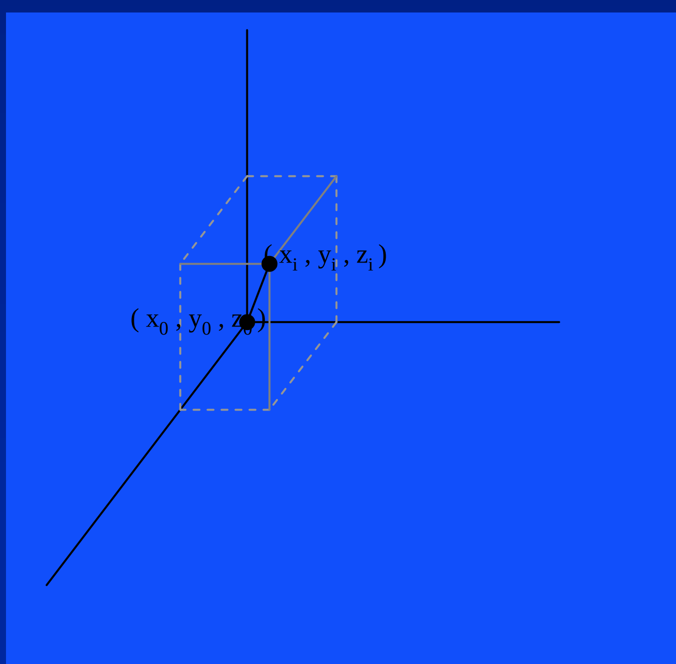
SCB and DC(T) show good correlation



TSRST

- To be performed at Turner Fairbanks
  - ✓Lab prepared beams
  - ✓Field beams

Acoustic Emission

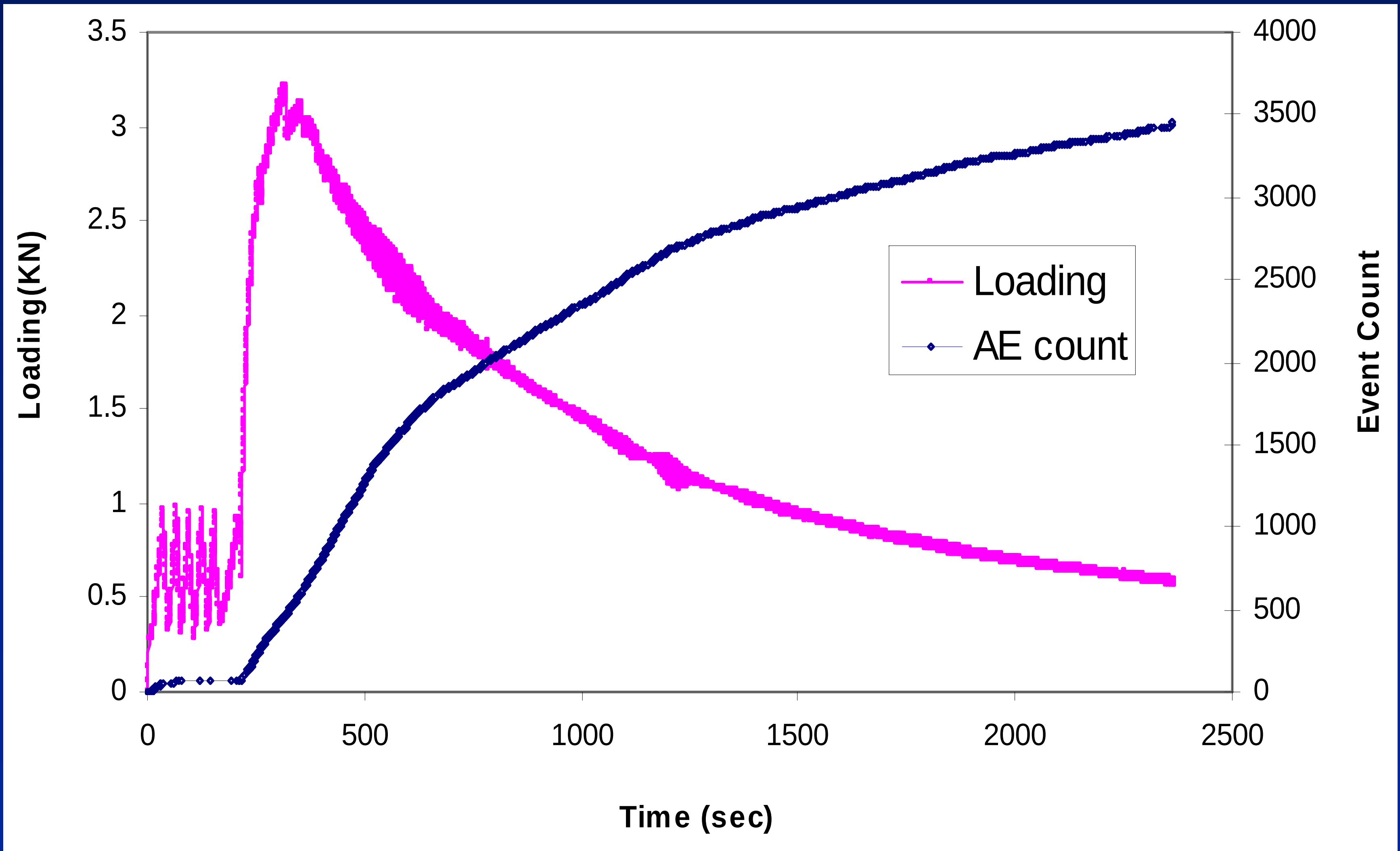


$$d_i = c_p (t_i - t_o) + \varepsilon_i$$

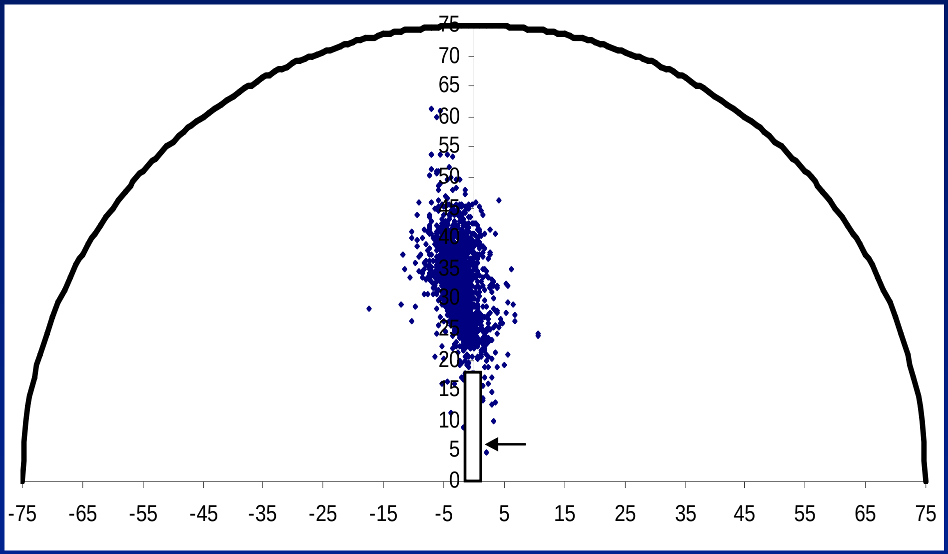
$$d_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$$

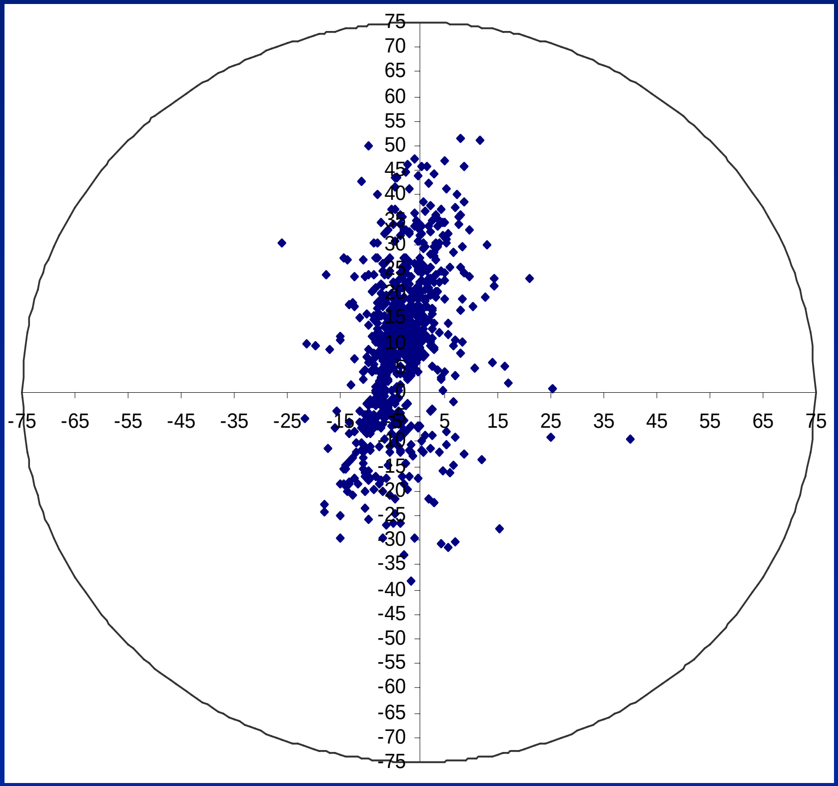
- C_p: Wave speed- from calibration
- T_i: Event Arrive time- from recording

Acoustic Emission



Acoustic Emission Event Location

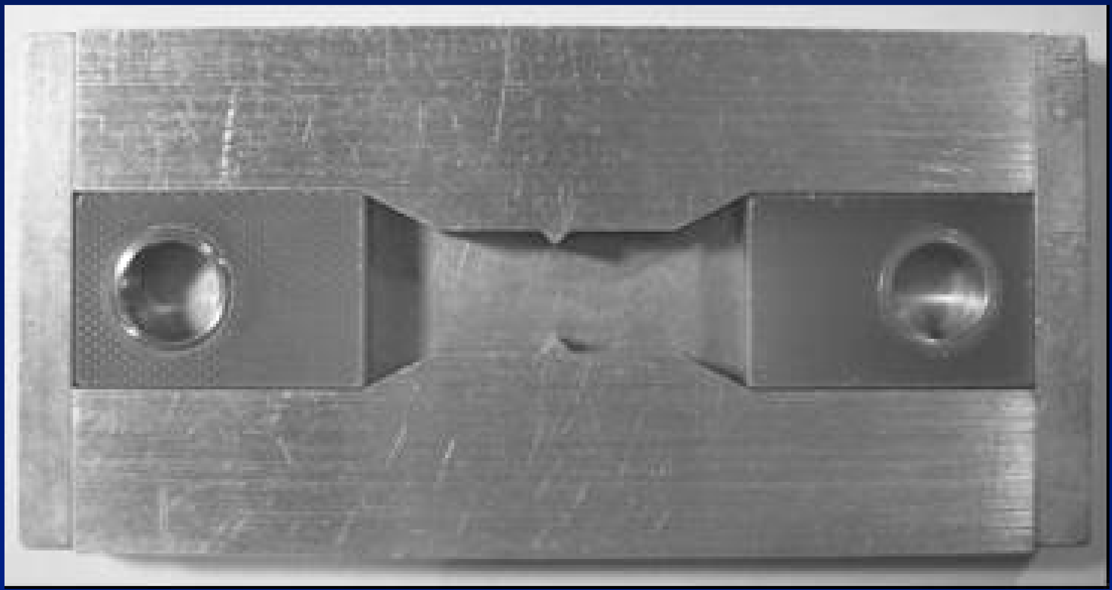


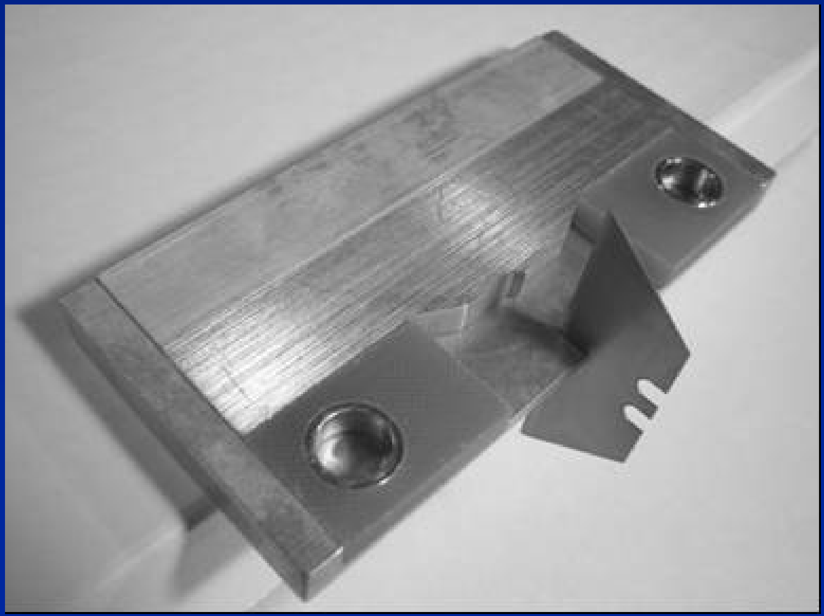


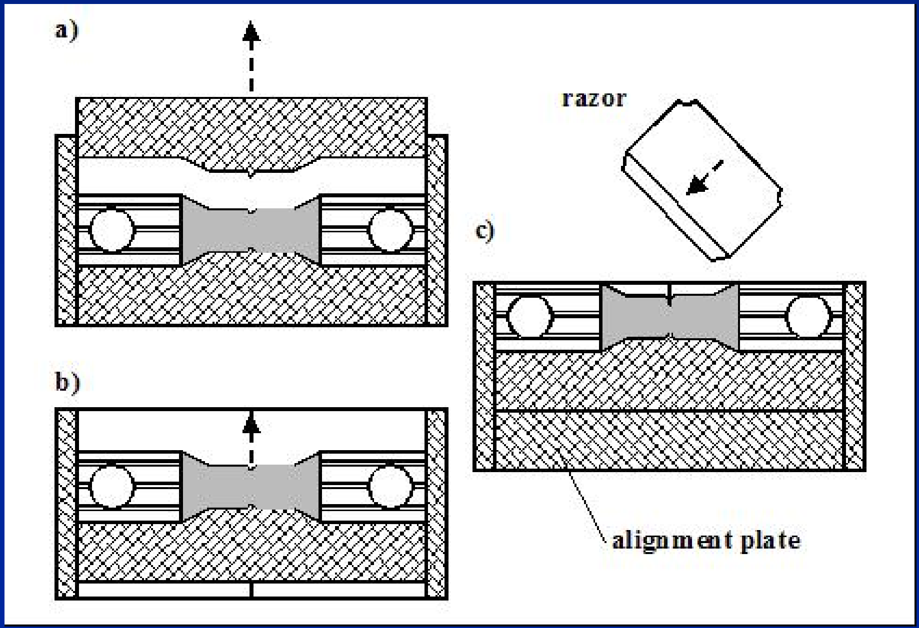
Binder Testing

- Binders used to prepare laboratory mixtures
- Binders recovered from top layer of field samples
- Test methods
  - ✓BBR – 1000s
  - ✓DT – 3%/min
  - ✓DENT – 1.8%/min
  - ✓All three after 1h and 20h conditioning

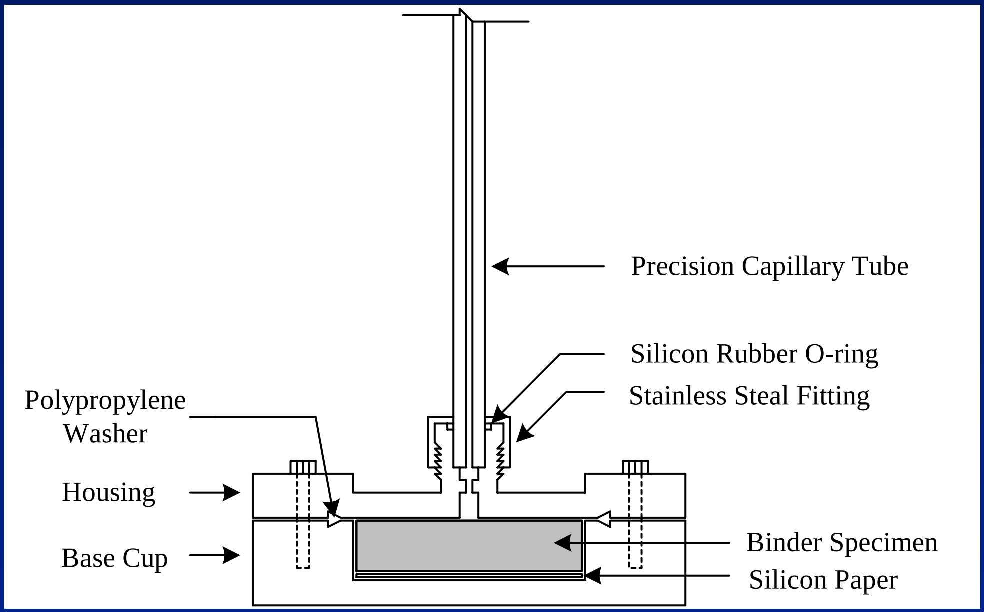
DENT





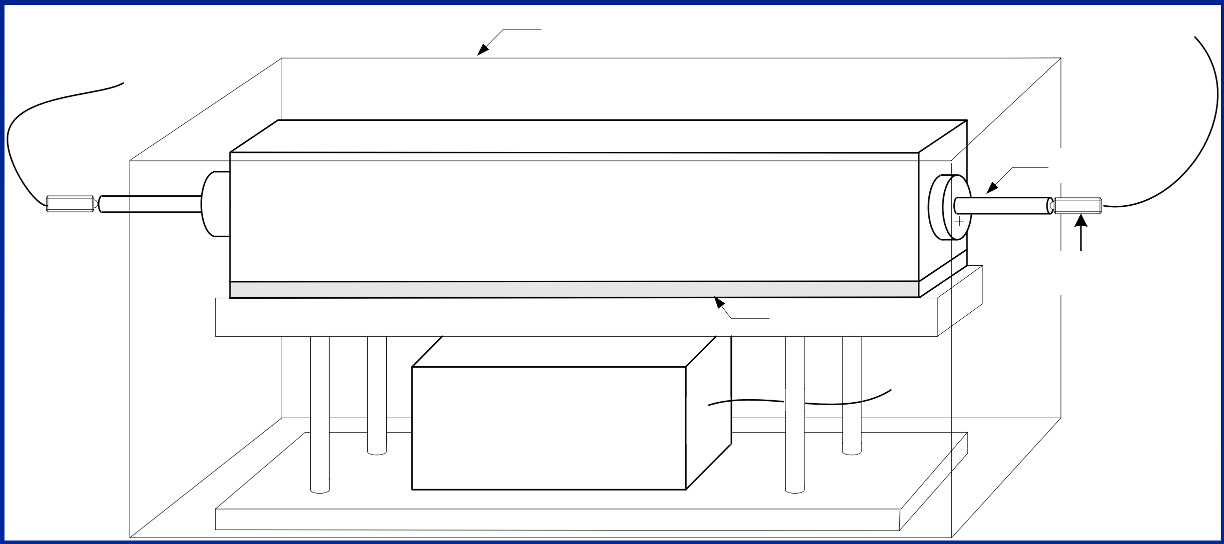


Dilatometric Measurements Wisc



Binder

Mixture

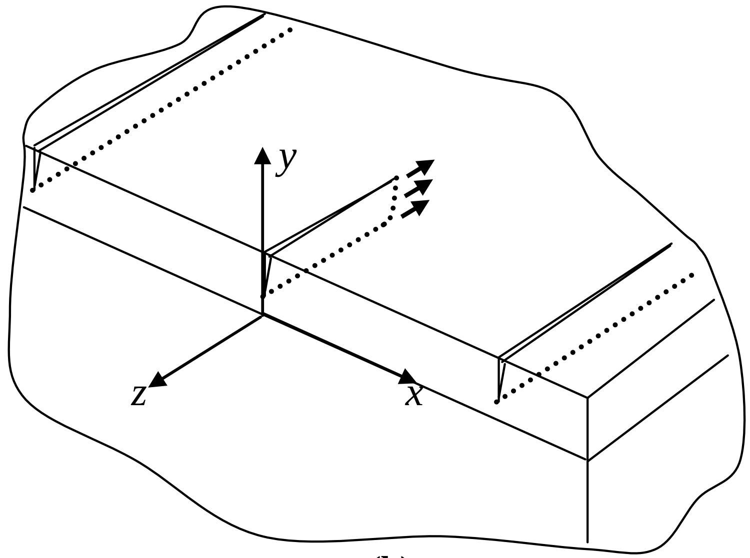


Experimental Data Analysis

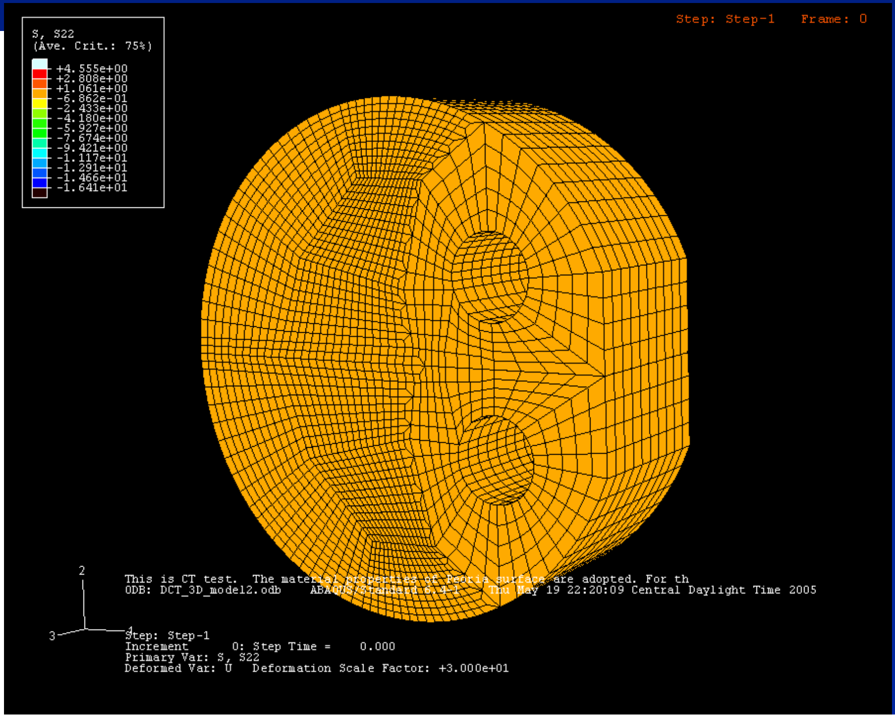
- Compare results obtained from the different mixture testing
  - ✓Similar information?
  - ✓Choose the simplest test that provides reasonable parameters
  - ✓Address the issue of specimen preparation
    - -Gyratory vs. beams
- Similar approach for binder data
- Study binder vs. mixture data
  - ✓Can binder data predict mixture fracture properties, also BBR vs. IDT Creep, etc.

Modeling

- Use experimental data in the modeling of fracture behavior of mixtures at low temperatures
- Two main modeling categories
  - ✓ Baseline, closed-form solutions
  - ✓ Fracture Simulations via Finite Element Analysis with Cohesive Zone Fracture Model
- Details will be provided in second presentation later this morning



(b)



Modeling Approaches

- Baseline, closed-form solutions
  - ✓ Allow Rapid Investigation of Pavement Response and Distress
  - ✓ Fully Verified, Robust Against Computational Errors and Artifacts
  - ✓ Useful in Verification of More Complex Simulation Results

- Fracture Simulations via Finite Element Analysis with Cohesive Zone Fracture Model
  - ✓ Allows More Complex Boundary Value Problems to be Investigated
    - Thermo-mechanical loading of 3D structures
    - Crack nucleation, initiation, and propagation
    - Complex cooling gradients
    - Complex material models and interface behavior

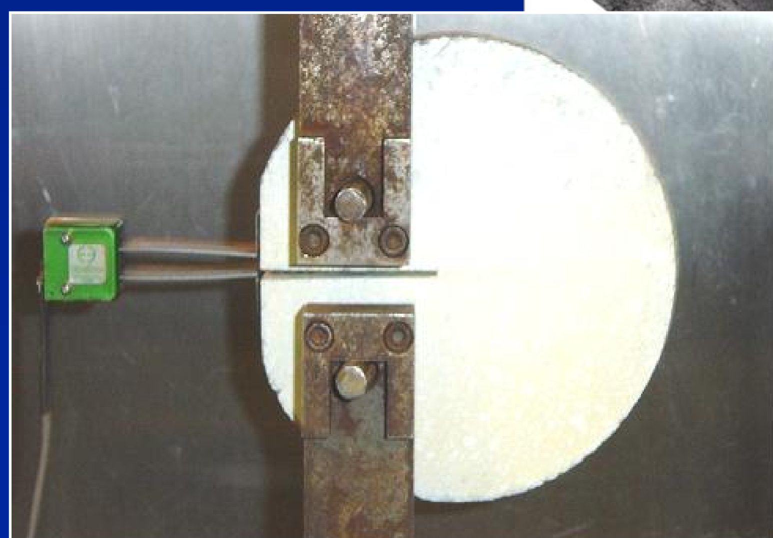
Further Work

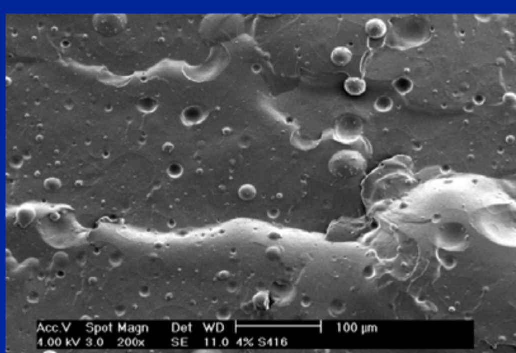
- Factor in loading rate
  - ✓Both mixture testing and binder testing
- Understand the role of physical hardening of the binders
- Aging effects (time, gradients)
- Obtain reliable pavement temperature data and thermal properties of mixtures
- Test simplification and standardization
- More field validation (phase II)


Thank you!


NVIDIA
Image © 2004 DigitalGlobe
©2004 keyhole.com
Pointer 45°15'22.01" N 93°42'07.23" W
Streaming 100%
Eye alt 428 ft


MnROAD Cell 18
0 10 20 40 60 80 100 Feet




Acc.V Spot Magn Det WD 100 µm
4.00 kV 3.0 200x SE 11.0 4% S416

A Brief Overview of Approach and Methodology

Low Temperature Cracking National Pooled Fund Study 776

William Buttlar

&

Glaucio H. Paulino, Huiming Yin, Andrew Braham

August 13, 2006

Department of Civil and Environmental Engineering

University of Illinois at Urbana-Champaign

Overview

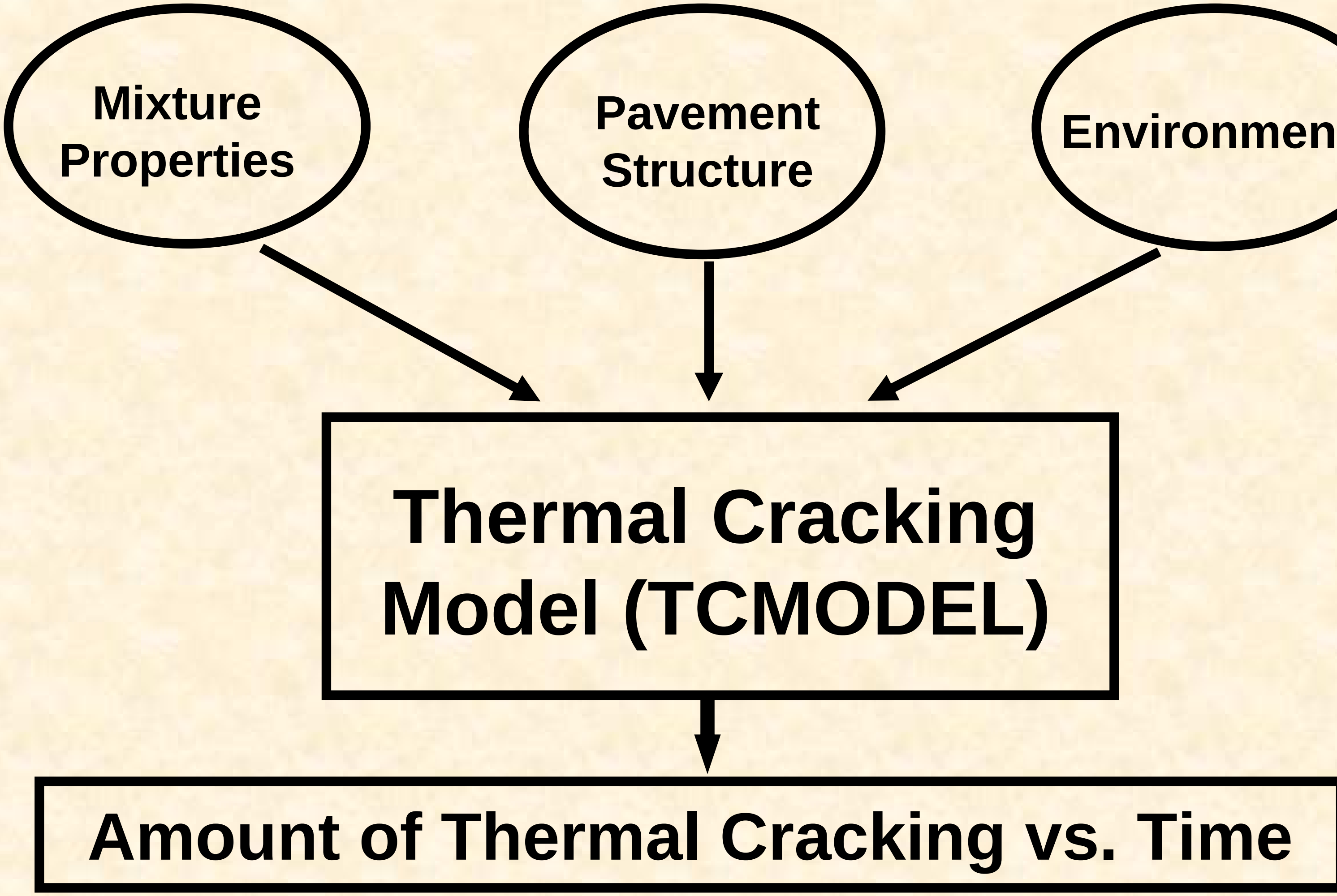
- Briefly Review Existing AASHTO MEPDG Mixture Thermal Cracking Specifications
- Discuss UIUC Areas of Research for Pooled Fund
  - Introduction to New Mixture Fracture Tests
  - Baseline Pavement Solutions (Thermal Stresses, Crack Spacing, etc.) – Elasticity
  - Introduction to Modeling Techniques
    - Cohesive Zone Fracture Model
    - Binder-to-Mixture Modeling - Micromechanics
  - Pavement Cracking Simulation – Illustrative Examples from NSF GOALI Study

Background - TCMODEL

- Developed During SHRP, Originally Completed in 1993
- Uses Measured Mixture Viscoelastic Properties and Tensile Strengths at Low Temperatures using IDT Device
- Features Viscoelastic Response Model, Paris Law Fracture Model, and Unique Probabilistic Crack Distribution Model
- Improved Coding and Re-Calibration with Additional Sections in AASHTO 1-37A

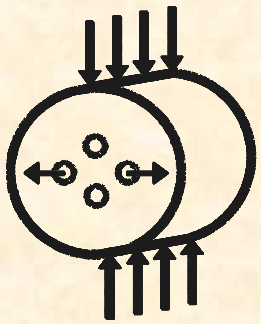
TCMODEL

Thermal Cracking Performance Prediction



TCMODEL Material Inputs & Models:

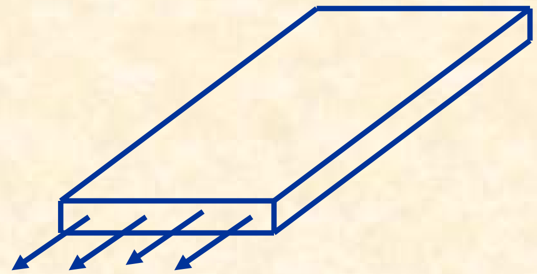
Fracture is not Directly Considered



IDT Creep Test - Viscoelastic Properties: D(t,T) and m

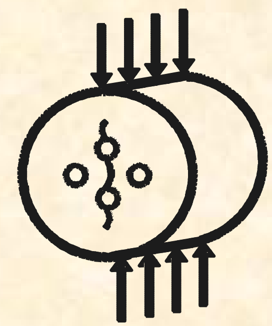
PAVEMENT RESPONSE MODEL

Strong Link



Thermal Stress

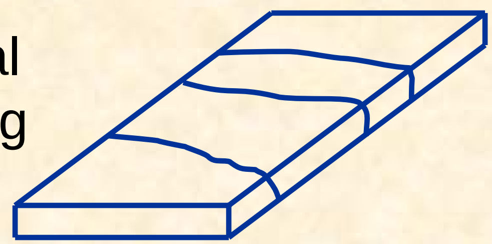
IDT Strength Test



Weak Link (Paris Law Based)

PAVEMENT DISTRESS MODEL

Thermal Cracking



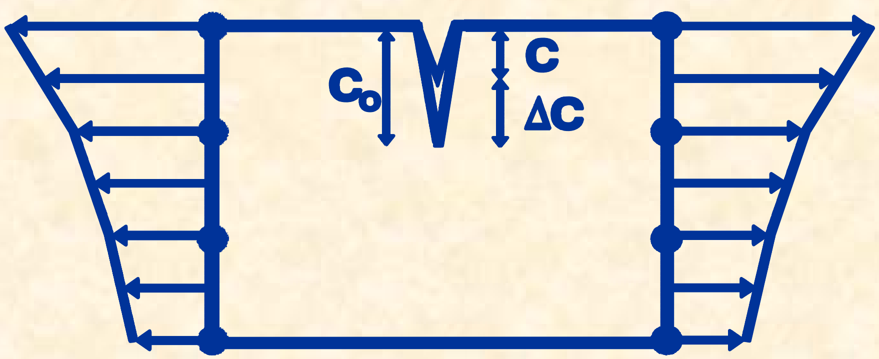
Paris' Law (1961)

$$\Delta C = A(\Delta K)^n$$

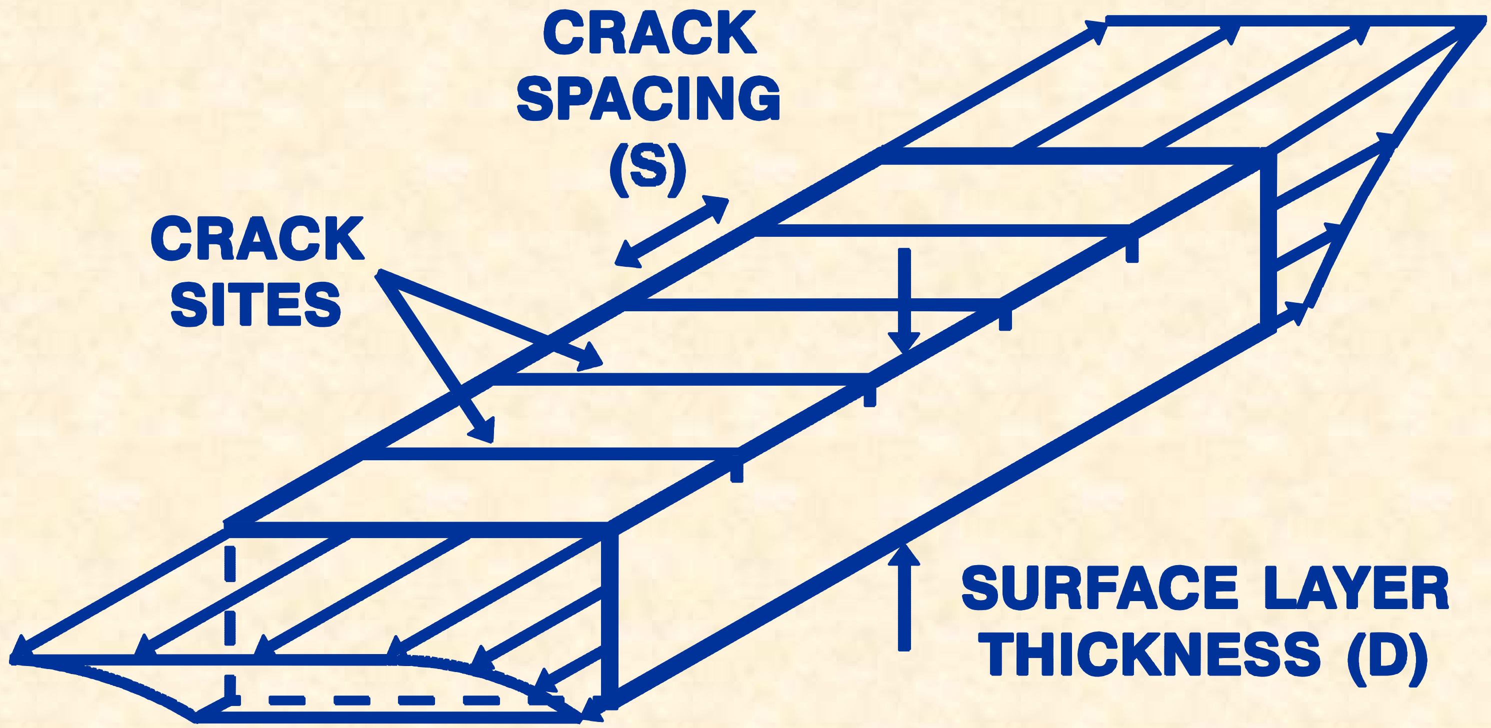
A, n = Paris Law Parameters

ΔC = Change in Crack Length

ΔK = Change in Stress Intensity Factor



Schematic: Physical Model of Pavement Section



Key TCMODEL Deficiencies in Physical Modeling of Cracks: Predefined Crack Sites, Crack Interaction not Considered, Interface with Lower Pavement Layers not Considered, Paris Law not Appropriate for Single-Event Thermal Cracking

Some Current Areas of Research

Testing and Modeling

- Improved Fracture Inputs
  - Rigorous Fracture Test – As Baseline Reference
  - Surrogate Fracture or Strength Test
- Improved Fracture Modeling
  - Baseline (closed-form) Models
  - Better Representation of Crack Initiation and Propagation
  - Better Ties to Material Fracture Parameters
  - Improved Handling of Aging Gradients as f(time)
  - Improved Approach for Reliability

Investigation of Low Temperature Cracking in Asphalt Pavements:

Development of Baseline Thermal Cracking Models

Huiming Yin

William Buttlar

Glaucio Paulino

Department of Civil and Environmental Engineering

University of Illinois at Urbana-Champaign

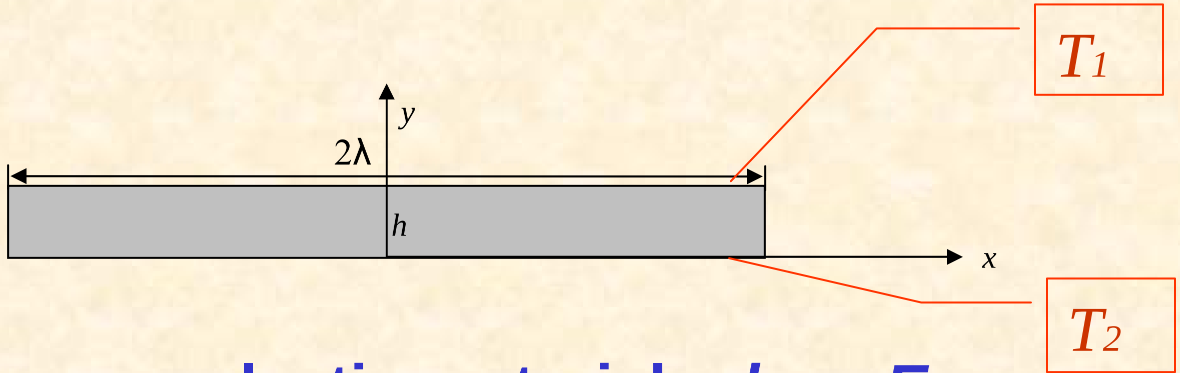
Three models are proposed for specific pavements

Full-depth cracks with frictional interface:
HMA on granular base
Full-depth HMA
HMA on a weakly bound layer

Full-depth cracks with bonded interface:
Composite pavements
HMA on CRCP
HMA on JRCP
HMA on CTB

Partial-depth cracks with rigid support:
HMA on CRCP
HMA on JRCP
HMA on CTB

General Solution



Homogeneous elastic materials: *k, α, E, v*

Plane layers stay in plane: $u_y(x,y) = u_y(y)$

Equilibrium:

$$\sigma_{x,x} + \tau_{xy,y} = 0$$

$$Eu_{x,xx} + \mu u_{x,yy} = 0$$

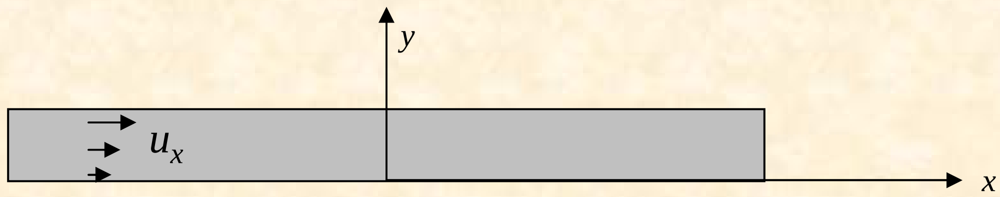
Plane strain: $E = E^0 / (1 - v^2)$

$$\mu = E^0 / 2 / (1 + v)$$

Timm DH, Guzina BB, Voller VR. Prediction of thermal crack spacing. Int. J. Solids Struct. 2003; 40:125-142

Xia ZC, Hutchinson JW, Crack patterns in thin films. J. Mech. Phys. Solids. 2000;48: 1107-1131.

General solution for displacement is obtained



Governing equation: $Eu_{x,xx} + \mu u_{x,yy} = 0$

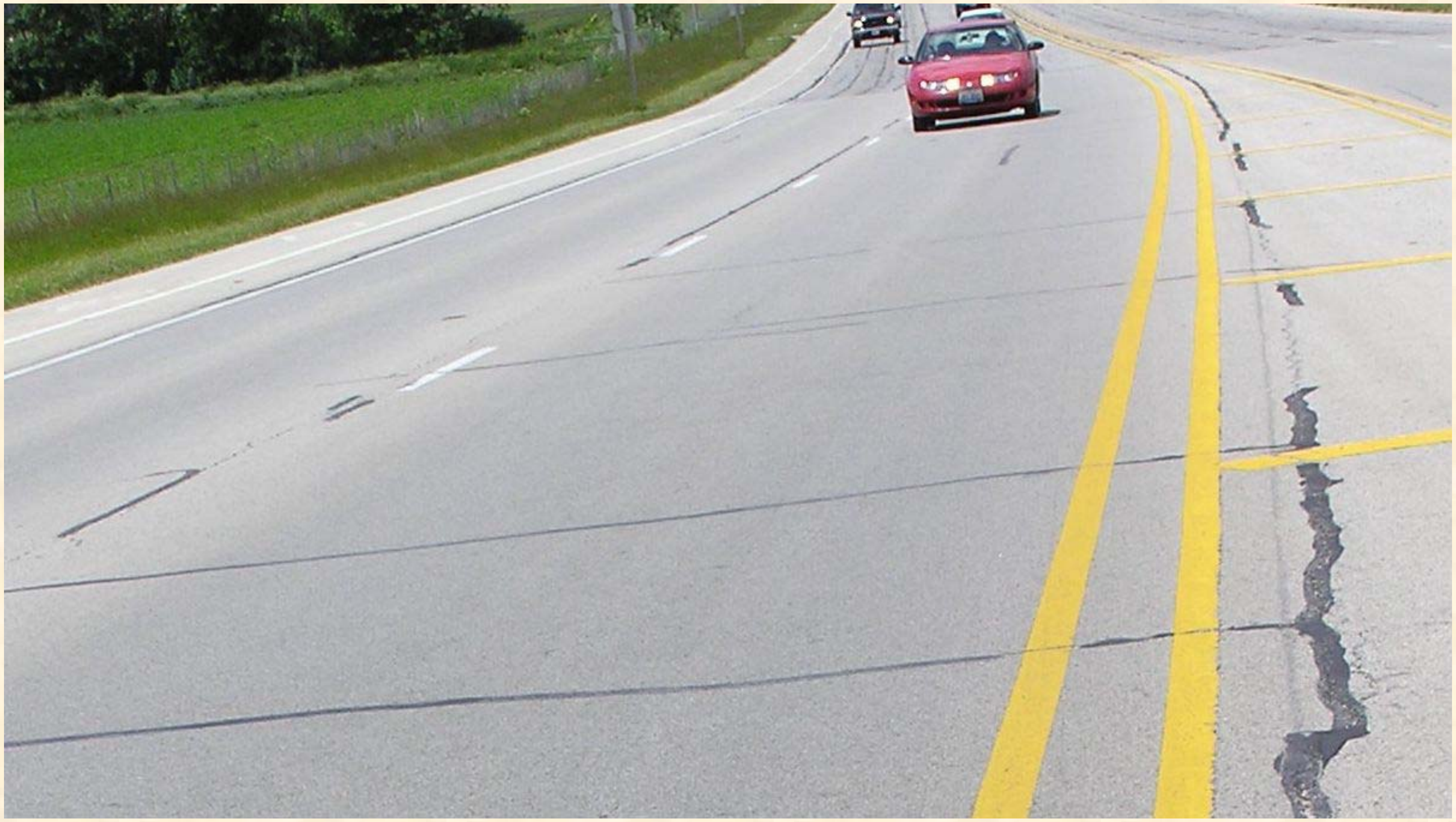
Symmetry and free surface: $u_x(0, y) = 0; \quad u_{x,y}(x, h) = 0$

General solution: $u_x(x, y) = B \sinh(cx/h) \cos d(1 - y/h)$

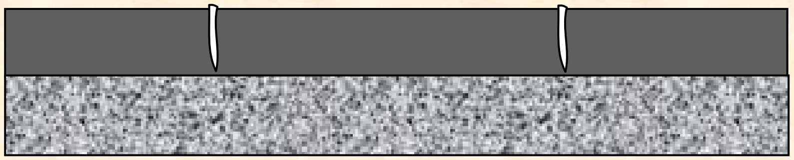
$$d = \sqrt{E/\mu}c$$

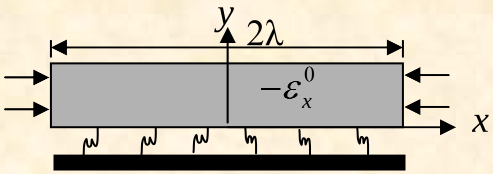
***c* and *B* are to be determined by the boundary conditions**

Asphalt pavement on a frictional interface



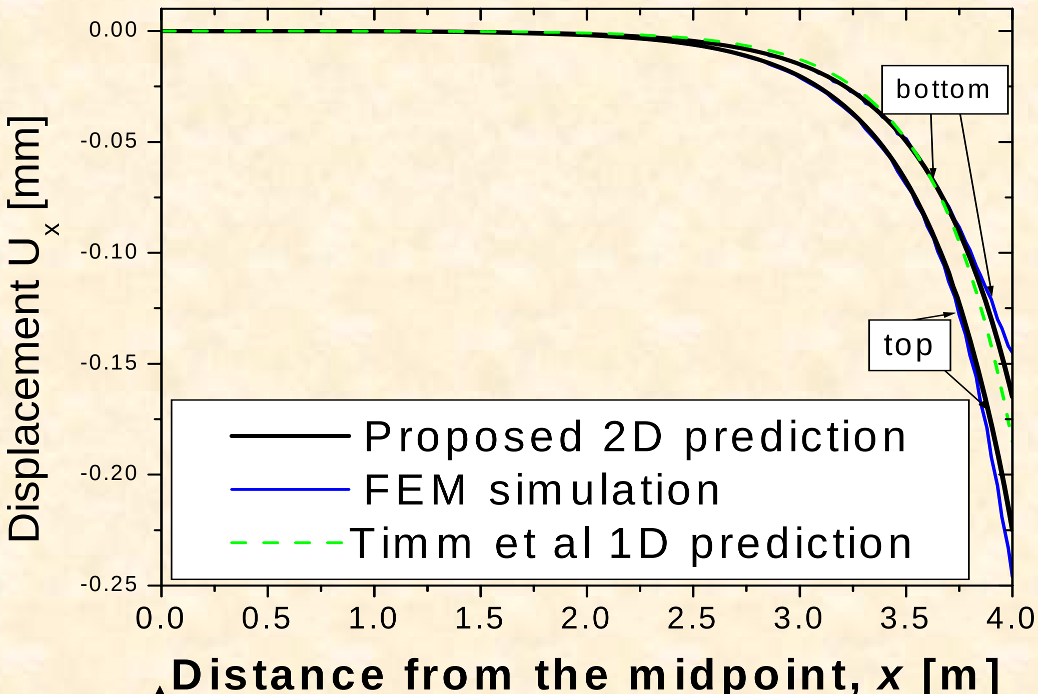
Elevation view:





Solution is verified by FEM results

Parameters: $B = \alpha dh \frac{T_1 + T_2}{2c\sin(dh)\left(e^{c\lambda} + e^{-c\lambda}\right)}$ $d = \frac{k}{\mu \tan(dh)}$ $c = \sqrt{\mu / E d}$

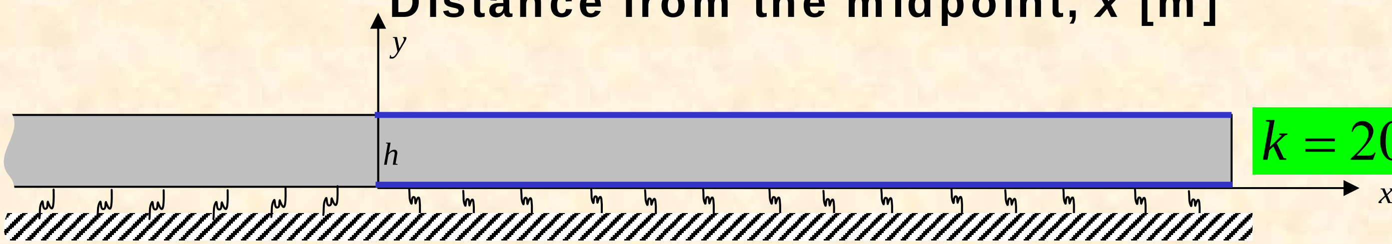


$E = 14.0GPa; \nu = 0.2;$

$\alpha = 1.8 * 10^{-5} 1/K;$

$T_1 = -30K; T_2 = -25K;$

$h = 0.2m; \lambda = 4m$



$k = 20GPa/m$

Timm DH, Guzina BB, Voller VR. Int. J. Solids Struct. 2003; 40:125-142

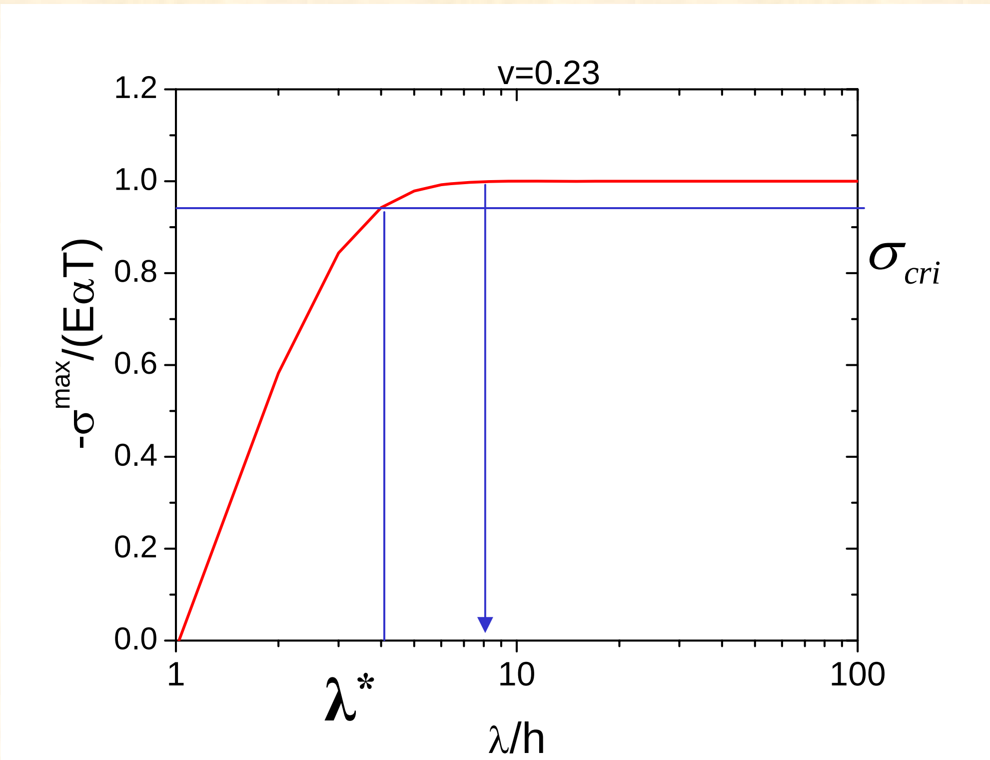
Small potential crack spacings predicted

Tensile strength

$$\sigma_x^{\max} \le \sigma_{cri} \,?$$

$$\sigma_x^{\max} = E\left(\alpha dh \frac{T_1 + T_2}{\sin(dh)\left(e^{c\lambda} + e^{-c\lambda}\right)} - \alpha T_1\right)$$

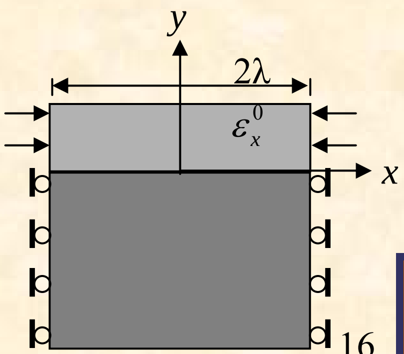
→ **λ**



Ex: Crack spacing is only 4 times thickness of the HMA

Full-depth cracks sometimes occur in asphalt overlays on PCC pavements

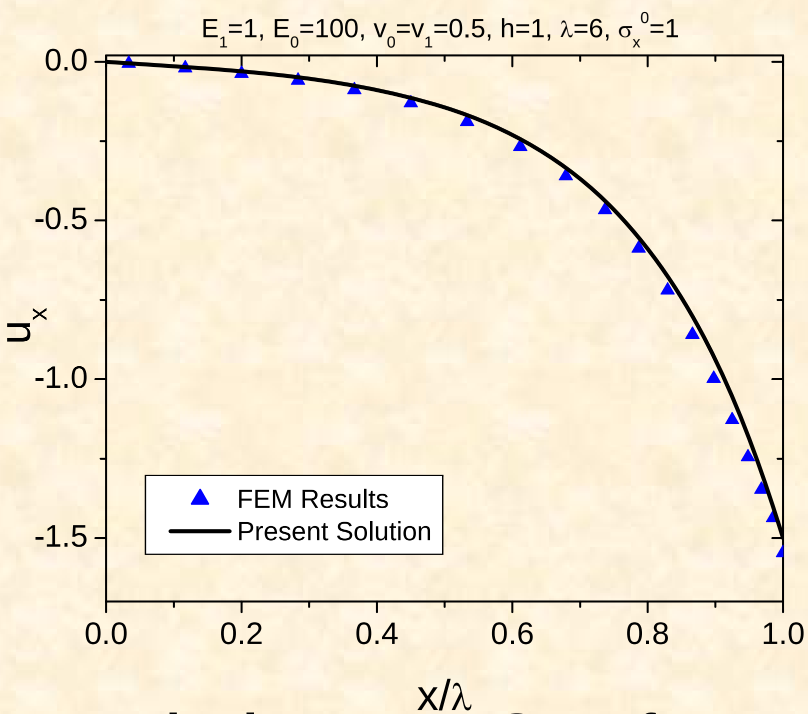
Elevation view:



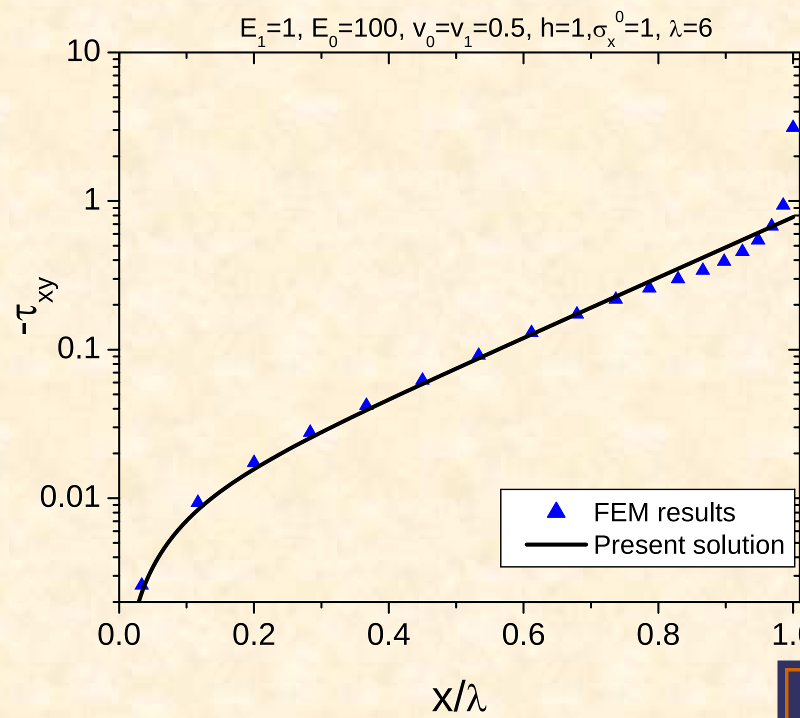
Solution verified by FEM results

Parameters: $c = \dfrac{2}{\pi g(\alpha,\beta)}$; $d = \sqrt{\dfrac{\bar{E}_1}{\mu_1}}c$

$$g(\alpha,\beta) \approx \frac{1.258 - 0.40\alpha - 0.26\alpha^3 - 0.30\alpha^4}{1-\alpha} \qquad \alpha = \frac{\bar{E}_1 - \bar{E}_0}{\bar{E}_1 + \bar{E}_0}$$



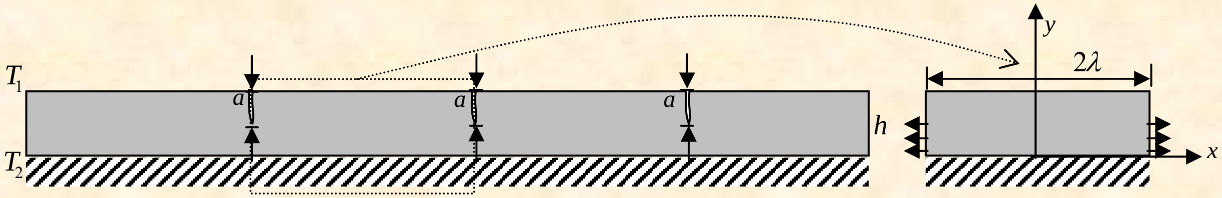
Displacement @ surface



Shear stress @ interface

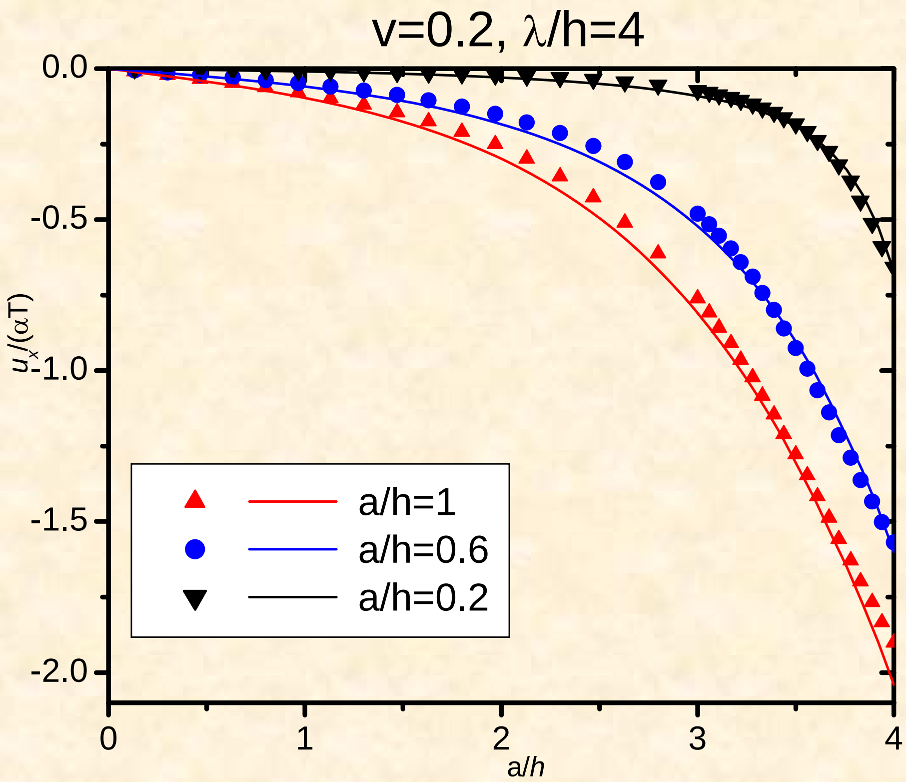
Partial-depth cracks can occur in asphalt overlays on rigid pavements

Elevation view:



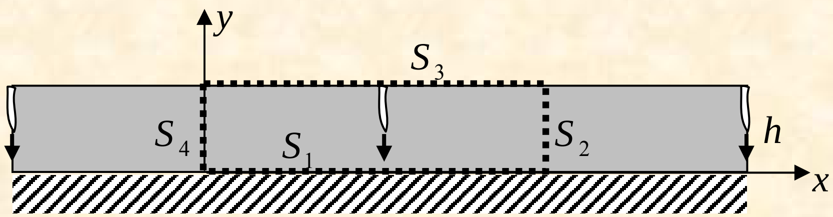
A series form solution is verified by FEM results

$$u_x\left(x,y\right)=\sum_{i=1}^{N}B_i\sinh\left(c_i x/h\right)\cos\left[d_i\left(1-y/h\right)\right]$$

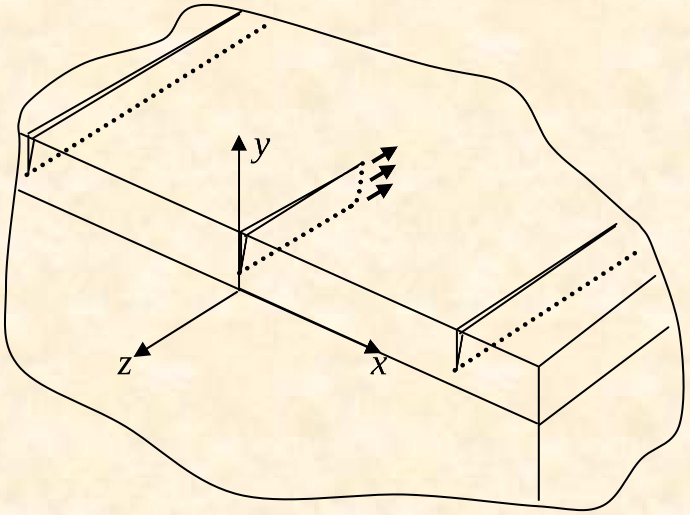


Two types of cracking can be analyzed

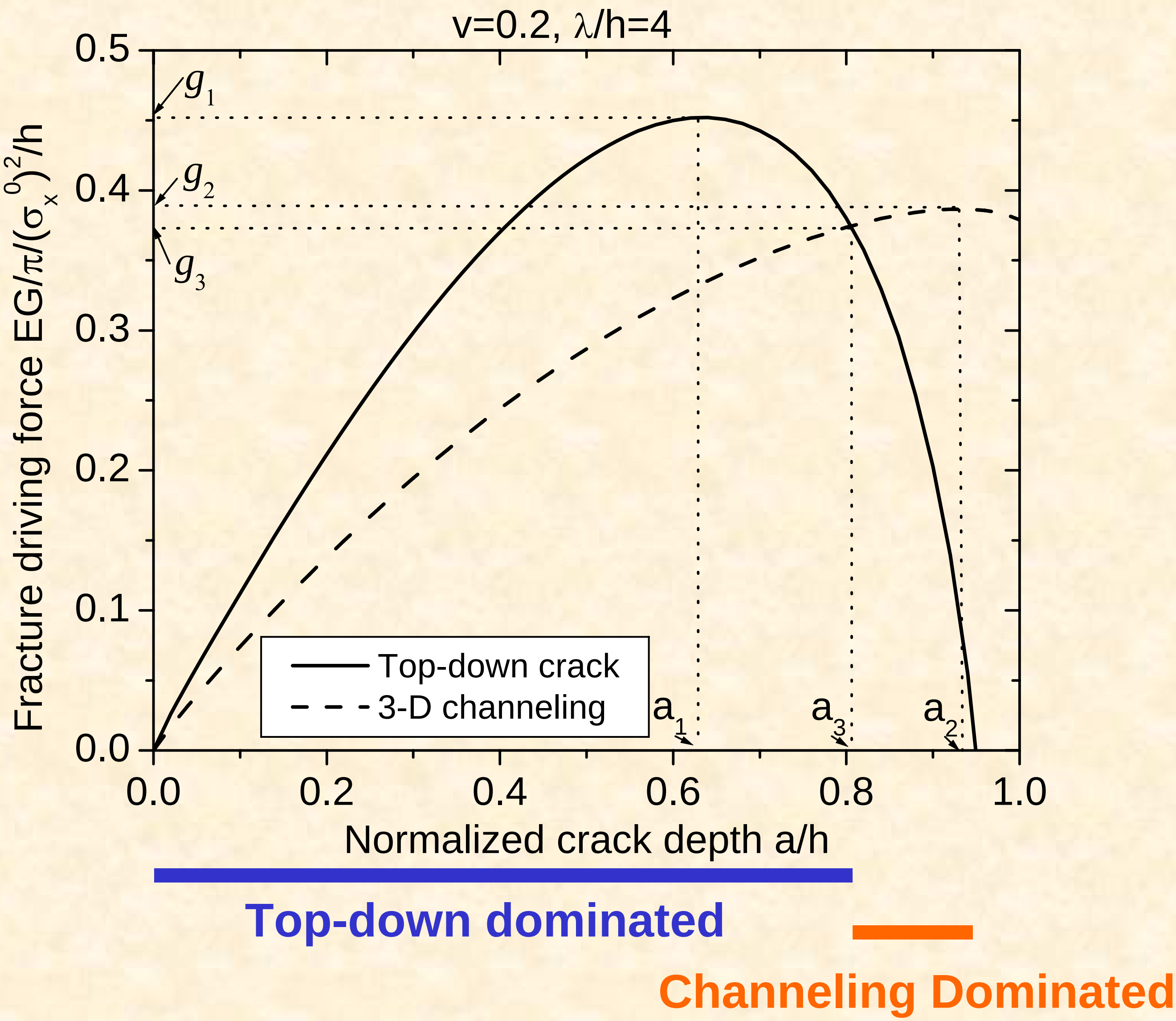
Top-down cracking:



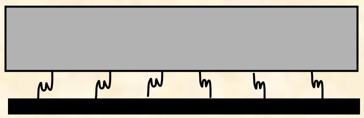
3D channeling:



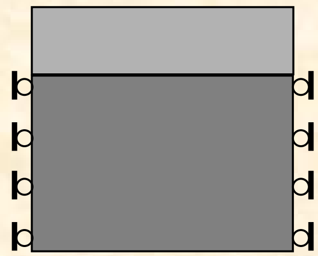
Channeling follows top-down cracking



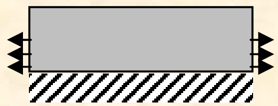
In summary, three models are developed



- Full-depth crack
- Frictional interface
- HMA/granular base
- Small crack spacing



- Full-depth crack
- Bonded interface
- HMA/PCC base
- Critical overlay thickness



- Partial-depth crack
- Rigid base
- HMA/CRCP
- Top-down/Channeling

H.M. Yin, W.G. Buttlar, G.H. Paulino, 2005, A two-dimensional elastic model of pavements with thermal failure discontinuities, *3rd MIT Conference on Computational Fluid and Solid Mechanics*, p. 539-542, June 14-17, Boston, MA.

H.M. Yin, W.G. Buttlar, G.H. Paulino, Periodic thermal cracking in an asphalt overlay bonded to a rigid pavement, *Journal of Transportation Engineering – ASCE* (in press).

H.M. Yin, G.H. Paulino, W.G. Buttlar, An explicit elastic solution for a brittle film with periodic crack, *Journal of the Mechanics and Physics of Solids* (to be submitted)

Limitations and Need for Further Modeling

Viscoelastic HMA layer(s)

Temperature field changing with time and location

Block cracking may be induced by temperature effects

Thermal cracking may interact with other types of cracking

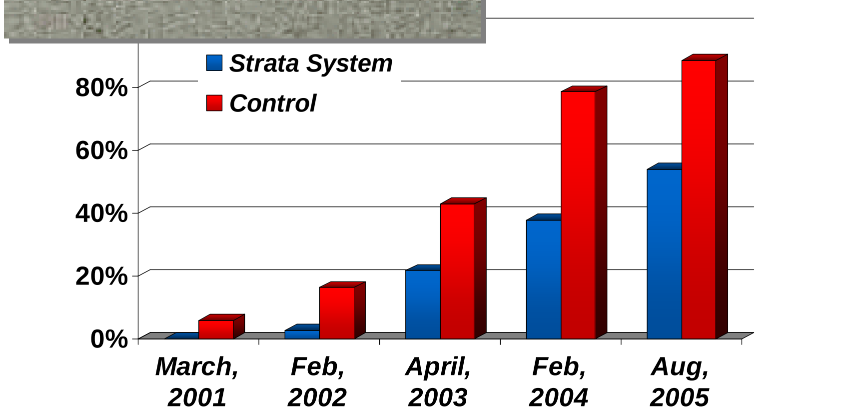
Crack geometry may be complex

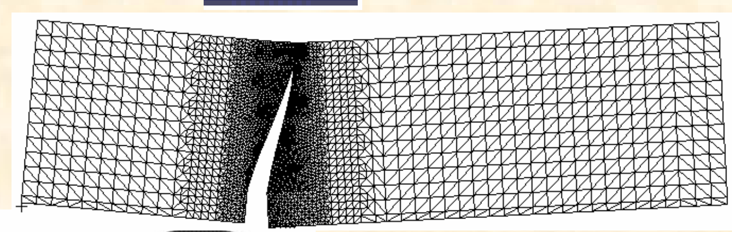
Some behaviors have to be studied by 3D simulations

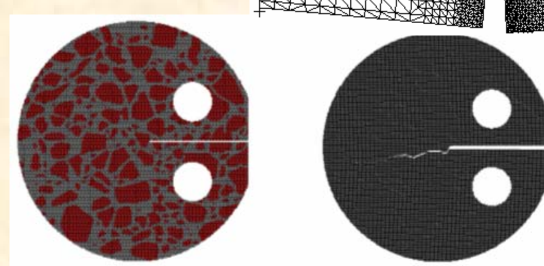
Fracture Testing and Need for Integration with Modeling: Overview of Concept used on a Related NSF GOALI Study

NSF GOALI* Study on Reflective Cracking

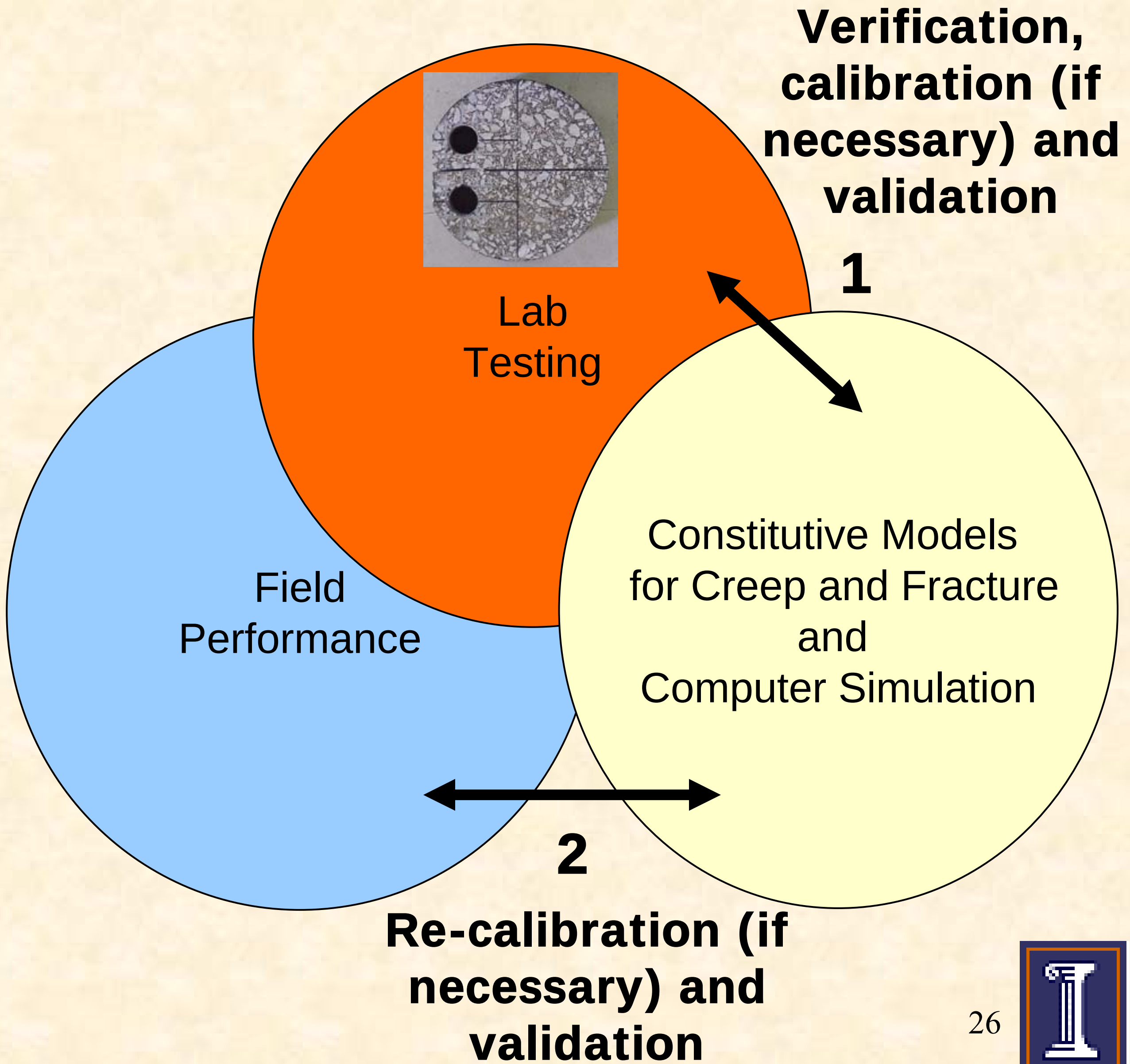
*Grant Opportunities for Academic Liaison with Industry





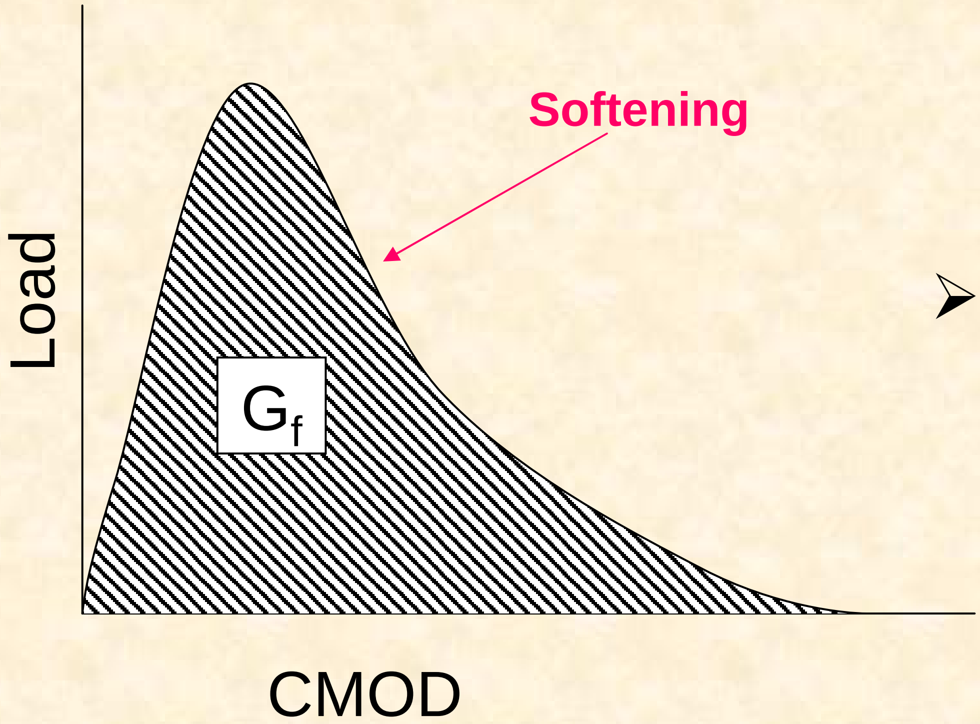


Integrated Approach



Fracture Properties

Quasi-brittle fracture

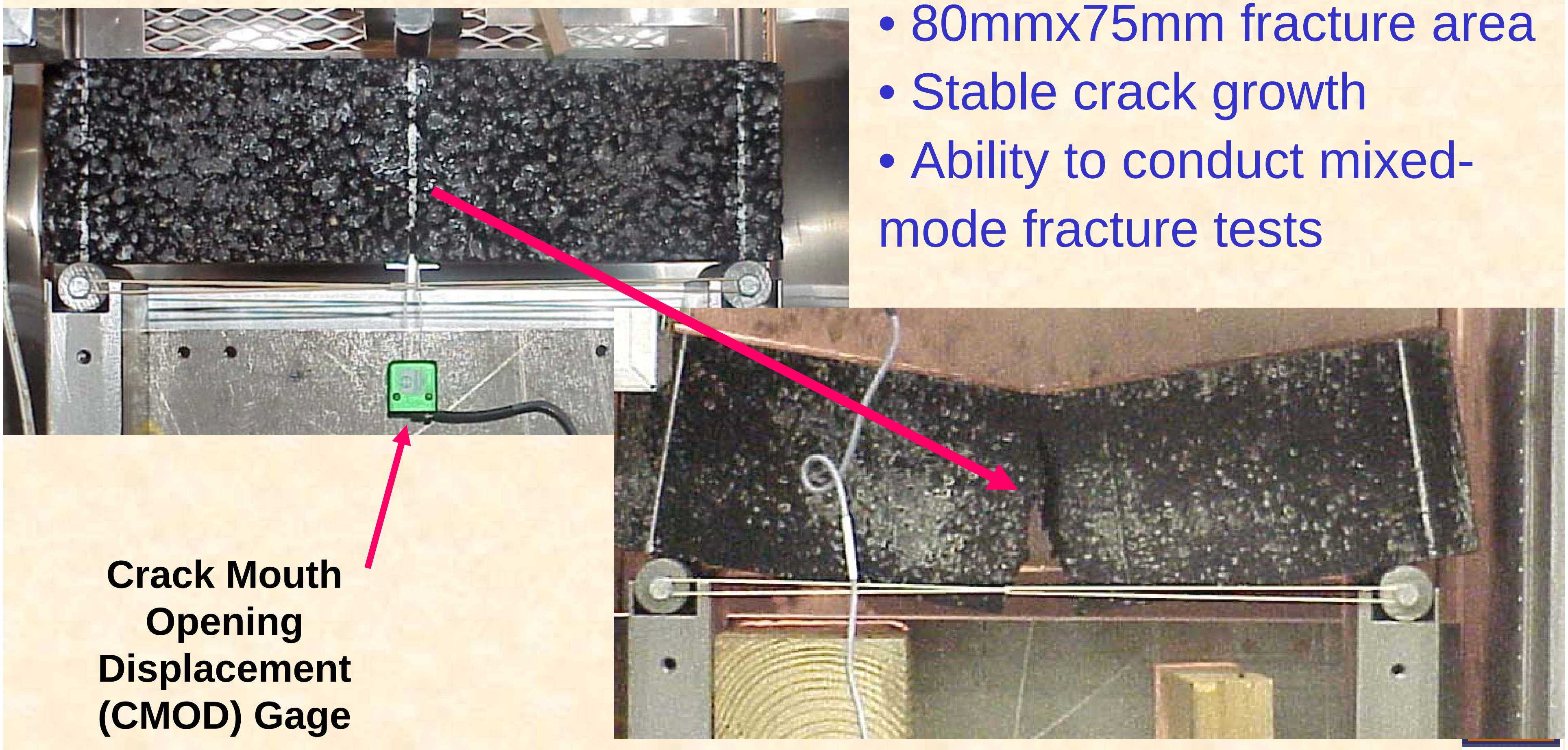


- **Needed to develop simple yet reliable tests to obtain fracture energy (G_f)**
- **Provide data for calibration of cohesive zone fracture model**

Single-Edged Notched Beam SE(B)

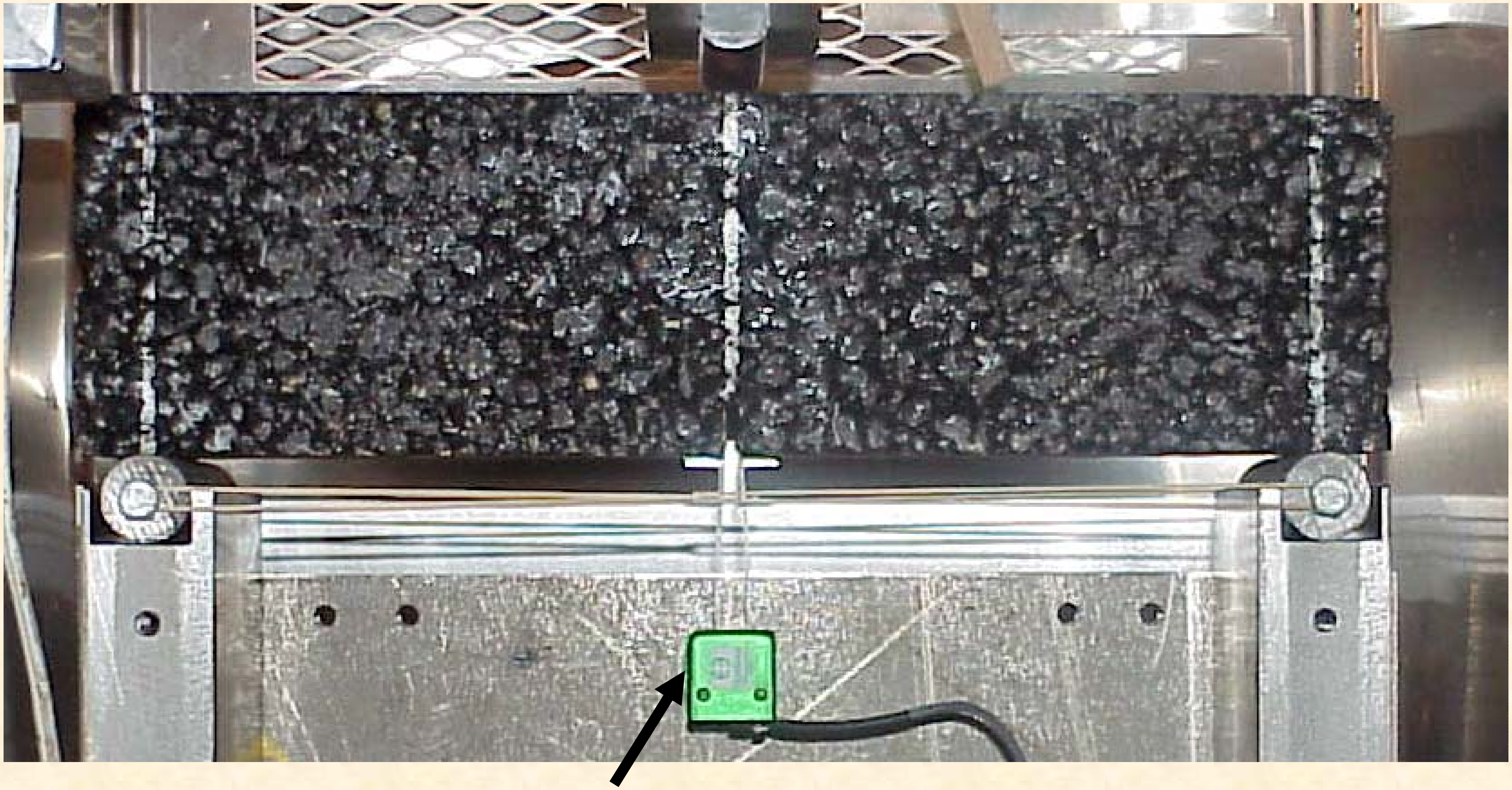
- **SE(B) test will serve as the baseline mixture fracture test for LTC study**

- 80mmx75mm fracture area
- Stable crack growth
- Ability to conduct mixed-mode fracture tests



Crack Mouth Opening Displacement (CMOD) Gage

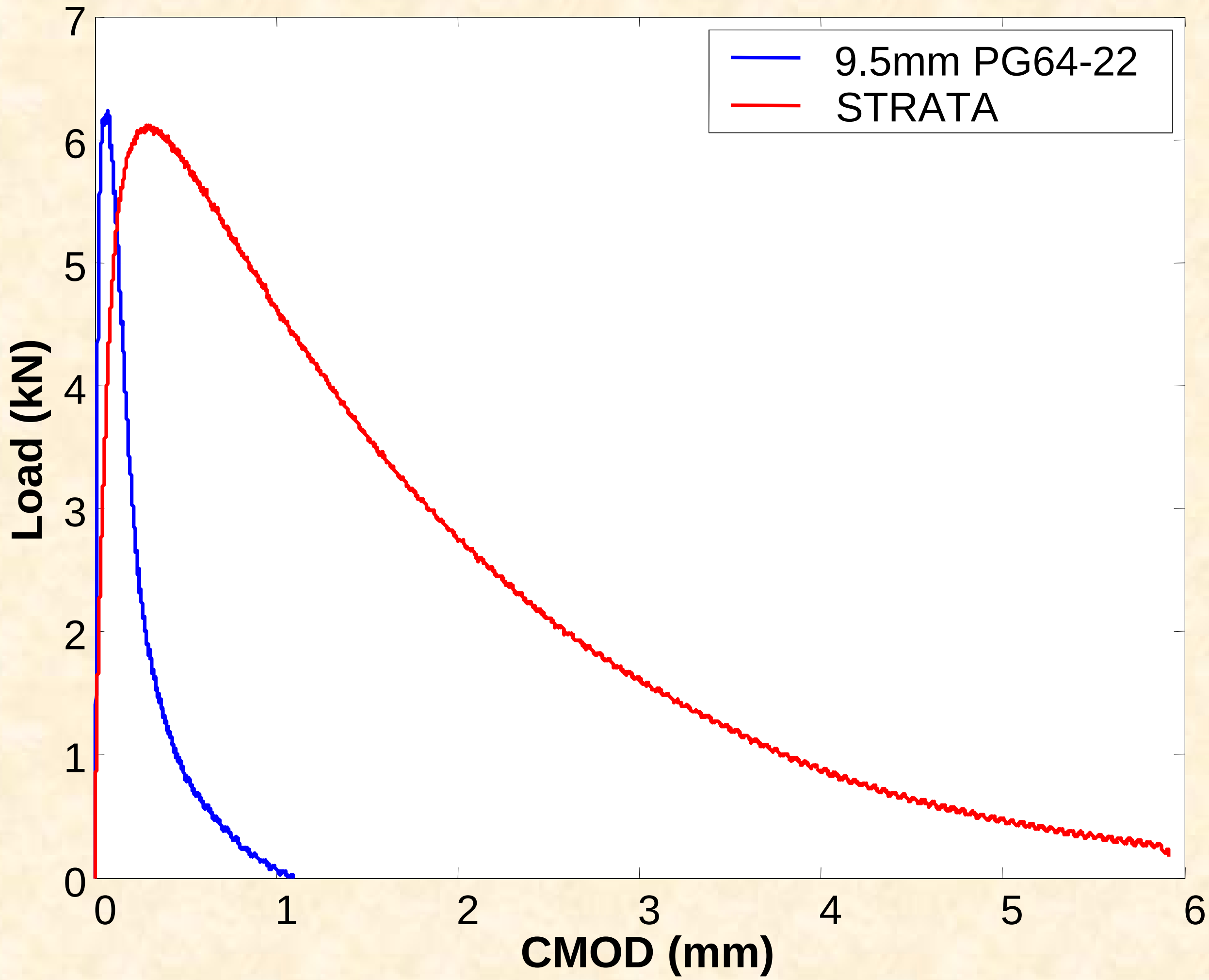
SE(B) Test



Crack Mouth Opening Gage is Used for Closed-Loop Control

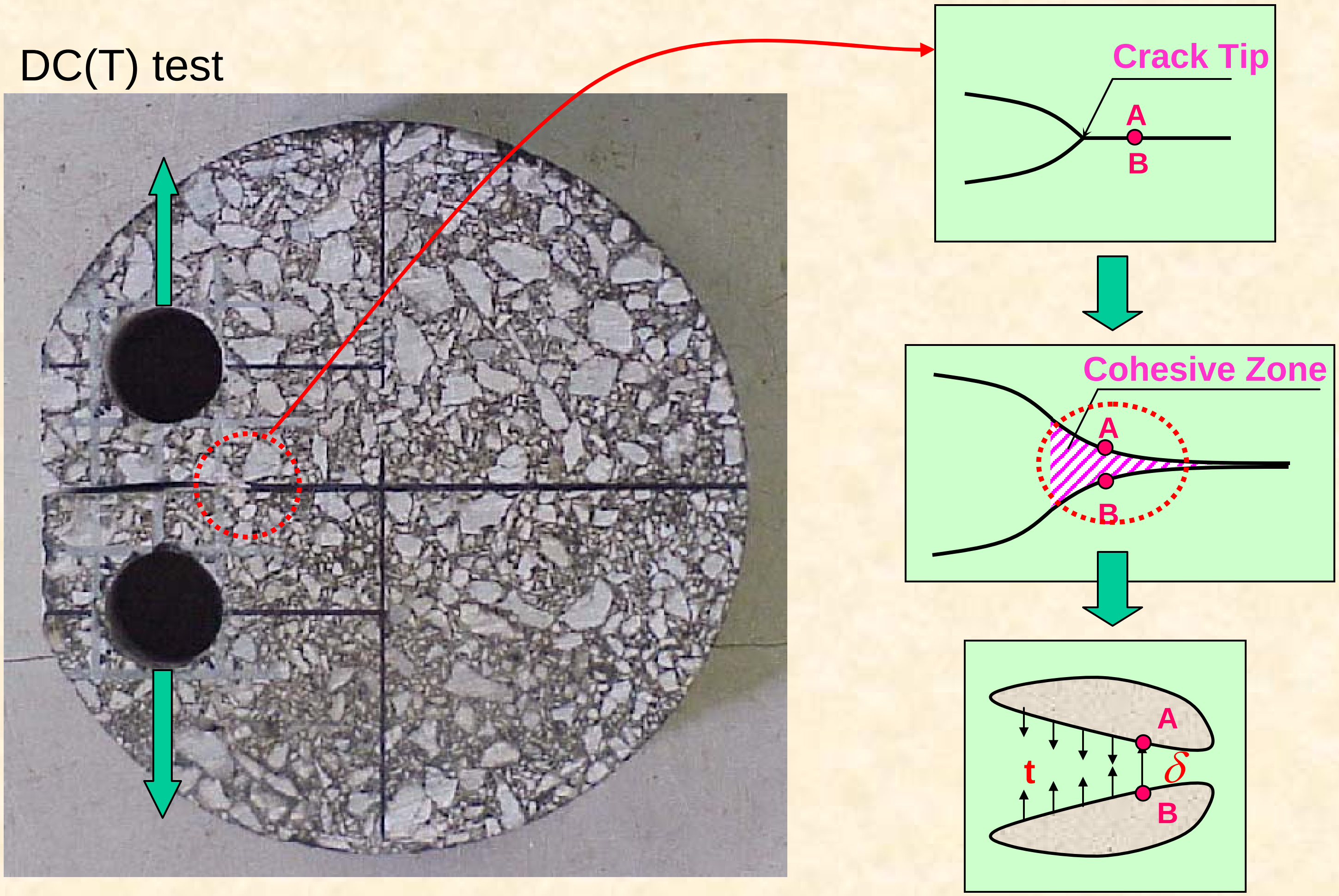
Wagoner, M. H., Buttlar, W. G., and G. H. Paulino, "Development of a Single-Ended Notched Beam Test for Fracture Testing of Asphalt Concrete," *ASTM Journal of Testing and Evaluation*, Vol. 33, No. 6, JTE12579, Nov. 2005.

Load-CMOD Curves



Cohesive Zone(Fracture) Model

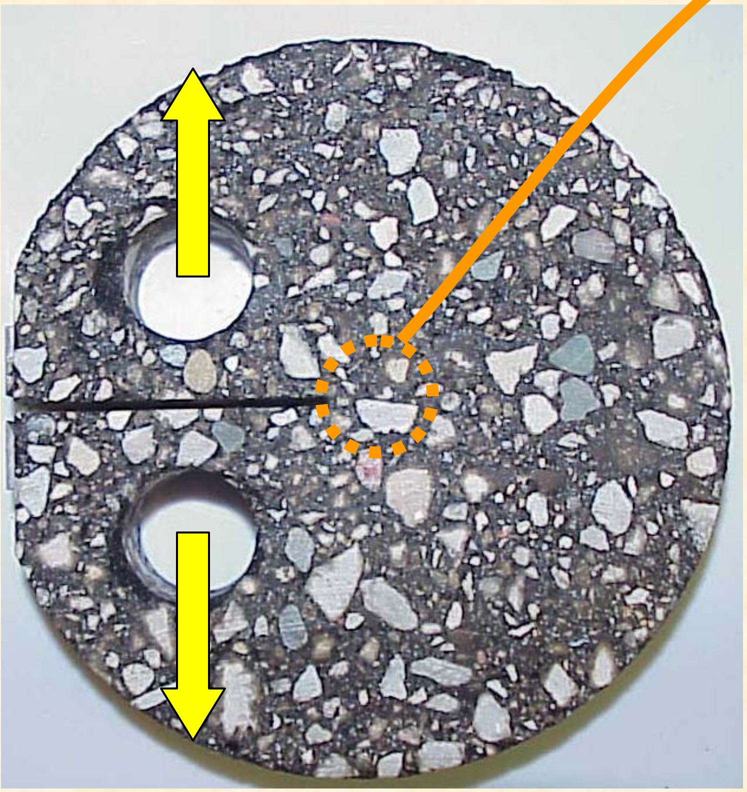
DC(T) test

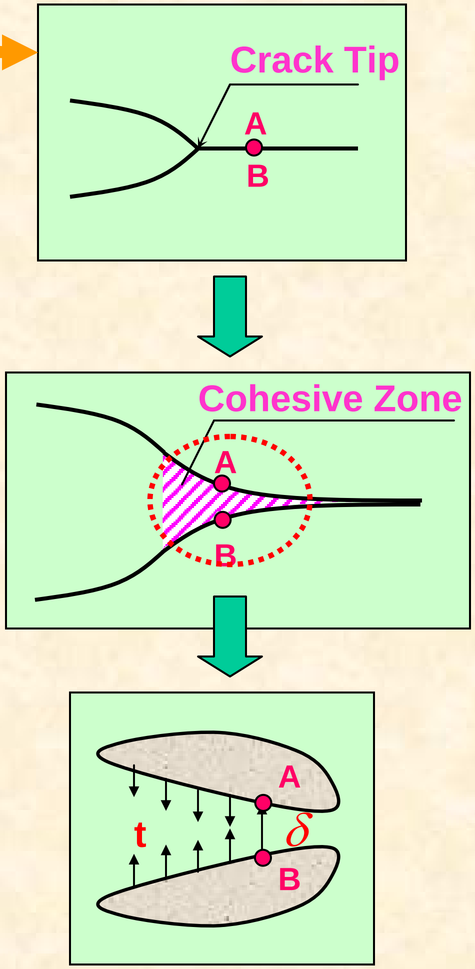


- The Cohesive Zone Model is applicable for both ductile and quasi-brittle materials. A numerical singularity at the crack tip is avoided by prescribing a maximum traction, t, equal to the tensile strength.

Cohesive Zone(Fracture) Model

DC(T) test

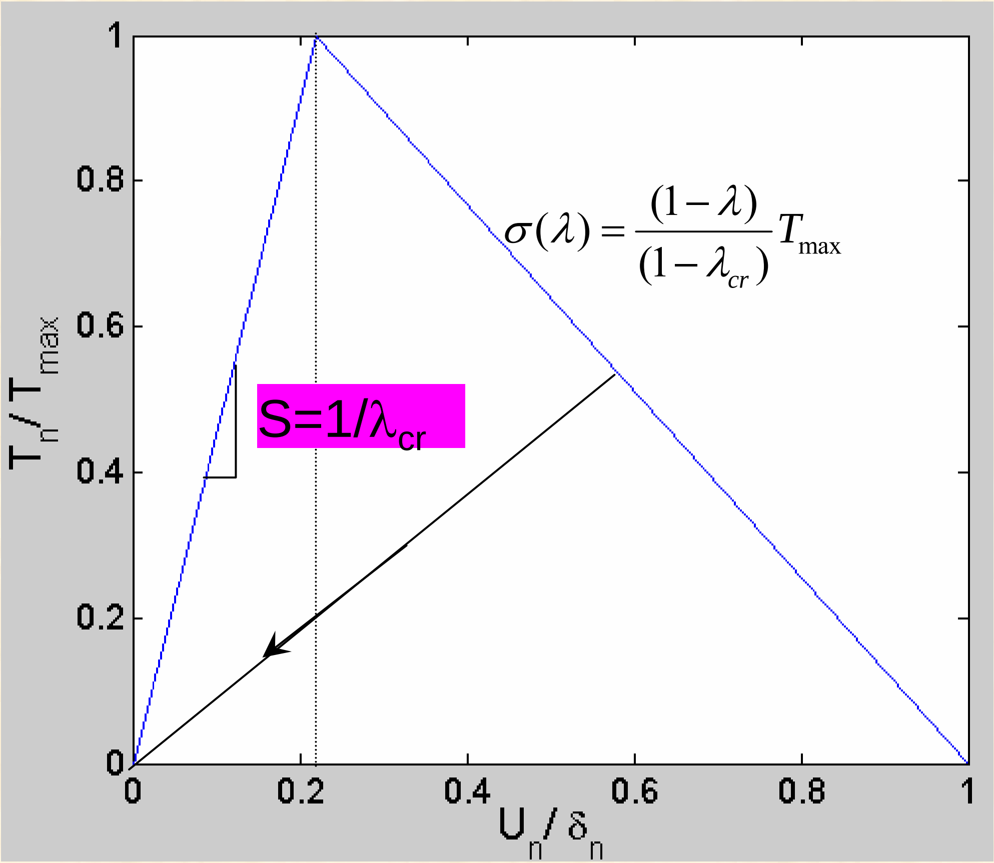




➢ The Cohesive Zone Model is applicable for both ductile and quasi-brittle materials. A numerical singularity at the crack tip is avoided by prescribing a maximum traction, t, obtained from the tensile strength.

For the Technically Curious…

➢ **Bilinear CZM - Constitutive Laws:**



➢ **Effective displacement**

$$\lambda = \sqrt{\left(\frac{U_n}{\delta_n}\right)^2 + \xi^2 \left(\frac{U_t}{\delta_t}\right)^2}$$

➢ **The energy potential**

$$\Phi(U_n, U_t) = \delta_n \int_0^{\lambda} \sigma(\lambda') d\lambda'$$

➢ **Normal Traction**

$$T_n = \frac{\partial \Phi}{\partial U_n} = \frac{\partial \Phi}{\partial \lambda} \frac{\partial \lambda}{\partial U_n} = \frac{1-\lambda}{\lambda} \left(\frac{U_n}{\delta_n}\right) \left(\frac{T_{max}}{1-\lambda_{cr}}\right)$$

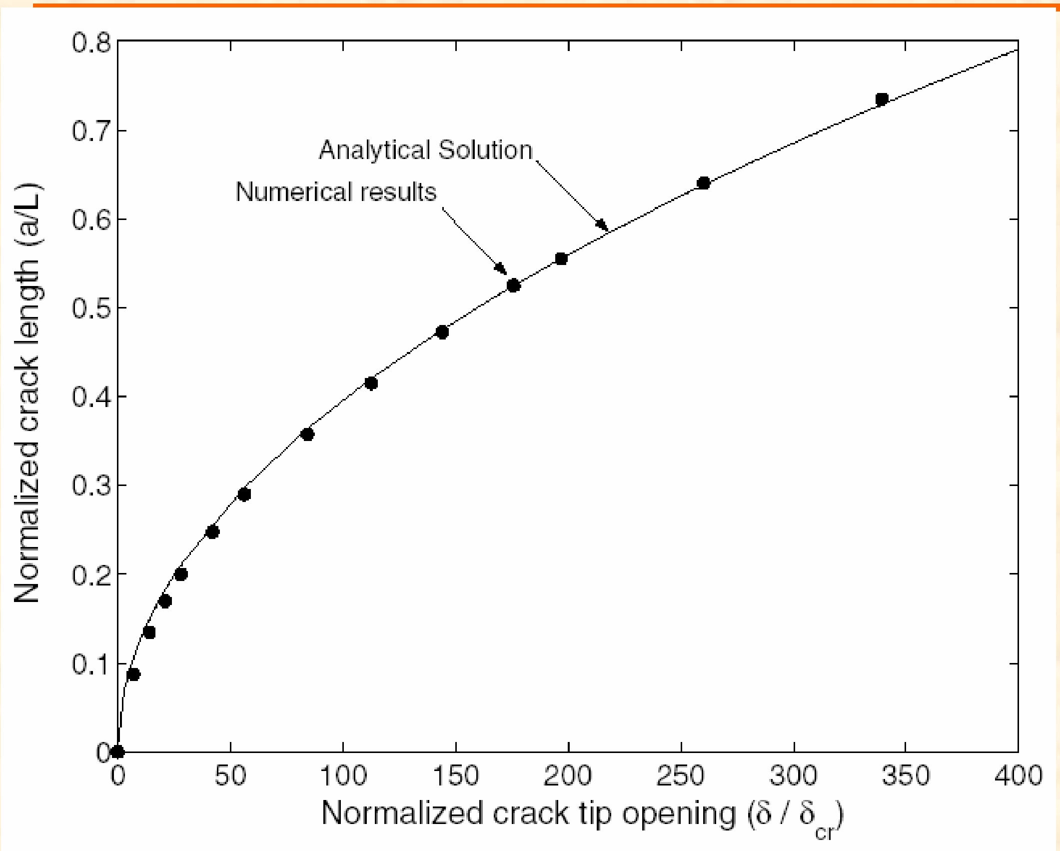
➢ **Fracture Energy**

$G=1/2\ \delta_n\ T_{max}$

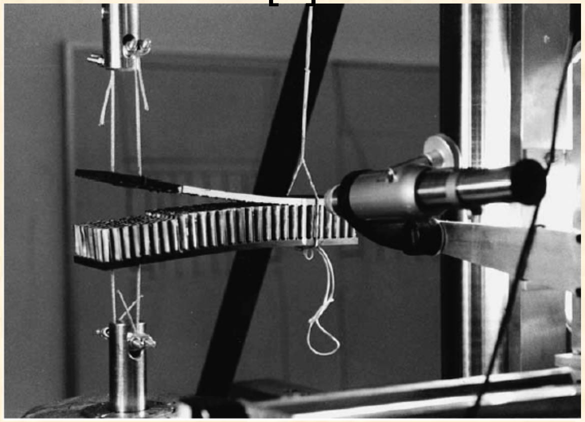
Espinosa, H.D. and Zavattieri, P.D. (2003) "A grain level model for the study of failure initiation and evolution in polycrystalline brittle materials. Part I: Theory and numerical implementation." *Mechanics of Materials*, 35, 333-364.

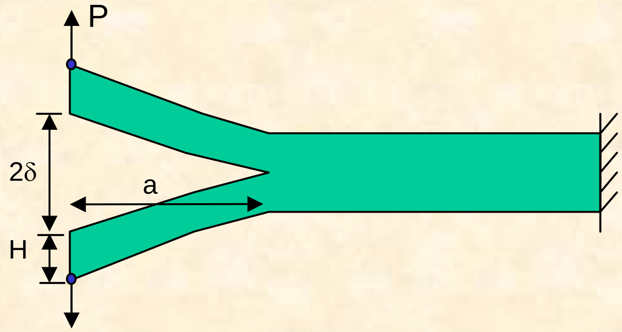
Song, S. H., Paulino, G. H., and W. G. Buttlar "Simulation of Mixed-Mode Crack Propagation in Asphalt Concrete," *Proceedings of the ASCE GeoFrontiers Conference*, Austin, TX, 2004.

Verification of CZM (DCB test)



- DCB test [1]



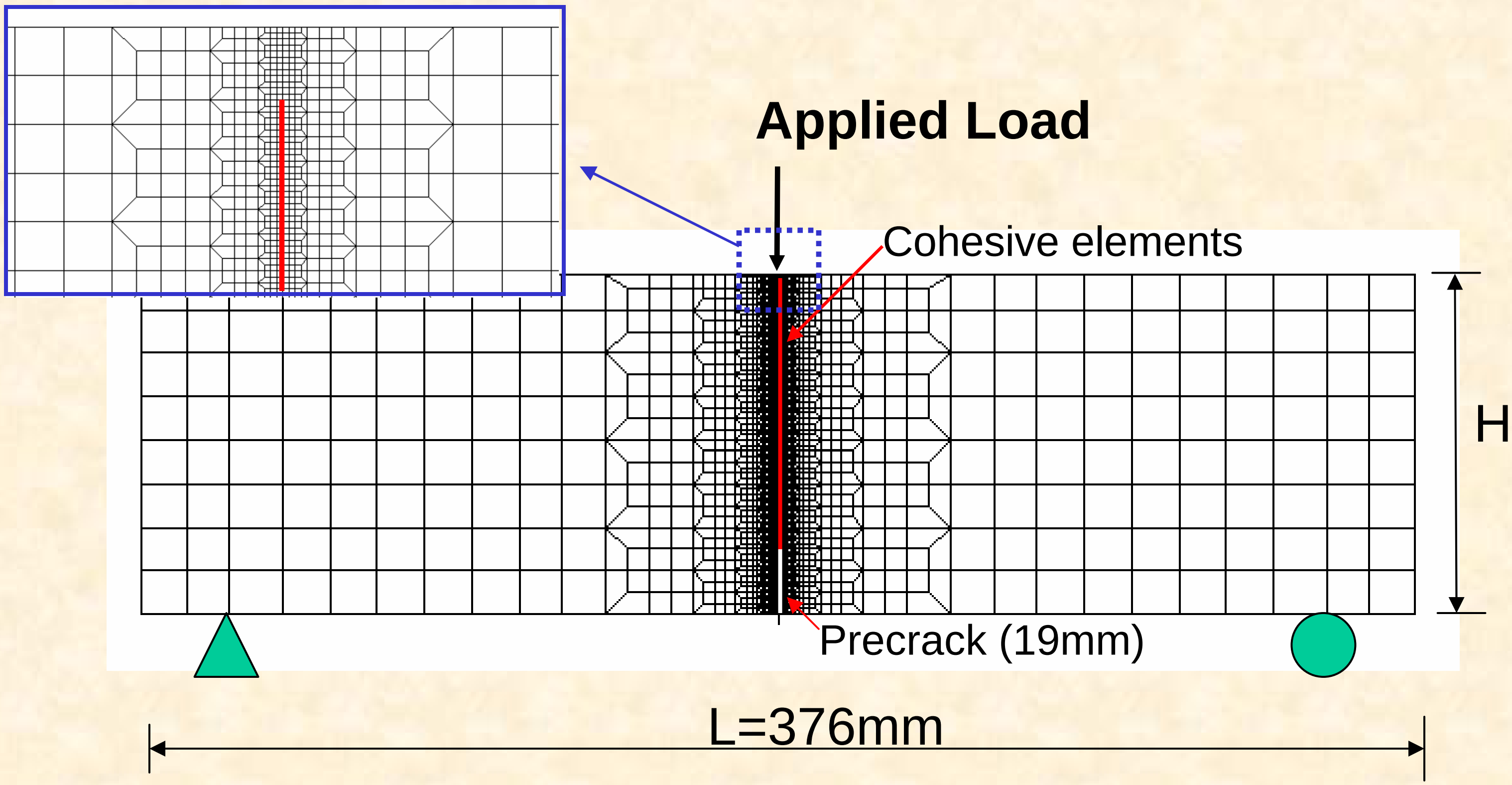


- Numerical results are almost identical with analytical solutions even for initial stage of propagation which is influenced by the boundary condition.

[1] Han, T.-S., Ural, A., Chen, C.-H., Zehnder, A. T., Ingraffea, A. R. and Billington, S. L. (2002), “Delamination buckling and propagation analysis of honeycomb panels using a cohesive element approach.” *International Journal of Fracture*, 115, 101-123.

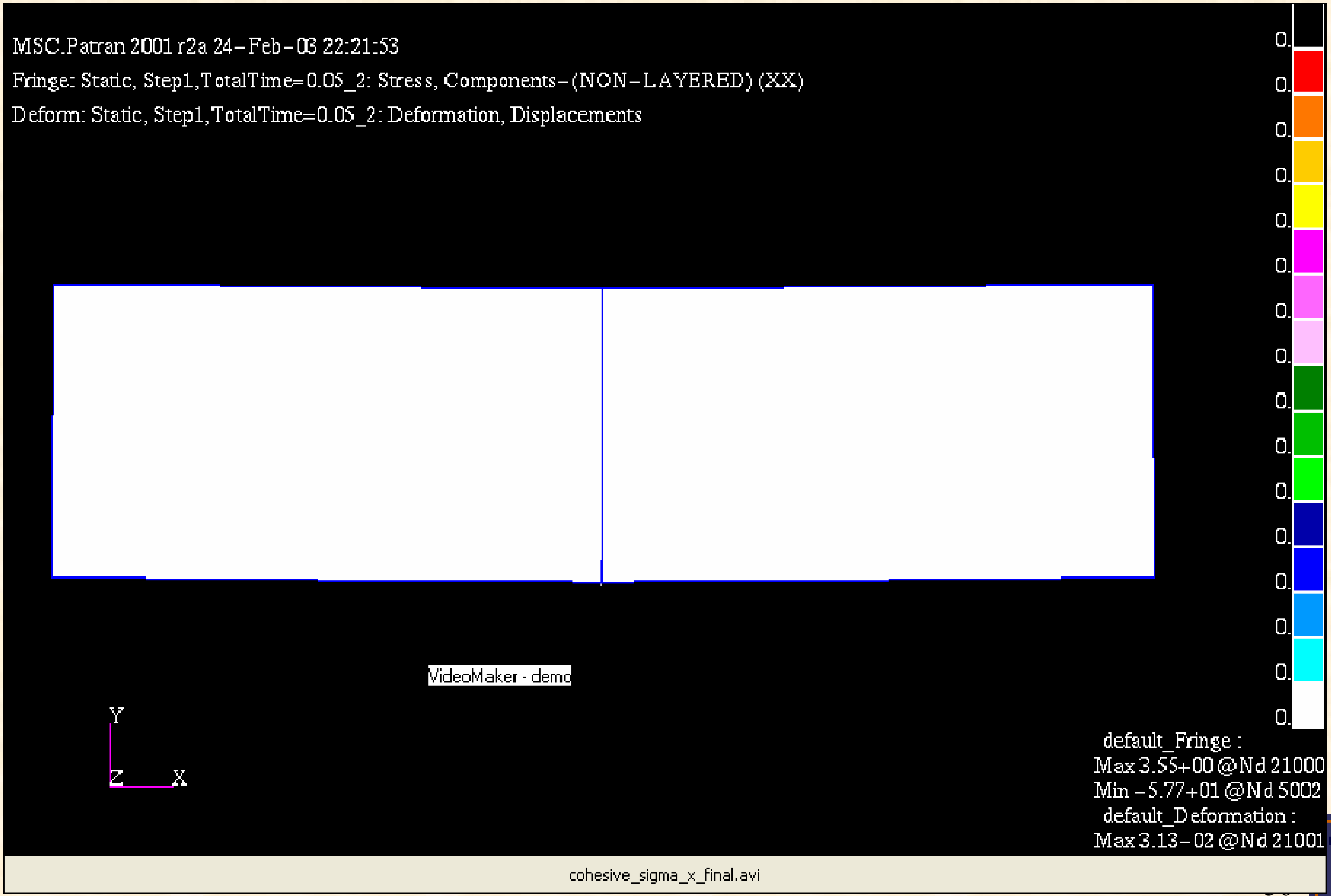
[2] Paulino, G. H., Song, S. H., and W. G. Buttlar, “Cohesive Zone Modeling of Fracture in Asphalt Concrete,” Proceedings of the Fifth RILEM International Conference on Cracking in Pavements, C. Petite I. Al-Qadi and A. Millien eds., May 5-7, Limoges, France, 2004, pp. 63-70.

SE(B) Test Simulation

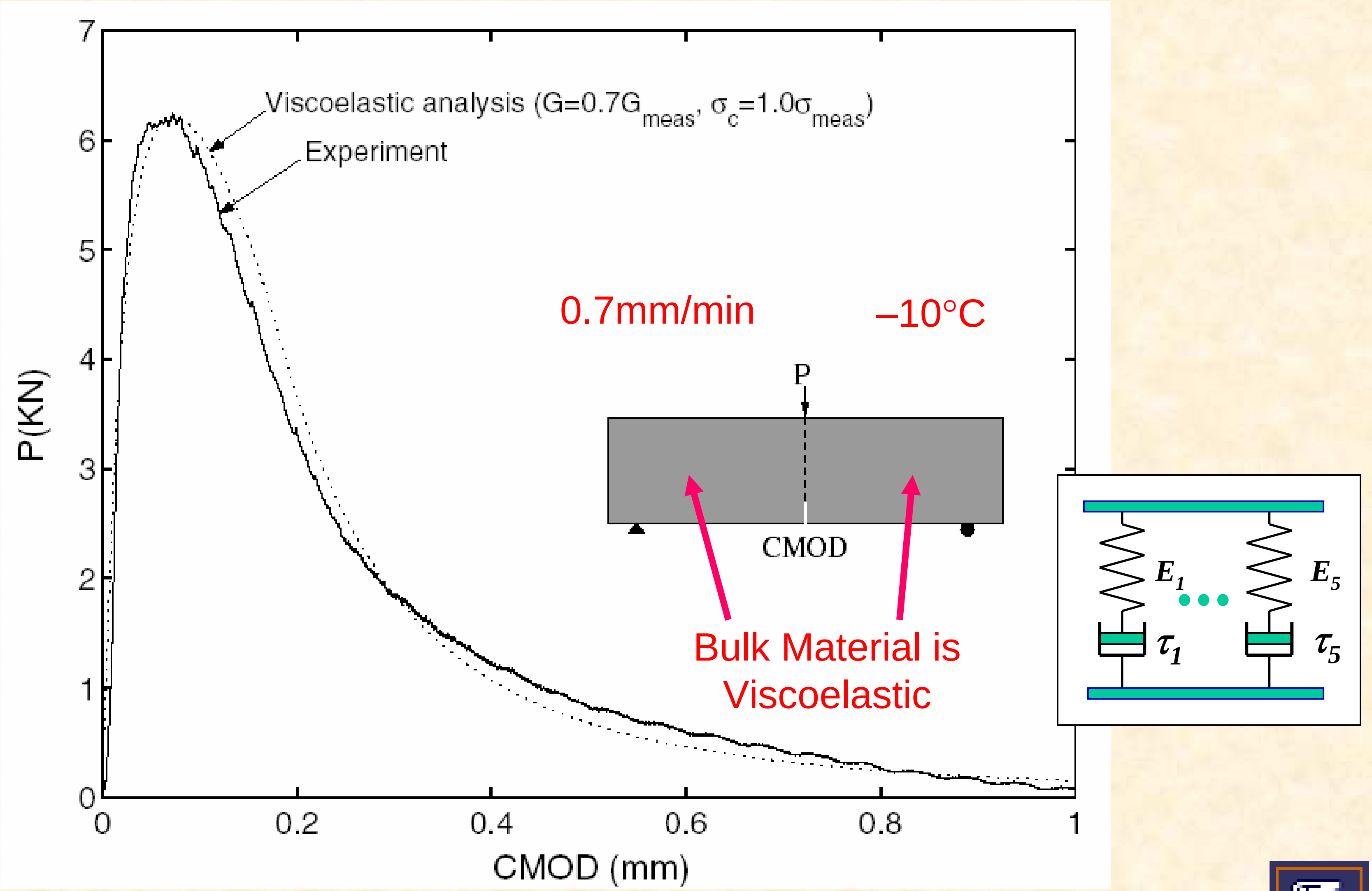


- Peoria surface course material properties used.
- Cohesive Properties : σ_c =3.56 MPa , Γ_o=344J/m^2
- Bulk Material Properties : E =14.2 GPa (@ 1Hz) , ν = 0.35
- Thickness = 75 mm

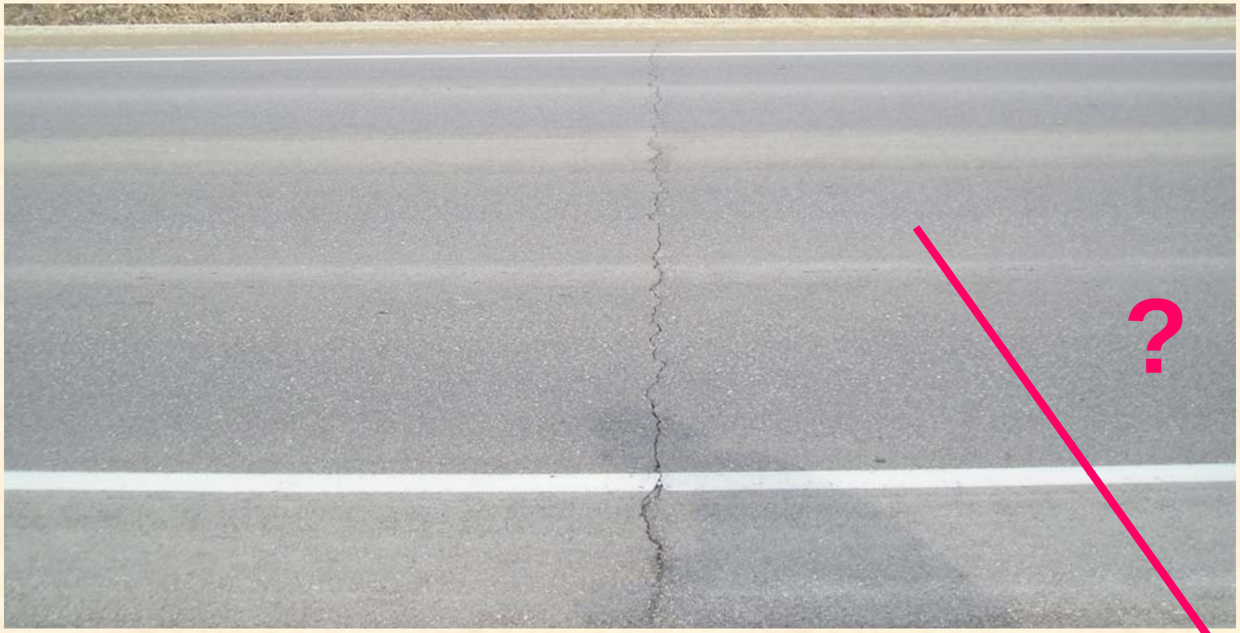
Animation of Mode I SE(B) (σ_x)

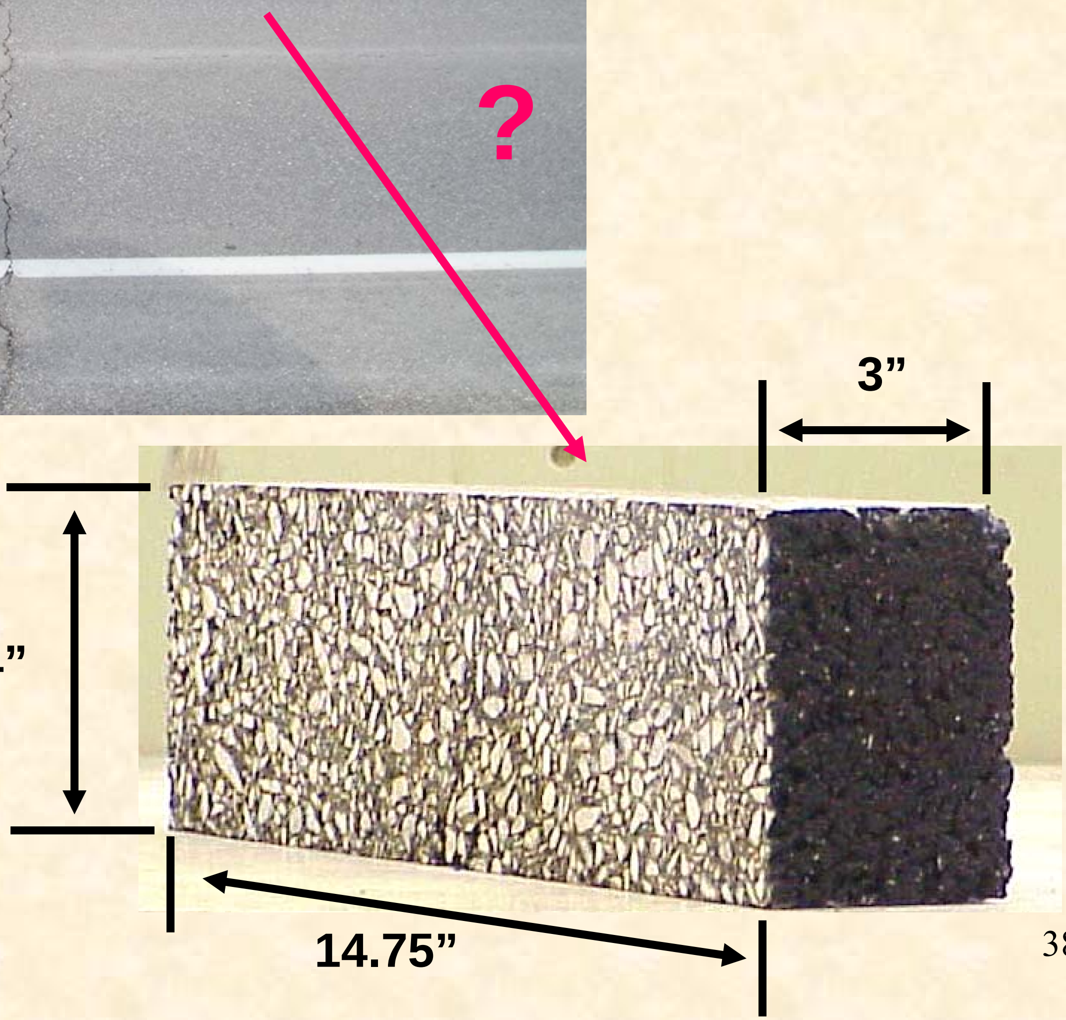


Calibration: Bi-Linear CZM w/ Viscoelastic Bulk



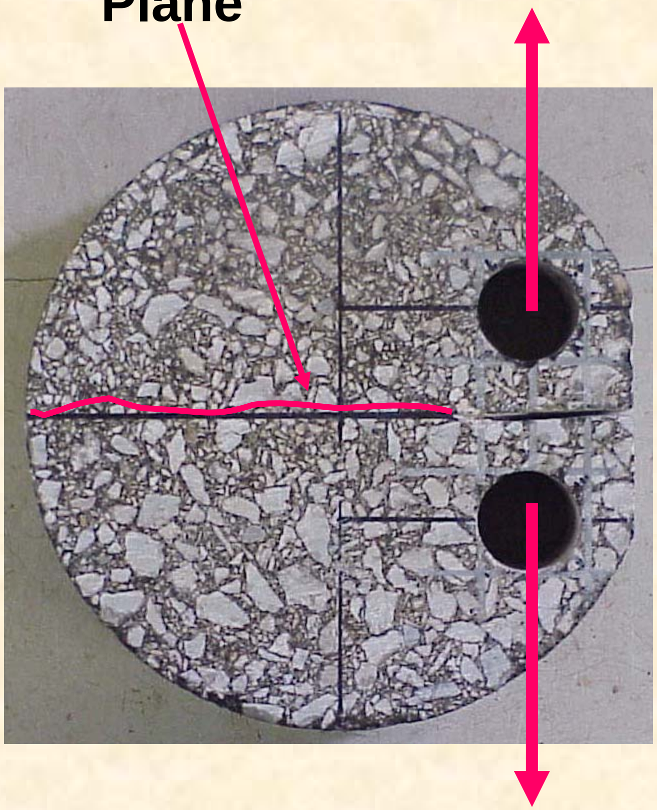
Disadvantage of SE(B)





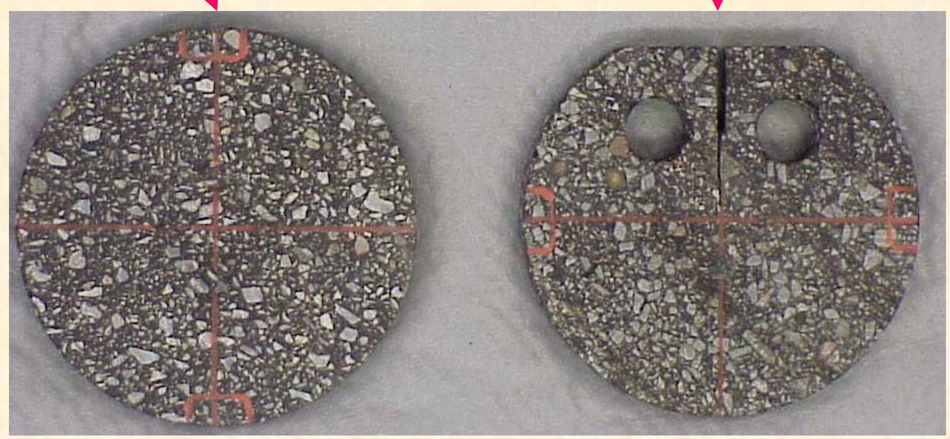
Disk-Shaped Compact Tension (DC(T))

Fracture Plane



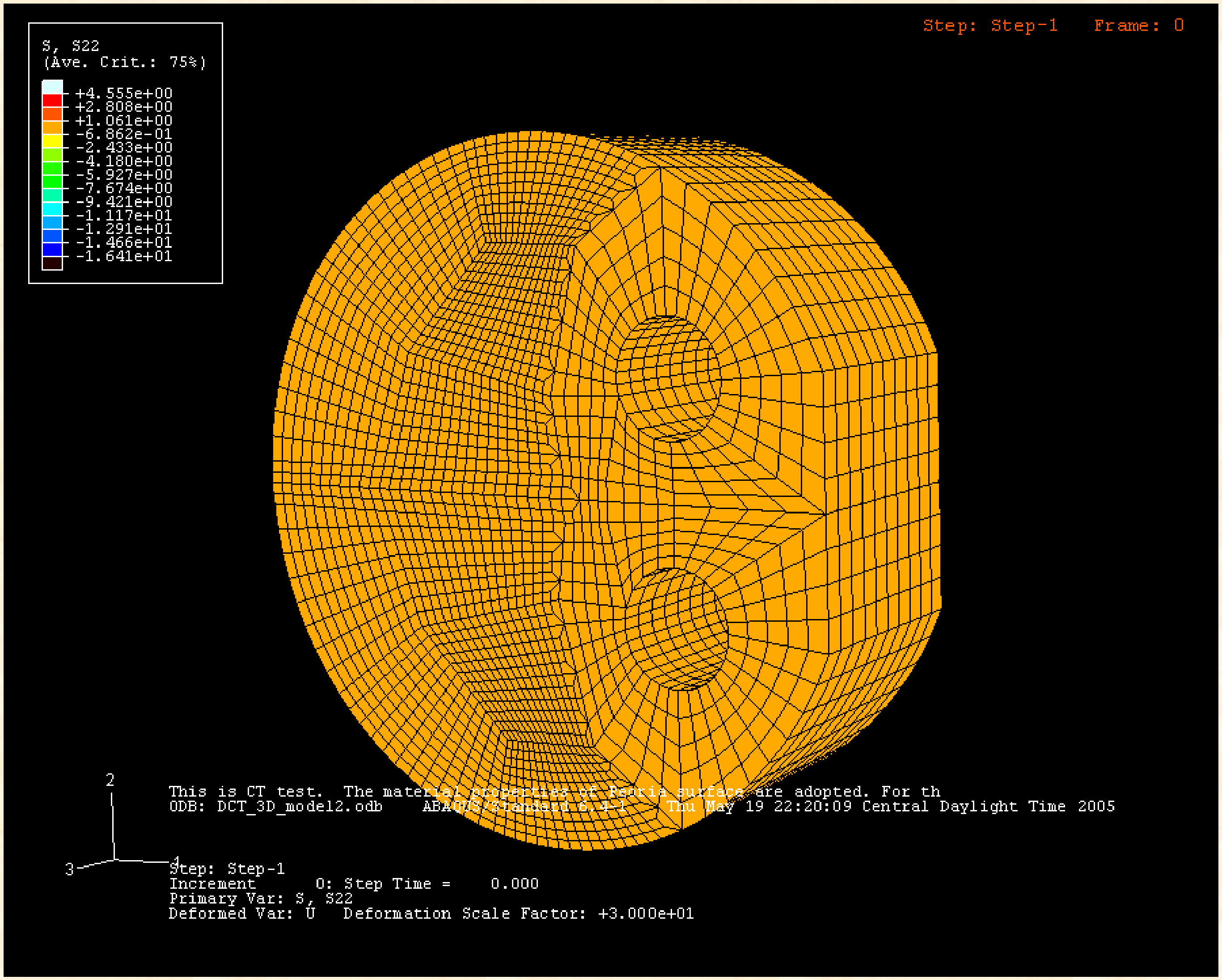
Can be Obtained from Field Cores

IDT Specimen **DC(T) Specimen**



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, June, 2005.

3D DC(T) Simulation



Simulation Courtesy of S.H. Song, UIUC

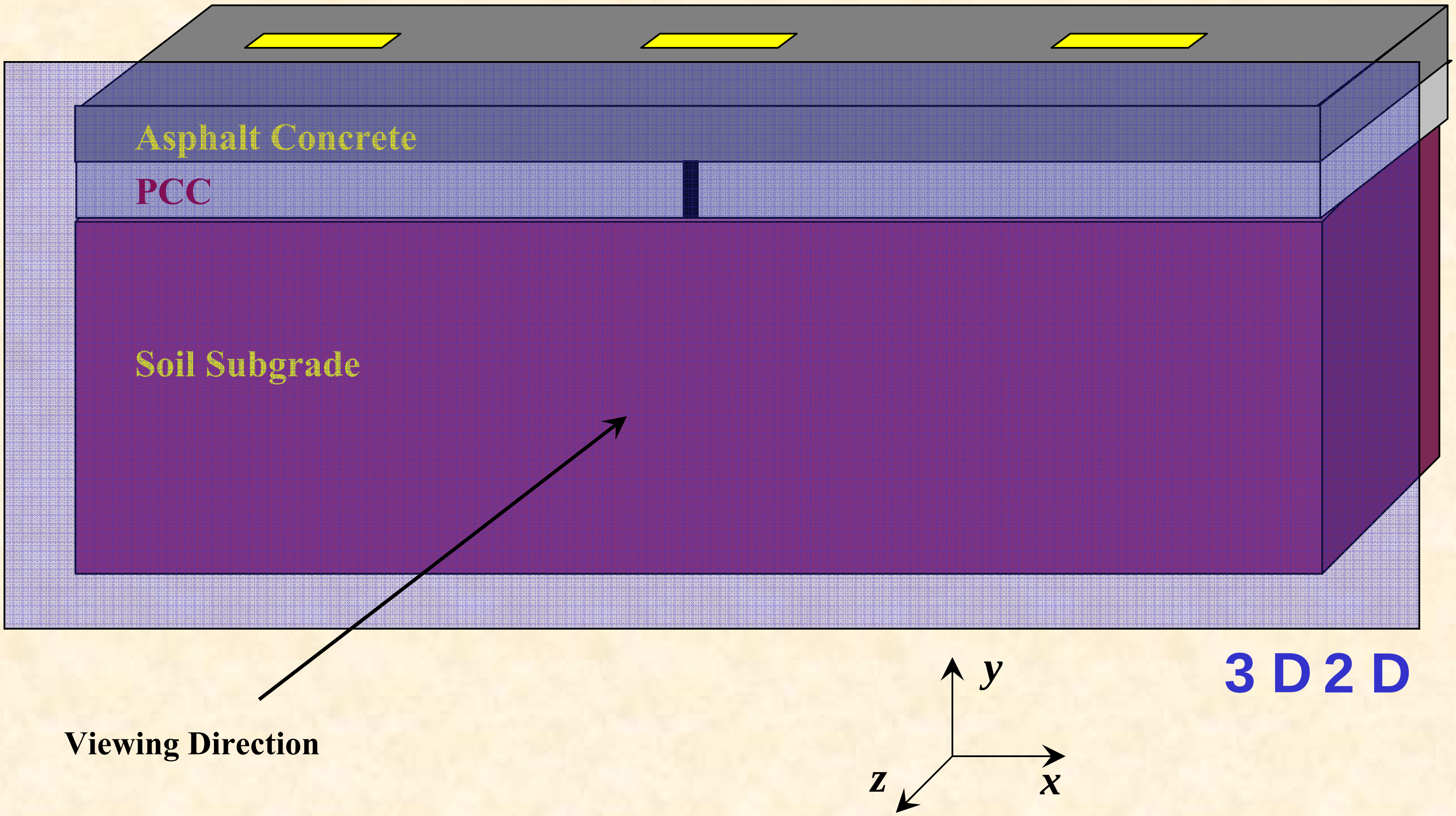
Field Investigation of Pavements in NSF GOALI Study

Bill Buttlar, Glaucio H. Paulino, Eshan Dave

Department of Civil and Environmental Engineering

University of Illinois at Urbana-Champaign

Model: Perspective



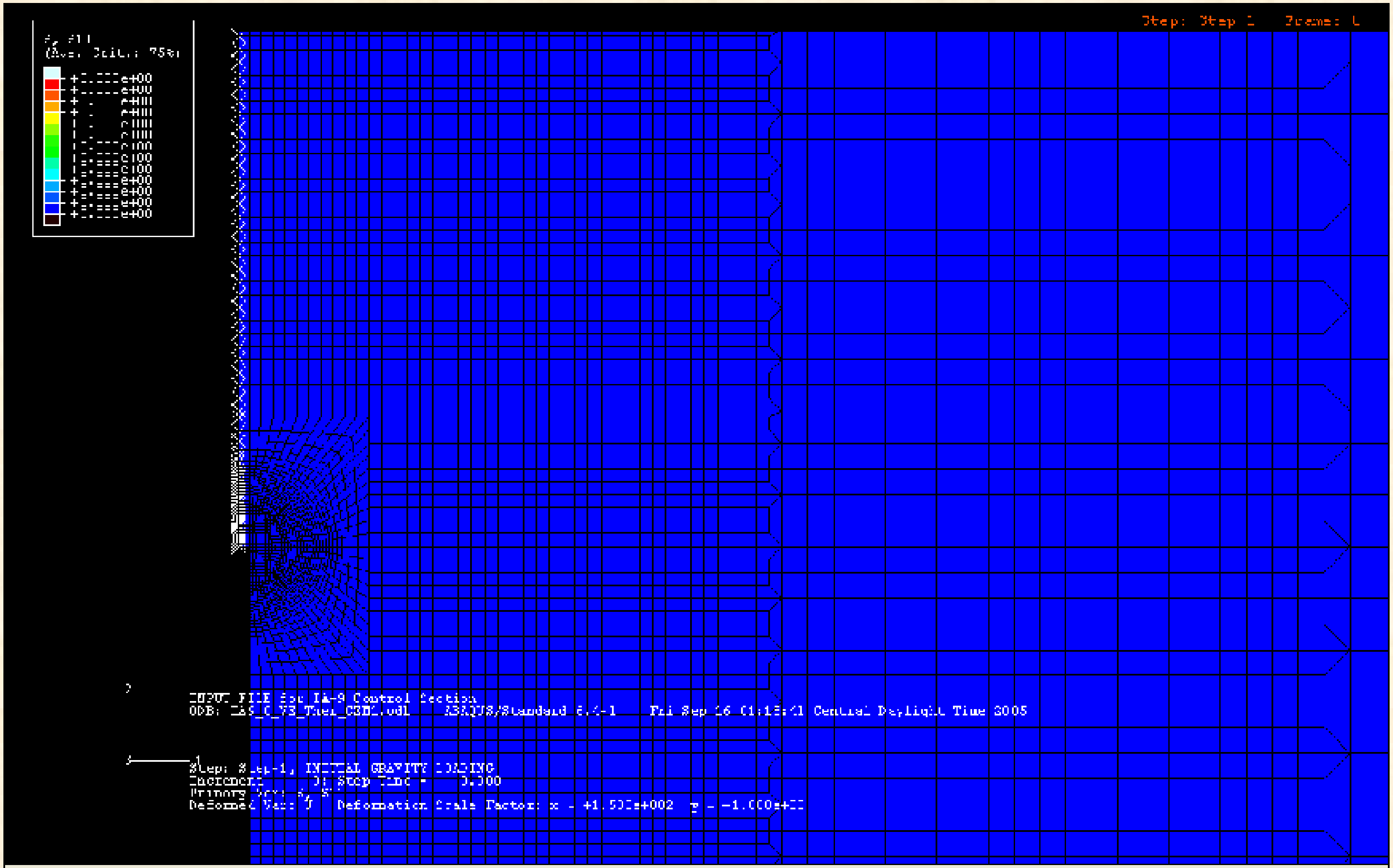
3 D 2 D

FEM Simulation ~ Examples

- **Simulation 1:**
  - **Thermal Loading**
  - **16 Hr Cooling Event**
- **Simulation 2:**
  - **Thermo-Mechanical Loading**
  - **5 Day Thermal Event and 9-kip Tire Load**

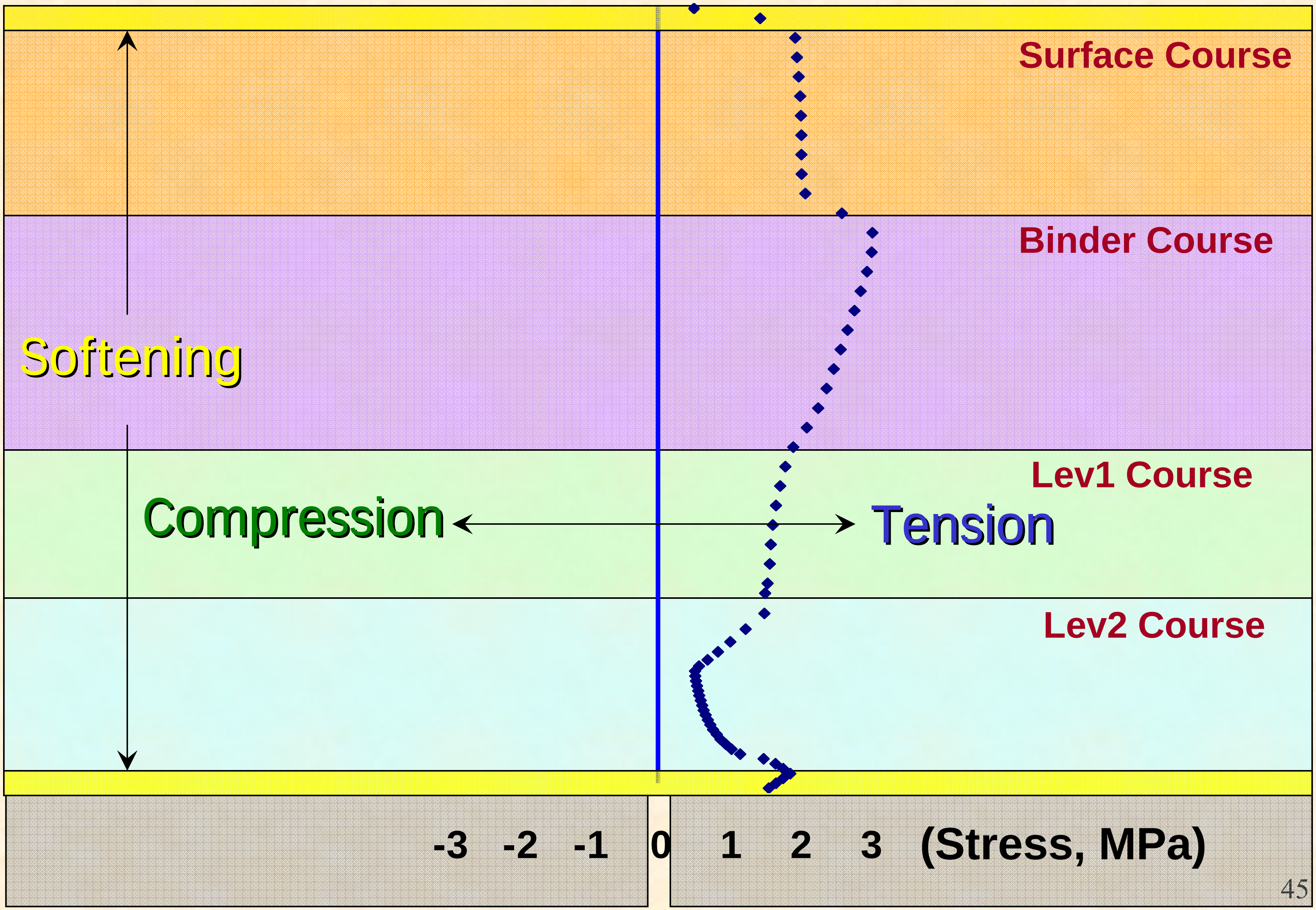
Simulations Courtesy of Mr. Eshan Dave, UIUC

Sim1: Thermal Loading:

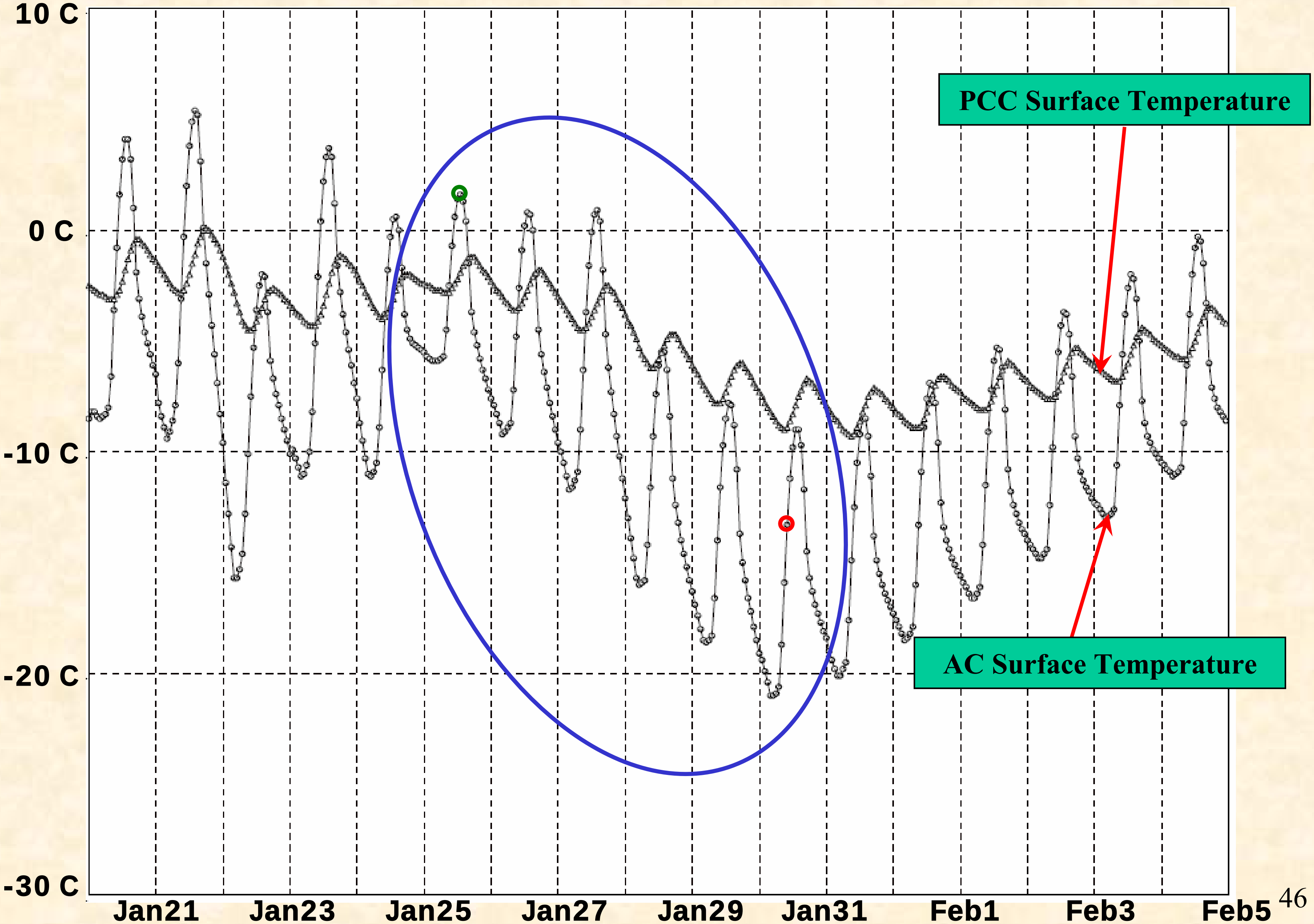


IA9_C_ThermalOnly.avi

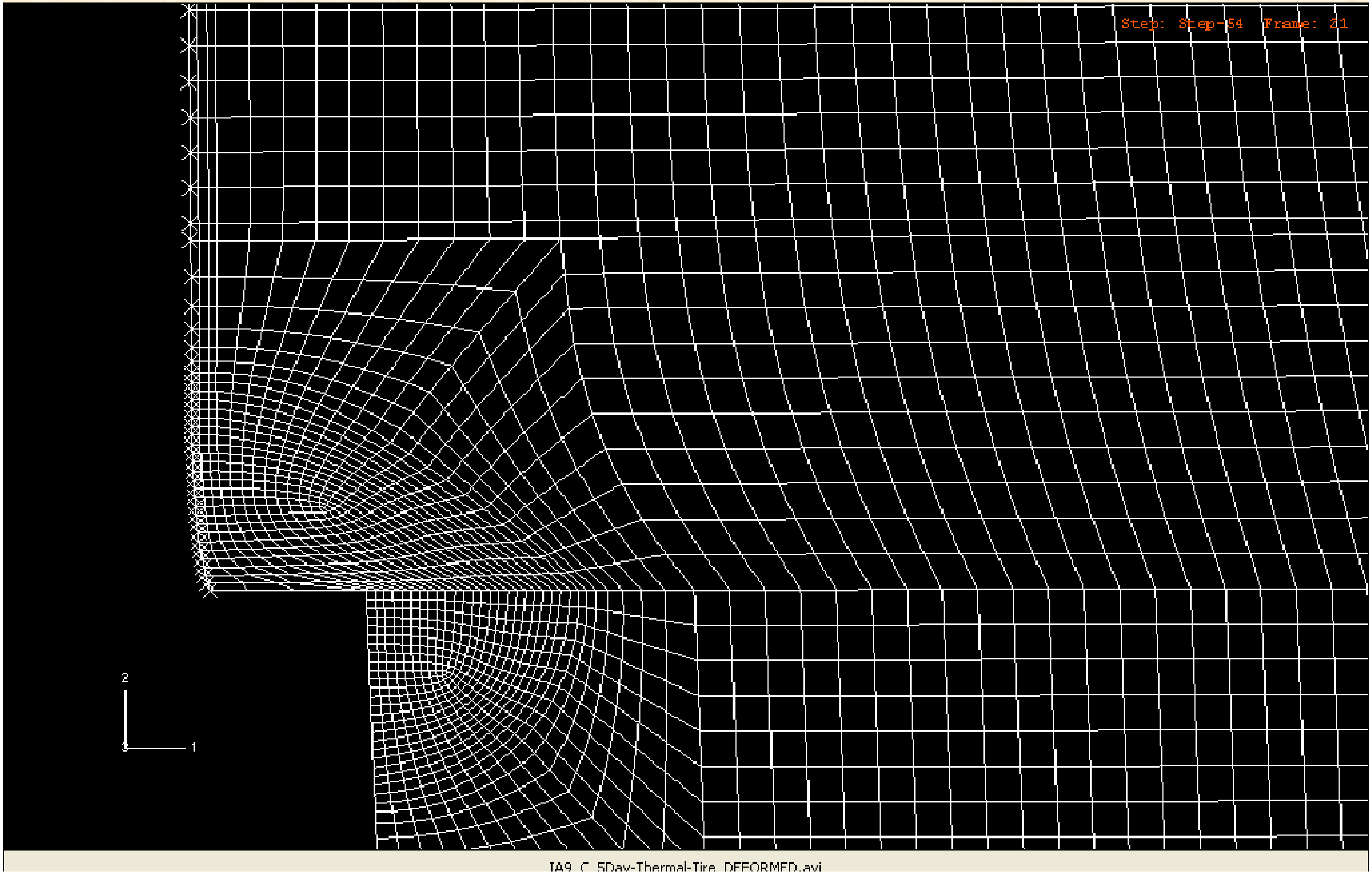
Sim1: Thermal Loading



5 Day Coolest Event

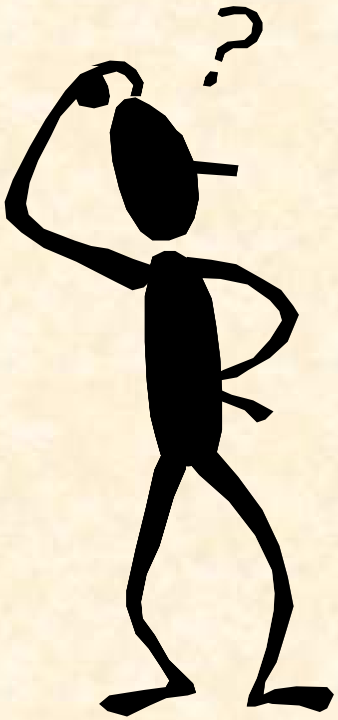


Sim2B: Thermo-Mechanical Loading, 5 Day Thermal



New Insights w/ Cohesive Zone Fracture Modeling

- Model Shows Excellent Calibration with Lab Results
  - Only Two Parameters Required, Only One Typ. Calibrated
- Aging Plays Very Important Role in Thermal Cracking Mechanism
- Cracks may ‘jump’ to Weak Layers
- High Fracture Energy Retention after Aging is Critical




THANK YOU

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ISSN 1504-5005