Sixth RILEM International Conference on Cracking in Pavements

Integration of Laboratory Testing, Field Performance Data, and Numerical Simulations for the Study of Low-Temperature Cracking

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Low Temperature Cracking

Thermal cracking is a major cause of pavement deterioration in regions with severe winter climates

Mechanism of Thermal Cracking

Asphalt concrete pavement contraction during cooling induces tensile thermal stresses

Thermal stresses are greatest at critical low temperatures or very fast cooling rates

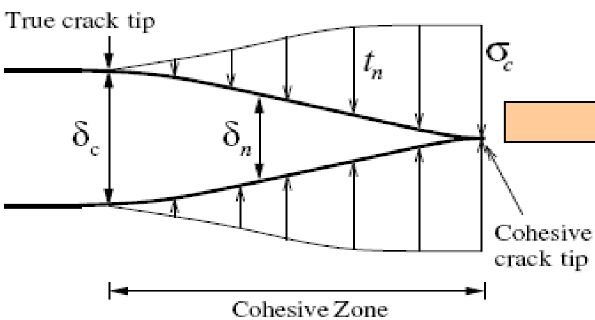
Crack initiation and propagation requires consideration of non-linear fracture process zone which develops ahead of crack tip

Integrated Approach:

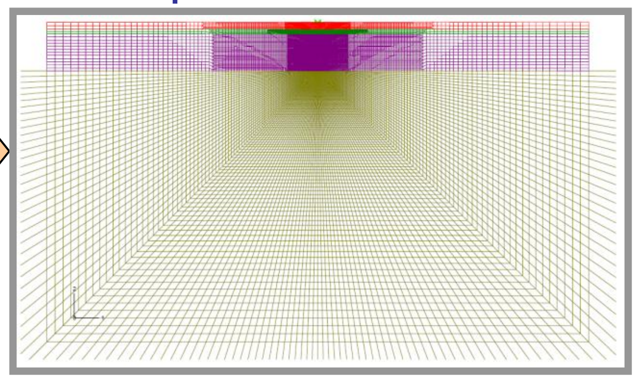
Current study utilizes integrated laboratory testing, field information and simulations to predict thermal-cracking potential

Integrated Approach

(a) Fracture Behavior

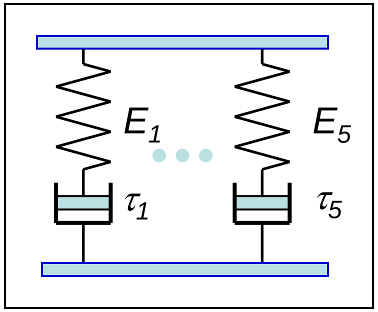


Computer Simulation



(d) Lab Testing

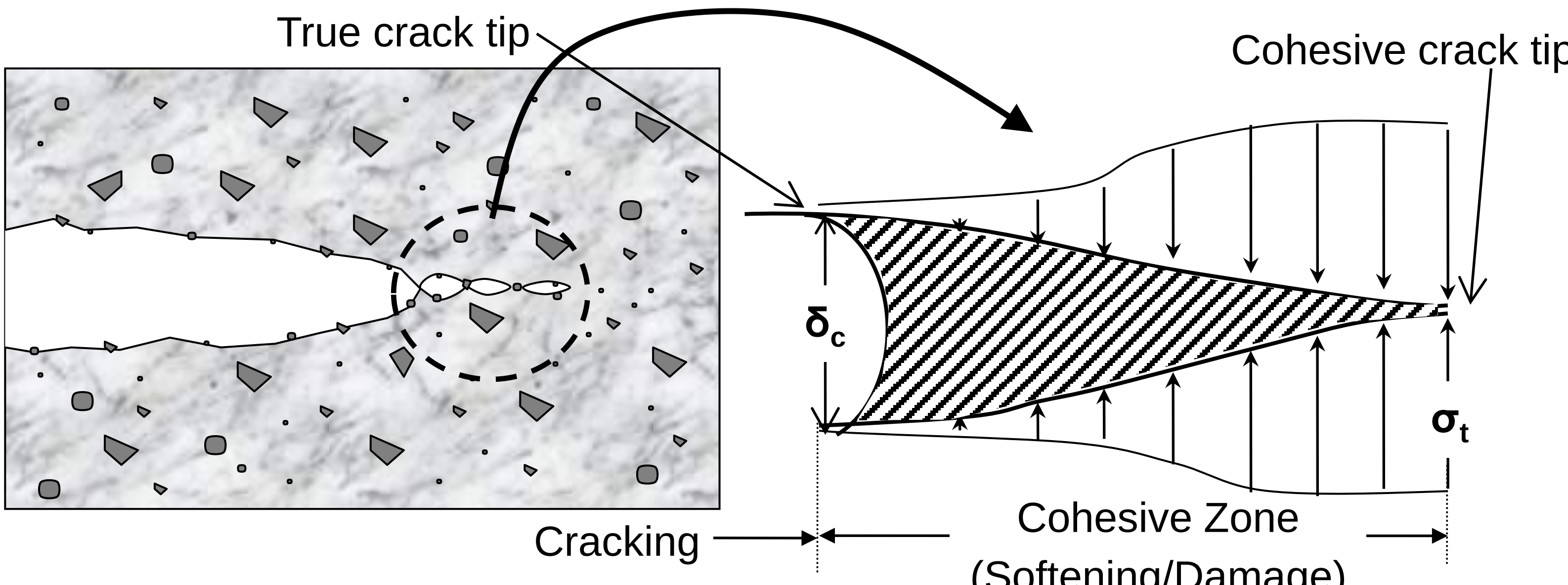
(b) Bulk Material Response



(c) Field Data and Performance

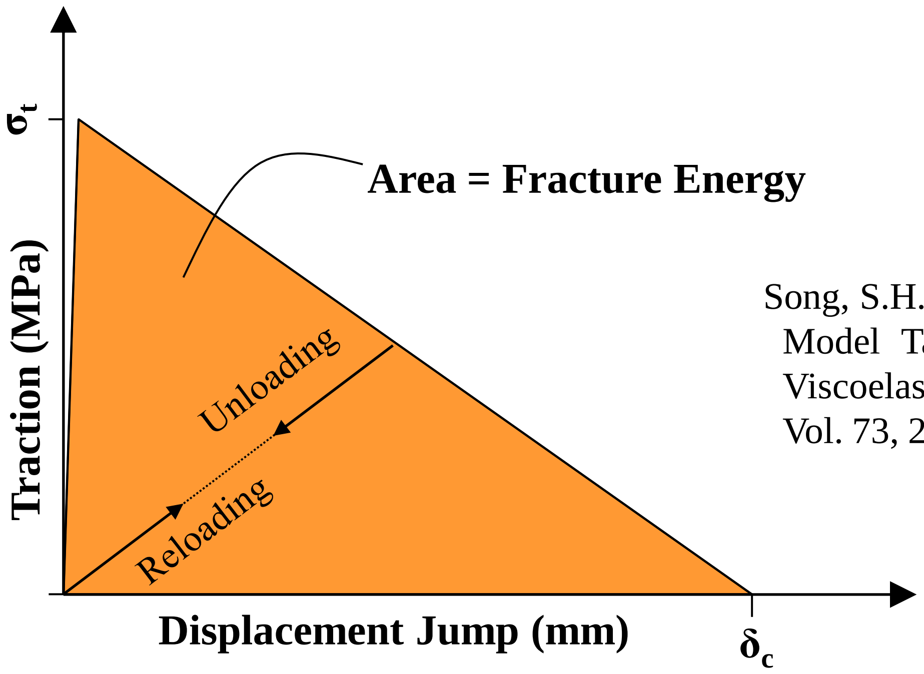
(a) Fracture Behavior

- Fracture of asphalt concrete is a non-linear phenomenon
- Cohesive zone model (CZM) is a computationally efficient way of modeling damage and cracking in asphalt concrete
- CZM Capabilities:
  - Softening (damage)
  - Complete separation



(a) Fracture Behavior: Cohesive Zone Model

- Model defines the relationship between separation and traction along the crack path
- Bilinear cohesive zone model investigated by Song et al. is being used



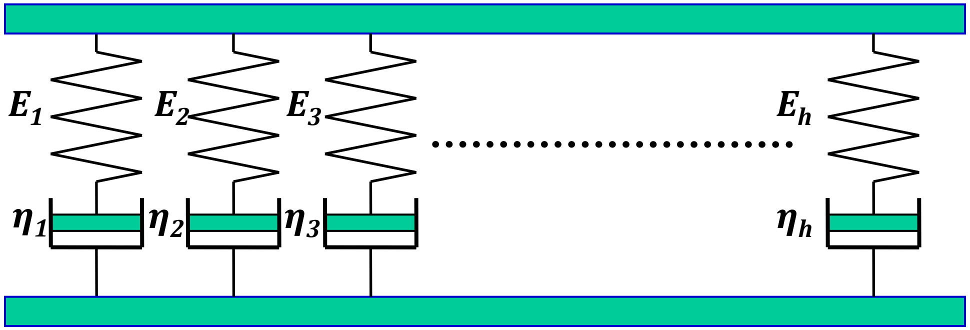
Song, S.H., Paulino, G.H., Buttlar, W.G. A Bilinear Cohesive Zone Model Tailored for Fracture of Asphalt Concrete Considering Viscoelastic Bulk Material. *Engineering Fracture Mechanics*, Vol. 73, 2006, pp. 2829-2848.

(b) Bulk Material Behavior

- Generalized Maxwell model (Prony series) with time-temperature superposition was used to describe the relaxation master curve.
- A 10-parameter Maxwell model was used

$$E(t) = \sum_{i=1}^{h} E_i \, Exp\left[-t/\tau_i\right]$$

$$\tau_i = \frac{\eta_i}{E_i}$$



(c) Pavement Sections

Asphalt Concrete	AC120/150	160-mm
Granular Base	Class 5 Sp.	101.6-mm
Granular Base	Class 3 Sp.	838.2-mm
Subgrade		

MnROAD Cell 03

Asphalt Concrete	AC20	198.1-mm
Granular Base	Class 3 Sp.	711.2-mm
Subgrade		

MnROAD Cell 19

Asphalt Concrete	PG58-XX	103-mm
Granular Base	Class 6 Sp.	305-mm
Subgrade		

MnROAD Cell 33, 34, and 35

AC Binder Grades:

Cell 33: PG58-28

Cell 34: PG58-34

Cell 35: PG58-40

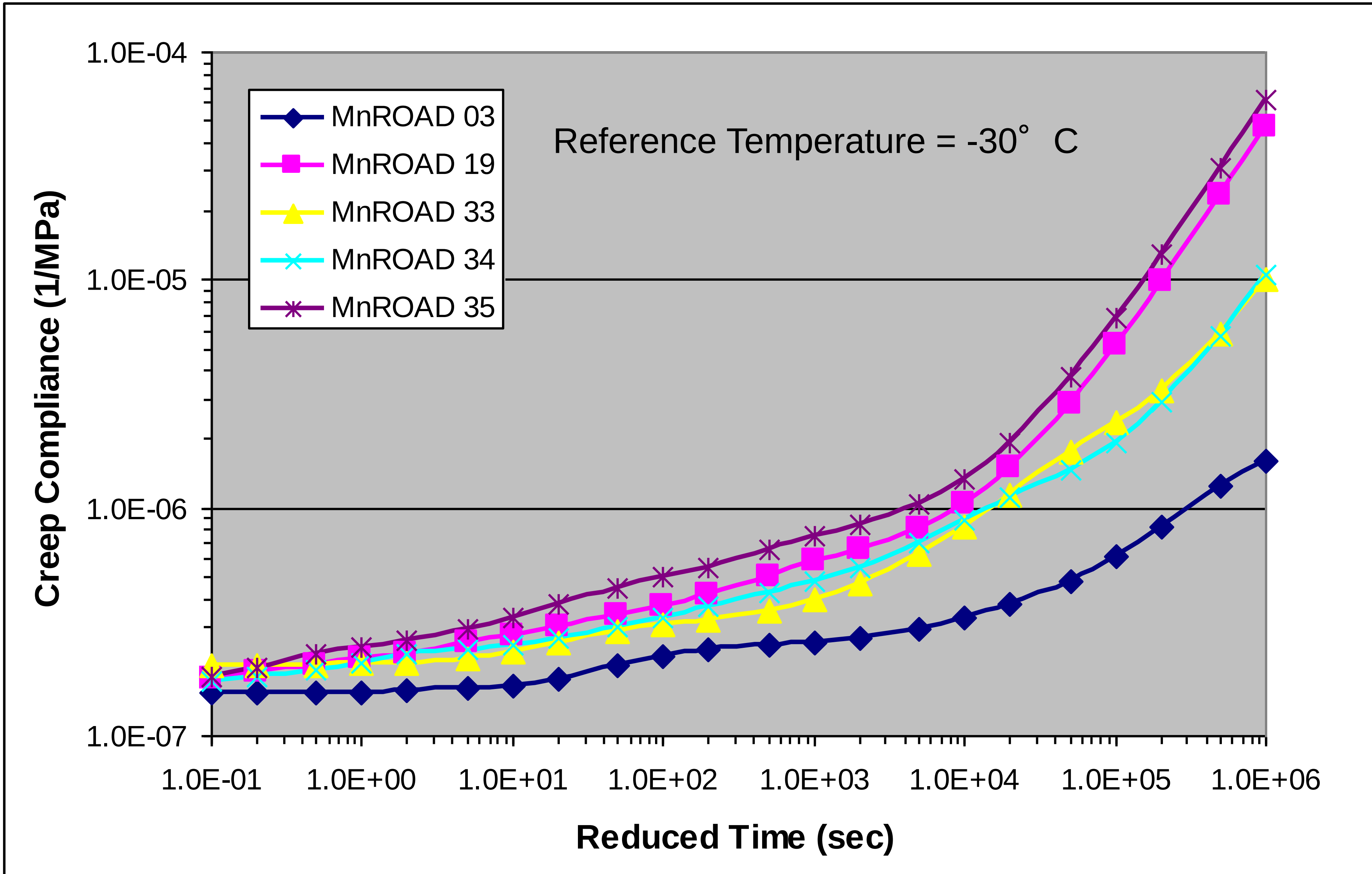
Acknowledgements: MnROAD/MnDOT for Sample Collection

(d) Laboratory Testing

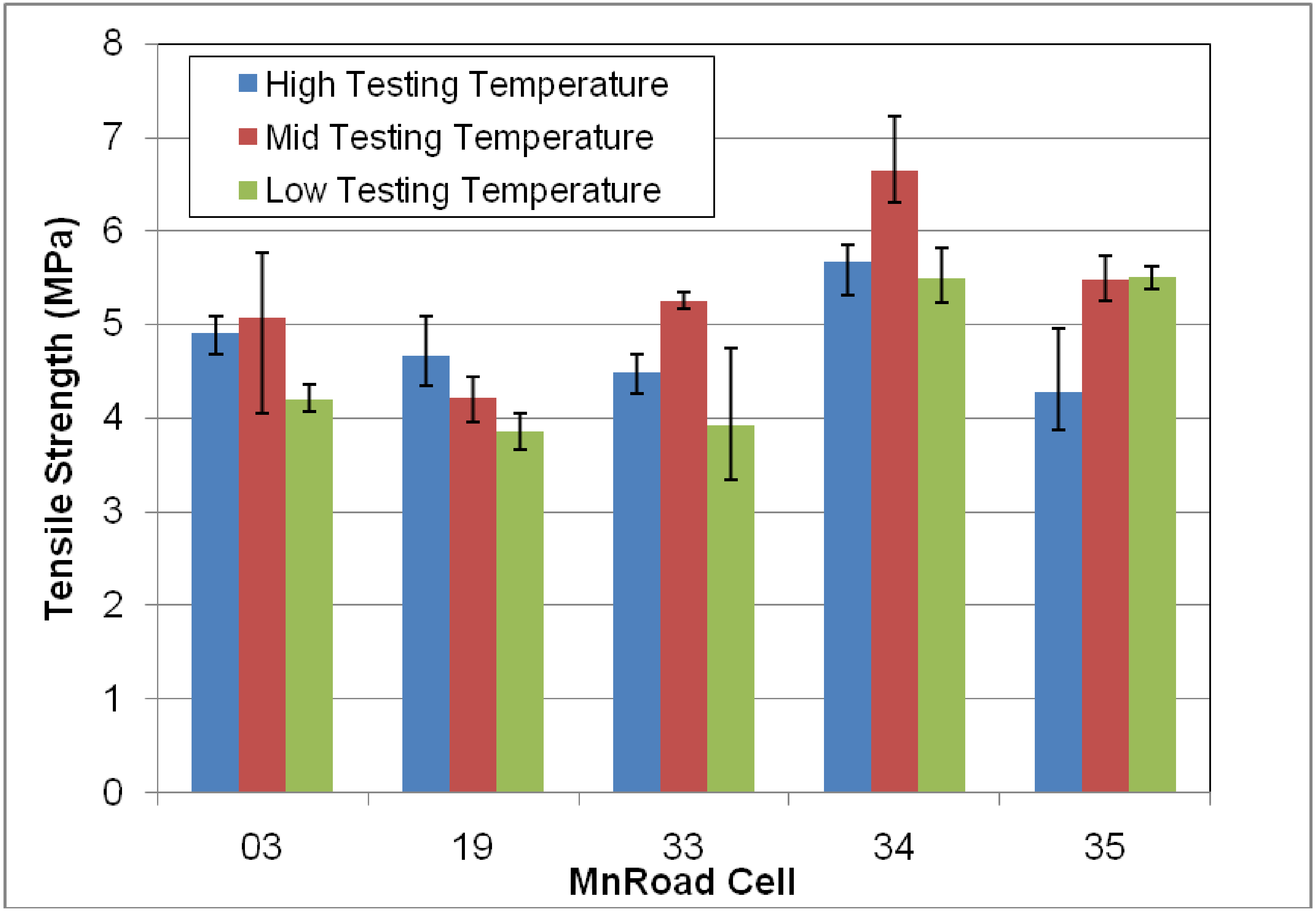
- Creep Compliance/Relaxation modulus master-curves using *AASHTO T322* (1000-second creep tests)
- Fracture energy from the Single-Edge Notch Beam, Semi-Circular Bend, and the Disk-Shaped Compact Tension (*ASTM D7313-06*) fracture tests
- Tensile strength from indirect tension testing (*AASHTO T322*)
- Coefficient of thermal contraction (Univ. of Wisconsin)
- Michigan Technological University and Iowa State University prepared laboratory samples

Section/Mix	PG Binder Grade	Testing Temperatures (°C)		
		High	Mid	Low
MnROAD 03	PG58-28 (120/150)	-6	-18	-30
MnROAD 19	PG58-34 (AC-20)	-12	-24	-36
MnROAD 33	PG58-28	-6	-18	-30
MnROAD 34	PG58-34	-12	-24	-36
MnROAD 35	PG58-40	-18	-30	-42

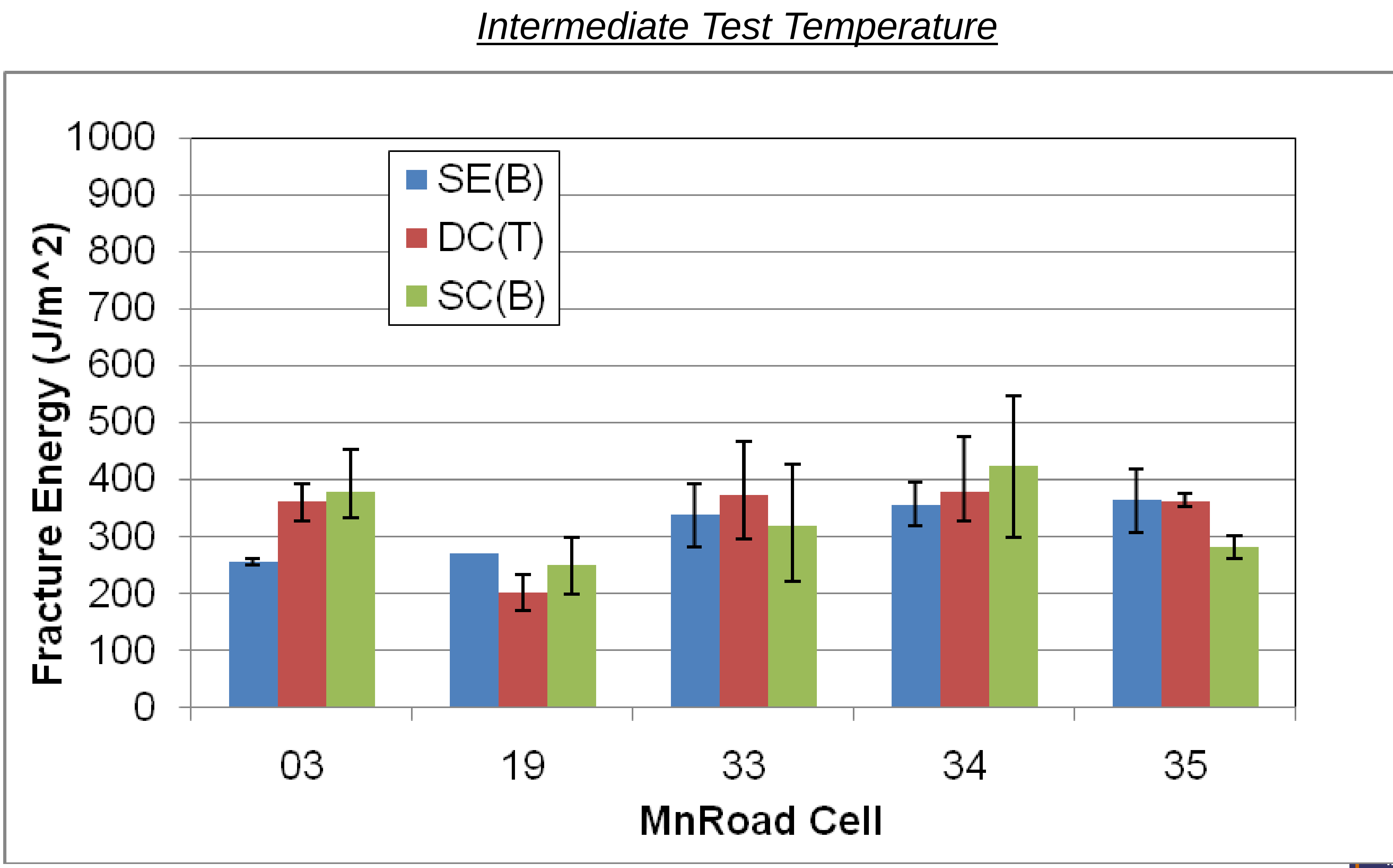
(d) Laboratory Testing: Creep Compliance



(d) Laboratory Testing: Tensile Strength



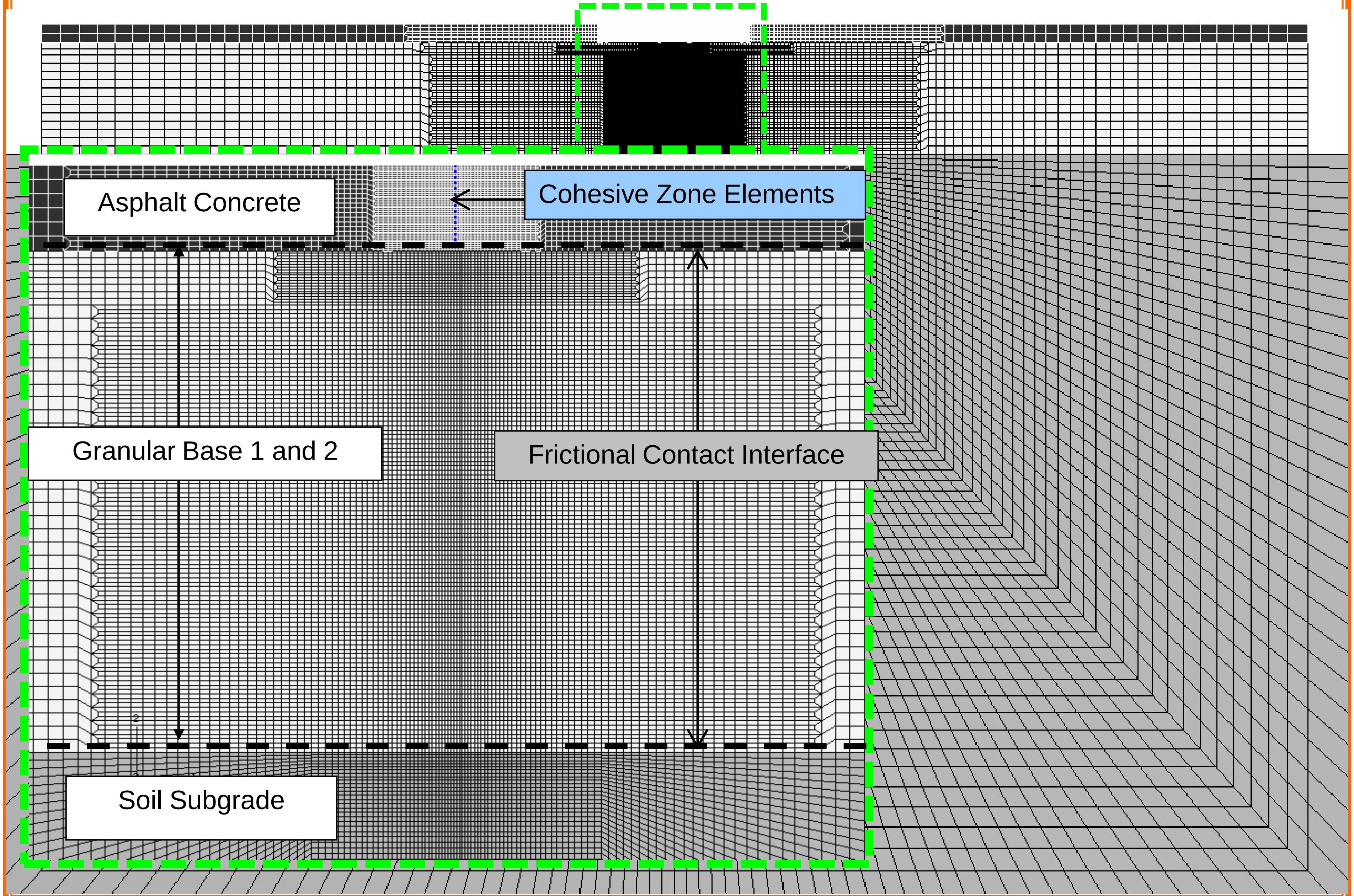
(d) Laboratory Testing: Fracture Energy



Pavement Model

- User element for softening and cracking in pavement (*Bilinear cohesive zone model*)
- User subroutines:
  - Temperature dependent coefficient of thermal expansion
  - Space and time dependent thermal load
- *Infinite elements* to simulate subgrade boundaries
- *Frictional contact* interfaces between asphalt concrete and granular base and granular base and subgrade
- Material Properties from Laboratory Testing:
  - Relaxation Modulus of AC: $E(t, T)$
  - Temperature Shift Factors for AC: $a(T)$
  - Fracture Energy of AC [DC(T)]: G_f
  - Tensile Strength of AC: σ_t
  - Coeff. Of Thermal Expansion: $\alpha(T)$

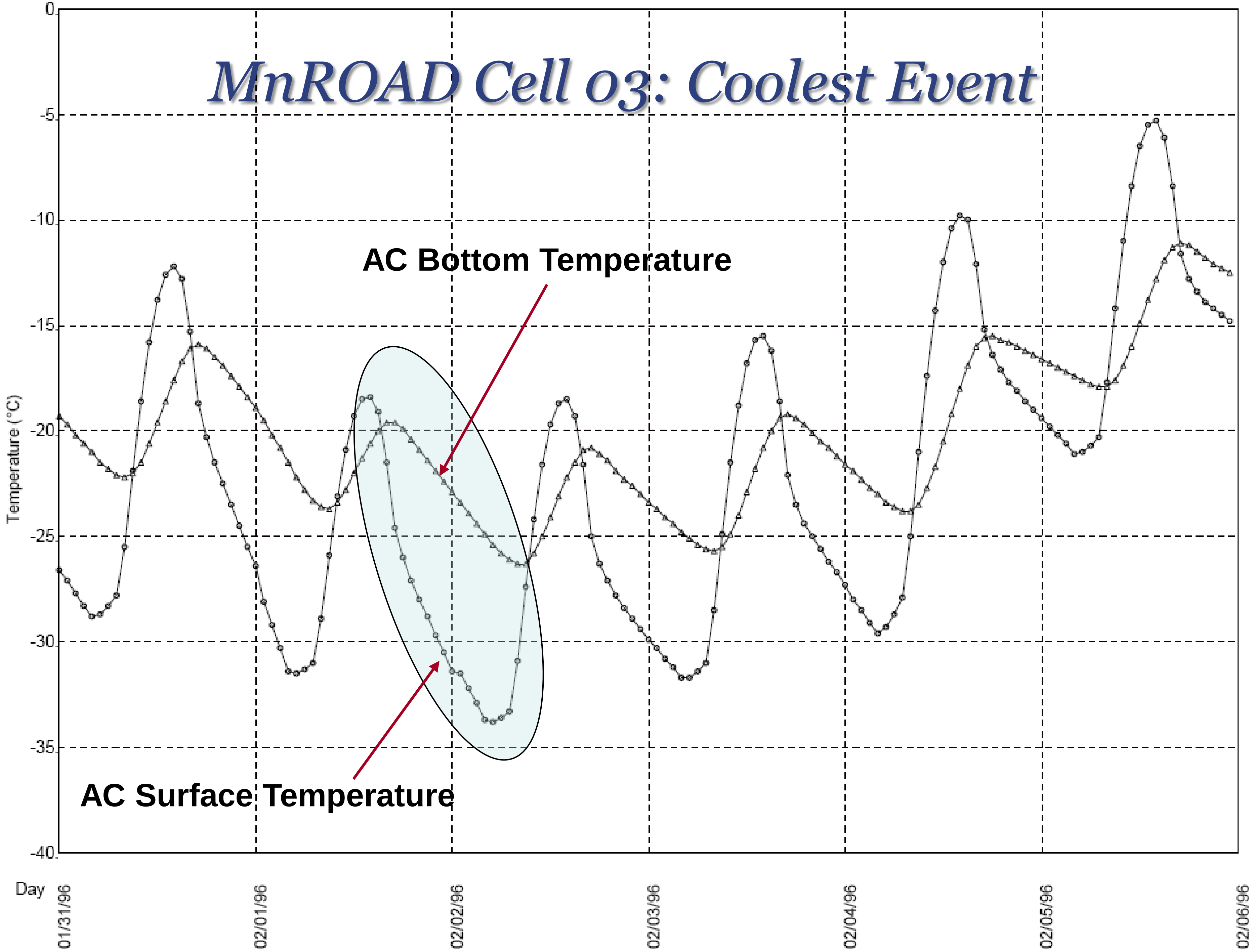
Finite Element Model



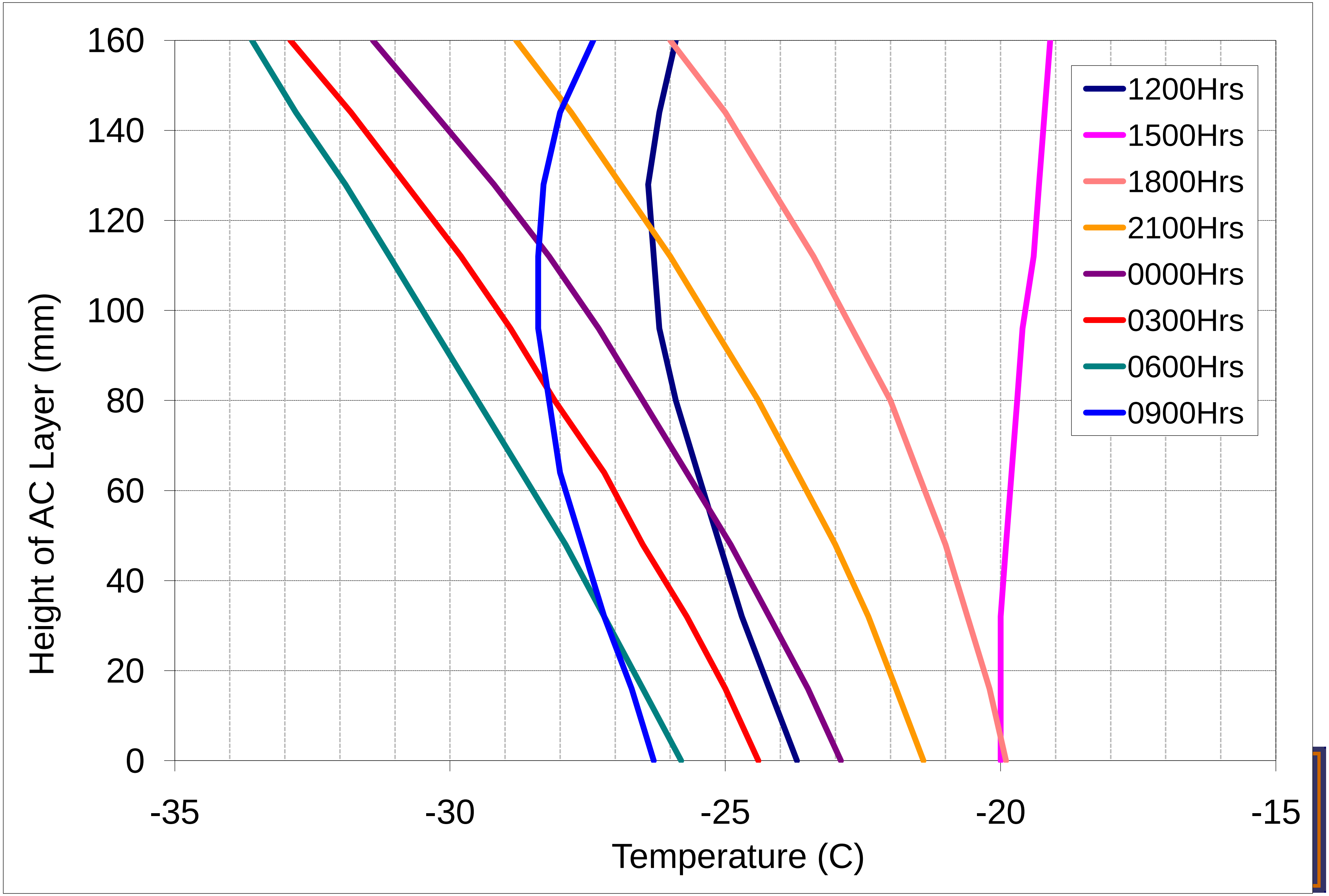
Critical Conditions Approach

- This approach follows identification and simulation of single critical low-temperature event
- Rationale:
  - Experimental fracture energies drop significantly at low temperatures
  - Ability of asphalt concrete to relax stress is greatly reduced at low temperature
  - Field data indicates most cracking during critical events
  - Practical simulation times and computational costs

MnROAD Cell 03: Coolest Event



Cell 03, Coolest Event: 02/01/96 – 02/02/96



Critical Event

- MnROAD Cells 03 and 19
  - 1st – 2nd February, 1996
  - Air Temperature = -40° C
- MnROAD Cells 33, 34, and 35
  - 30th – 31st December, 2004
  - Air Temperature = -31.1° C

Simulation Results: Thermal Loading

- MnROAD 03 and 19
  - Thermal Loading (Critical Event): Cracking through asphalt concrete thickness
  - Strong potential for thermal cracking

- MnROAD 33, 34 and 35
  - Very limited potential for thermal cracking due to single event
  - Cell 33 (PG58-28) underwent highest thermal straining
  - Cells 34 (PG58-34) and 35 (PG58-40) showed insignificant thermal straining

Simulation Results: Thermo-Mechanical Loading

- Single 9-kip tire load applied at coolest pavement surface temperature
- Results for MnROAD 33, 34 and 35
- Significant softening in all sections
- MnROAD Cell 34 (PG58-34) shows smallest extent of softening
  - Highest tensile strength
- Cell 35 (PG58-40) undergoes highest softening
  - Extremely compliant mixture
  - Excessive deformations
  - Fracture properties are similar to Cell33 (PG58-28)

Simulation Results vs. Field Performance

Section (AC Grade)	Simulation Results		Field Performance (2006)
	Percent Thickness Softened	Percent Thickness Cracked	Observed Cracking (m/100m)
Cell 03 (AC120/150)	----	100%	36.4
Cell 19 (AC20)	----	100%	109.4
Cell 33 (PG58-28)	53% from bottom	0%	18.2
Cell 34 (PG58-34)	23% from bottom	0%	1.2
Cell 35 (PG58-40)	61% from bottom	0%	149.4

1867

Summary

- Integrated testing and modeling approach should be preferred for predicting low-temperature cracking performance of asphalt pavements and overlays
- In general, the simulation results were found to be in good agreement with field observations
- Cohesive zone fracture model provides accurate and efficient way to model damage and fracture in asphalt concrete
- The framework of the techniques presented herein could be utilized for study of thermal and reflective cracking in pavements

In-Progress

- Phase-II of the Pooled Fund Study on Low Temperature Cracking (LTC)
- Proposed Outcomes:
  - Level – I, Simple Procedure (Table/Chart)
  - Level – II, Rigorous Analysis (Stand-alone FE based integrated modeling tool)

Acknowledgements

- Minnesota Road Research Section (MnROAD)

- Sponsors and partners of National Pooled Fund Study 776
  - CT, IA, IL, MN, ND, NY, WI DOTs
  - Local Road Research Board
  - University of Minnesota
  - University of Wisconsin
  - Michigan Technological University / Iowa State University