

Thermal Cracking Analysis Model AND Pavement Temperature Profile Prediction Model

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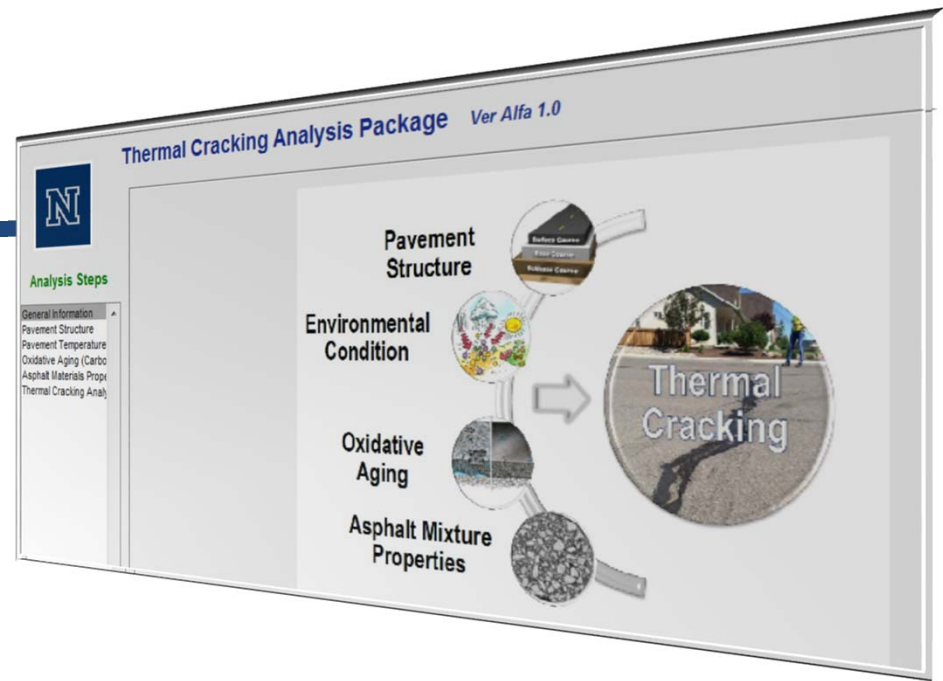
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***FHWA Asphalt Mixture Expert Task Group
Baton Rouge, Louisiana – September 17-19, 2014***





Comprehensive Evaluation of Thermal Cracking in Asphalt Pavements

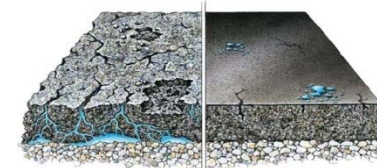
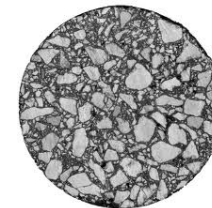
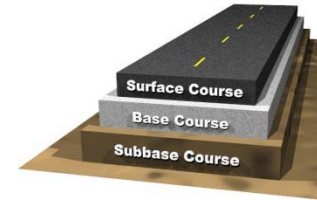
THERMAL CRACKING ANALYSIS PACKAGE (TCAP)



Thermal Cracking Analysis

Influential Factors

- **Pavement Structure**
 - Asphalt layer thickness.
 - Interface condition.
- **Environmental Conditions**
 - Pavement temperatures.
 - Cooling/warming rates.
- **Asphalt mixture properties**
 - Viscoelastic properties
 - Thermal Volumetric properties
 - Fracture and Crack Initiation Properties
- **Asphalt mixture aging**
 - Property change with oxidative aging



Thermal Cracking Analysis

Existing Models

- **Aging** of asphalt binder over time is **not considered**
“viscoelastic, fracture, and volumetric properties of asphalt material constant over time.”
- **Thermal coefficient of contraction (CTC)** is considered **constant** with temperature and usually **estimated**.
- **Tensile strength** is considered **constant** with temperature and time.
- **Pavement temperature model** (currently EICM) **can be improved**.



Thermal Cracking Analysis

Supportive Experimental Plan *(Morian, N. 2014)*

Asphalt Binder Testing

- 15 asphalt binder types
Unmodified, polymer modified, lime modified
- Testing
 - Carbonyl Area (FT-IR)
 - Binder Master Curves and LSV

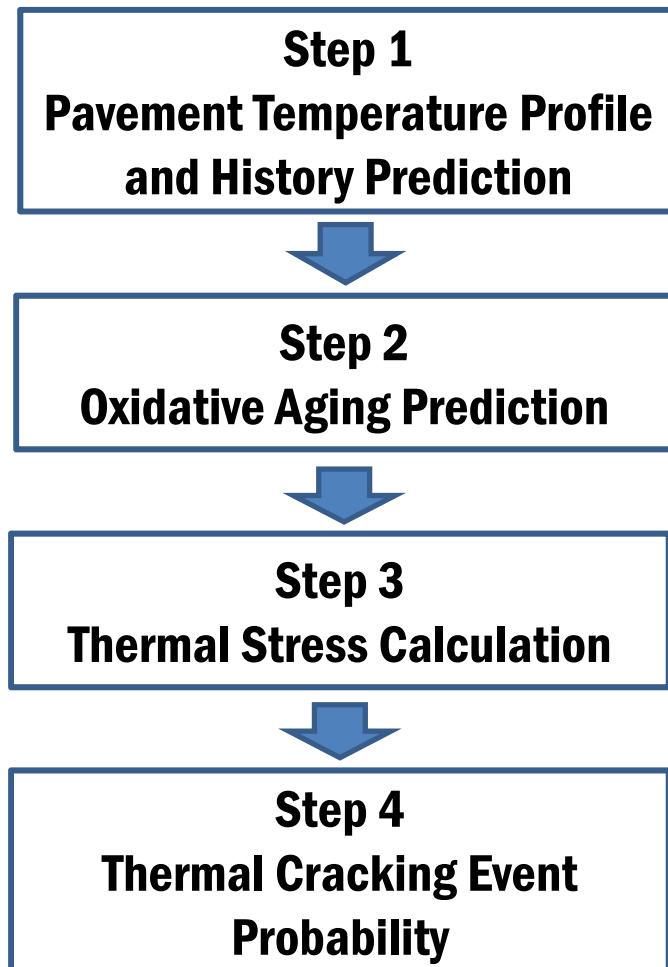
1 mm film asphalt binder pan aging
over different times and durations
(50, 60, 85 and 100°C up to 320 days)

Asphalt Mixture Testing (partial factorial)

- 5 Agg. Sources (Abs. from 0.9 to 5.97%)
- 3 Gradations (coarse, interm. & fine)
- 2 Binders (PG64-22, PG64-28 SBS mod.)
- Binder Contents (3.62 to 9.14% TWM)
- 3 Air Void levels (4, 7, 11%)
- Testing
 - Dynamic modulus (E^*)
 - Uniaxial Thermal Stress & Strain Test (UTSST)

Asphalt Mixture aging: 4 Levels
(0, 3, 6, and 9 months at 60°C)

Thermal Cracking Analysis Proposed Model



Predicted pavement temperature (Step 1)
(over time and at depth z)

Predicted carbonyl (CA) (Step 2)
(over time and at depth z)

Asphalt mixture Relaxation modulus

- Directly from the E^* complex modulus
- based on continuous relaxation spectrum
- Age dependent

Coefficient of thermal contraction (CTC)

- Temperature dependent CTC
- Obtained from the thermal strain curve
- Age dependent

1-D Linear viscoelastic model



Thermal Cracking Analysis

Prediction of Field Aging *(Numerical solution using FCVM)*

Pavement location: **Reno, NV**

Aggregate: **Northern Nevada**

Binder type: **PG64-28 (SBS mod.)**

Binder content: **5.22%**

Air voids: **7%**

$E_a = 72.53$ kJol/mol

$AP^\alpha = 4.08 E+8$ ln(CA/day)

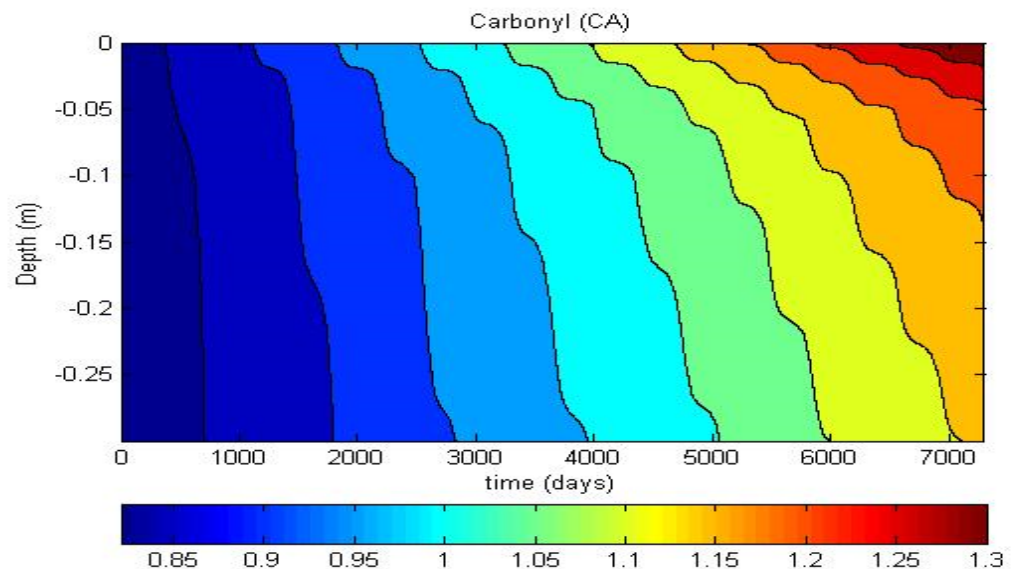
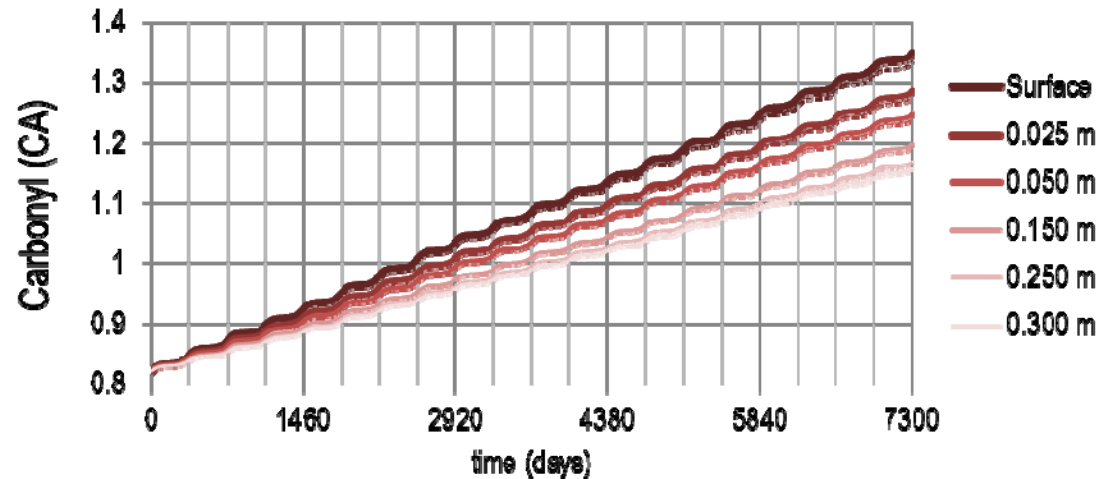
$HS = 2.7$ (1/CA)

$m = 9.24$ (poise)

Air void diameter = **0.5 mm**

Eff. aging zone = **1.0 mm**

(film thickness)

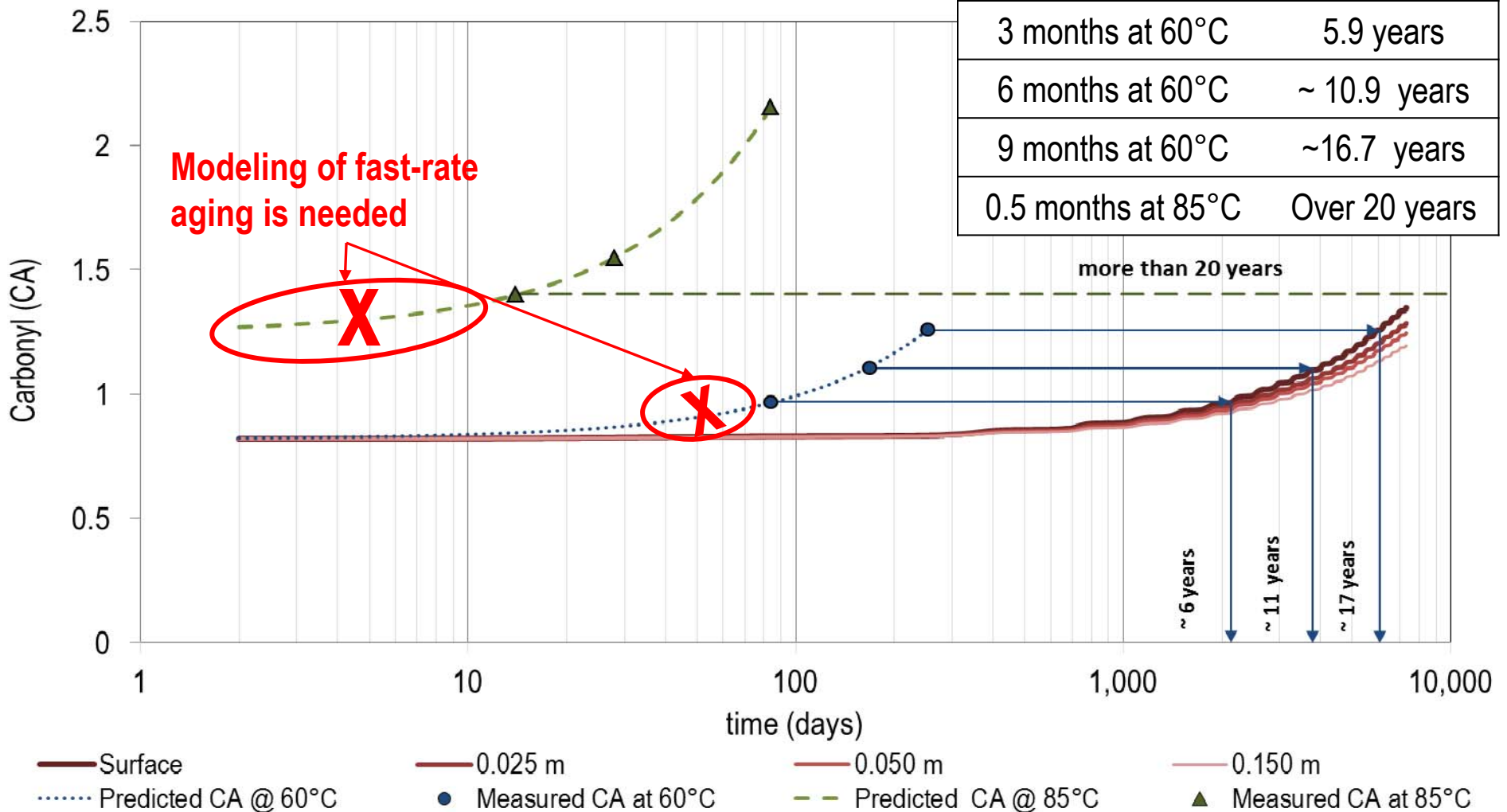


Thermal Cracking Analysis

Lab Simulation of Field Aging

NV_PG64-28(SBS)_5.22%AC_7.0%Va

long-term lab aging	Field aging (Reno, NV)
3 months at 60°C	5.9 years
6 months at 60°C	~ 10.9 years
9 months at 60°C	~16.7 years
0.5 months at 85°C	Over 20 years



Thermal Stress Calculation

- 1D linear viscoelastic constitutive equation with oxidative aging effect.

$$\sigma_{Th}(t, CA) = \int_0^t E(\xi(t) - \xi'(t), CA) \frac{\partial \varepsilon_{Th}(t, CA)}{\partial t'} dt'$$

Relaxation Modulus
Function of time,
temperature, and aging

Thermal strain rate
Function of temperature and
age-dependent CTC



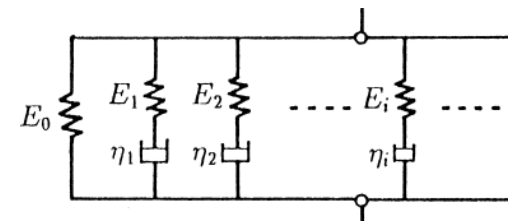
Age-Dependent Relaxation Modulus

- Relaxation modulus determined from dynamic complex modulus.
 - Continuous relaxation spectrum directly obtained by inverse Laplace Fourier Transform of complex E^* (2S2P1D, *Olard & Di Benedetto, 2003*).

$$E_r(t) = E_0 + \int_{-\infty}^{+\infty} H(\rho) \cdot e^{\left(\frac{-t}{\rho}\right)} d\ln(\rho)$$

$$H(\rho) = \pm\pi^{-1} \text{Im}E^*(\rho^{-1} \cdot e^{\pm i\pi})$$

$$E^*(i\omega) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}}$$



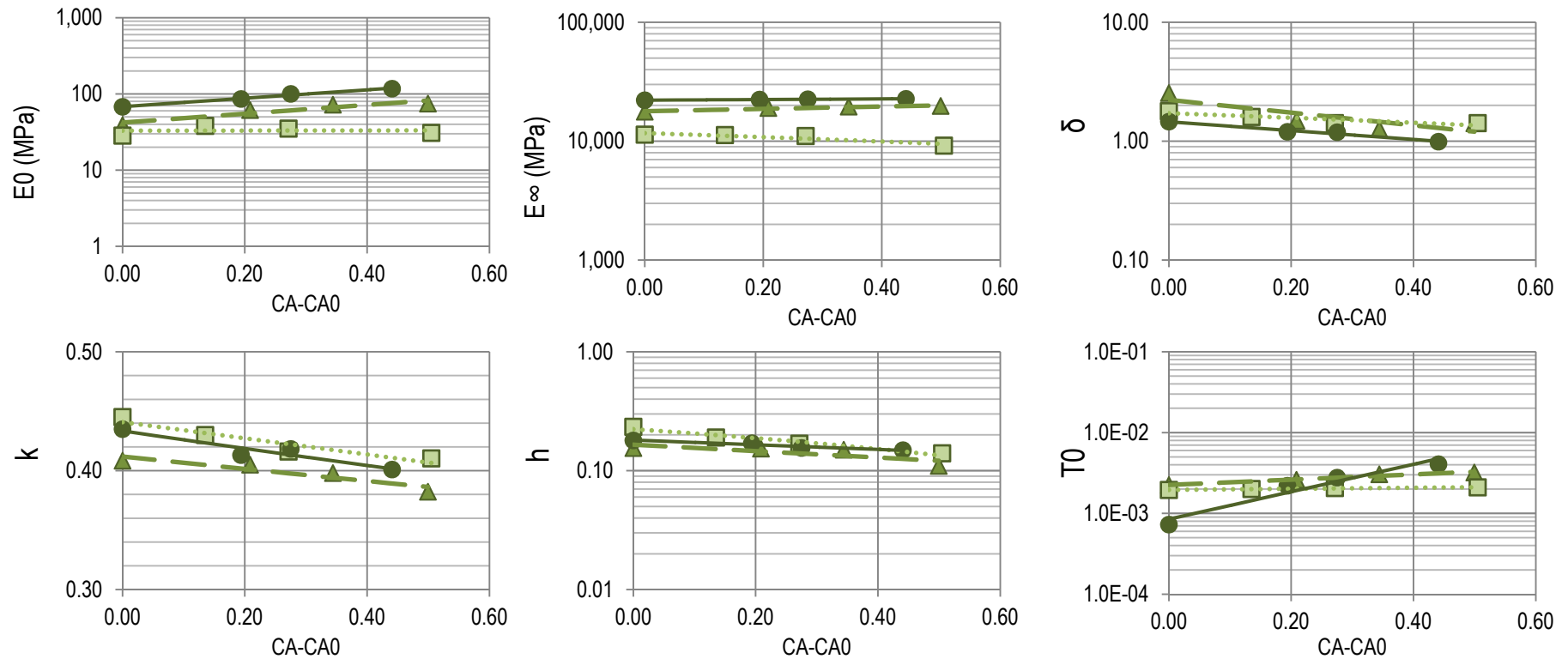
Ideal viscoelastic model

- ▶ ω : 2π *frequency, the pulsation
- ▶ E_0 : static modulus when $\omega \rightarrow 0$
- ▶ E_∞ : limit of complex modulus when $\omega \rightarrow \infty$,
- ▶ h, k : exponents such as $1 > h > k > 0$,
- ▶ δ : dimensionless constant.
- ▶ β : dimensionless constant, $\beta = \eta_i \cdot \tau^{-1} / (E_\infty - E_0)$; when $\omega \rightarrow 0$, then $E^*(i\omega\tau) \sim E_0 + i\omega\eta_i$.
- ▶ τ : characteristic time, which varies only with temperature



Thermal Cracking Analysis

Evolution of 2S2P1D Coefficient with Aging



● NV19I28_5.22_4%_60°C

▲ NV19I28_5.22_7%_60°C

■ NV19I28_5.22_11%_60°C

Consistent trends were found for the evaluated mixtures!

$$(2S2P1D \text{ coeff})_j = A_j \times e^{B_j(CA-CA_0)}$$



Thermal Cracking Analysis

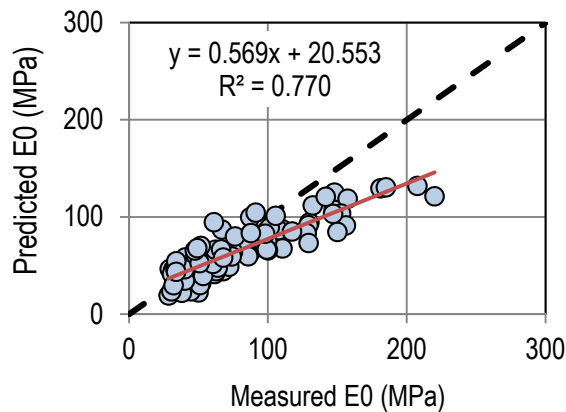
Evolution of 2S2P1D Coefficient with Aging

2S2P1D coeff.	Mixture variable						
	CA	V _a (%)	Abs. (%)	LSV _{Tank} (poise)	B.C. (%)	Retained # 8	Passing # 200
E ₀	✓	✓	✓	✓	✓		
E _∞	✓	✓	✓	✓	✓	✓	✓
δ	✓	✓	✓	✓	✓		✓
k	✓		✓	✓			✓
h	✓			✓	✓		
T ₀	✓		✓				✓

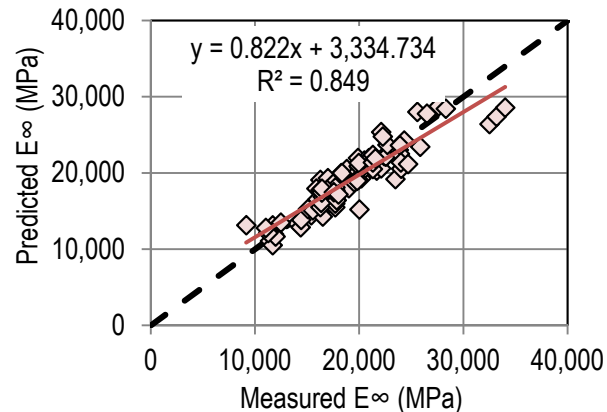


Thermal Cracking Analysis

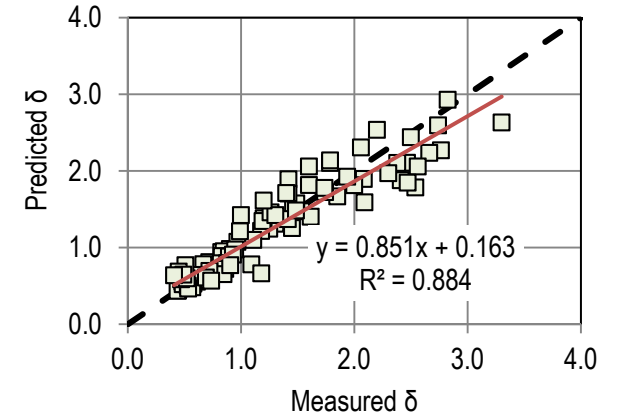
Evolution of 2S2P1D Coefficient with Aging



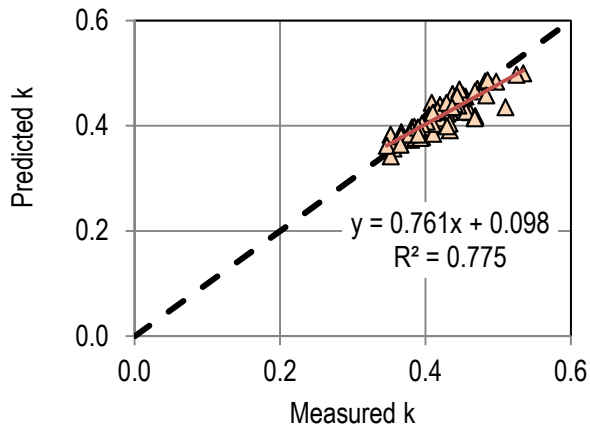
○ E0 (MPa) — Line of Equality



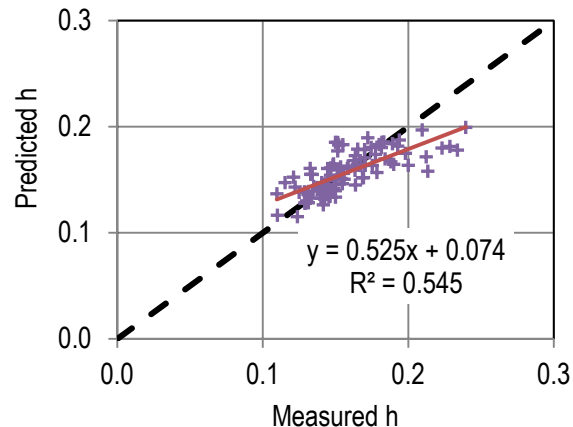
◇ E∞ — Line of Equality



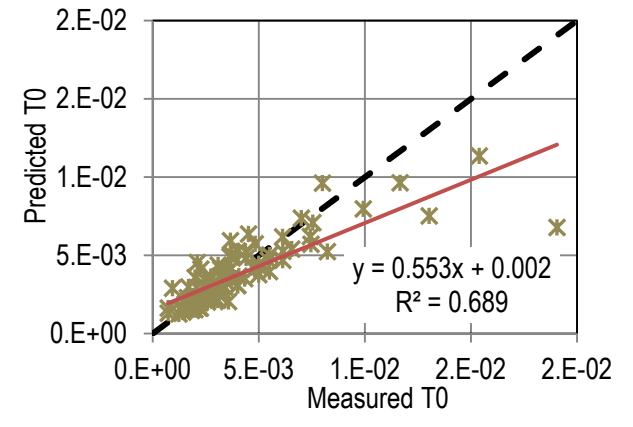
□ δ — Line of Equality



△ k — Line of Equality



+ h — Line of Equality

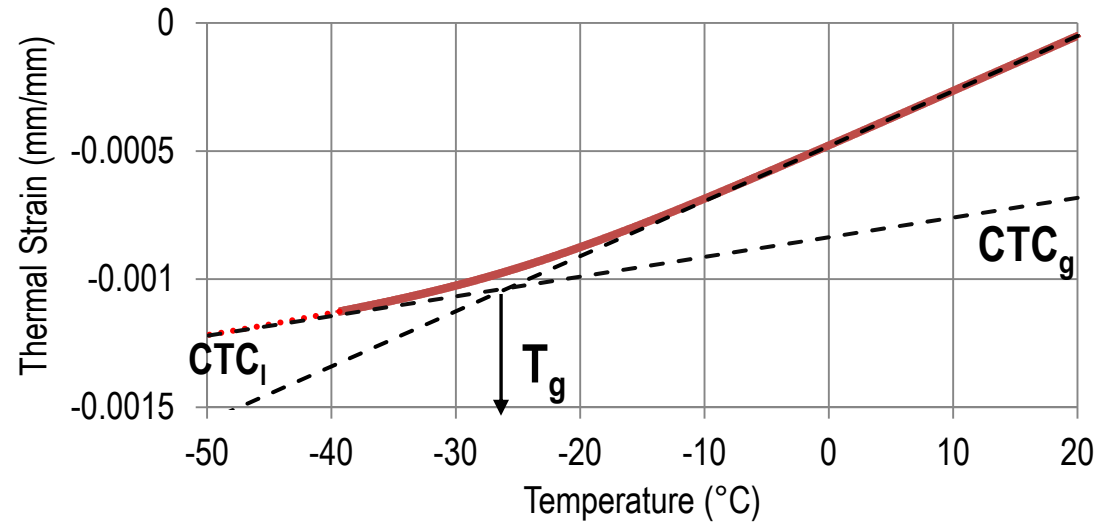
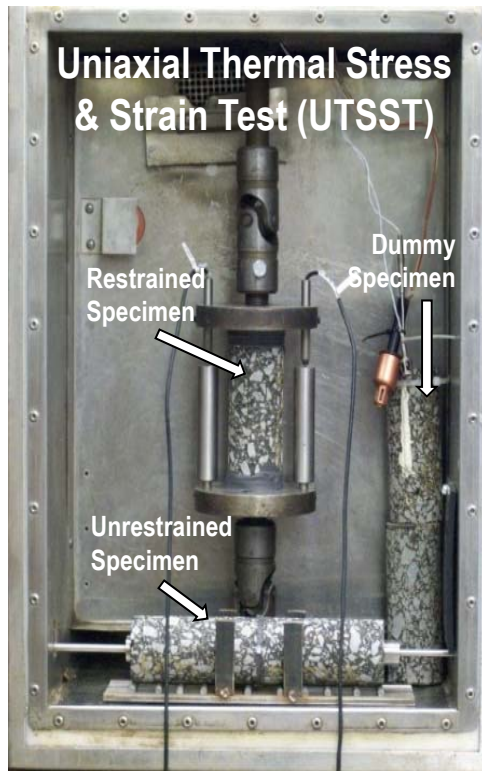


× T0 — Line of Equality



Thermal Cracking Analysis

Temperature and Age-Dependent CTC



$$\varepsilon_{th} = \frac{\Delta l}{l_0} = C + CTC_g(T - T_g) + \ln \left\{ \left[1 + e^{\frac{(T-T_g)}{R}} \right]^{R(CTC_L - CTC_g)} \right\}$$

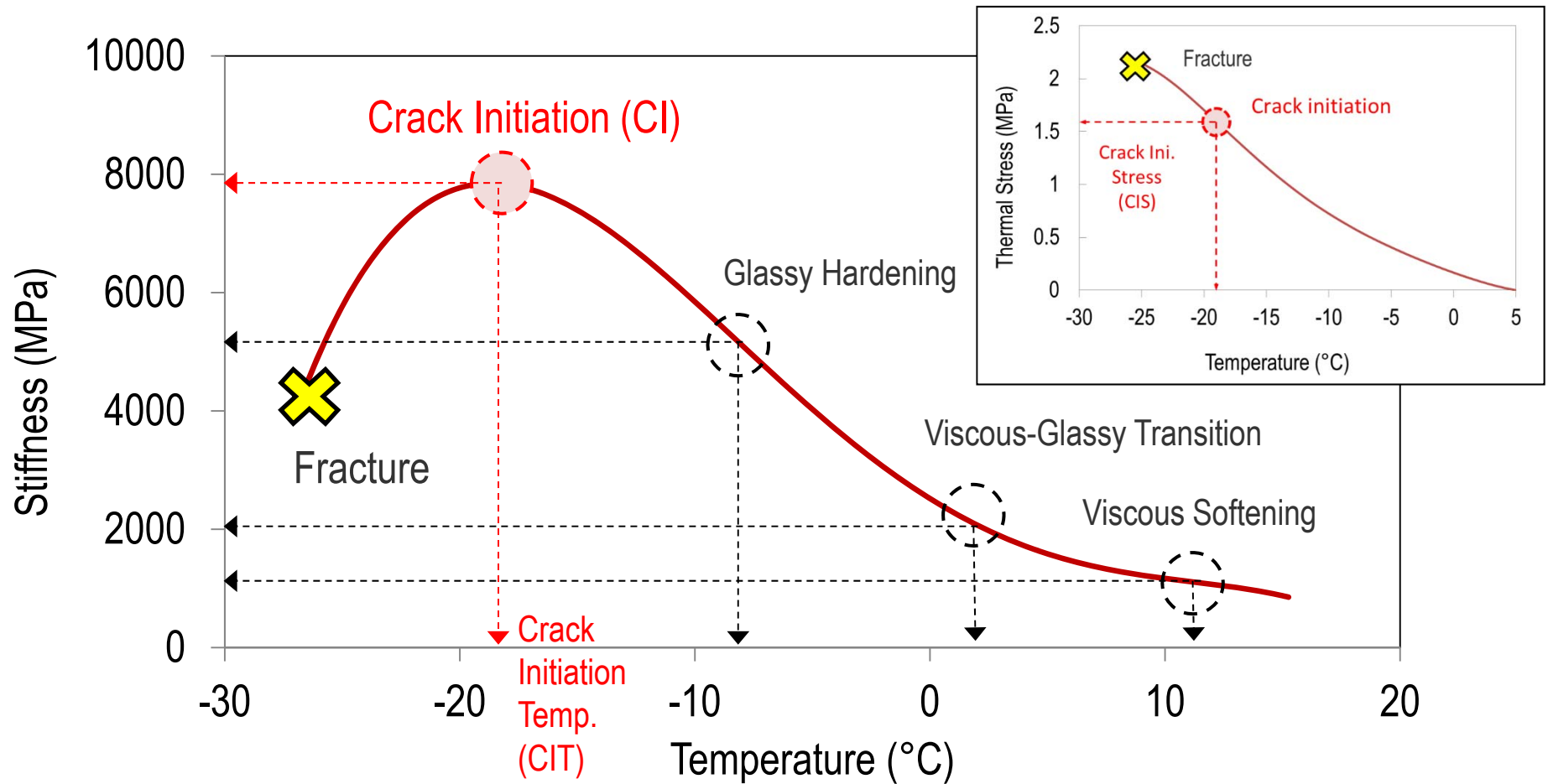
$$CTC(T) = CTC_g + \frac{(CTC_L - CTC_g) \times e^{\frac{T-T_g}{R}}}{(1 + e^{\frac{T-T_g}{R}})}$$

$$\varepsilon(T(t)) = \int_{T_0}^{T(t)} CTC(T(t)) \times dT'$$



Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

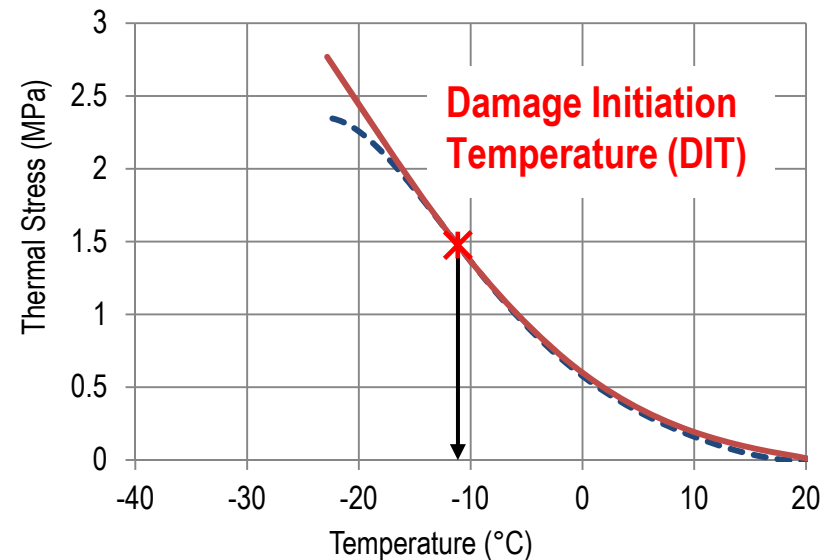
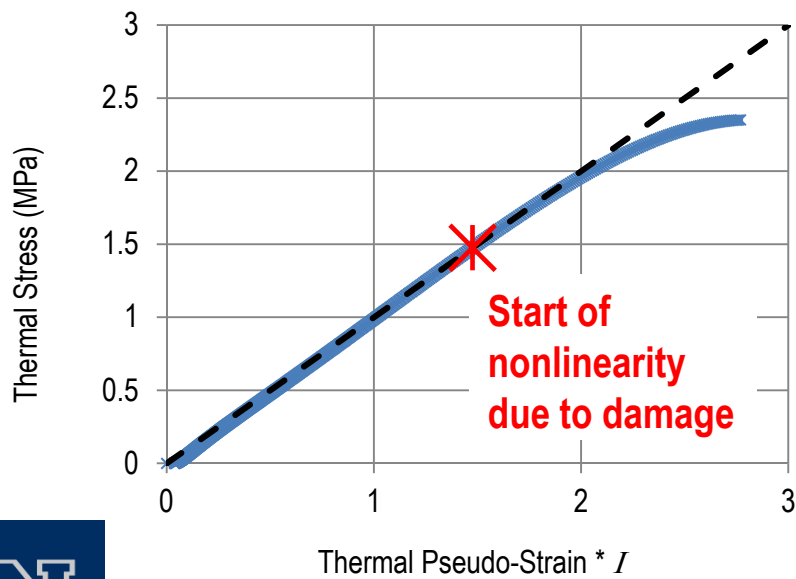


Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

- Validation of CIS with VECD.
 - Elastic-Viscoelastic Correspondence Principle

$$\sigma_{Th}(t) = E_R \times I \times \varepsilon_{Th}^R(t) \quad \varepsilon_{Th}^R(t) = \frac{1}{E_R} \int_0^t -E_r(\xi(t) - \xi(t')) \frac{\partial \varepsilon_{Th}(t')}{\partial t'} dt'$$

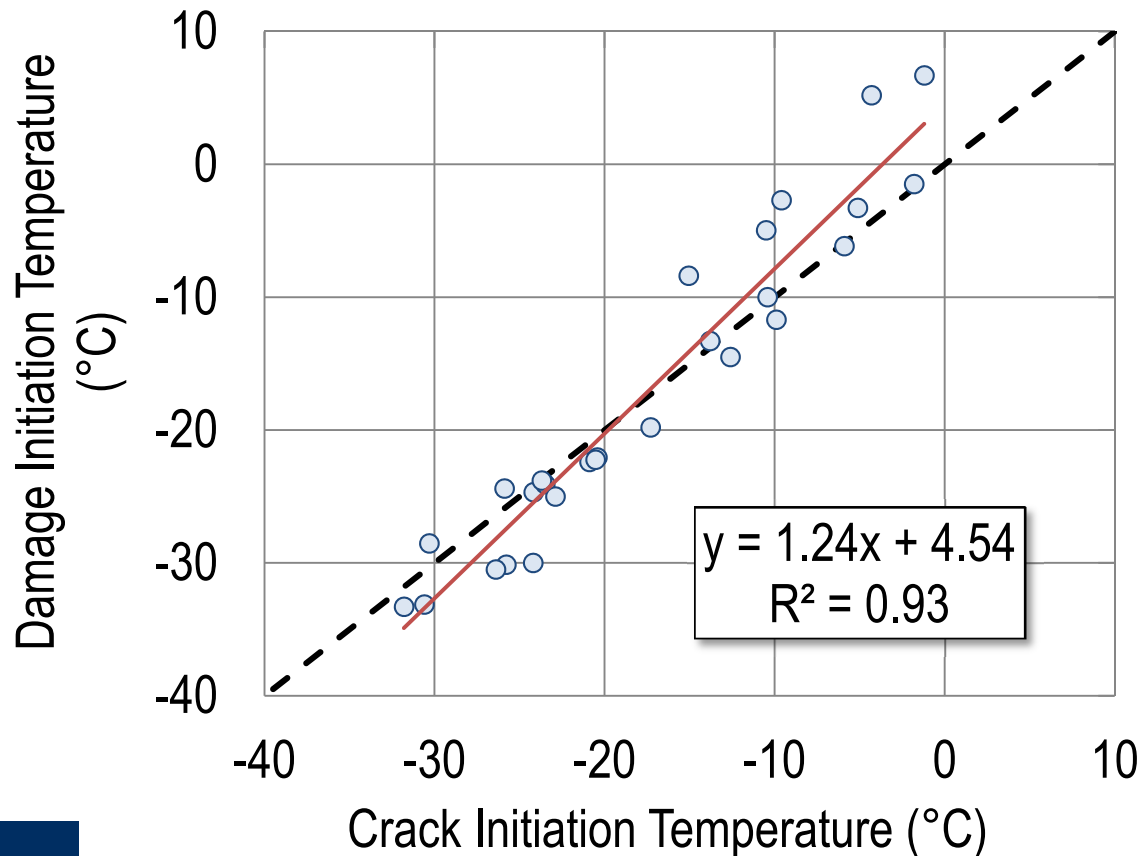


--- Measured thermal stress from UTSST
— Predicted stress without continuum damaging



Age-Dependent Crack Initiation Stress (CIS)

- Validation of CIS with VECD.

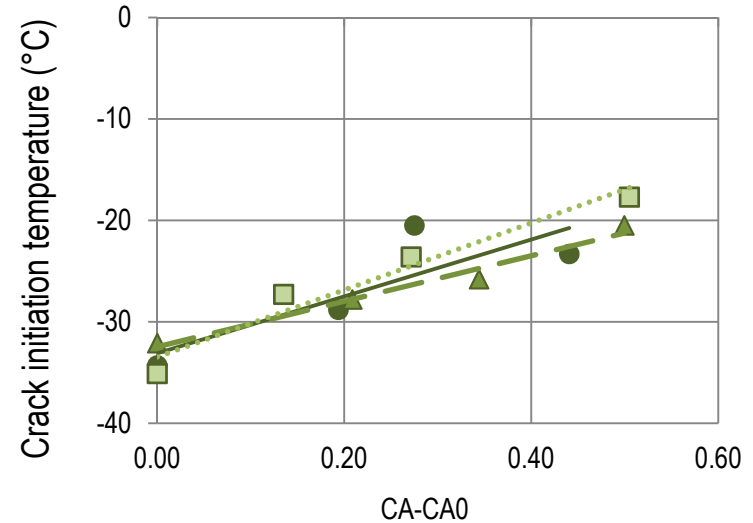
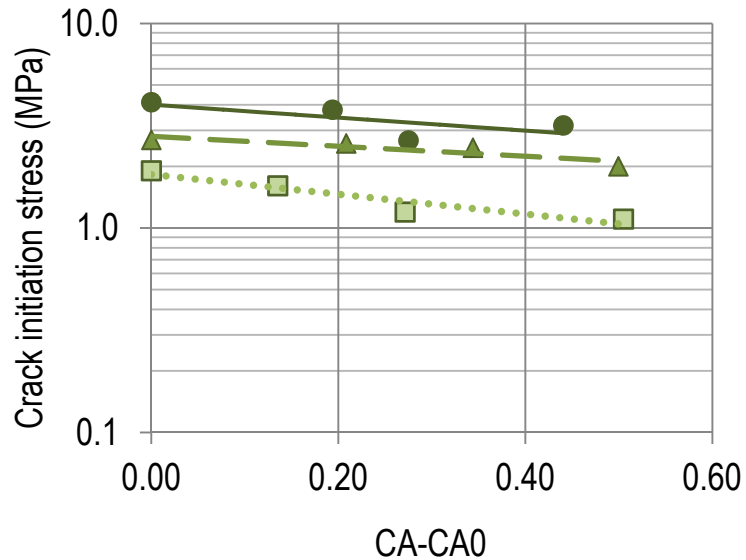


Various mixtures with different binder grades, aggregates, and mix designs.



Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)



Similar trends were observed for all evaluated mixtures!

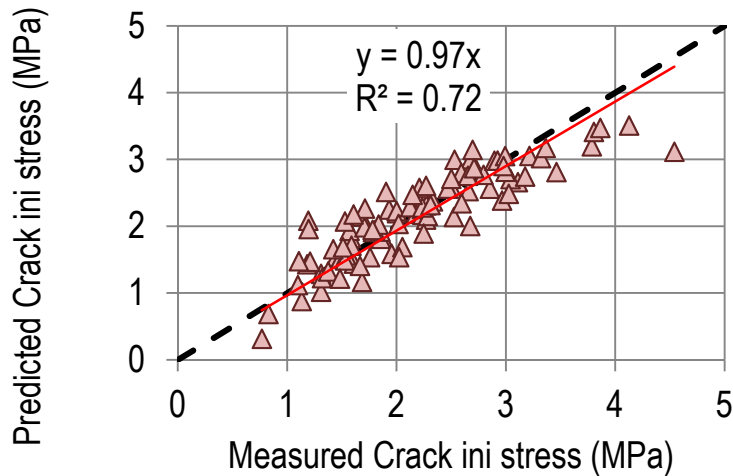
$$CIS = E \times e^{F(CA-CA_0)}$$



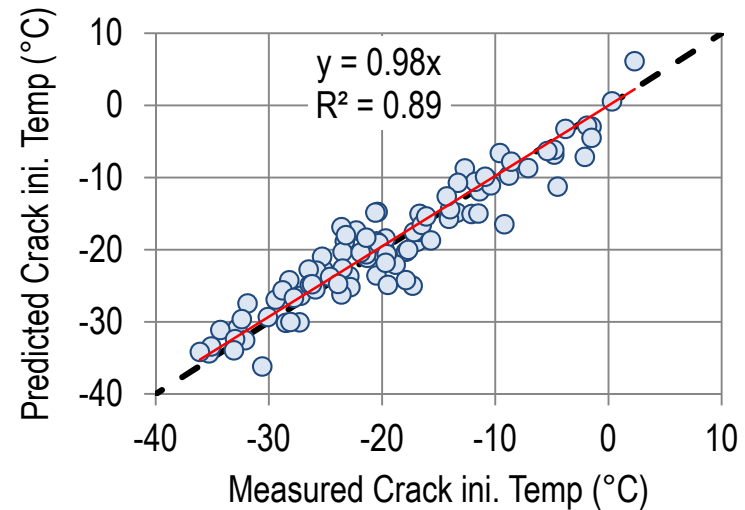
Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

	Mixture variable						
	CA	Va (%)	Abs. (%)	LSV _{Tank} (poise)	B.C. (%)	Retained # 8	Passing # 200
CIS	✓	✓	✓	✓			✓
CIT	✓	✓		✓	✓	✓	✓



△ Crack initiation stress - - Line of equality



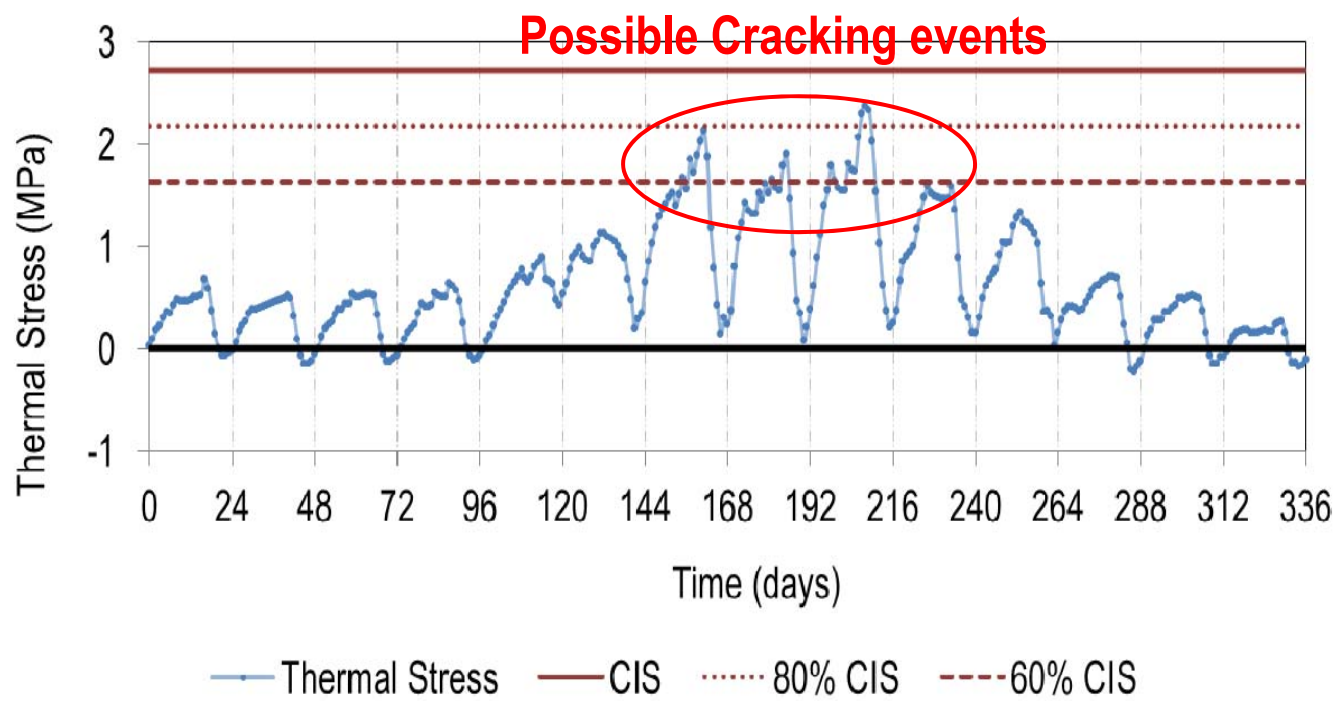
○ Crack initiation temperature - - Line of equality



Thermal Cracking Analysis

Thermal Cracking Event Probability

- The accumulative events during which thermal stress reaches a defined percentage of the asphalt mixture **Crack Initiation Stress (CIS)** over the analysis period!



MATLAB Graphical User Interface (GUI)

Thermal Cracking Analysis Package (TCAP)

The image displays two screenshots of the Thermal Cracking Analysis Package (TCAP) GUI. The left screenshot shows the main interface with a central diagram illustrating the relationship between Pavement Structure, Environmental Condition, Oxidative Aging, and Asphalt Mixture Properties leading to Thermal Cracking. Below this diagram is a 'General Information' section with input fields for Project Name (NV28-4%-Reno), Analysis Period (20), Construction Date (August 1, 2000), and a Project Description area. The right screenshot shows the 'Thermal Cracking Analysis' results window, featuring a 'Run Analysis' button and several plots: 'Thermal stress (MPa)' vs 'time (hours) x 10⁴', 'Thermal cracking event' vs 'time (hours) x 10²', and 'Cracking index' vs 'time (hours) x 10²'.



Examples: TCAP Analysis

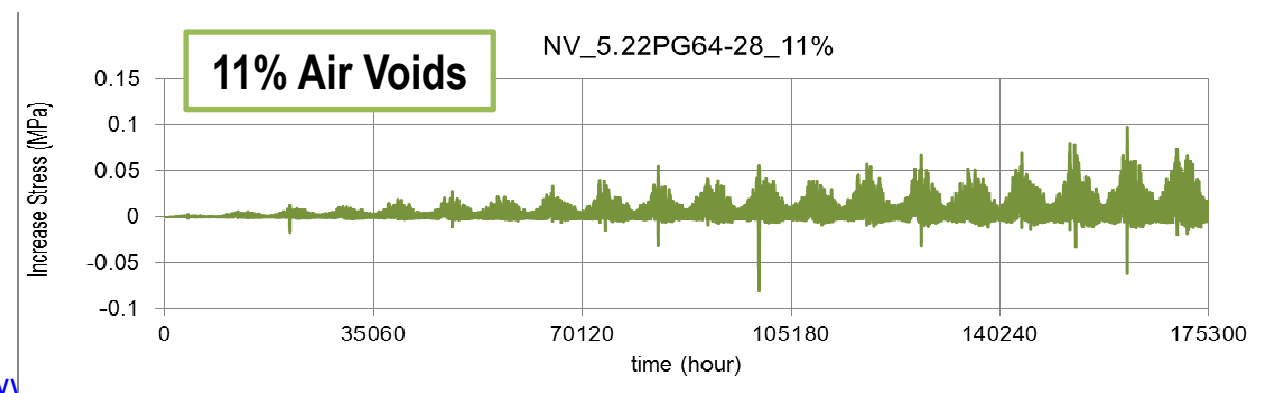
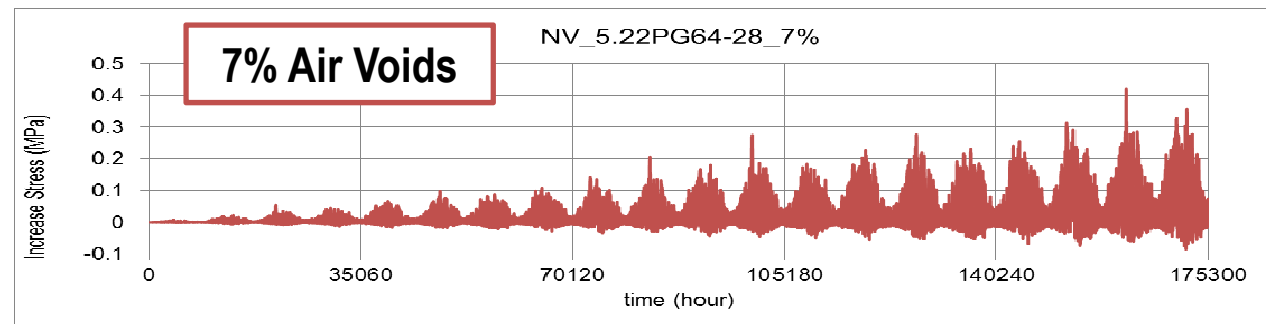
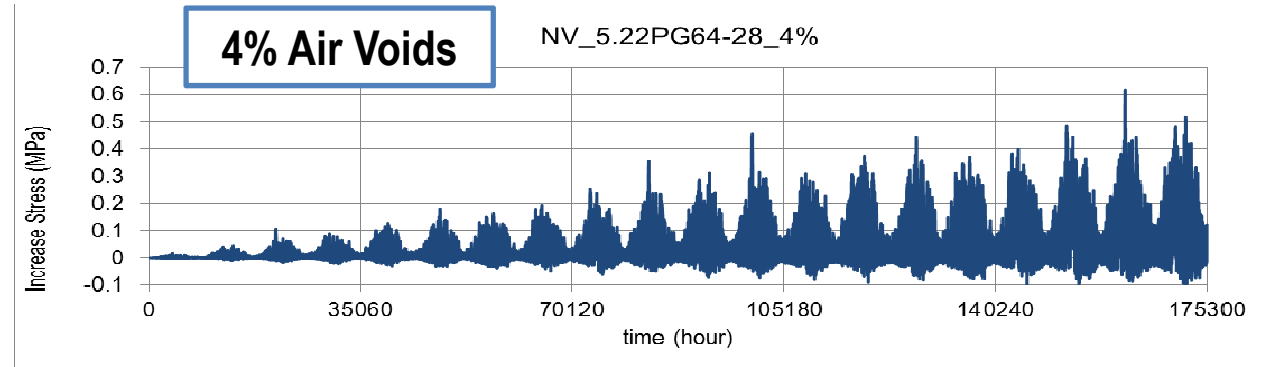
- **Pavement Location**
 - Reno, Nevada
- **Asphalt Mixtures:**
 - **Polymer-modified PG64-28; 3 air void levels:**
 - NV_5.22PG64-28_4%; NV_5.22PG64-28_7%; NV_5.22PG64-28_11%
- **Design Period**
 - 20 years



Examples: TCAP analysis

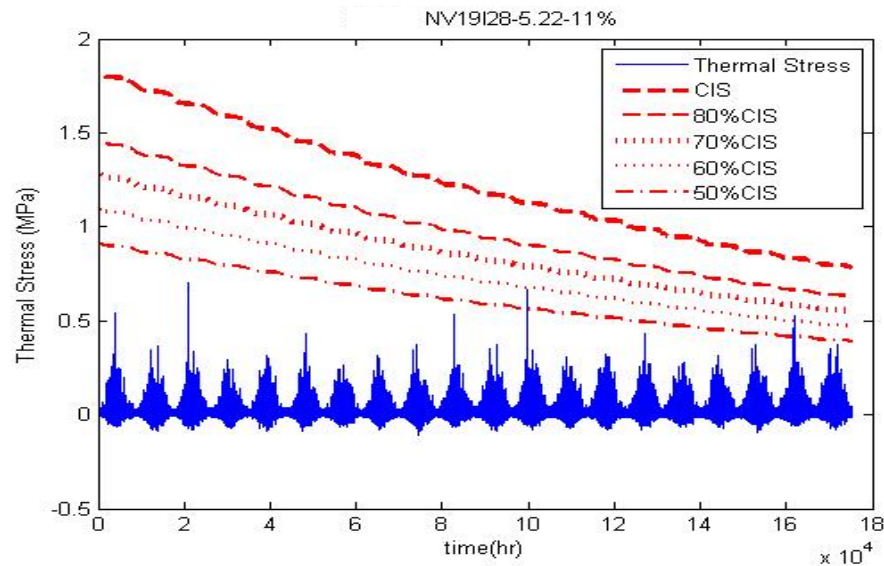
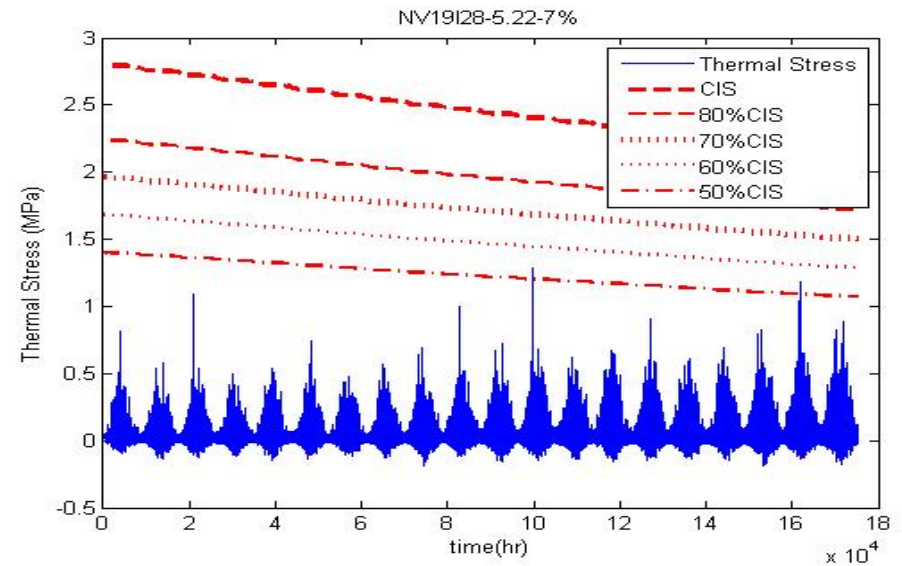
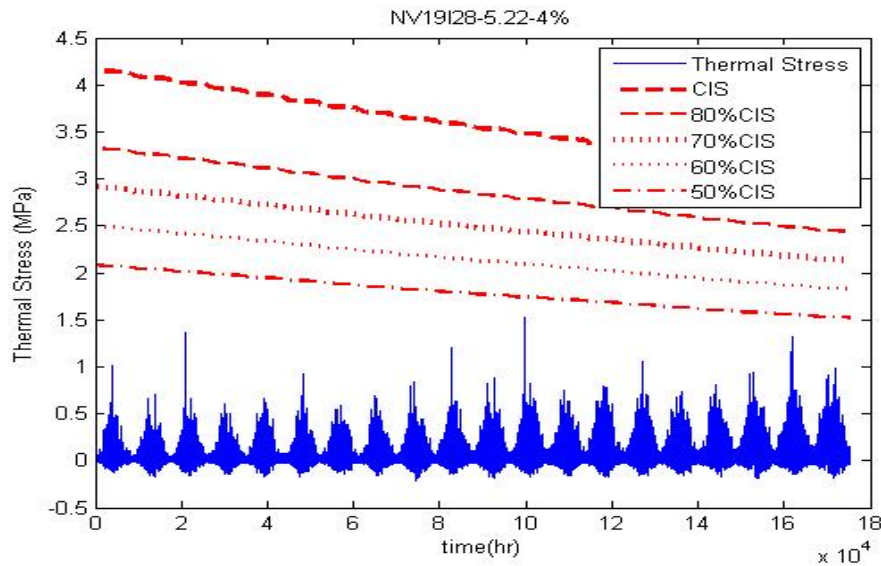
Effect of Oxidative Aging on Thermal Stresses

Difference in predicted thermal stresses between aging and no-aging effect analyses.



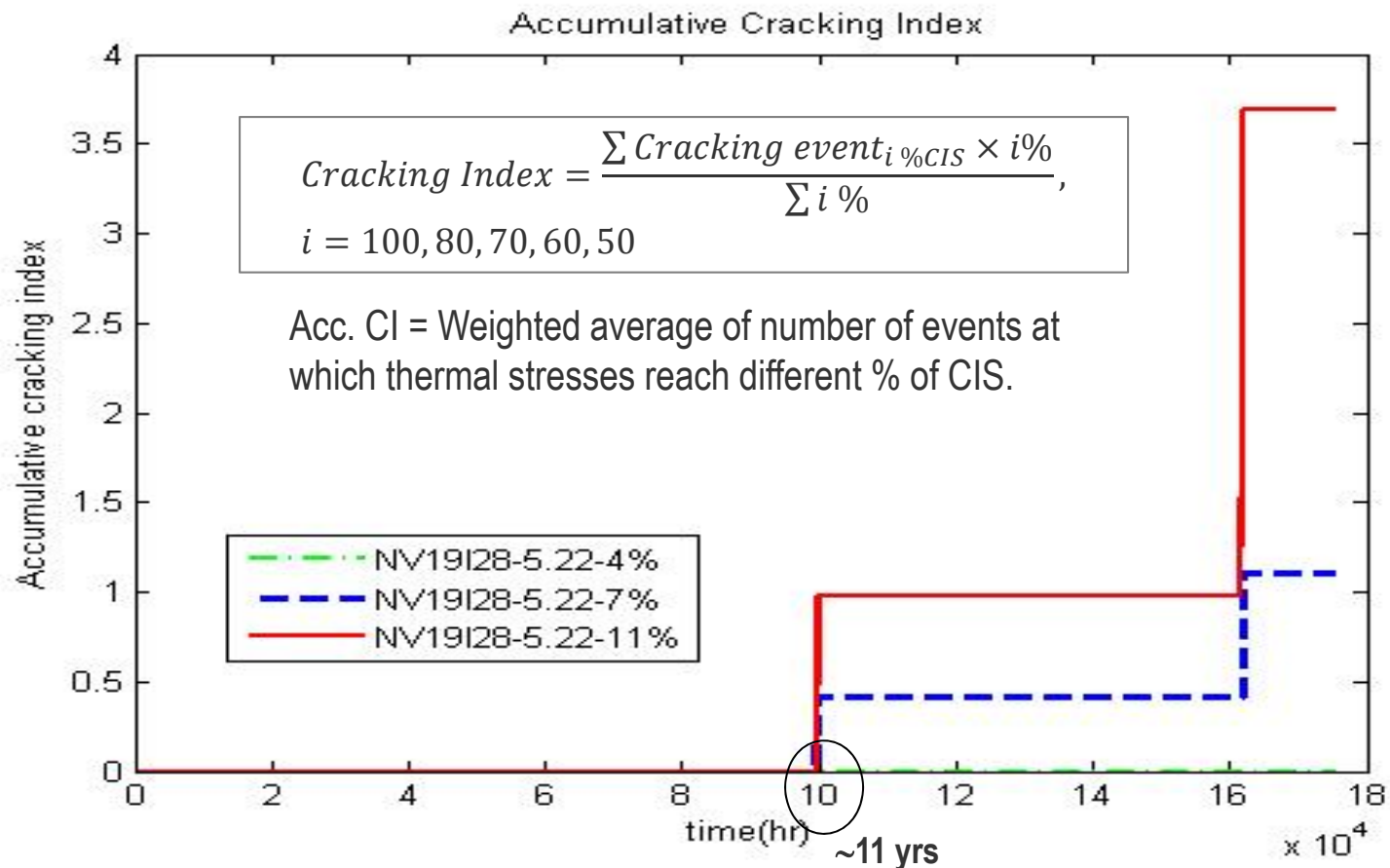
Examples: TCAP analysis

Thermal Stress vs. Crack Initiation Stress (CIS)



Examples: TCAP analysis

Effect of Mixtures Air Voids

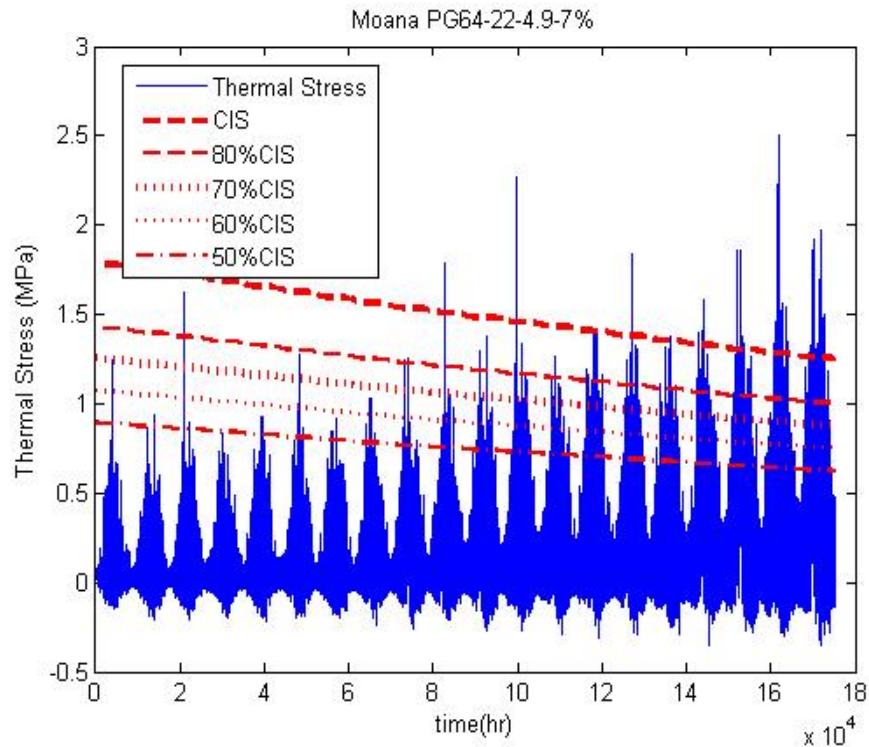


Cracking likelihoods increase for mixture with higher air voids level....

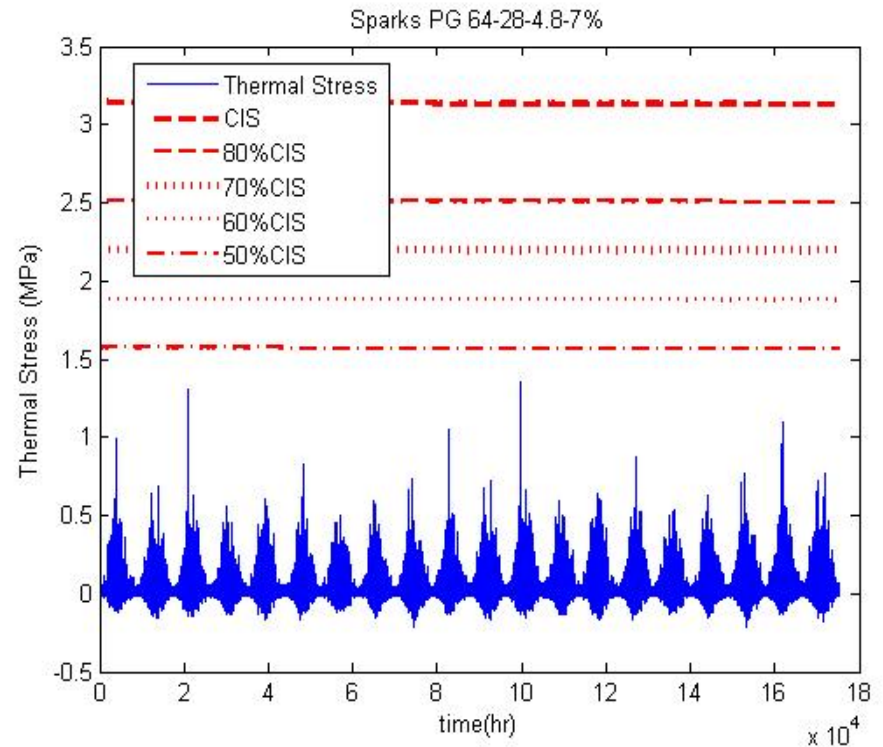


Examples: TCAP analysis

Effect of Modification (Two field projects from Reno, NV)



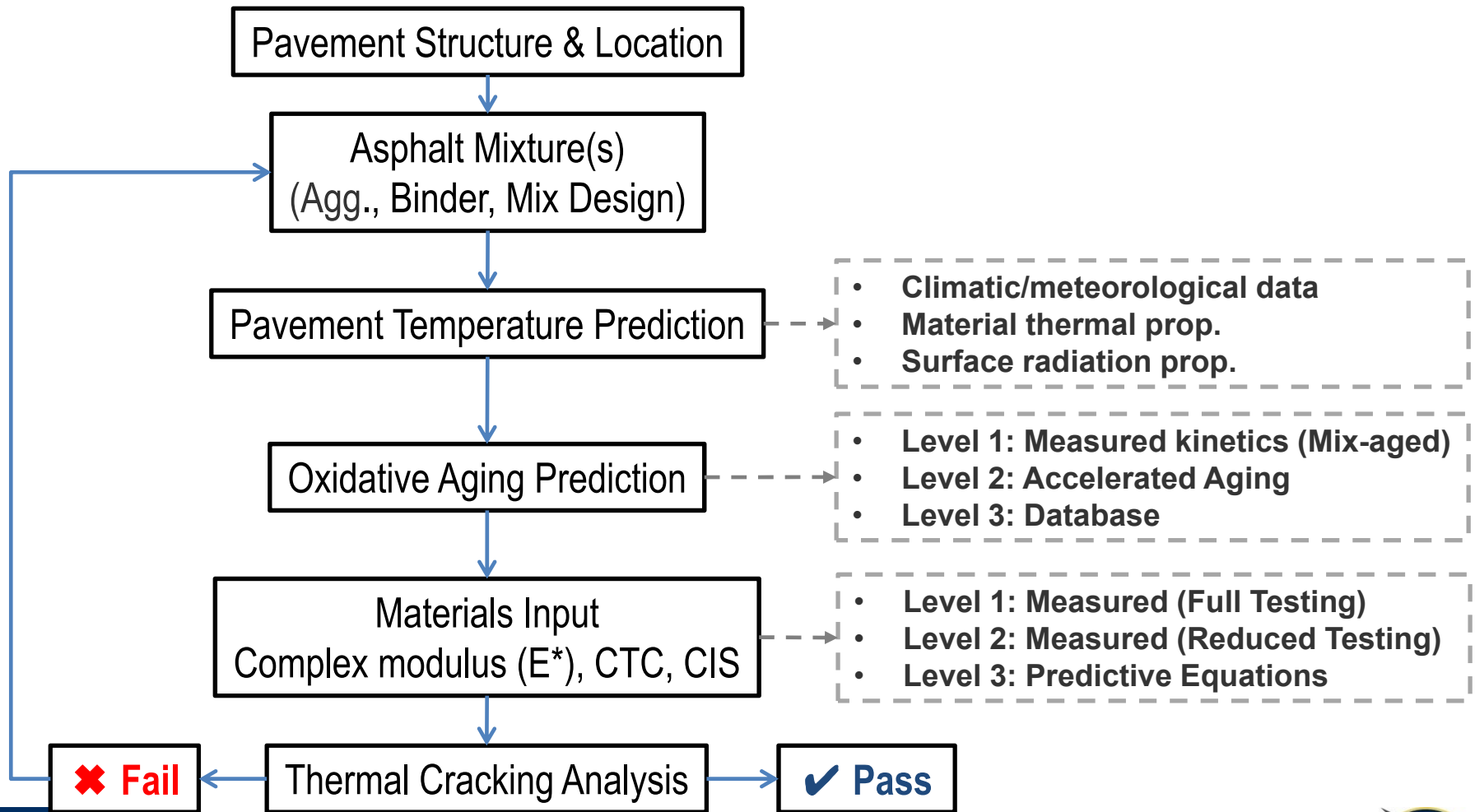
**Un-modified
PG64-22 (Moana, 2006)**



**SBS polymer-modified
PG64-28 (Sparks, 2008)**



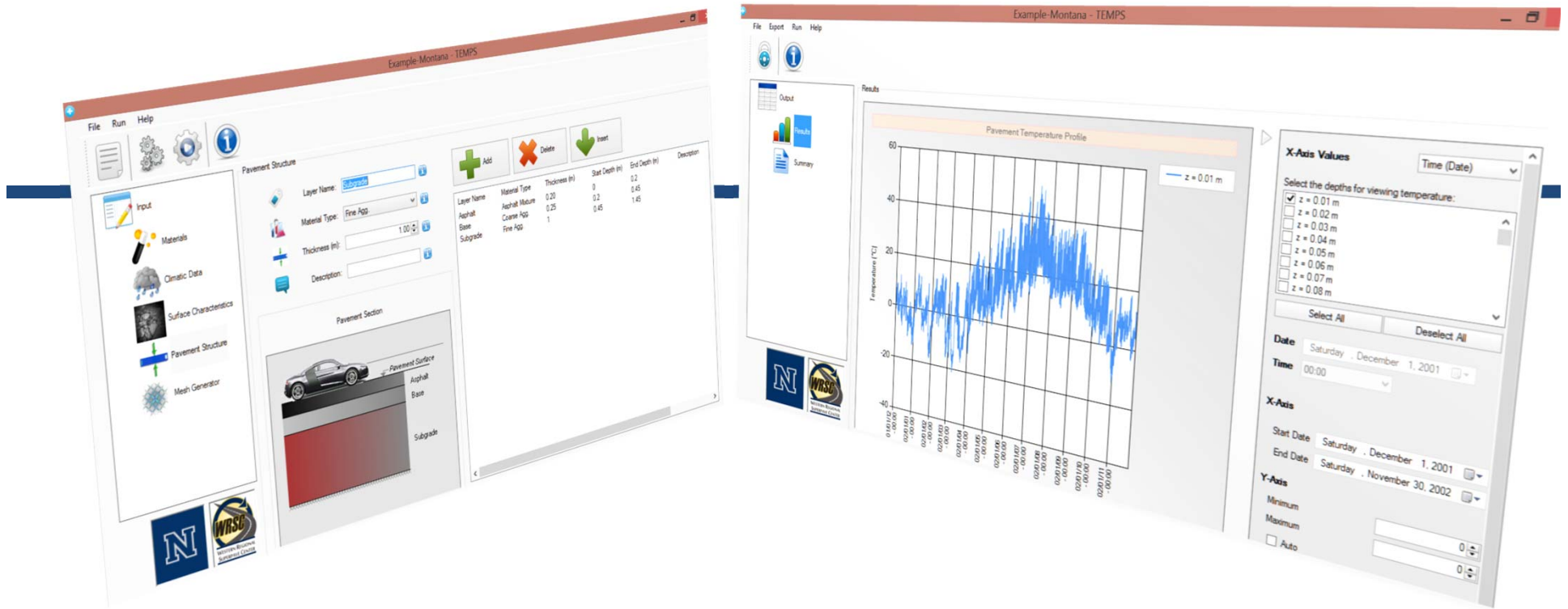
TCAP Implementation



Future Research and Improvements

- Field validation of TCAP model.
- Sensitivity analysis of TCAP model.
- Level 3 material input:
 - Regression models for materials oxidative aging, viscoelastic, and crack initiation properties.
- Development of a stand-alone TCAP software.





Pavement Temperature Profile History

TEMPERATURE ESTIMATE MODEL FOR PAVEMENT STRUCTURES (TEMPS)



Pavement Temperature Profile Prediction

⑩ Improvement of the *Heat Transfer* model [Han et al., 2011 (TAMU)]

- Enhanced boundary conditions.
- Variable pavement surface radiation properties.

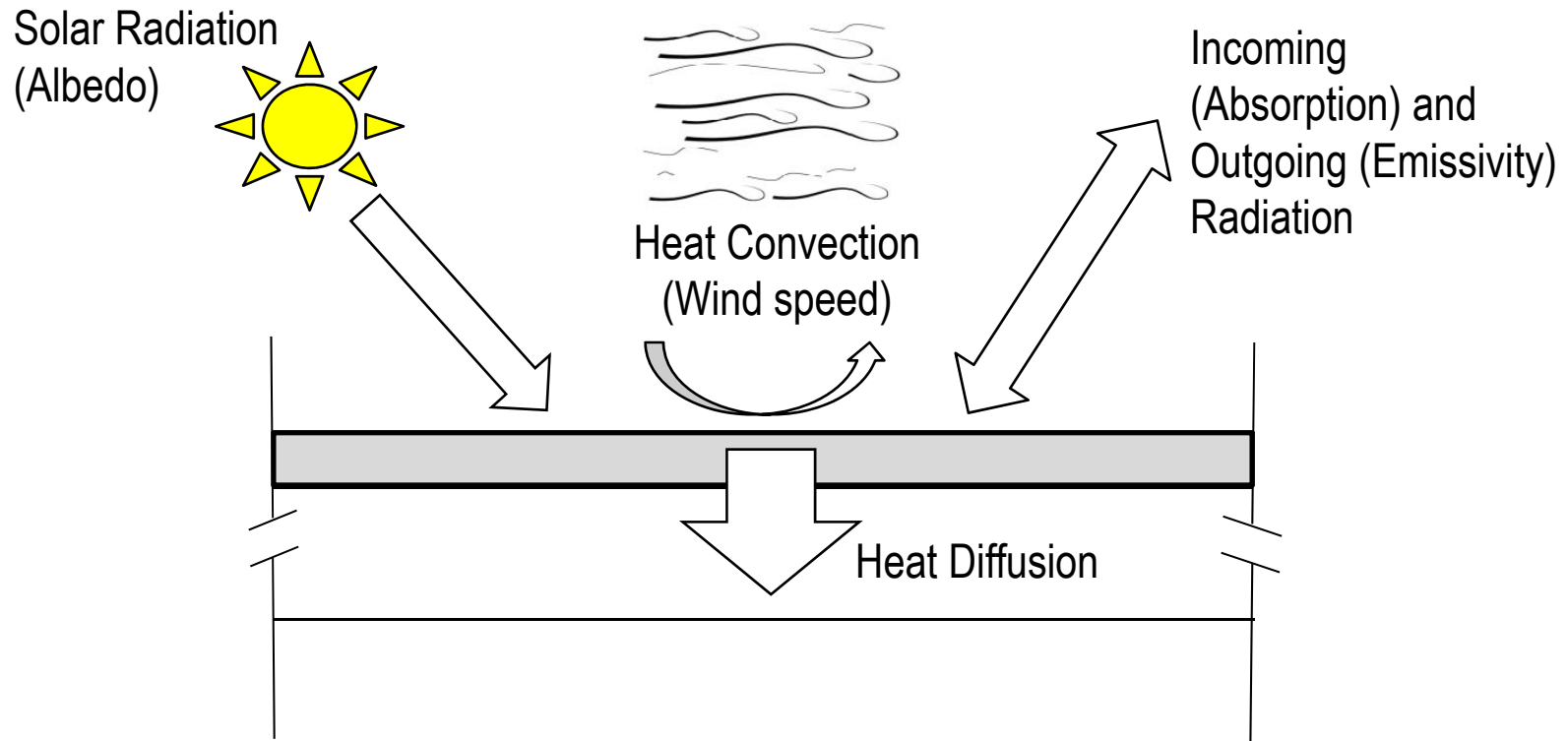
⑩ Application of Finite Control Volume method (FCV) with Implicit Scheme [Alavi et al., 2014 (UNR)]

- Considering discontinuity in pavement layers' material.
- Improving the time efficiency of calculation.



Pavement Temperature Profile Prediction

Heat Transfer Model Concept



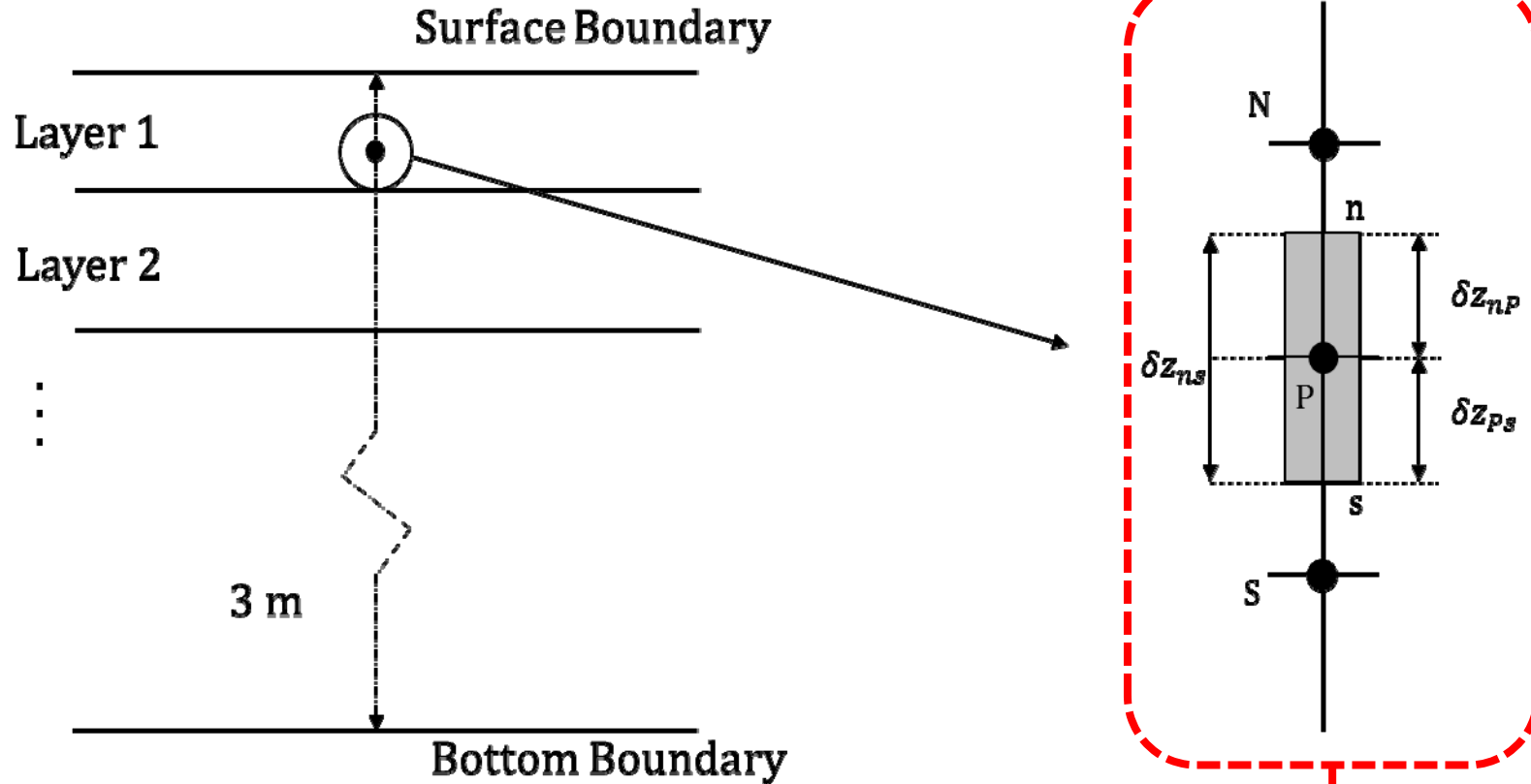
Heat Transfer Balance Between Pavement Structure & Surrounding Environment

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\alpha \times \frac{\partial T}{\partial z} \right), \quad \alpha = \frac{k}{\rho \cdot c}$$



Pavement Temperature Profile Prediction

Numerical Computation: Finite Control Volume Method (FCVM)



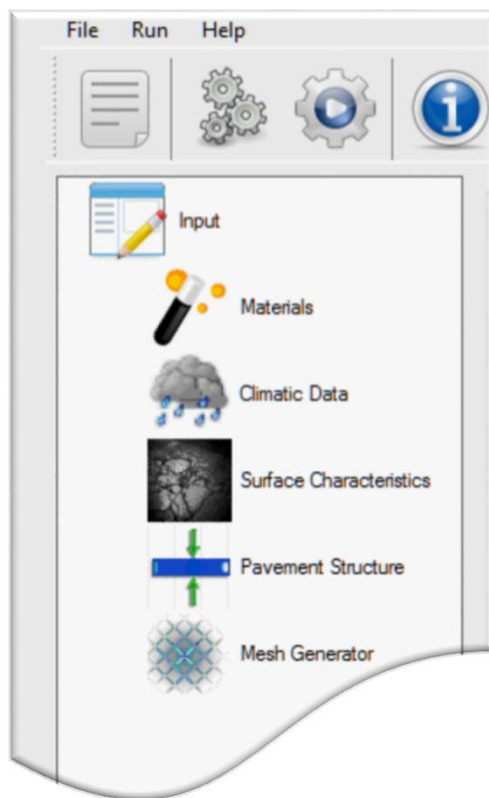
Energy Balance in Each of Control Elements



Pavement Temperature Profile Prediction

Standalone Software: TEMPS (Alpha Version)

Temperature Estimate Model for Pavement Structures (TEMPS)



INPUT MODULES:

- Materials
- Climatic Data
- Surface Characteristics
- Pavement Structure
- Mesh Generator

Pavement Temperature Profile Prediction

TEMPS – Materials Input

Material

Material Type:

Identifier Color:

Specific Heat Capacity (J/kg*K):

Conductivity (W/m*K):

Density (kg/m³):

Description:

Material Type	Identifier Color	Specific Heat Capacity (J/kg*K)	Conductivity (W/m*K)	Density (kg/m³)
Asphalt Mixture	Black	921	1.21	2250
Coarse Agg.	Silver	1900	1.00	1800
Fine Agg.	Brown	1900	1.00	1500



Pavement Temperature Profile Prediction

TEMPS – Climatic Data Input

Example-Montana - TEMPS

File Run Help

Input
Materials
Climatic Data
Surface Characteristics
Pavement Structure
Mesh Generator

Climatic Data

Year	Day	Month	Hour	Air Temperature(°C)	Wind Speed(m/s)	Solar Radiation
2001	1	12	0	-1	19	0
2001	1	12	1	-1	16	0
2001	1	12	2	-1	15	0
2001	1	12	3	0	22	0
2001	1	12	4	-1	19	0
2001	1	12	5	-1	18	0
2001	1	12	6	0	21	0

Plot: Air Temperature
Type: Line

X-Axis
Start Date: Saturday, December 1, 2001
End Date: Saturday, November 30, 2002

Y-Axis
Minimum: 0

Climatic Data Sources

- 1. National Climate Data Center (NCDC)**
The following website provides free hourly temperature data:
<http://gis.ncdc.noaa.gov/>
- 2. National Solar Radiation Data Base (NSRDB)**
The following website provides you with a good source for hourly air temperature, hourly solar radiation and hourly wind speed data which are available mostly for airports:
http://redc.nrel.gov/solar/old_data/nsrdb/
- 3. Long Term Pavement Performance (LTPP)**
The following website provides LTPP data, which are monitored on pavement sections in the United States over years:
<http://www.infopave.com/>



Pavement Temperature Profile Prediction

TEMPS – Surface Characteristics Input

Example-Montana - TEMPS

File Run Help

Input Materials Climatic Data Surface Characteristics Pavement Structure Mesh Generator

Surface Characteristics

C. J. Glover's Suggested Values (May 2010)

LTPP Section: 30-8129

State: Montana

Parameter: Albedo

Summer Value: 0.2

Winter Value: 0.35

User-defined Values

Input Data Type: Monthly Values

Month: January

Albedo: 0.00

	January	February	March	April	May	June	July	August	September
Albedo	0	0	0	0	0	0	0	0	0
Emissivity	0	0	0	0	0	0	0	0	0
Albedo	0	0	0	0	0	0	0	0	0

N **WRSC**
WESTERN REGIONAL SUPERPAVE CENTER



Pavement Temperature Profile Prediction

TEMPS – Pavement Structure

Example-Montana - TEMPS

File Run Help

Input
Materials
Climatic Data
Surface Characteristics
Pavement Structure
Mesh Generator

Pavement Structure

Layer Name:

Material Type:

Thickness (m):

Description:

+ Add ✖ Delete ↓ Insert

Layer Name	Material Type	Thickness (m)	Start Depth (m)	End Depth (m)	Description
Asphalt	Asphalt Mixture	0.20	0	0.2	
Base	Coarse Agg.	0.25	0.2	0.45	
Subgrade	Fine Agg.	1	0.45	1.45	

Pavement Section

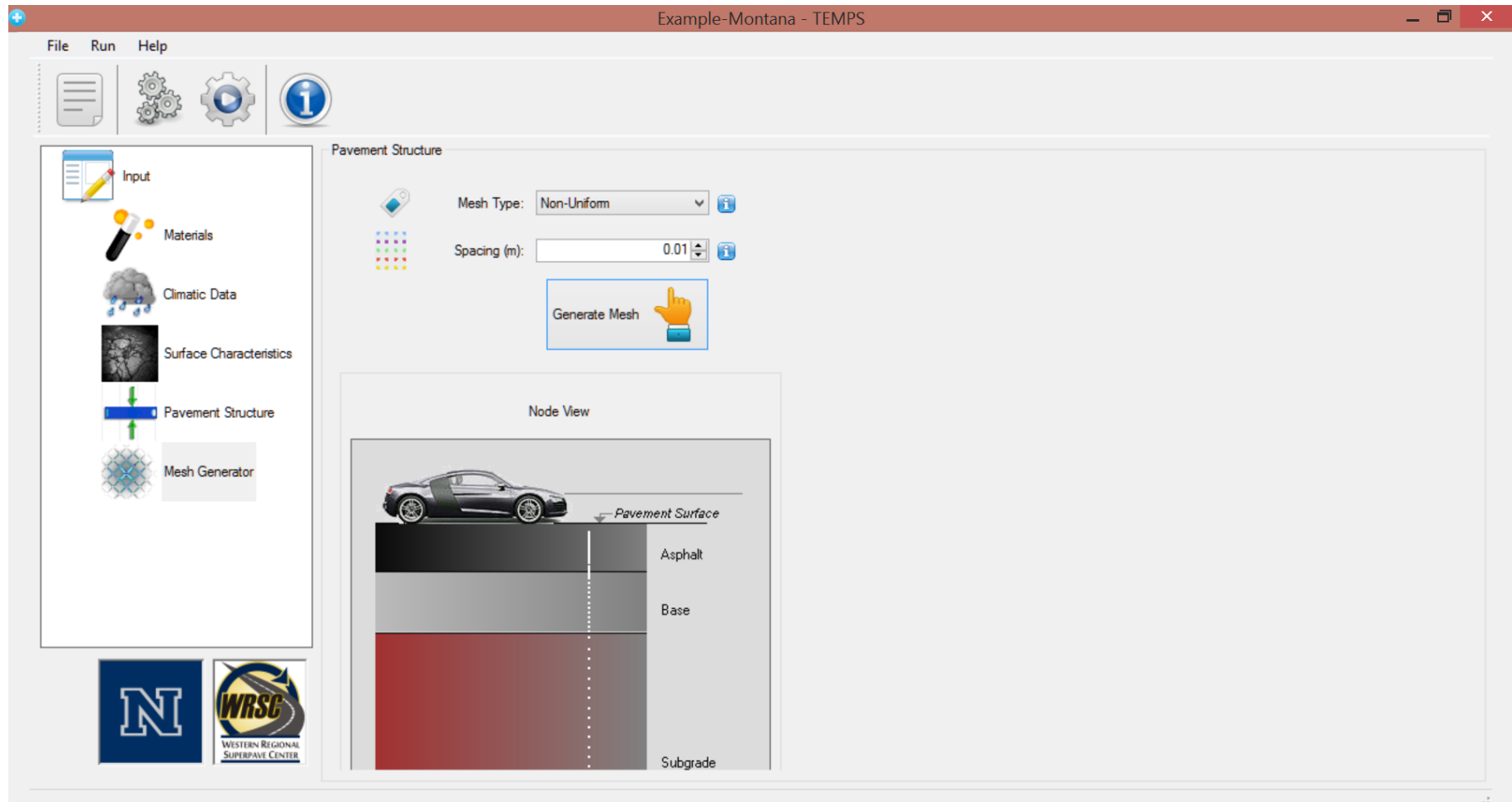
Pavement Surface

Asphalt
Base
Subgrade



Pavement Temperature Profile Prediction

TEMPS – Mesh Generator



TEMPS – Run Analysis

Time Efficiency of Computation: Implicit Scheme

Run time for **1 years** analysis period
(3.10 GHz proc. and 4.00 GB RAM)

< 10 seconds using 1 hour time step*

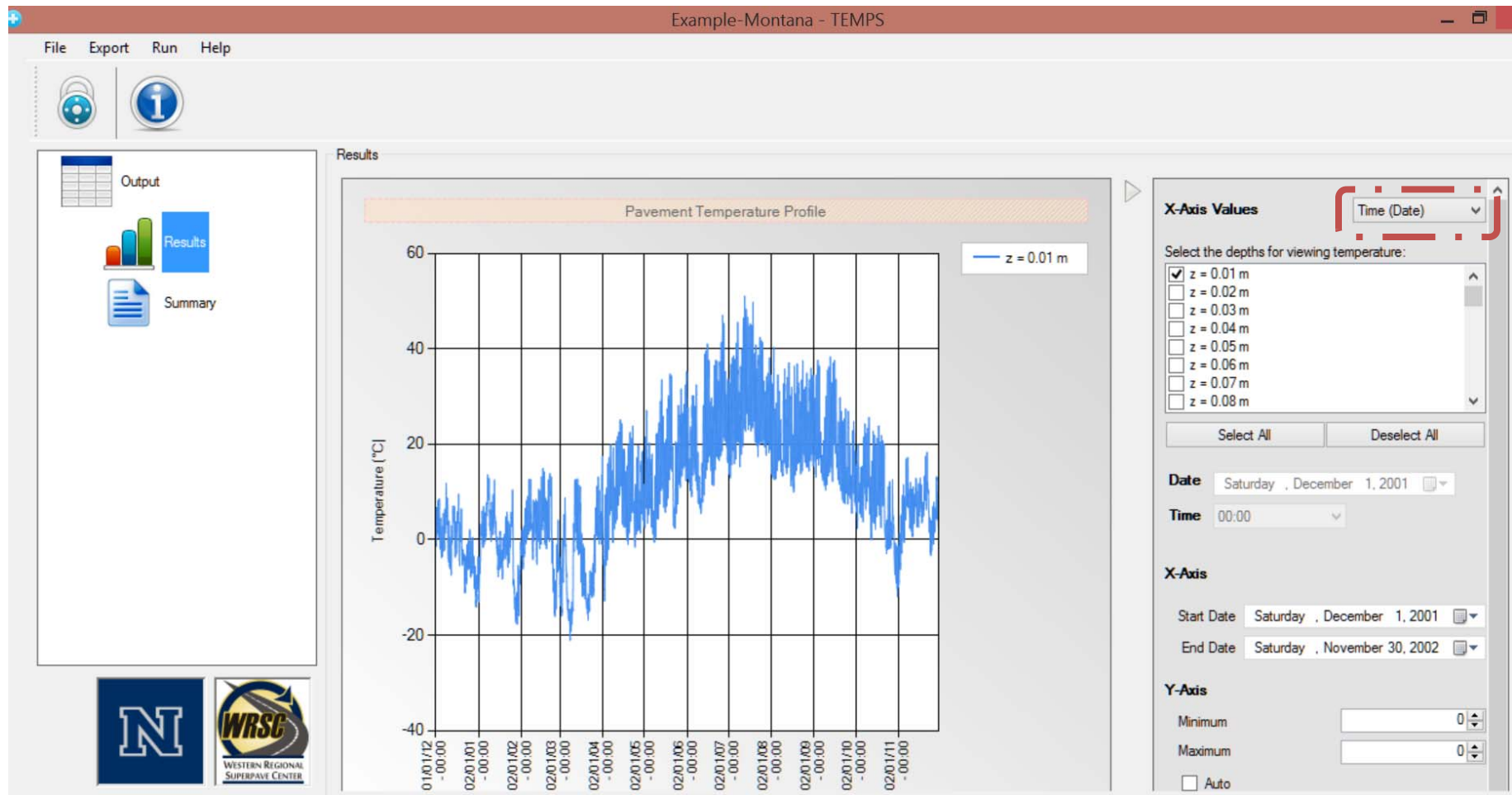


* Note: 1 hour time step was chosen without jeopardizing the model accuracy for prediction.



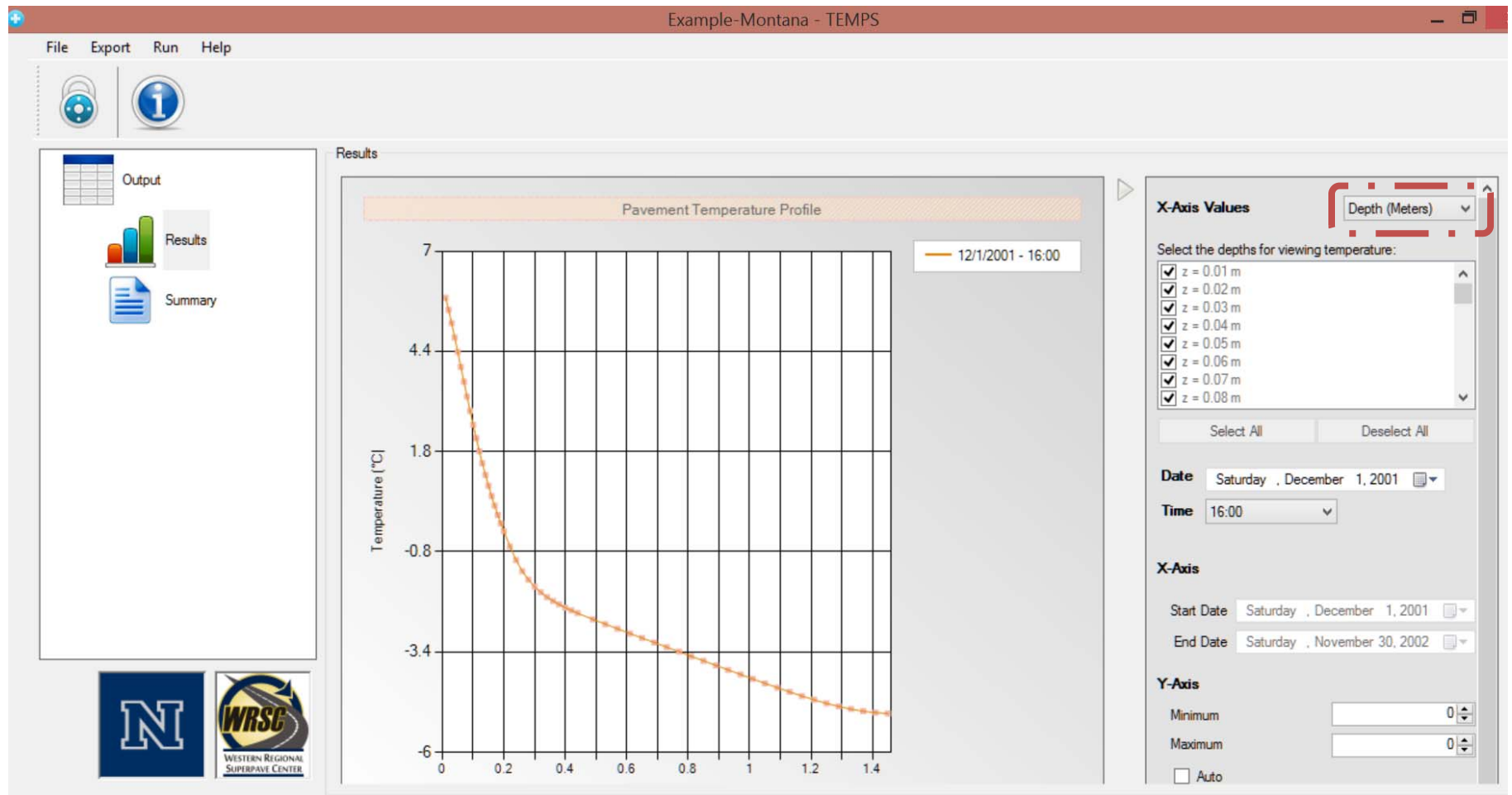
Pavement Temperature Profile Prediction

TEMPS – Output Results



Pavement Temperature Profile Prediction

TEMPS – Output Results



Pavement Temperature Profile Prediction

TEMPS – Output Summary

Example-Montana - TEMPS

File Export Run Help

Output Results Summary

Pavement Temperature Profile Summary



Date-Time ↓	Depth →	z = 0.01 m	z = 0.02 m	z = 0.03 m	z = 0.04 m	z = 0.05 m	z = 0.06 m	z = 0.07 m	z = 0.08 m	z = 0.09 m	z = 0.1 m
12/1/2001 - 0:00		-1.14°C	-1.17°C	-1.2°C	-1.23°C	-1.26°C	-1.29°C	-1.32°C	-1.35°C	-1.38°C	-1.41°C
12/1/2001 - 1:00		-1.39°C	-1.37°C	-1.36°C	-1.36°C	-1.36°C	-1.37°C	-1.39°C	-1.4°C	-1.42°C	-1.44°C
12/1/2001 - 2:00		-1.47°C	-1.46°C	-1.45°C	-1.44°C	-1.44°C	-1.44°C	-1.45°C	-1.46°C	-1.47°C	-1.49°C
12/1/2001 - 3:00		-1.29°C	-1.33°C	-1.36°C	-1.38°C	-1.4°C	-1.42°C	-1.44°C	-1.46°C	-1.48°C	-1.5°C
12/1/2001 - 4:00		-0.97°C	-1.06°C	-1.13°C	-1.2°C	-1.25°C	-1.3°C	-1.34°C	-1.38°C	-1.42°C	-1.45°C
12/1/2001 - 5:00		-1.14°C	-1.16°C	-1.19°C	-1.23°C	-1.26°C	-1.3°C	-1.33°C	-1.36°C	-1.4°C	-1.43°C
12/1/2001 - 6:00		-1.16°C	-1.19°C	-1.22°C	-1.24°C	-1.27°C	-1.3°C	-1.33°C	-1.36°C	-1.39°C	-1.42°C
12/1/2001 - 7:00		-0.91°C	-0.99°C	-1.06°C	-1.12°C	-1.17°C	-1.22°C	-1.27°C	-1.31°C	-1.35°C	-1.38°C
12/1/2001 - 8:00		-0.86°C	-0.93°C	-0.99°C	-1.05°C	-1.1°C	-1.16°C	-1.21°C	-1.25°C	-1.3°C	-1.34°C
12/1/2001 - 9:00		-0.57°C	-0.68°C	-0.78°C	-0.87°C	-0.95°C	-1.03°C	-1.09°C	-1.16°C	-1.21°C	-1.27°C
12/1/2001 - 10:00		0.53°C	0.23°C	-0.02°C	-0.24°C	-0.42°C	-0.58°C	-0.72°C	-0.84°C	-0.95°C	-1.05°C

General Summary Detailed Summary

Overall Minimum Pavement Temperature: -21.12°C Occured On: 3/8/2002 - 8:00, At the Depth of: 0.01 m

Overall Maximum Pavement Temperature: 51.04°C Occured On: 7/12/2002 - 16:00, At the Depth of: 0.01 m

Export General Summary



Pavement Temperature Profile Prediction

TEMPS – Output Summary

Example-Montana - TEMPS

File Export Run Help

Output Results Summary



Pavement Temperature Profile Summary

Date-Time ↓	Depth →	z = 0.01 m	z = 0.02 m	z = 0.03 m	z = 0.04 m	z = 0.05 m	z = 0.06 m	z = 0.07 m	z = 0.08 m	z = 0.09 m	z = 0.1 m
12/1/2001 - 0:00		-1.14°C	-1.17°C	-1.2°C	-1.23°C	-1.26°C	-1.29°C	-1.32°C	-1.35°C	-1.38°C	-1.41°C
12/1/2001 - 1:00		-1.39°C	-1.37°C	-1.36°C	-1.36°C	-1.36°C	-1.37°C	-1.39°C	-1.4°C	-1.42°C	-1.44°C
12/1/2001 - 2:00		-1.47°C	-1.46°C	-1.45°C	-1.44°C	-1.44°C	-1.44°C	-1.45°C	-1.46°C	-1.47°C	-1.49°C
12/1/2001 - 3:00		-1.29°C	-1.33°C	-1.36°C	-1.38°C	-1.4°C	-1.42°C	-1.44°C	-1.46°C	-1.48°C	-1.5°C
12/1/2001 - 4:00		-0.97°C	-1.06°C	-1.13°C	-1.2°C	-1.25°C	-1.3°C	-1.34°C	-1.38°C	-1.42°C	-1.45°C
12/1/2001 - 5:00		-1.14°C	-1.16°C	-1.19°C	-1.23°C	-1.26°C	-1.3°C	-1.33°C	-1.36°C	-1.4°C	-1.43°C
12/1/2001 - 6:00		-1.16°C	-1.19°C	-1.22°C	-1.24°C	-1.27°C	-1.3°C	-1.33°C	-1.36°C	-1.39°C	-1.42°C
12/1/2001 - 7:00		-0.91°C	-0.99°C	-1.06°C	-1.12°C	-1.17°C	-1.22°C	-1.27°C	-1.31°C	-1.35°C	-1.38°C
12/1/2001 - 8:00		-0.86°C	-0.93°C	-0.99°C	-1.05°C	-1.1°C	-1.16°C	-1.21°C	-1.25°C	-1.3°C	-1.34°C
12/1/2001 - 9:00		-0.57°C	-0.68°C	-0.78°C	-0.87°C	-0.95°C	-1.03°C	-1.09°C	-1.16°C	-1.21°C	-1.27°C
12/1/2001 - 10:00		0.53°C	0.23°C	-0.02°C	-0.24°C	-0.42°C	-0.58°C	-0.72°C	-0.84°C	-0.95°C	-1.05°C

General Summary Detailed Summary

Start Date: Saturday, December 1, 2001 End Date: Saturday, November 30, 2002 Depth: z = 0.01 m Update Export

Date	Average Pavement Temperature (°C)	Minimum Pavement Temperature (°C)	Maximum Pavement Temperature (°C)	Pavement Temperature Standard Deviation (°C)
12/1/2001	1.64	-1.47	6.74	2.81
12/2/2001	3.77	1.23	8.16	2.39
12/3/2001	3.16	0.31	8.58	2.64
12/4/2001	0.25	-2.33	4.51	2.25
12/5/2001	-1.84	-3.79	2.79	1.93
12/6/2001	0.13	-3.01	5.49	2.75
12/7/2001	1.21	-2.21	6.39	2.75
12/8/2001	5.92	1.52	11.81	3.41
12/9/2001	4.1	-2.33	8.69	2.97

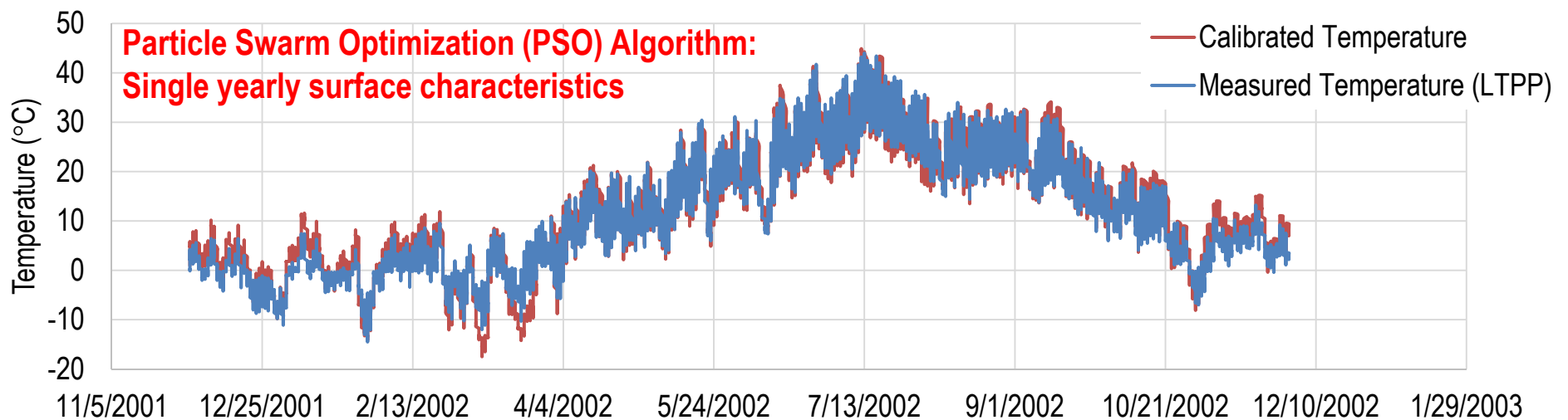
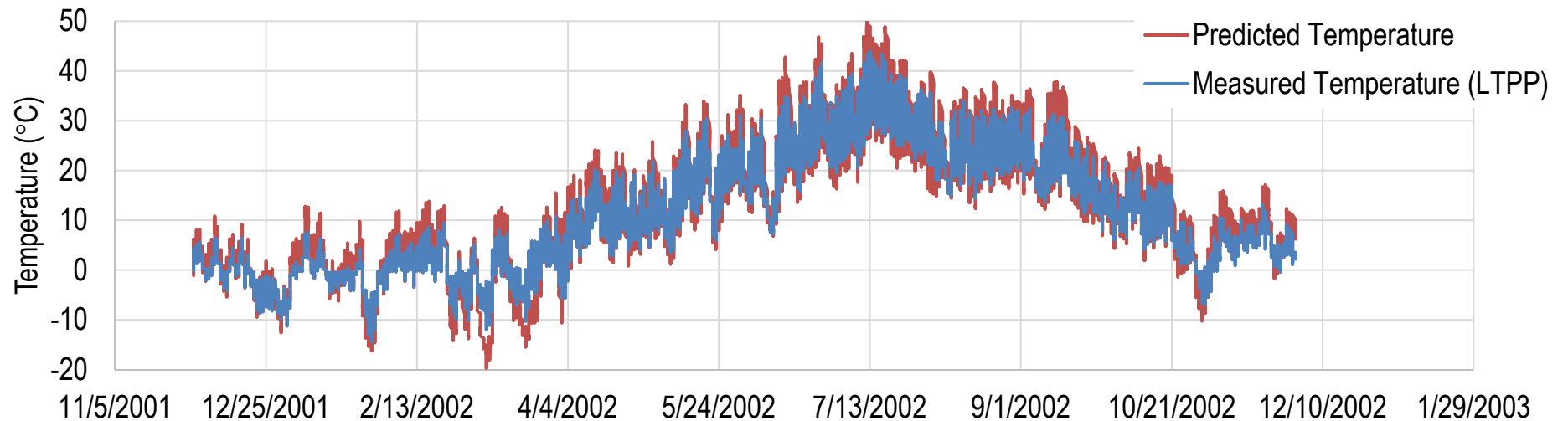
 



Pavement Temperature Profile Prediction

TEMPS – Predicted versus Measured

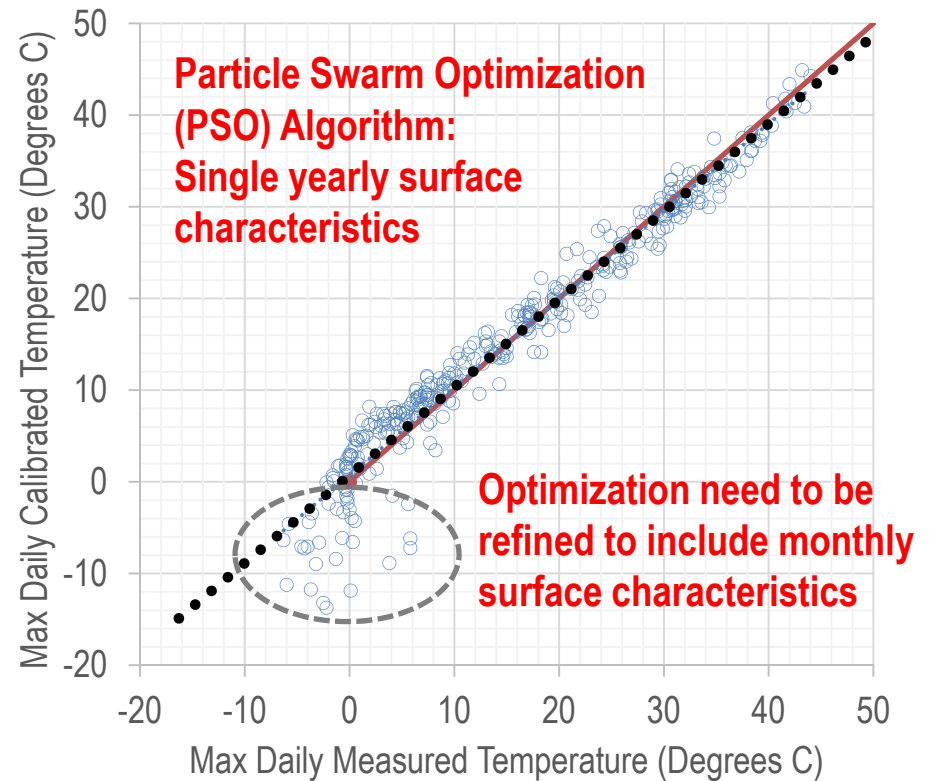
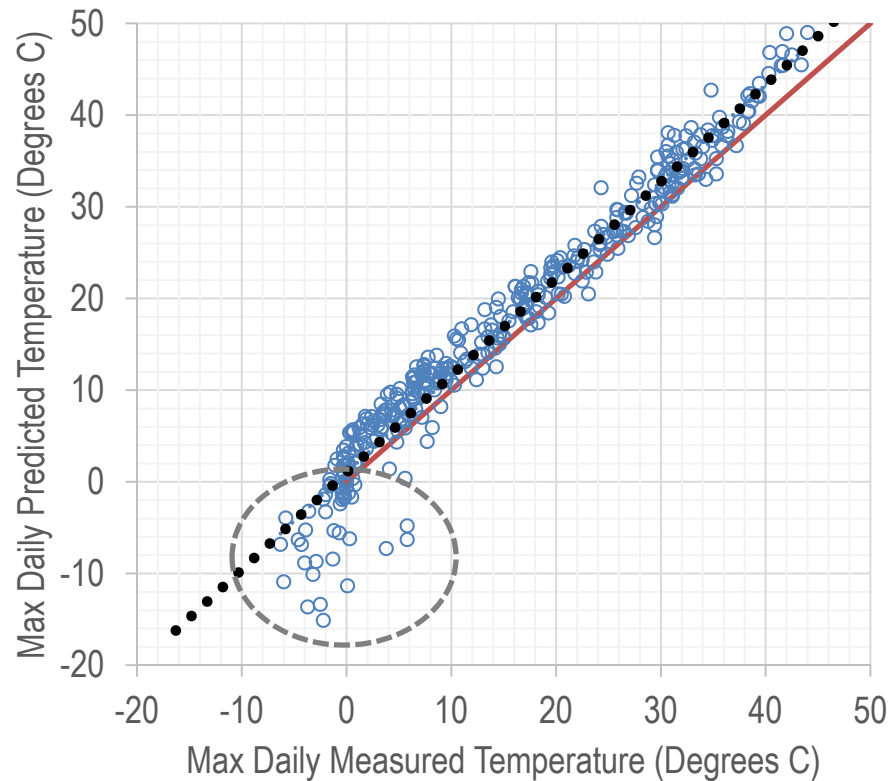
Great Falls, MT at depth of 0.09 m (3.5 inch)



Pavement Temperature Profile Prediction

TEMPS – Predicted versus Measured

Great Falls, MT at depth of 0.09 m (3.5 inch)



TEMPS – Additional Improvements

- Optimize the surface characteristics for the US (Albedo, Emissivity, Absorption) using Particle Swarm Optimization (PSO) Algorithm
 - Monthly or seasonal values.
- Create/Include input files for LTPP SMP sections.
- Provide a summary of the average 7-day pavement temperature at various depths.
- Provide a summary of pavement cooling/warming rates



Thank You!

