

# Thermal Cracking Analysis Model AND Pavement Temperature Profile Prediction Model

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Baton Rouge, Louisiana – September 17-19, 2014***





Comprehensive Evaluation of Thermal Cracking in Asphalt Pavements

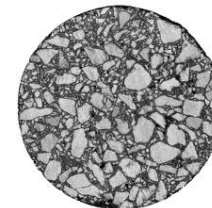
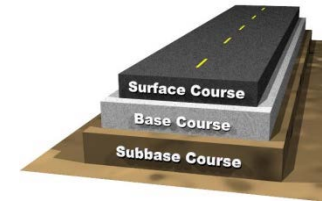
# THERMAL CRACKING ANALYSIS PACKAGE (TCAP)



# 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.
- Pavement temperature model (currently EICM) **can be improved**.

## 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

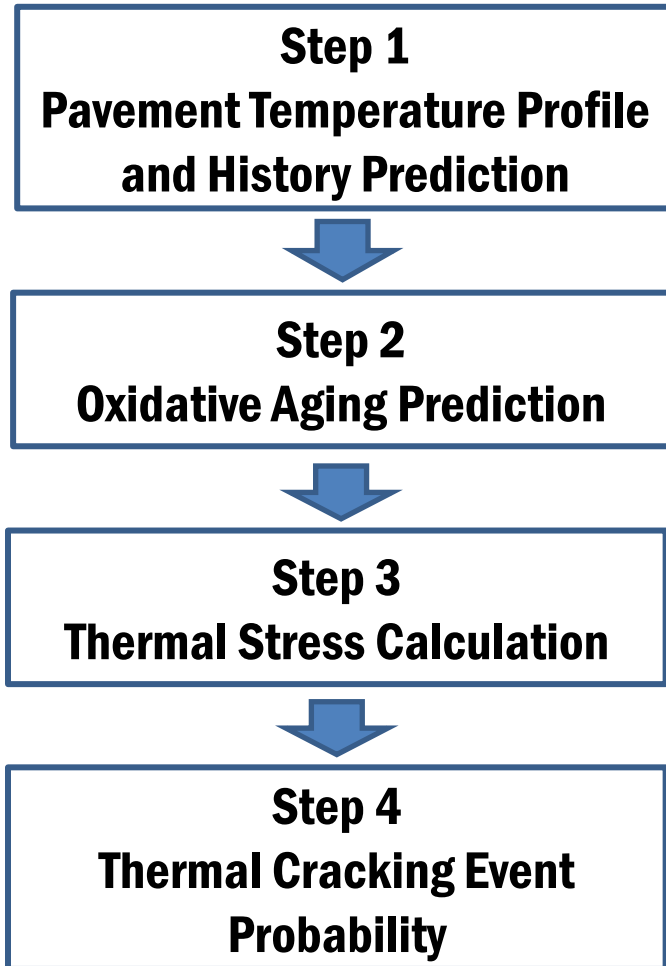
**1 mm film asphalt binder pan aging**  
over different times and durations  
(50, 60, 85 and 100°C up to 320 days)

### *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%**

$$E_a = 72.53 \text{ kJol/mol}$$

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

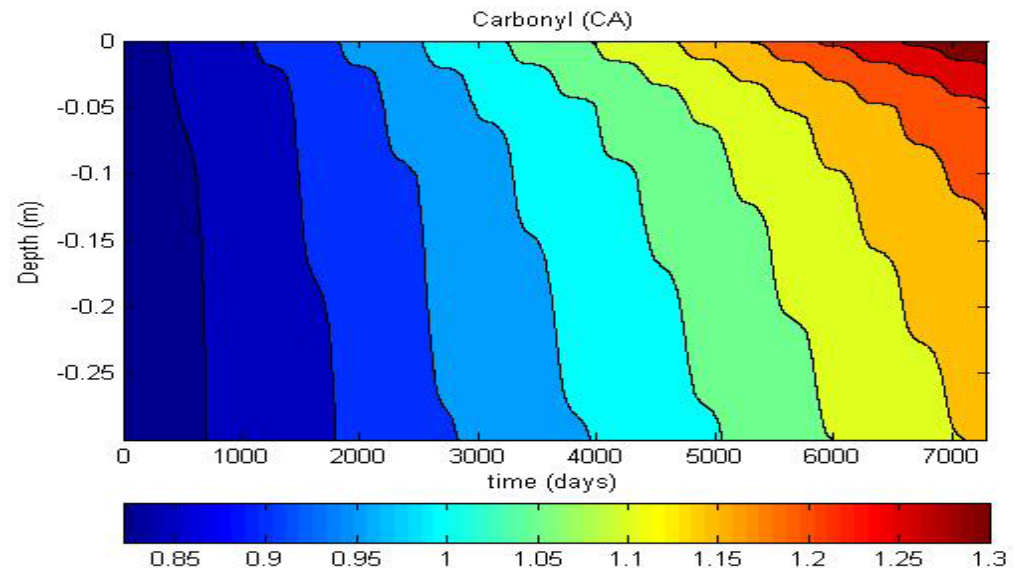
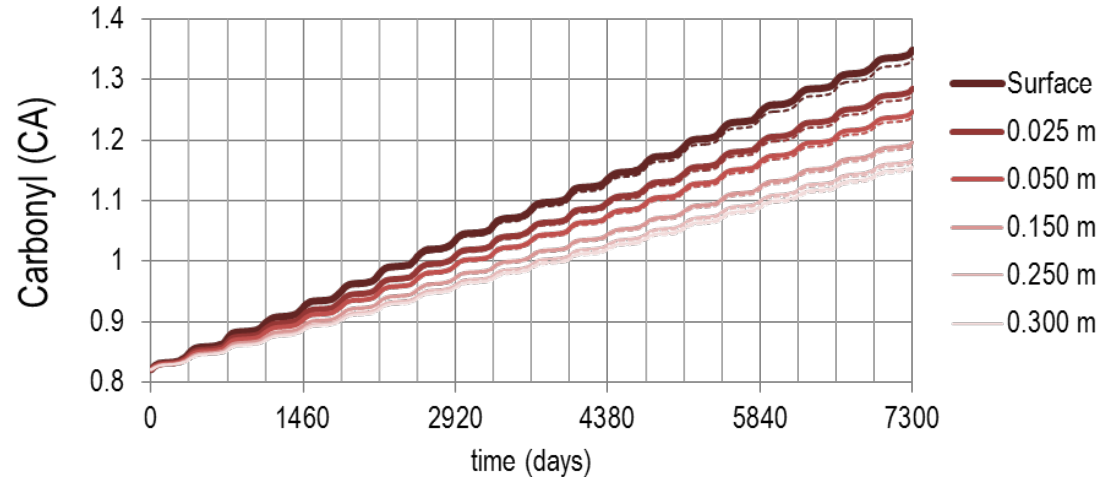
$$HS = 2.7 (1/\text{CA})$$

$$m = 9.24 \text{ (poise)}$$

$$\text{Air void diameter} = 0.5 \text{ mm}$$

$$\text{Eff. aging zone} = 1.0 \text{ mm}$$

*(film thickness)*

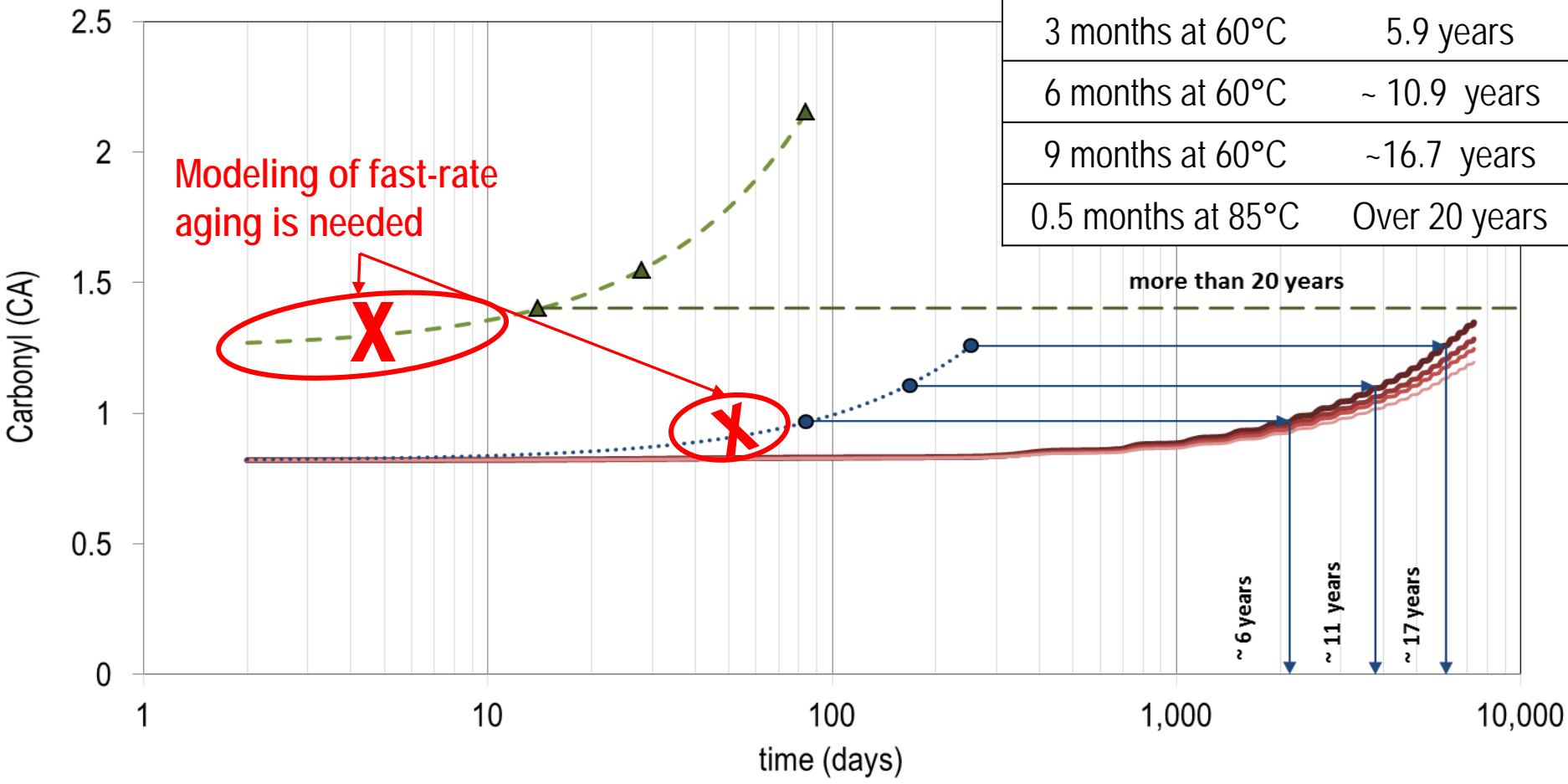


# Thermal Cracking Analysis

## 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          |



- Surface
- 0.025 m
- 0.050 m
- 0.150 m
- ⋯ Predicted CA @ 60°C
- Measured CA at 60°C
- - - Predicted CA @ 85°C
- ▲ Measured CA at 85°C



## 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

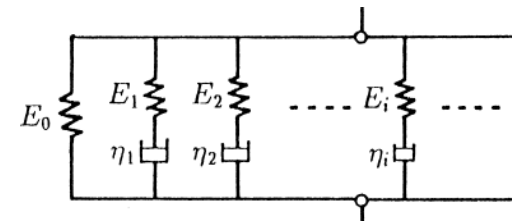
## Age-Dependent Relaxation Modulus

- 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*).

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

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

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

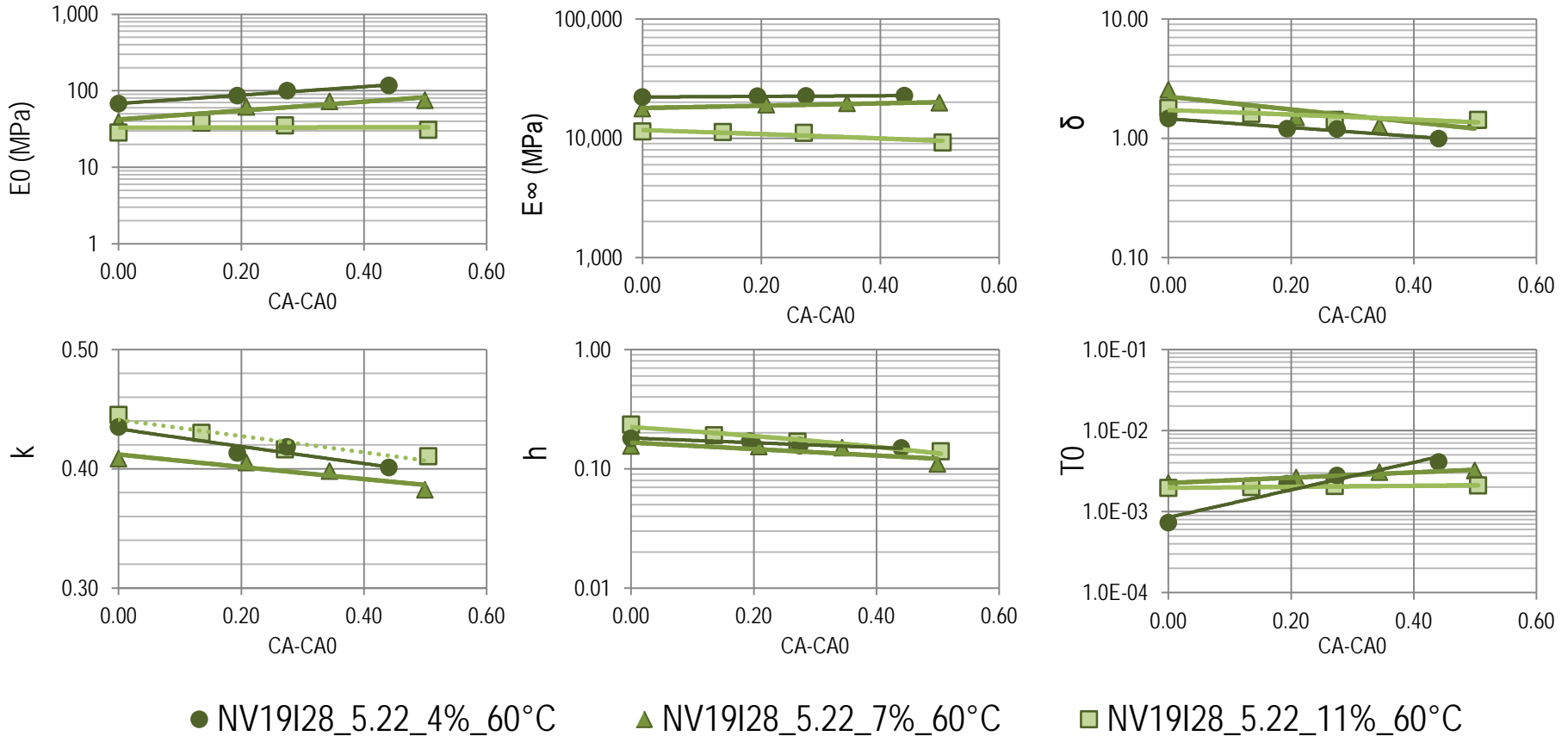


Ideal viscoelastic model

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

# Thermal Cracking Analysis

## Evolution of 2S2P1D Coefficient with Aging



*Consistent trends were found for the evaluated mixtures!*

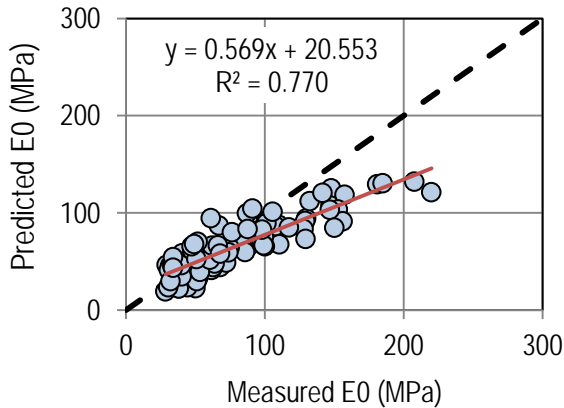
$$(2S2P1D \text{ coeff})_j = A_j \times e^{B_j(CA-CA_0)}$$

# Evolution of 2S2P1D Coefficient with Aging

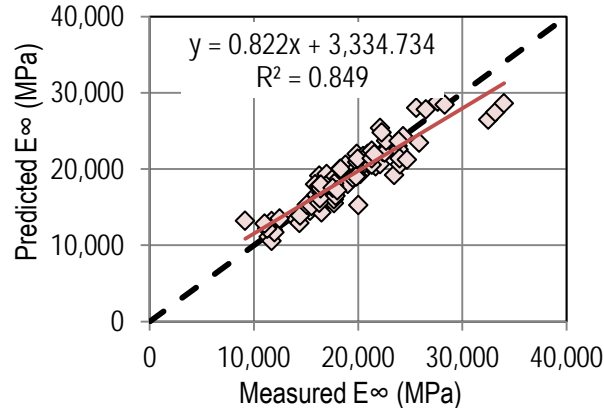
| 2S2P1D<br>coeff. | Mixture variable |                    |          |                                |          |              |               |
|------------------|------------------|--------------------|----------|--------------------------------|----------|--------------|---------------|
|                  | CA               | V <sub>a</sub> (%) | Abs. (%) | LSV <sub>Tank</sub><br>(poise) | B.C. (%) | Retained # 8 | Passing # 200 |
| E <sub>0</sub>   | ✓                | ✓                  | ✓        | ✓                              | ✓        |              |               |
| E <sub>∞</sub>   | ✓                | ✓                  | ✓        | ✓                              | ✓        | ✓            | ✓             |
| δ                | ✓                | ✓                  | ✓        | ✓                              | ✓        |              | ✓             |
| k                | ✓                |                    | ✓        | ✓                              |          |              | ✓             |
| h                | ✓                |                    |          | ✓                              | ✓        |              |               |
| T <sub>0</sub>   | ✓                |                    | ✓        |                                |          |              | ✓             |

# Thermal Cracking Analysis

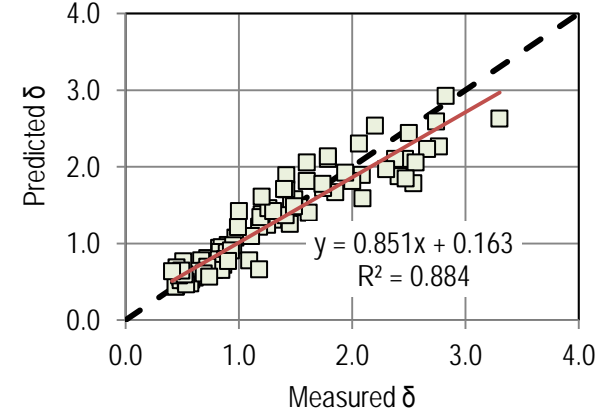
## Evolution of 2S2P1D Coefficient with Aging



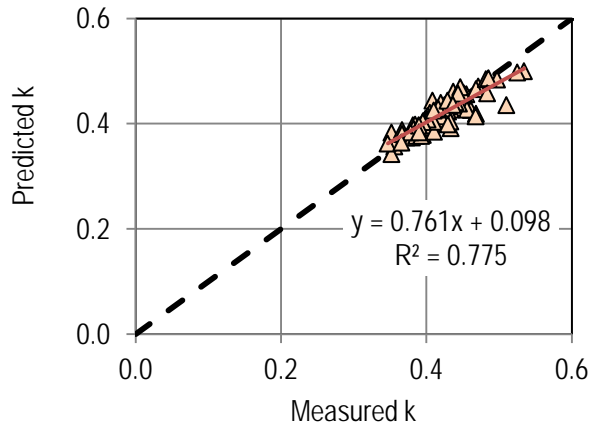
○  $E_0$  (MPa)      — Line of Equality



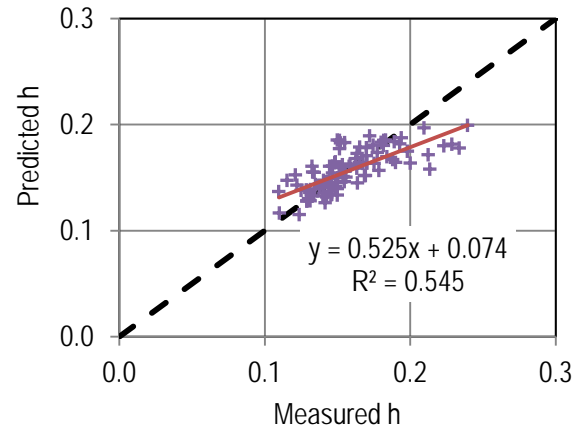
◇  $E_\infty$       — Line of Equality



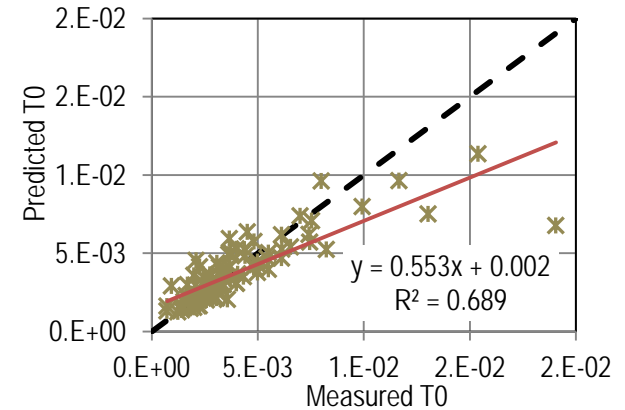
□  $\delta$       — Line of Equality



△  $k$       — Line of Equality



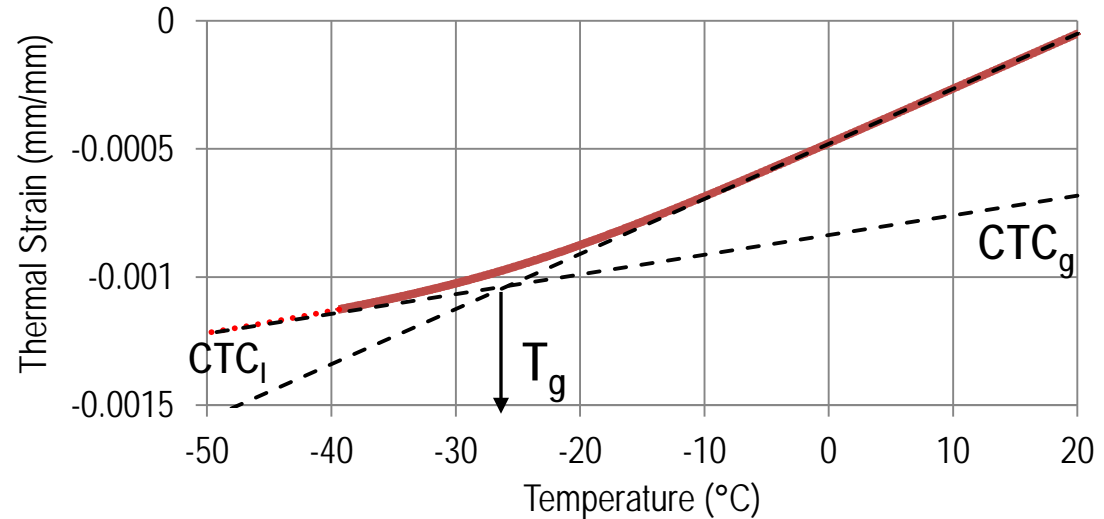
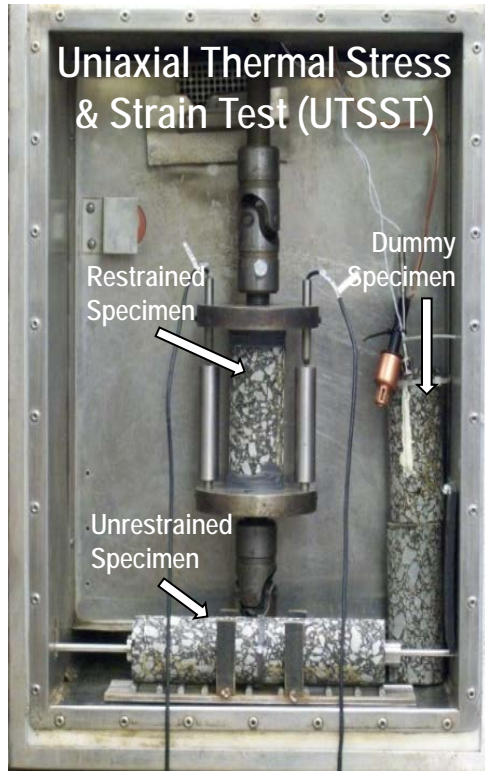
+  $h$       — Line of Equality



×  $T_0$       — Line of Equality

# Thermal Cracking Analysis

## Temperature and Age-Dependent CTC

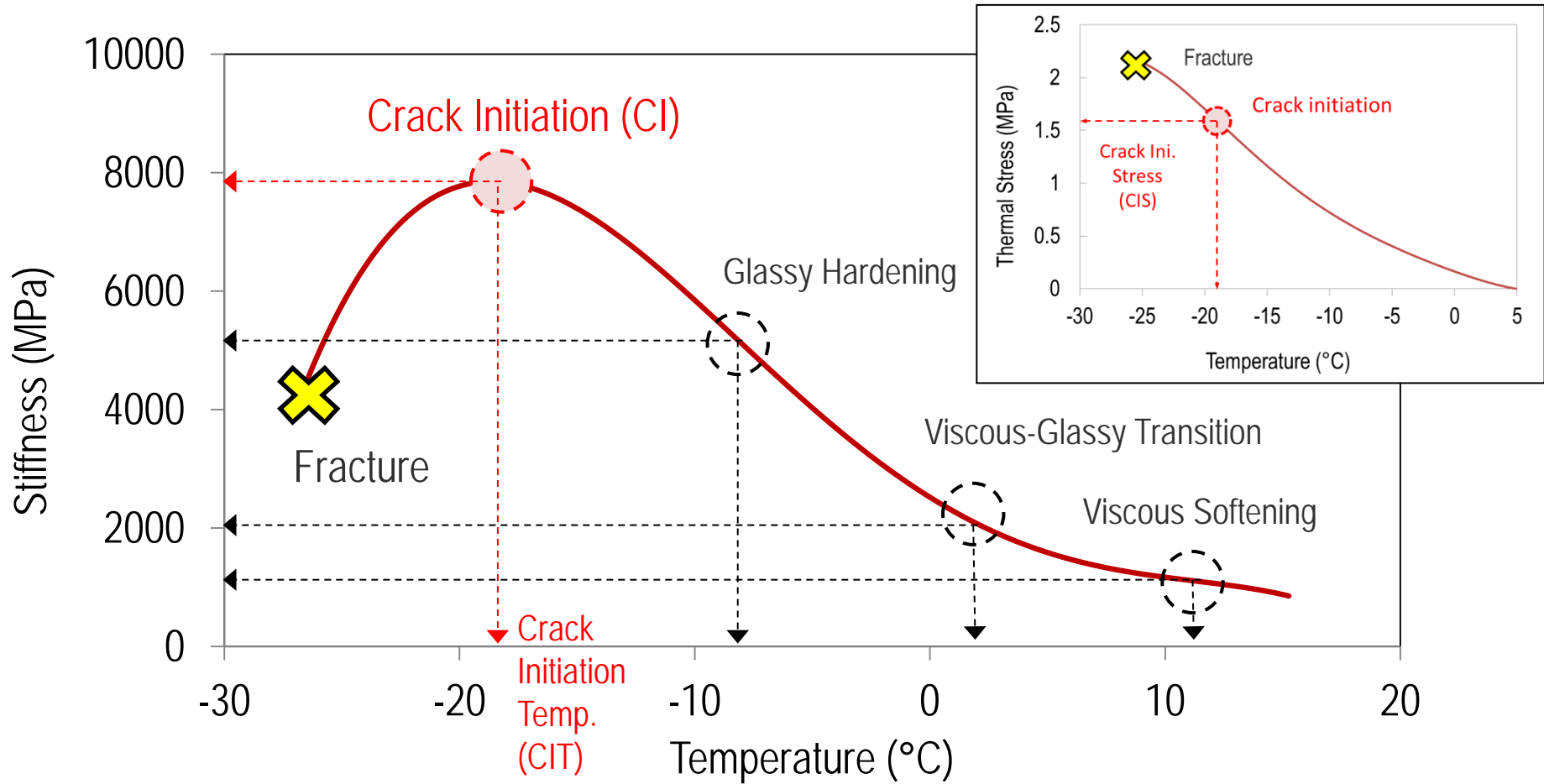


$$\varepsilon_{th} = \frac{\Delta l}{l_0} = C + CTC_g(T - T_g) + \ln \left\{ \left[ 1 + e^{\frac{(T-T_g)}{R}} \right]^{R(CTC_L - CTC_g)} \right\}$$

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

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

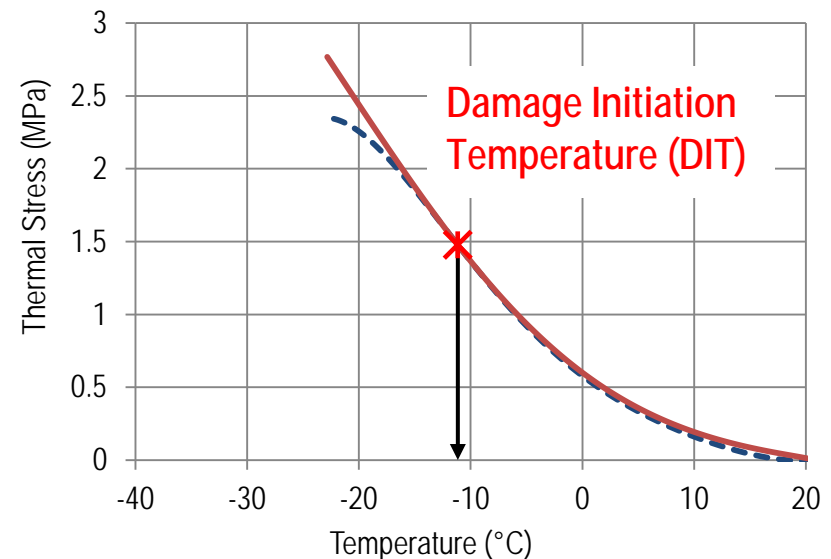
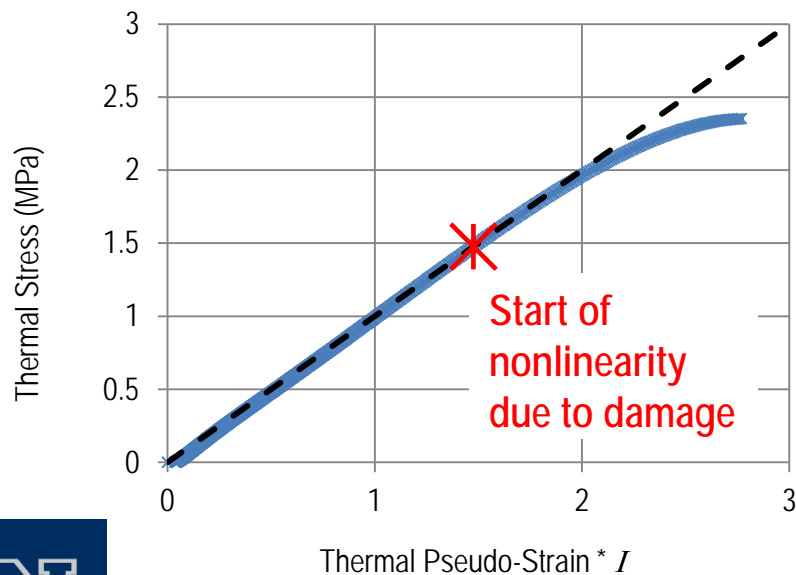
## Age-Dependent Crack Initiation Stress (CIS)



## Age-Dependent Crack Initiation Stress (CIS)

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

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

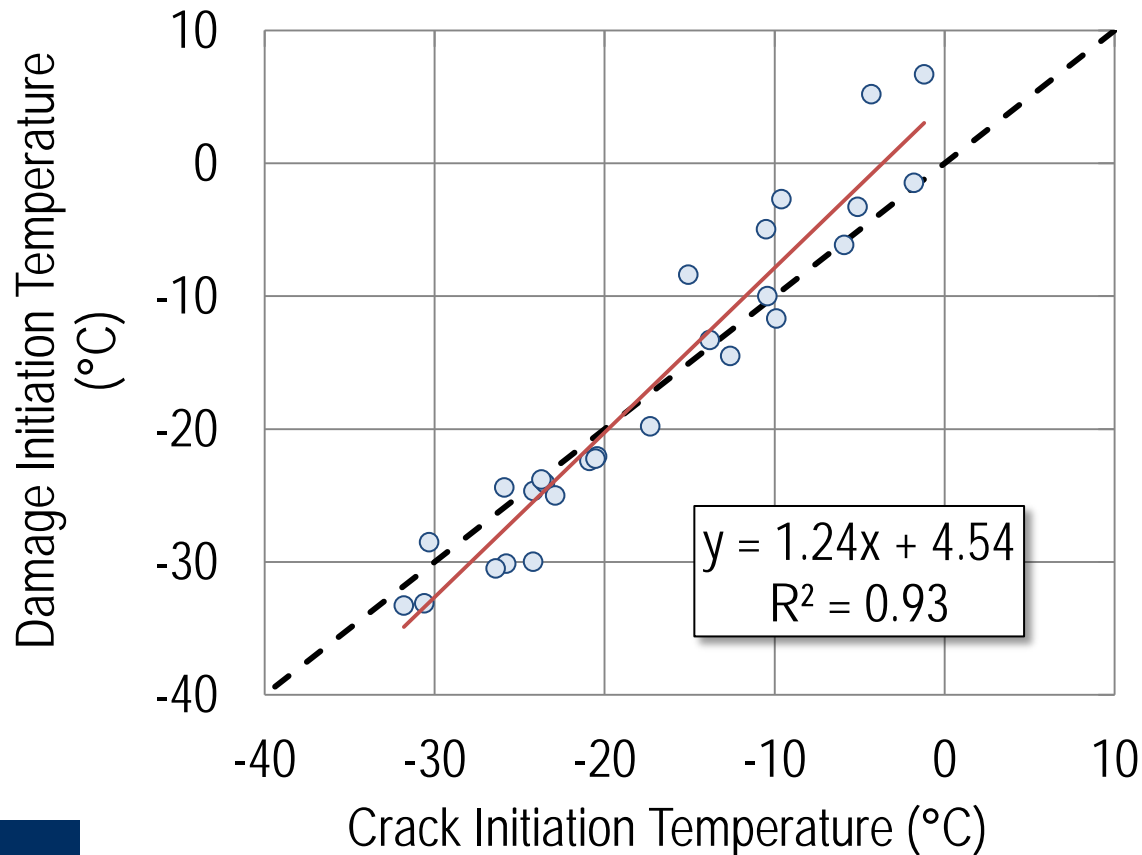


--- Measured thermal stress from UTSST  
--- Predicted stress without continuum damaging



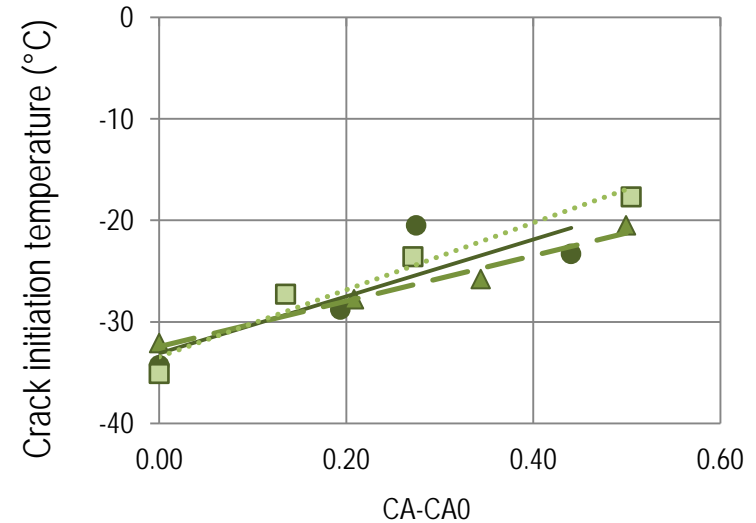
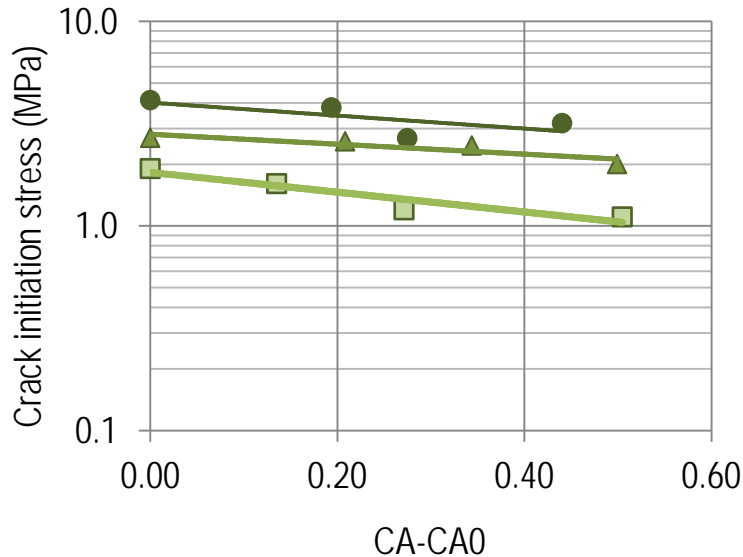
## Age-Dependent Crack Initiation Stress (CIS)

- Validation of CIS with VECD.



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

## Age-Dependent Crack Initiation Stress (CIS)

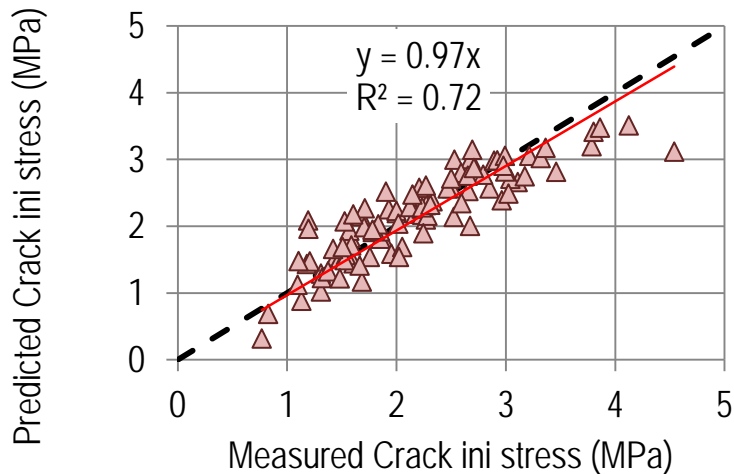


Similar trends were observed for all evaluated mixtures!

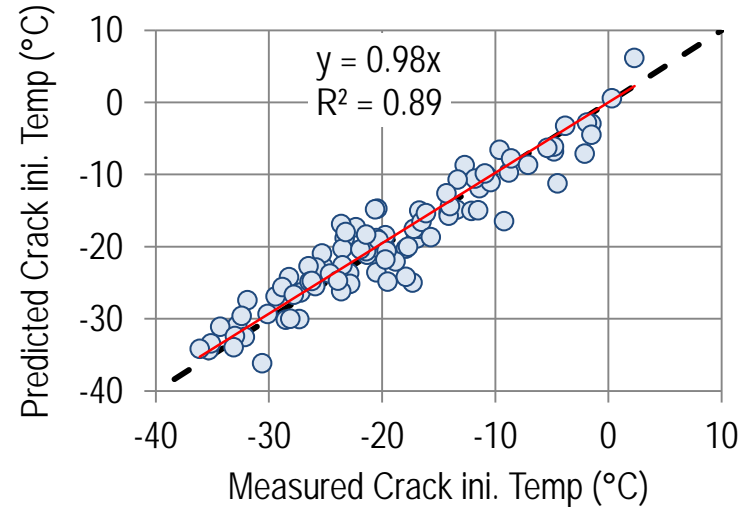
$$CIS = E \times e^{F(CA-CA_0)}$$

## Age-Dependent Crack Initiation Stress (CIS)

|     | Mixture variable |        |          |                             |          |              |               |
|-----|------------------|--------|----------|-----------------------------|----------|--------------|---------------|
|     | CA               | Va (%) | Abs. (%) | LSV <sub>Tank</sub> (poise) | B.C. (%) | Retained # 8 | Passing # 200 |
| CIS | ✓                | ✓      | ✓        | ✓                           |          |              | ✓             |
| CIT | ✓                | ✓      |          | ✓                           | ✓        | ✓            | ✓             |



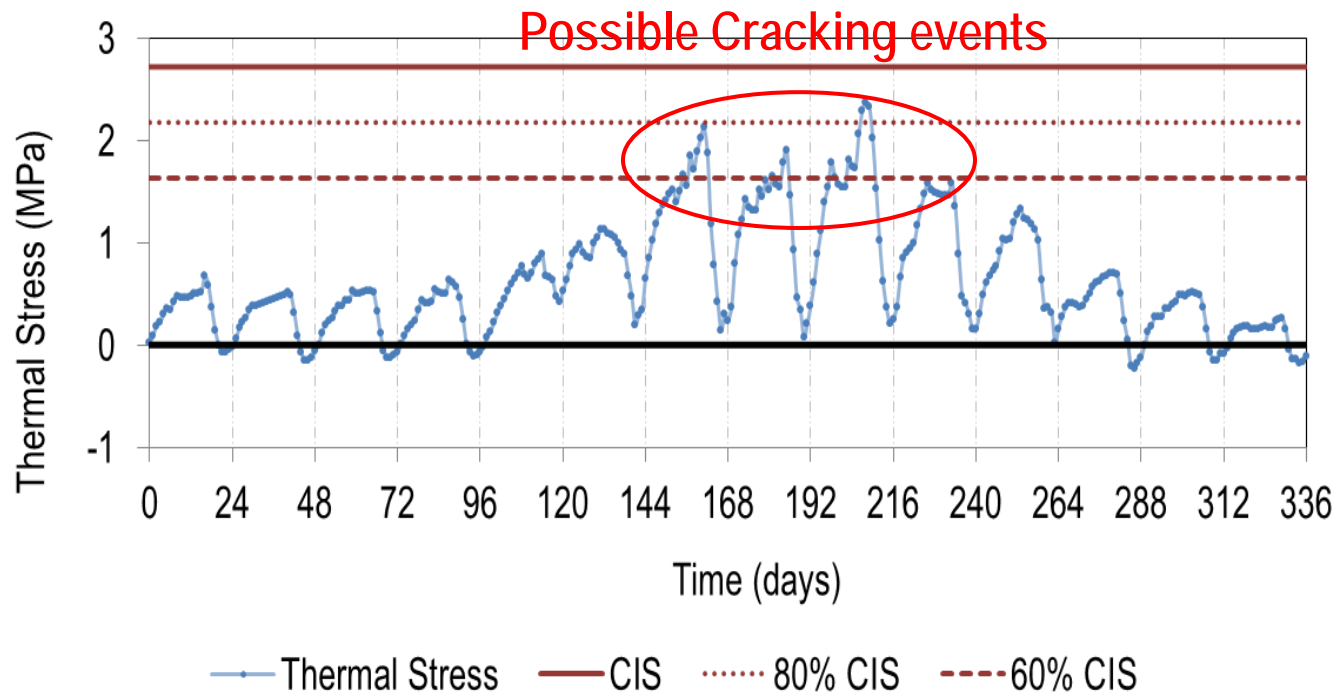
▲ Crack initiation stress    - - Line of equality



○ Crack initiation temperature    - - Line of equality

## 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!



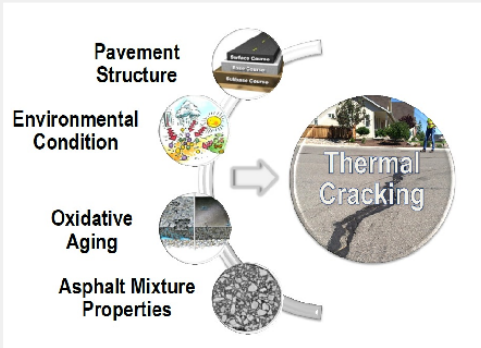
# MATLAB Graphical User Interface (GUI) Thermal Cracking Analysis Package (TCAP)



Thermal Cracking Analysis Package Ver Alfa 1.0

About TCAP

## Analysis Steps



- General Information
- Pavement Structure
- Pavement Temperature
- Oxidative Aging (Carbo)
- Asphalt Materials Prop
- Thermal Cracking Anal

### General Information

Project Name: NV28-4%-Reno

Analysis Period: 20

Construction Date: month: August, Days: 1, year: 2000

Project Discription

Example of calculation

Refresh Accept



Thermal Cracking Analysis Package Ver Alfa 1.0

About TCAP

## Analysis Steps

- General Information
- Pavement Structure
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- Oxidative Aging (Carbo)
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- Thermal Cracking Anal

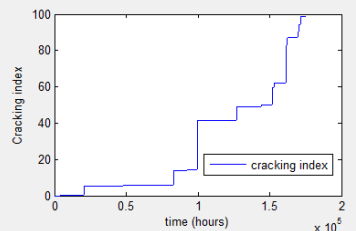
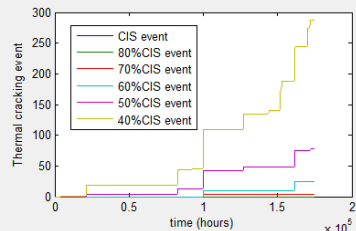
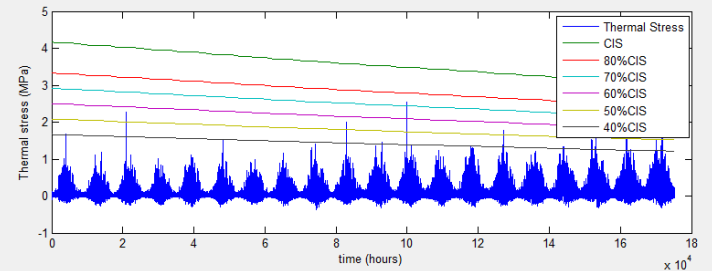
Import CA predictions

C:\TCAP software July2014\TCAP-Newcode\NV284air.csv

Run Analysis

Aging interval: 1

output file name: Results



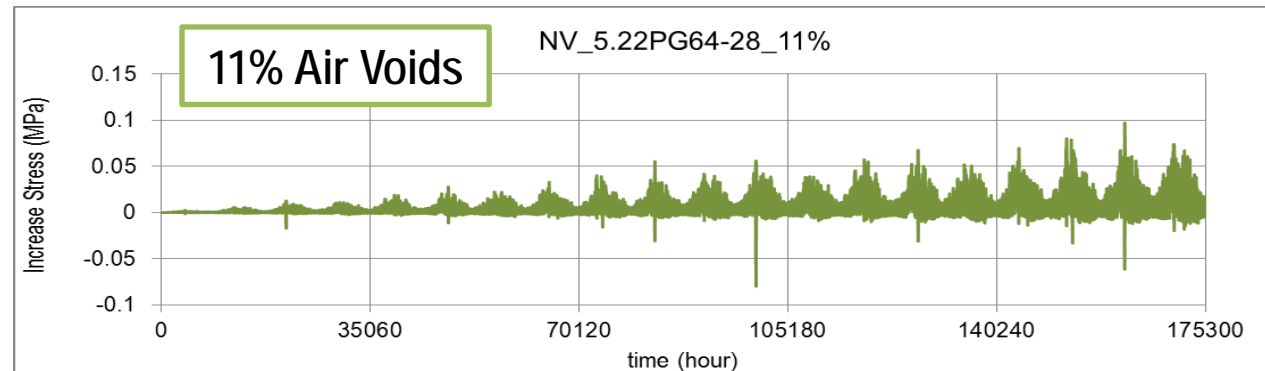
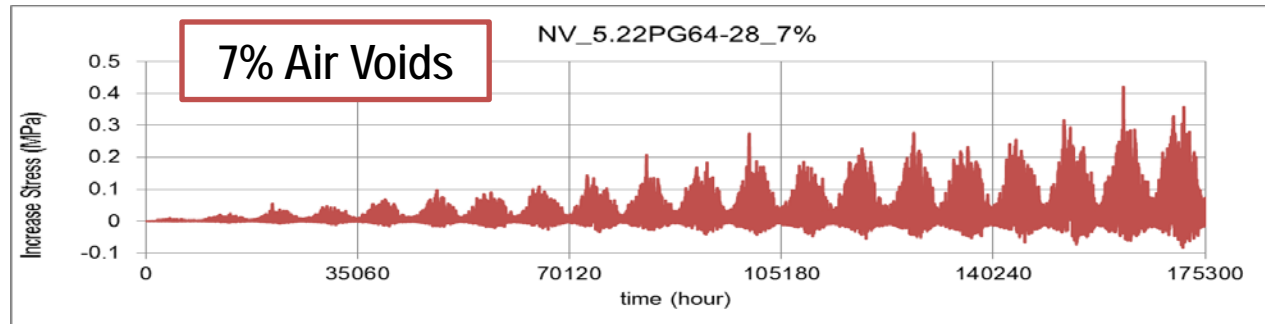
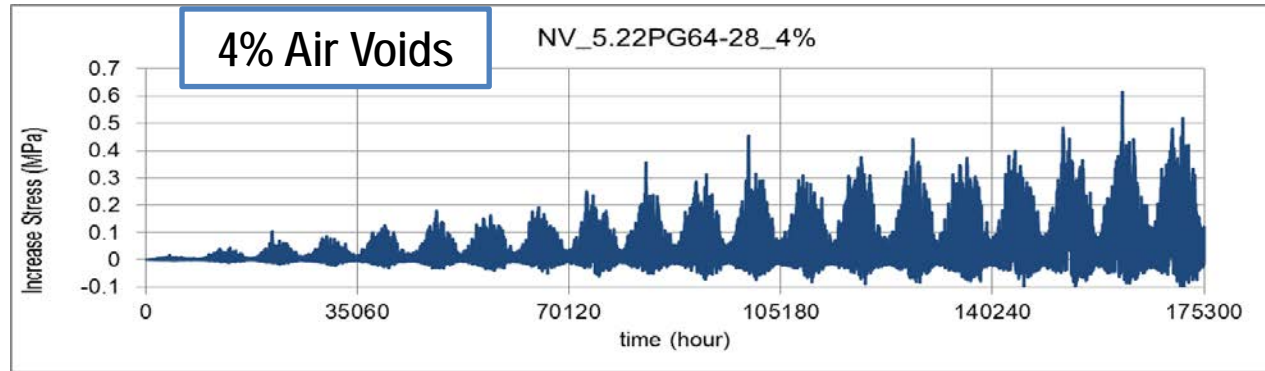
# Examples: TCAP Analysis

- 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

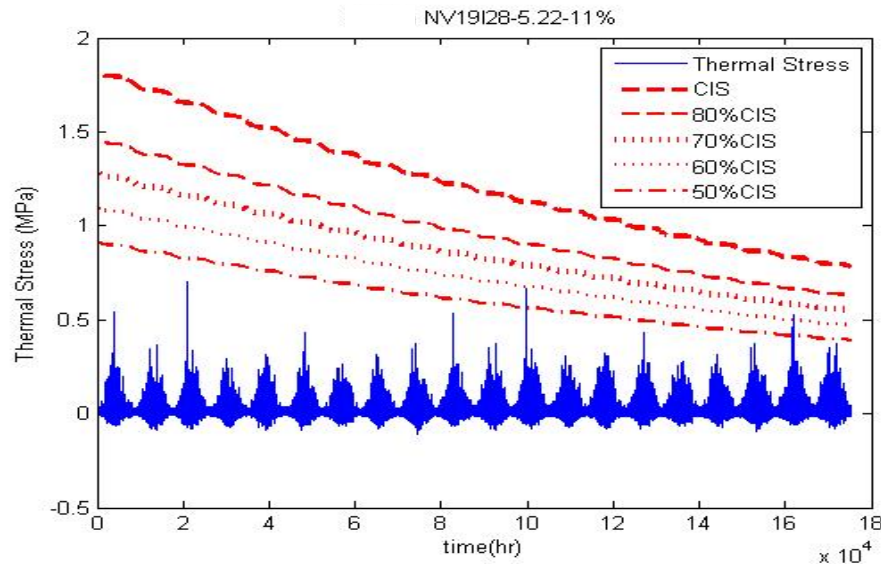
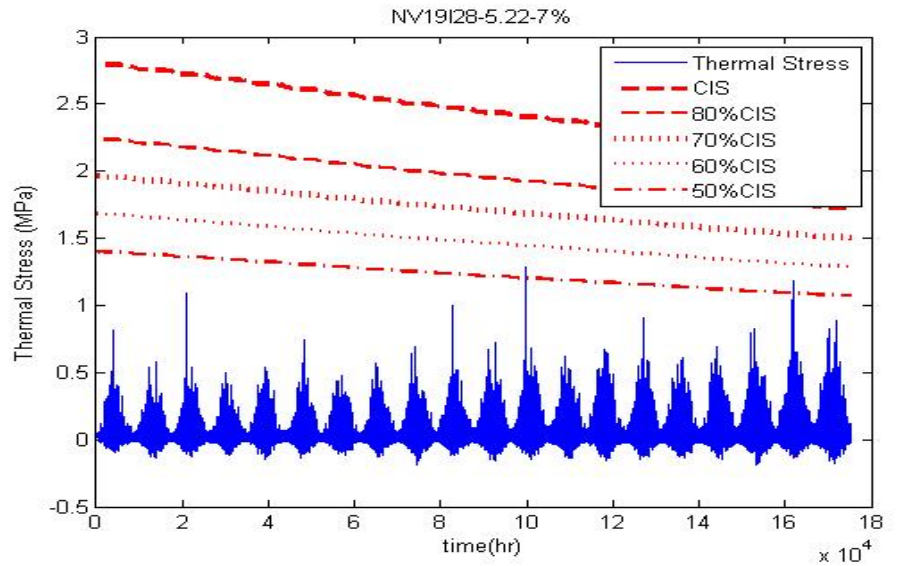
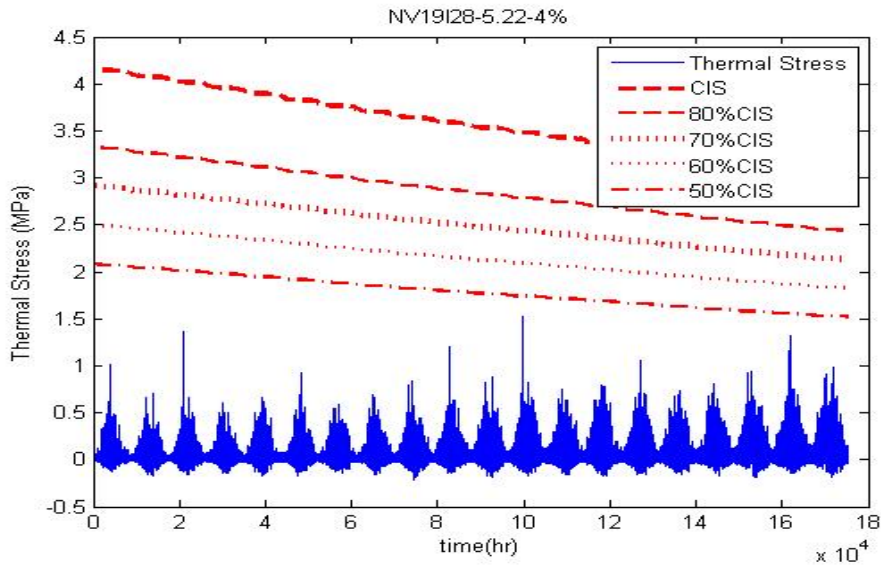
# Effect of Oxidative Aging on Thermal Stresses

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



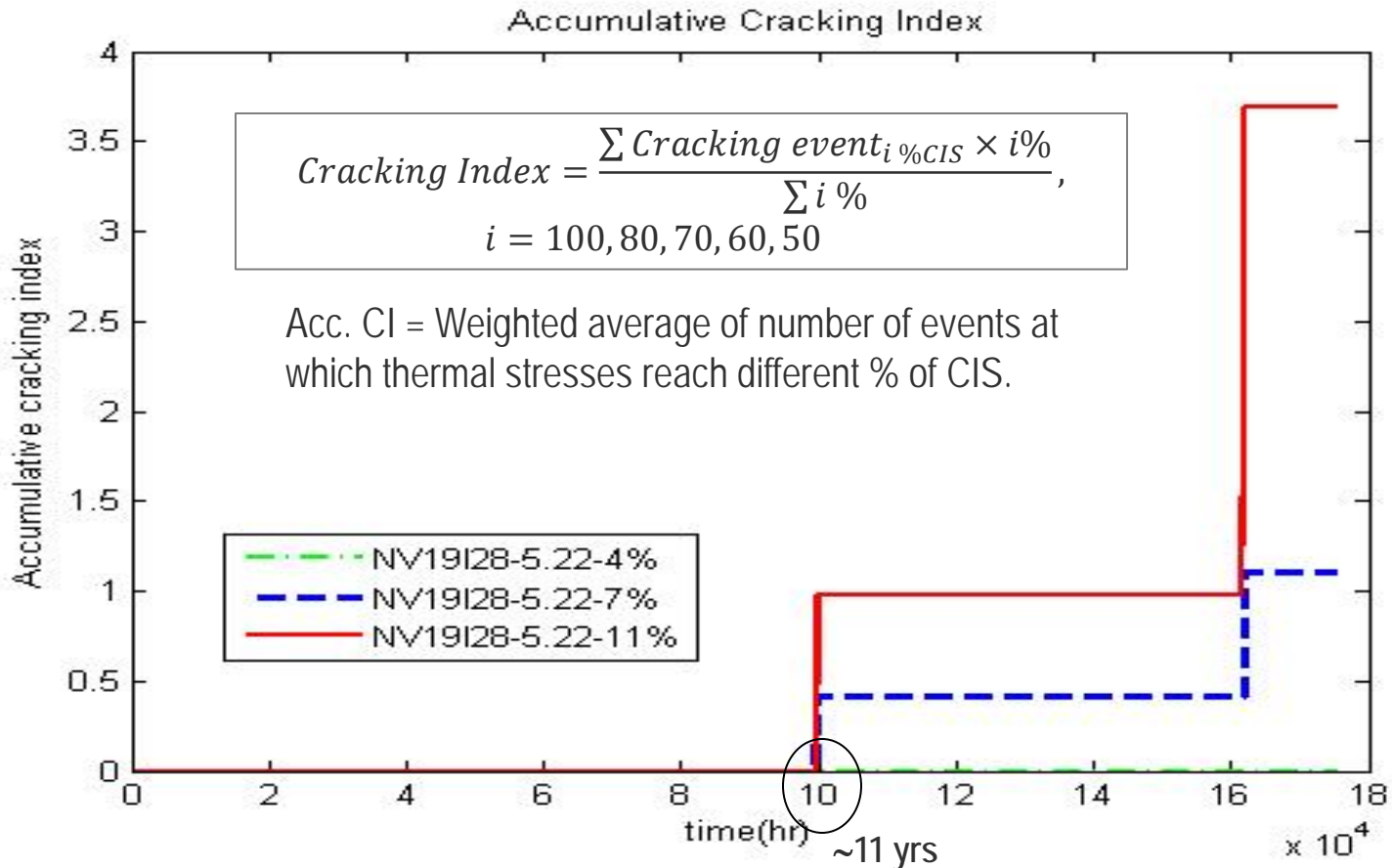
## Examples: TCAP analysis

# Thermal Stress vs. Crack Initiation Stress (CIS)





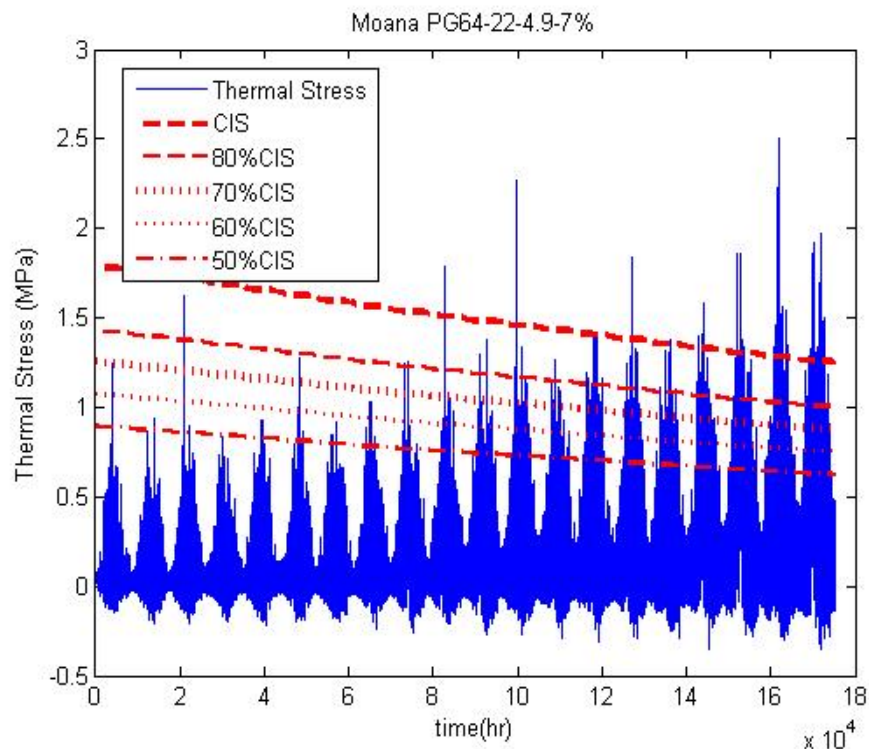
# Effect of Mixtures Air Voids



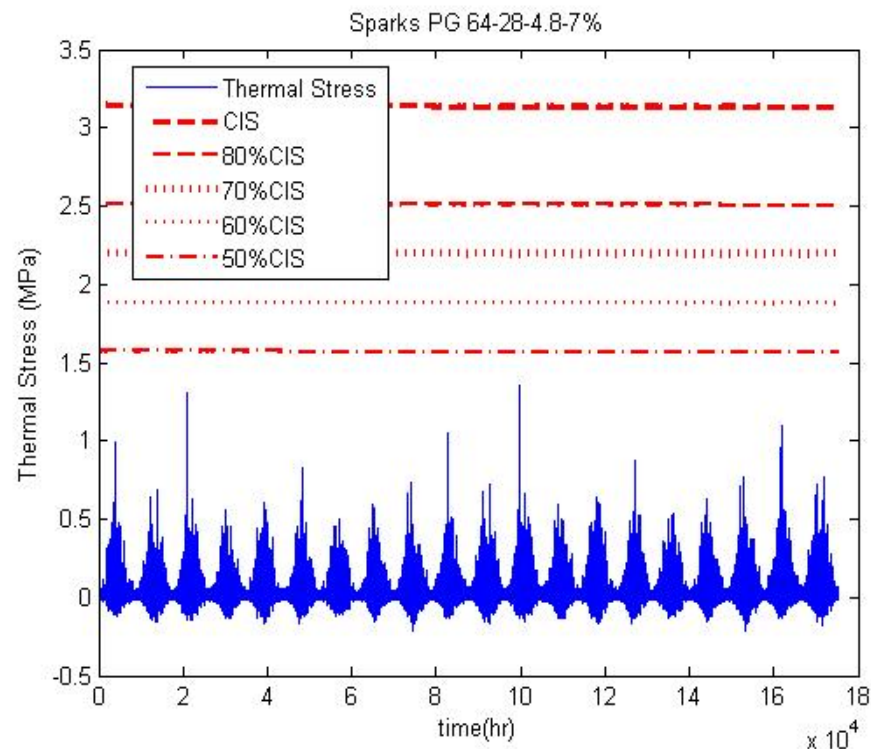
Cracking likelihoods increase for mixture with higher air voids level....

## Examples: TCAP analysis

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

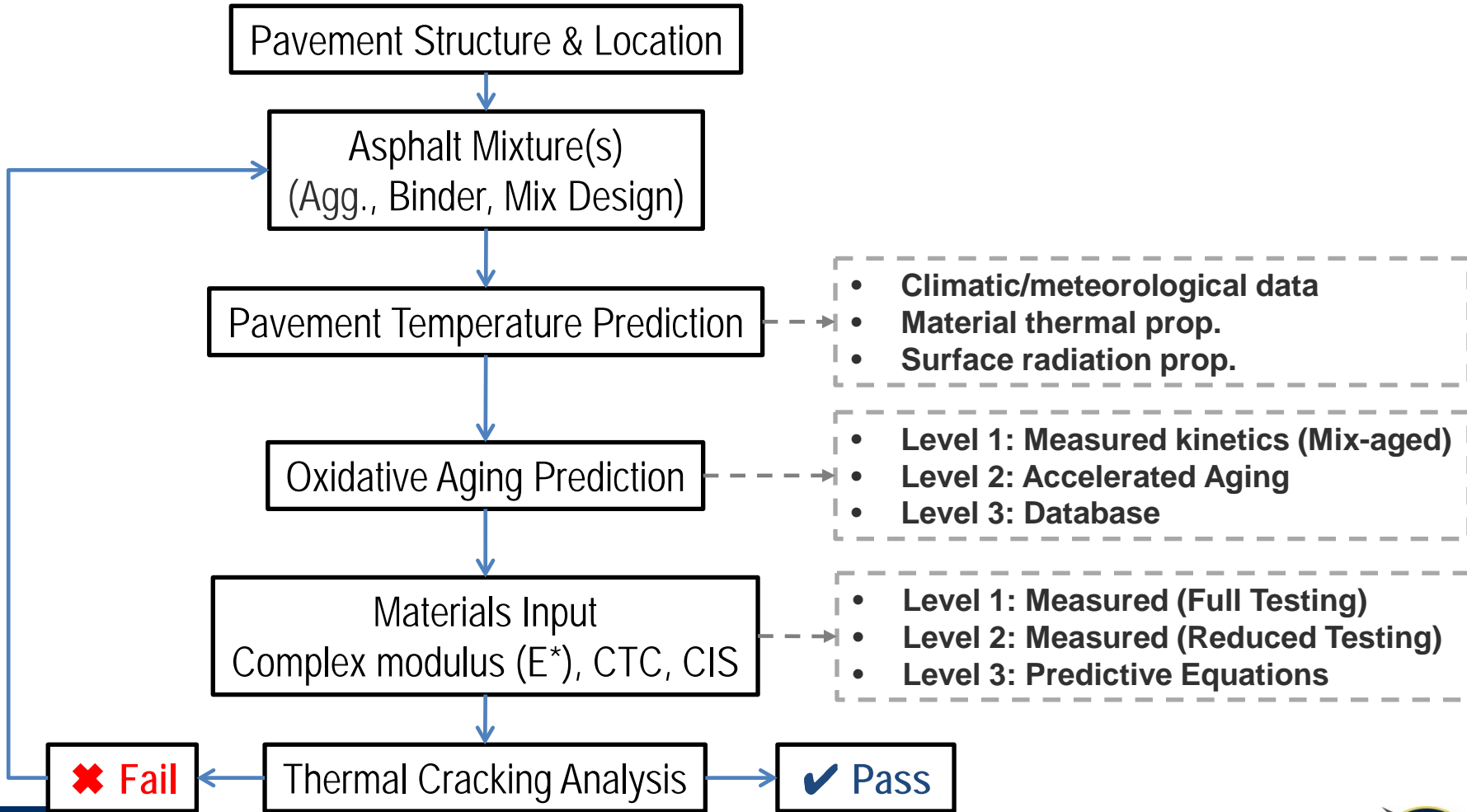


Un-modified  
PG64-22 (Moana, 2006)



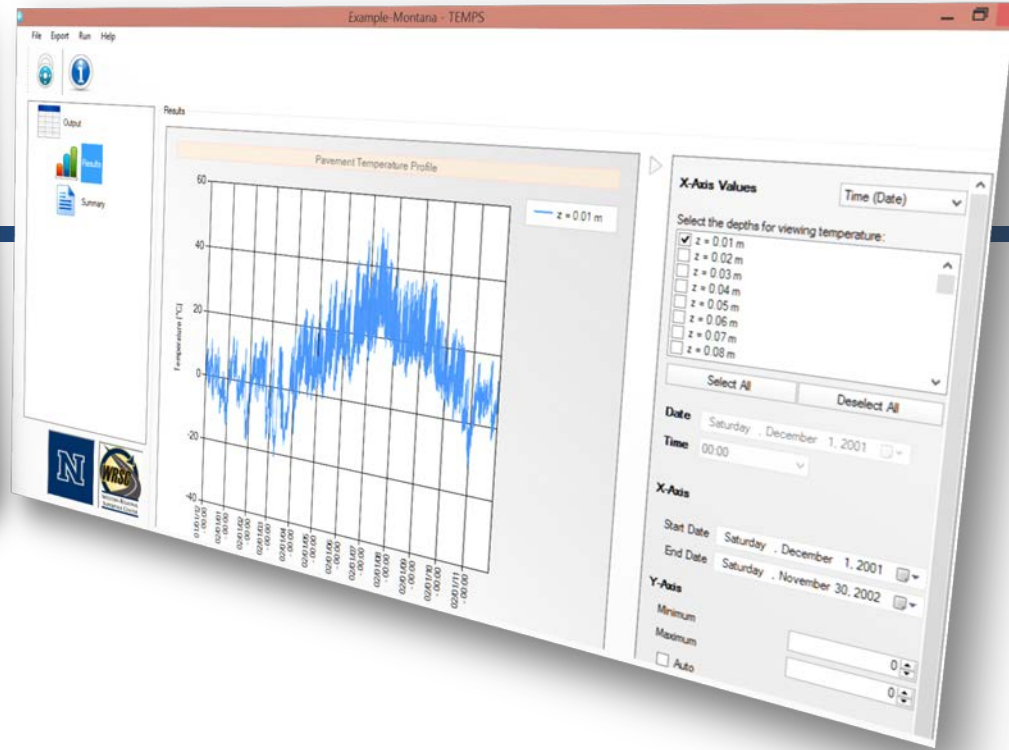
SBS polymer-modified  
PG64-28 (Sparks, 2008)

# 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)]

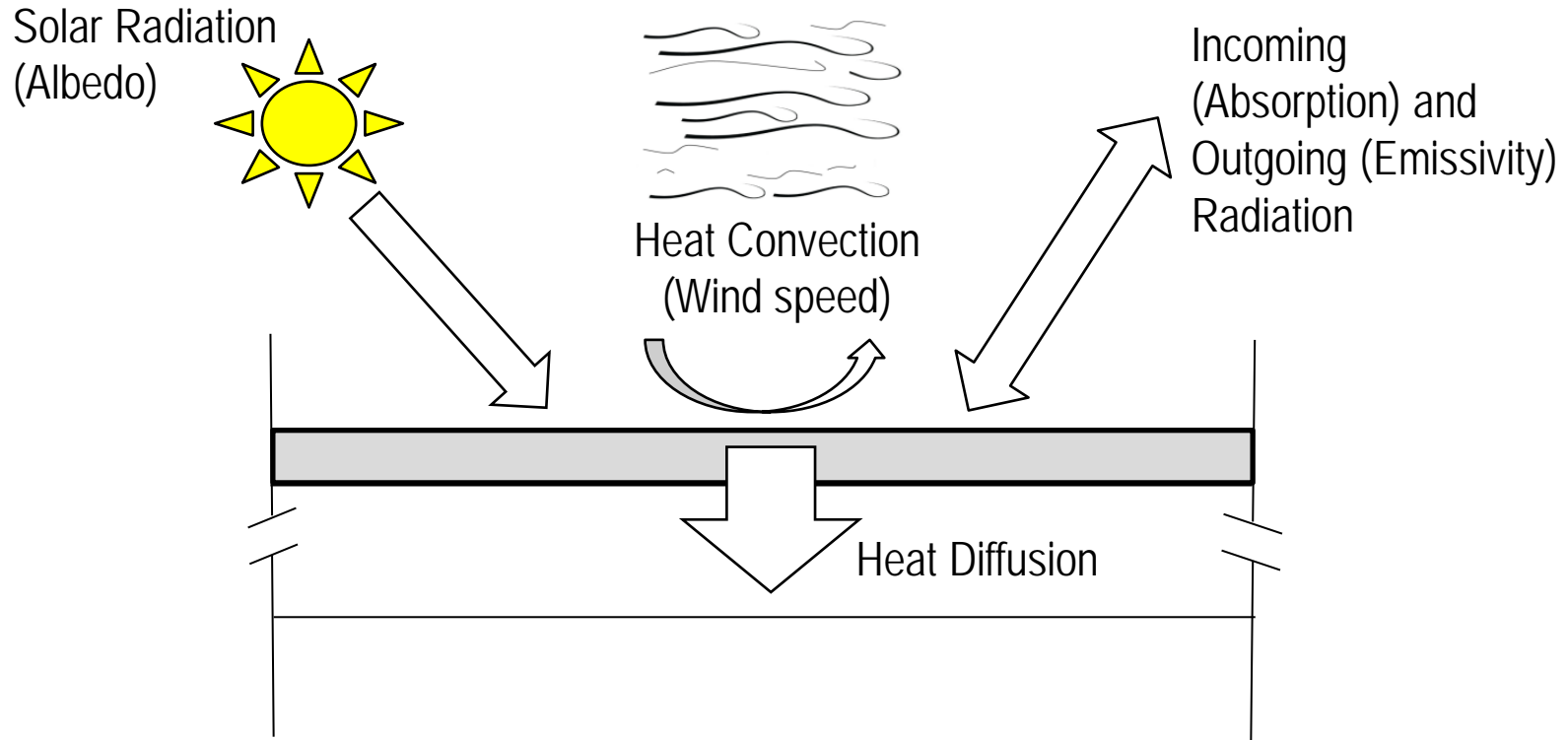
- Enhanced boundary conditions.
- Variable pavement surface radiation properties.

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

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

# Pavement Temperature Profile Prediction

## Heat Transfer Model Concept

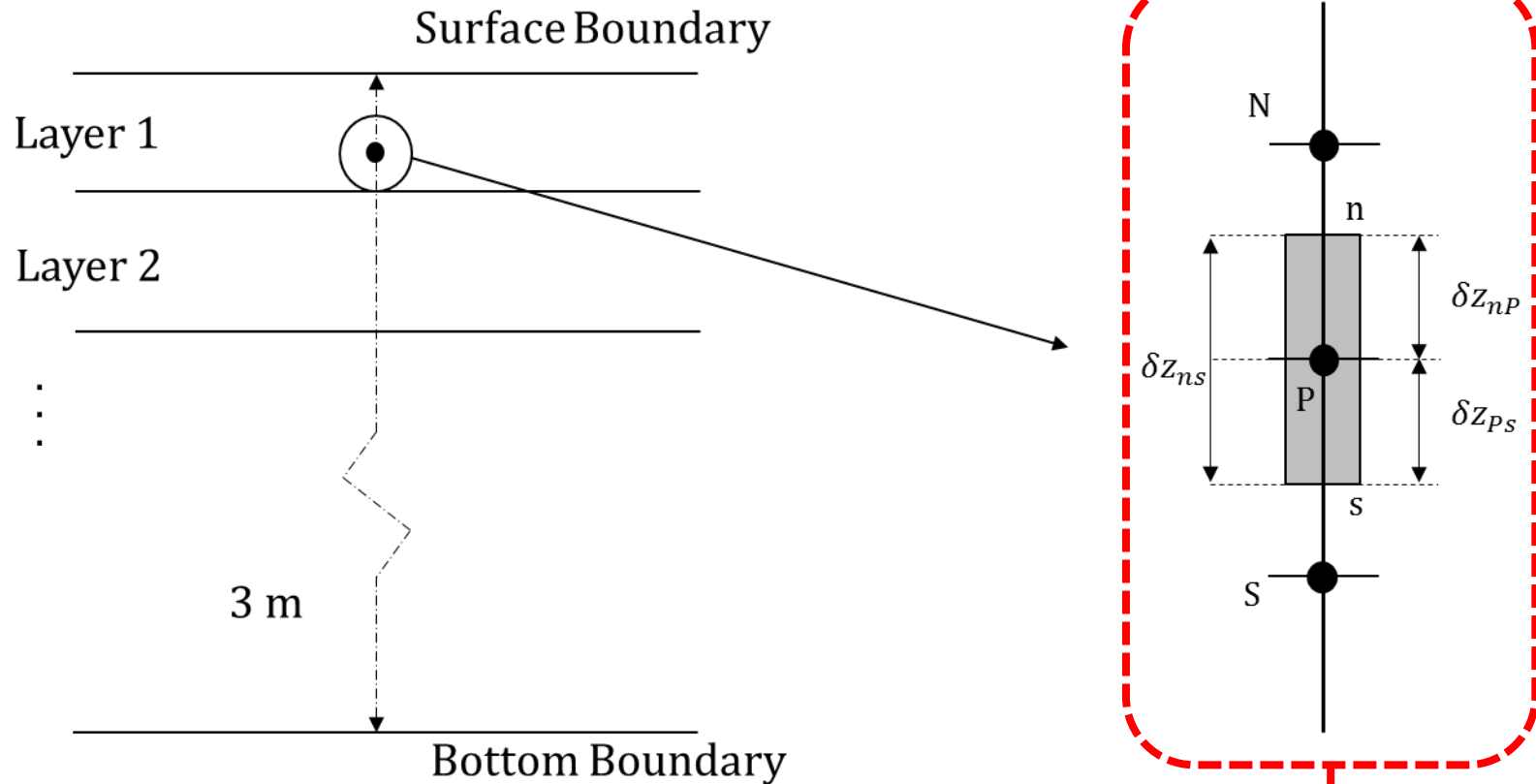


*Heat Transfer Balance Between Pavement Structure & Surrounding Environment*

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

# Pavement Temperature Profile Prediction

## Numerical Computation: Finite Control Volume Method (FCVM)

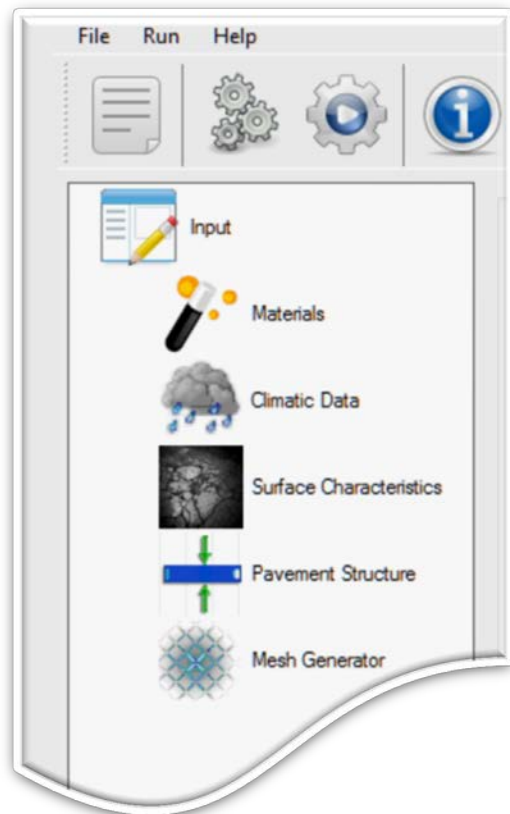


Energy Balance in Each of Control Elements



# 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

The screenshot shows the TEMPS software interface for material input. The window title is "Example-Montana - TEMPS". The menu bar includes "File", "Run", and "Help". The toolbar contains icons for a list, settings, play, and help. The left sidebar has icons for "Input", "Materials", "Climatic Data", "Surface Characteristics", "Pavement Structure", and "Mesh Generator". The main area is titled "Material" and contains input fields for "Material Type" (Material1), "Identifier Color" (Brown), "Specific Heat Capacity (J/kg\*K)" (1900), "Conductivity (W/m\*K)" (1.00), "Density (kg/m³)" (1500), and "Description". To the right are buttons for "Add", "Delete", "Insert", and up/down arrows. Below these is a table of material properties.

| 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/](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:

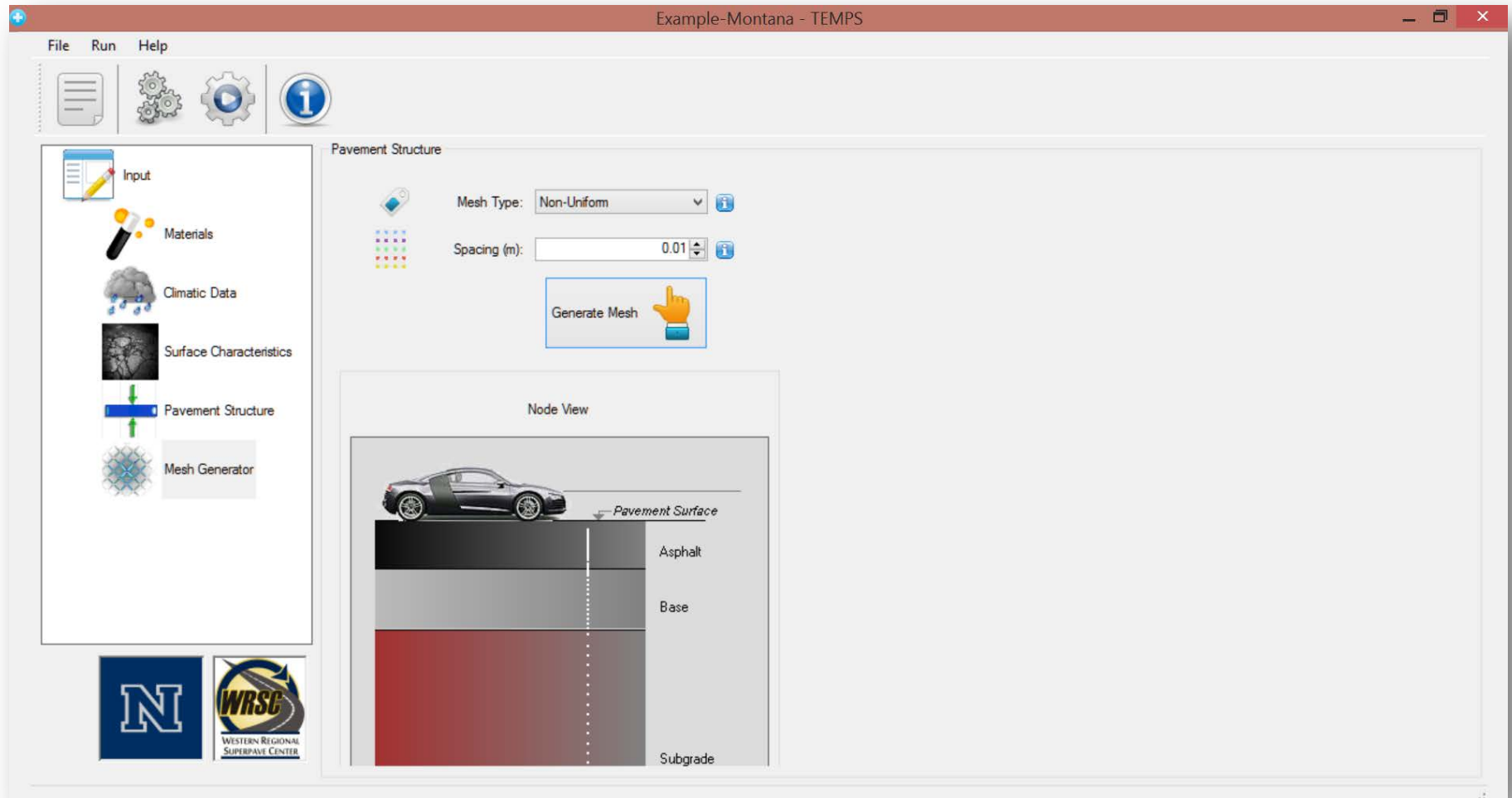
+ Add    X Delete    ↓ Insert

| 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

Asphalt  
Base  
Subgrade

# Pavement Temperature Profile Prediction TEMPS – Mesh Generator



# Pavement Temperature Profile Prediction

## 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\*

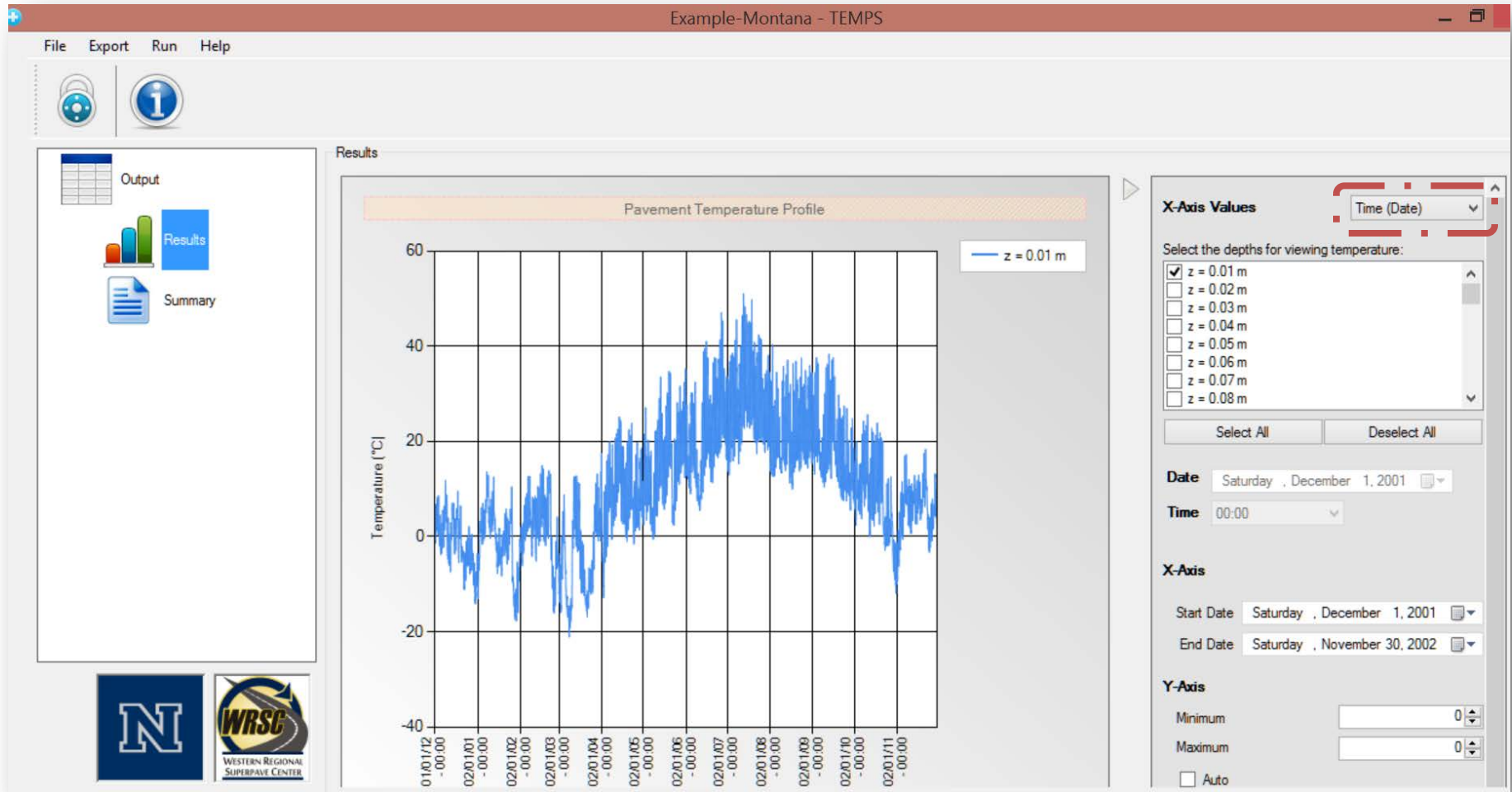


\* Note: 1 hour time step was chosen without jeopardizing the model accuracy for prediction.



# Pavement Temperature Profile Prediction

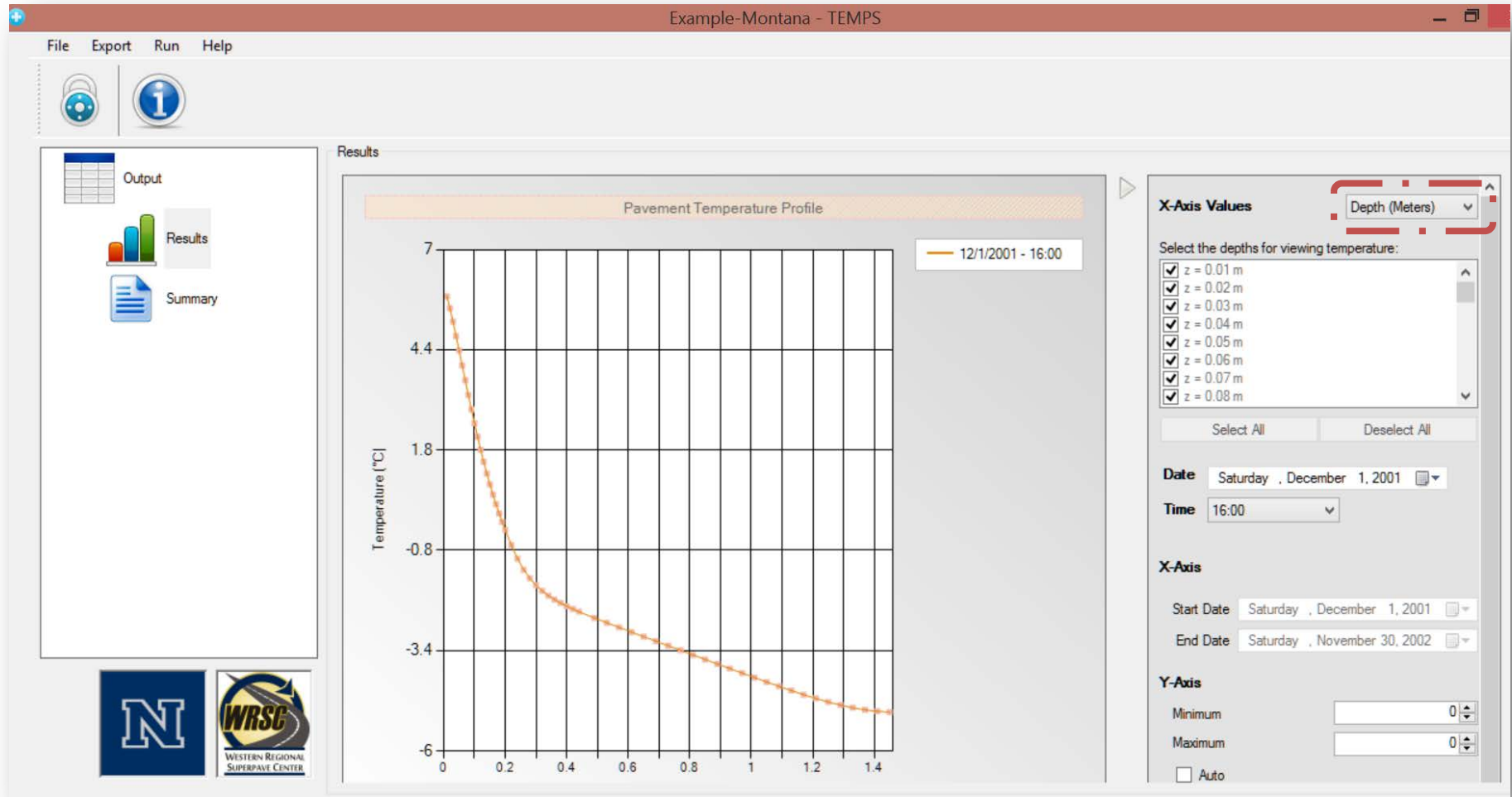
## TEMPS – Output Results





# 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

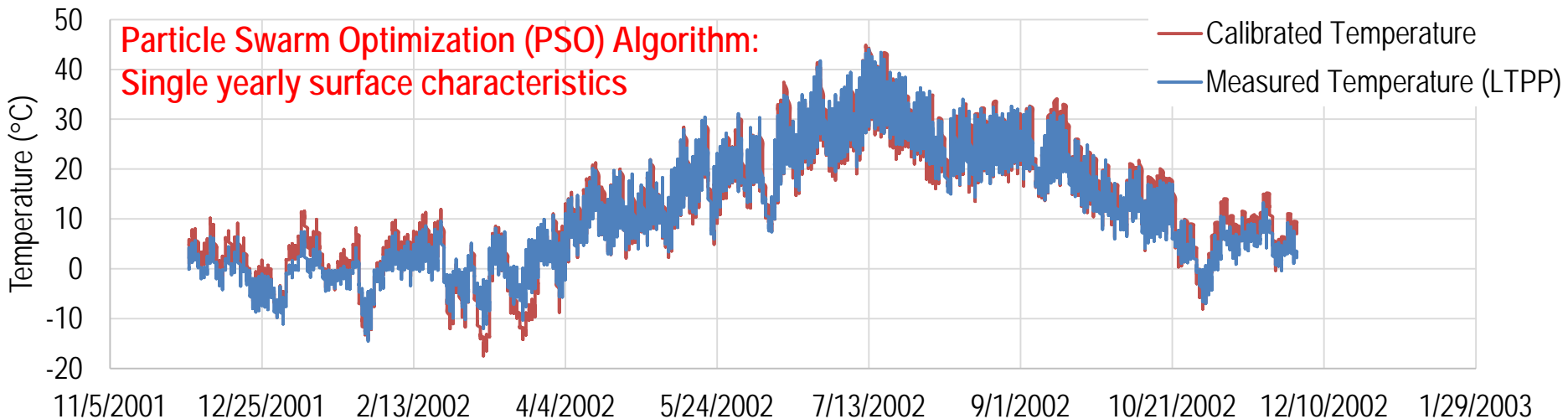
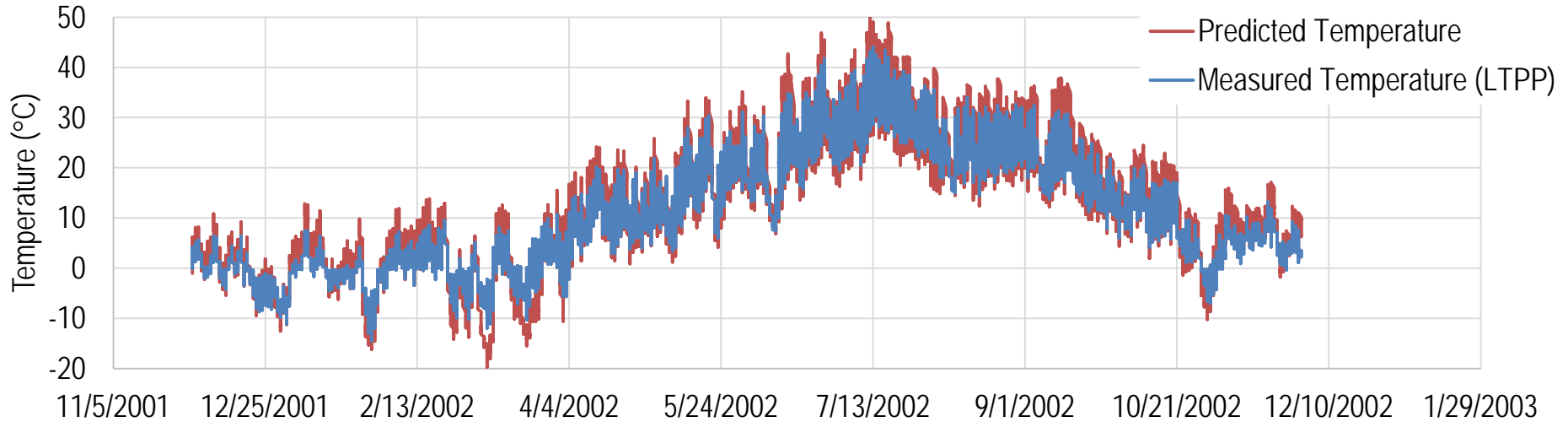
| Date      | Average Pavement Temperature (°C) | Minimum Pavement Temperature (°C) | Maximum Pavement Temperature (°C) | Pavement Temperature Standard Deviation (°C) |
|-----------|-----------------------------------|-----------------------------------|-----------------------------------|--|
| 12/1/2001 | 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

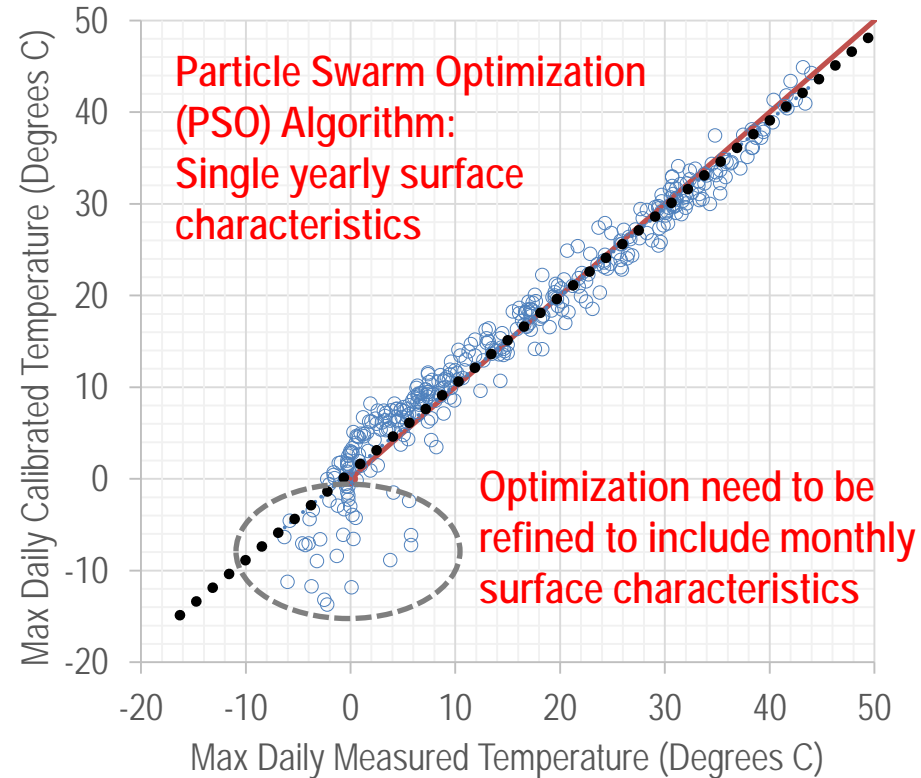
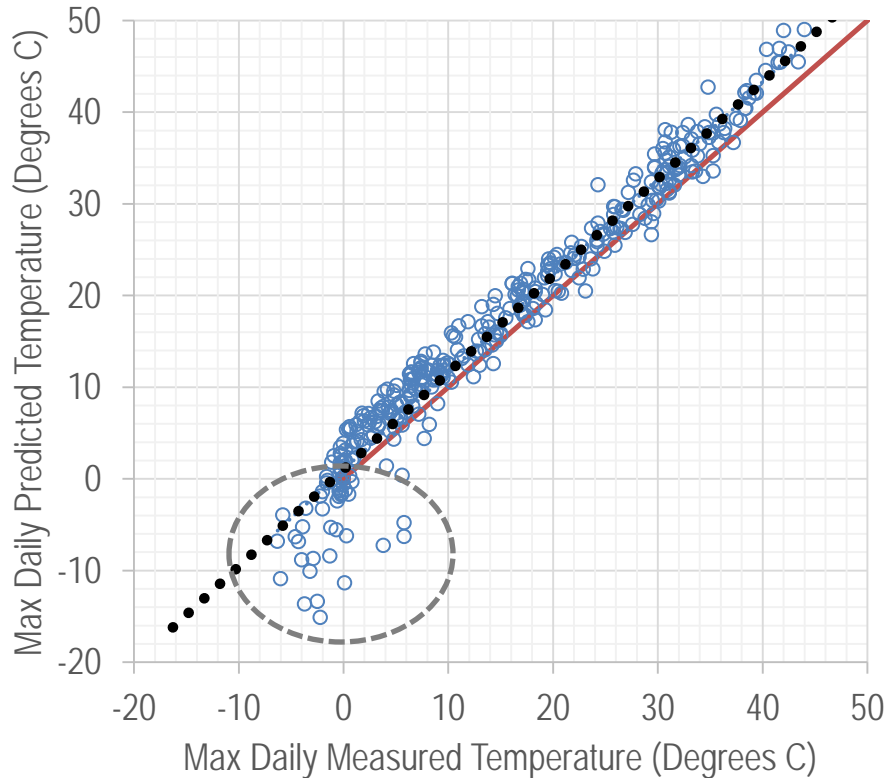
*Great Falls, MT at depth of 0.09 m (3.5 inch)*



# 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!

