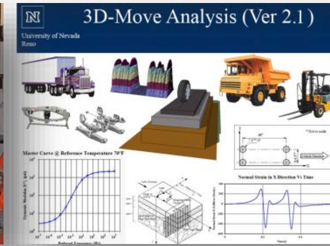


ARC Deliverables/Products Presentation and Workshop

http://www.arc.unr.edu/

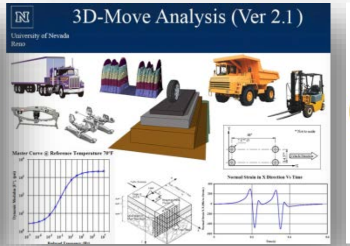
Western Regional Superpave Center (WRSC)
University of Nevada, Reno

Washington, DC – January 15, 2015

ARC
Asphalt Research Consortium

11:05 – 11:30:	**Pavement Engineering Software: Pavement Response Model to Dynamic Loads (3D-Move).**
11:35 – 12:00:	**Rutting Performance of Asphalt Mixtures Under Critical Conditions.**
1:00 – 1:25:	**Mix Design for Cold in-Place Recycling (CIR).**
1:30 – 1:55:	**Pavement Engineering Software: Thermal Cracking Analysis Package (TCAP).**

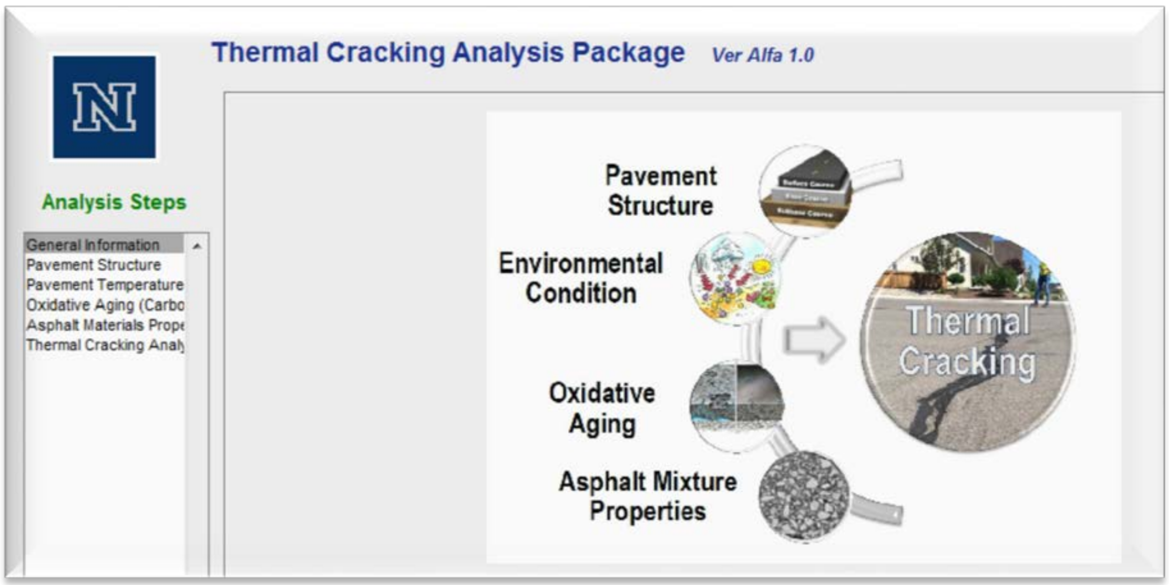


ARC Deliverables/Products Presentation and Workshop

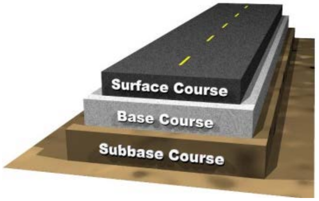
Comprehensive Thermal Cracking Analysis Model for Asphalt Concrete Pavements

Thermal Cracking Analysis Package (TCAP)



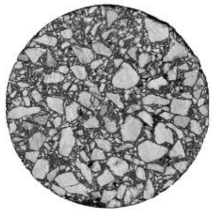
Thermal Cracking Analysis
Influential Factors

- 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

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**.

Proposed Model

Step 1
Pavement Temperature Profile and History Prediction

↓

Step 2
Oxidative Aging Prediction

↓

Step 3
Thermal Stress Calculation

↓

Step 4
Thermal Cracking Event Probability

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^{α} = 4.08 E+8 ln(CA/day)

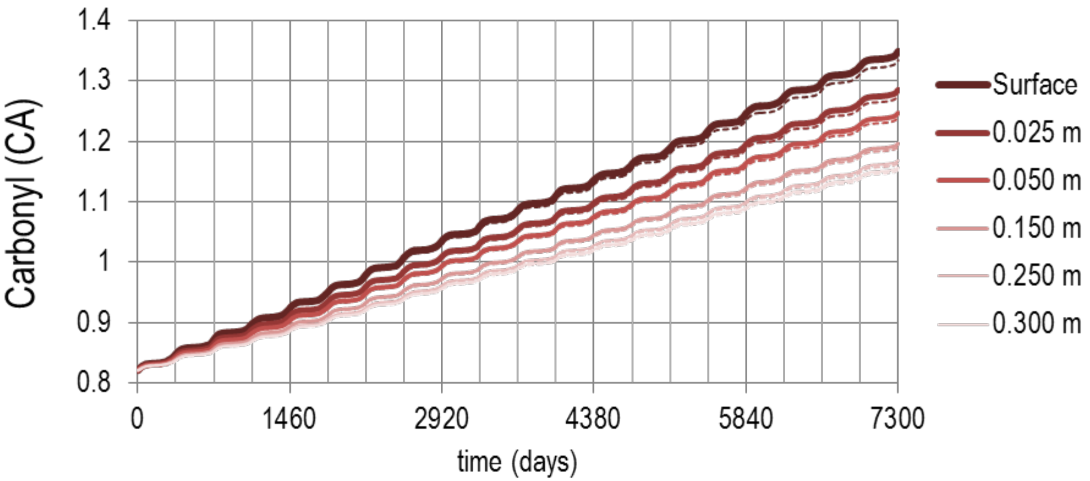
HS = 2.7 (1/CA)

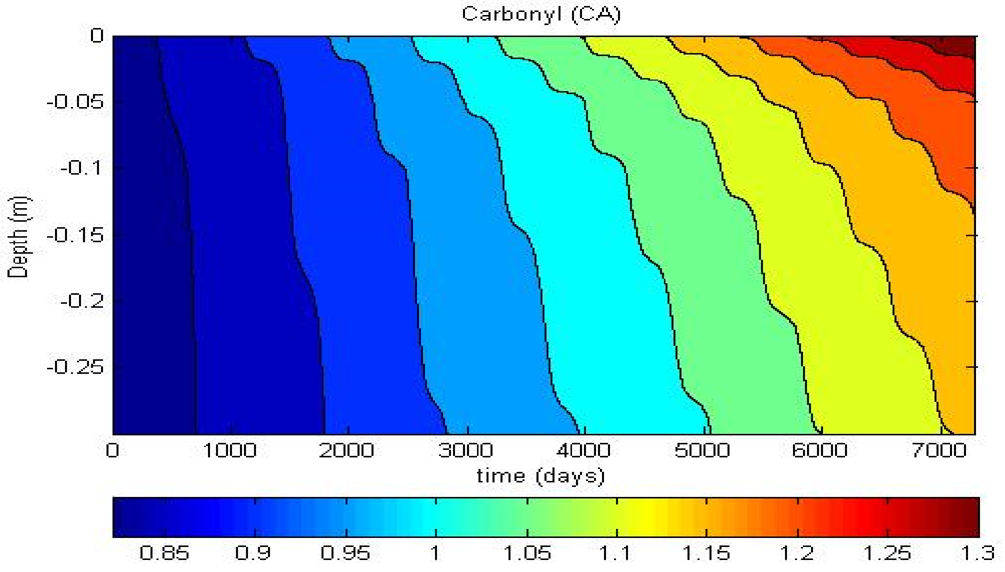
m = 9.24 (poise)

Air void diameter = 0.5 mm

Eff. aging zone = 1.0 mm

(film thickness)





Thermal Stress Calculation

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

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

Relaxation Modulus
Function of time, temperature, and aging

Thermal strain rate
Function of temperature and age-dependent CTC

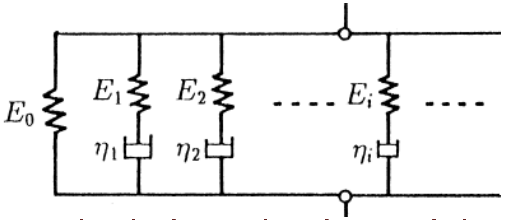
Age-Dependent Relaxation Modulus

- 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)*.

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

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

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

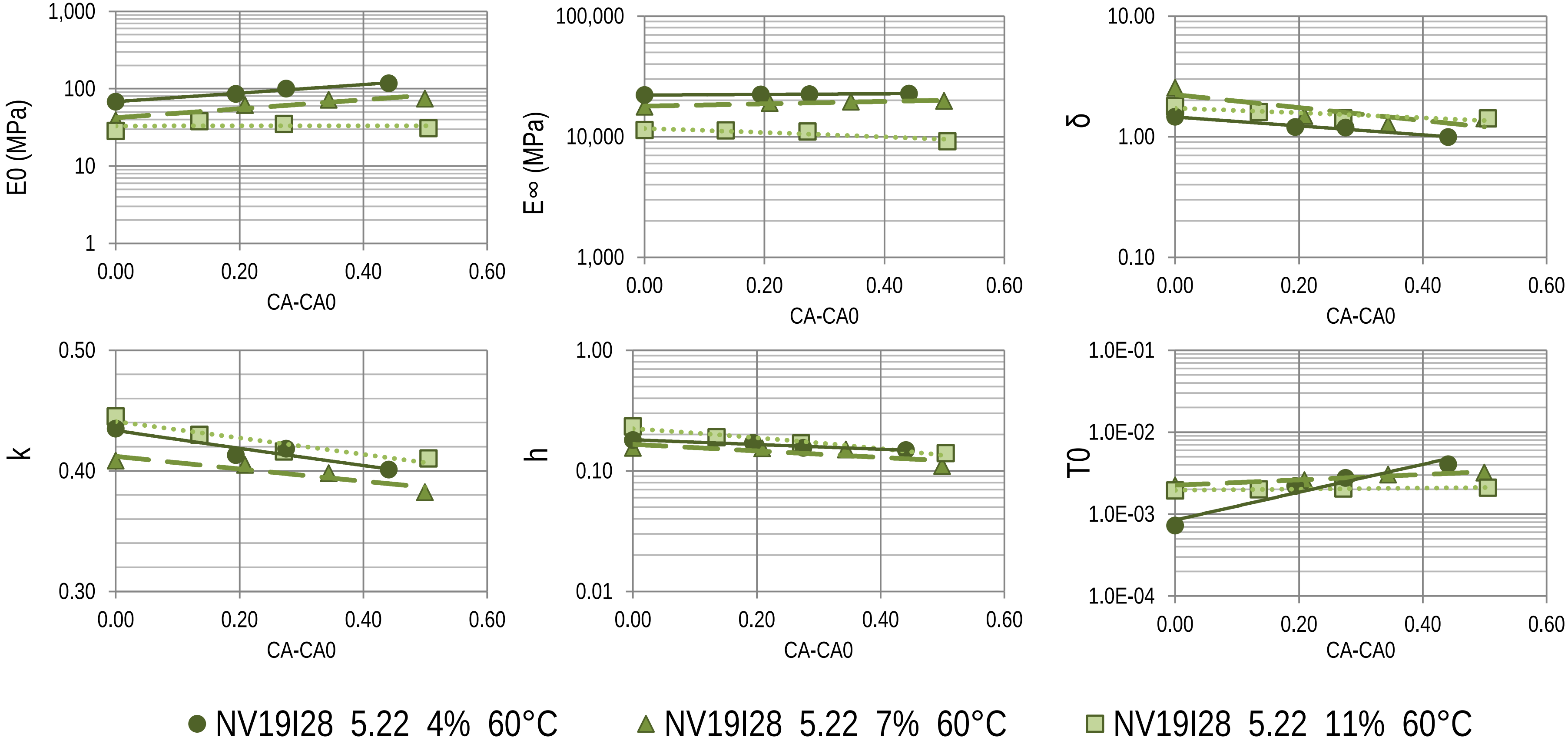


Ideal viscoelastic model

- 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, $\beta = \eta.\tau^{-1}/(E_\infty - E_0)$; when $\omega \rightarrow 0$, then $E^*(i\omega\tau) \sim E_0 + i\omega\eta$.
- τ : characteristic time, which varies only with temperature

Thermal Cracking Analysis

Evolution of 2S2P1D Coefficient with Aging



Consistent trends were found for the evaluated mixtures!

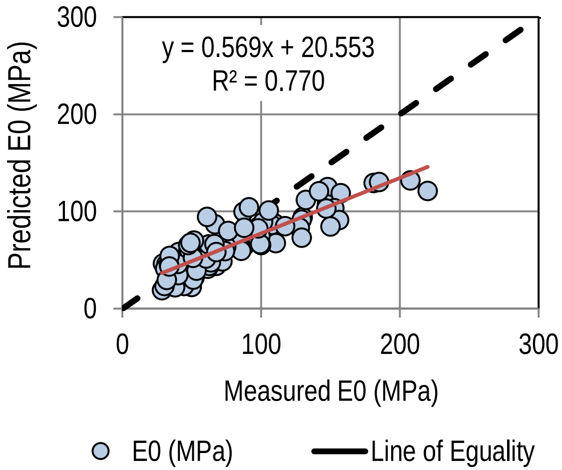
$$(2S2P1D\ coeff)_j = A_j \times e^{B_j(CA-CA_0)}$$

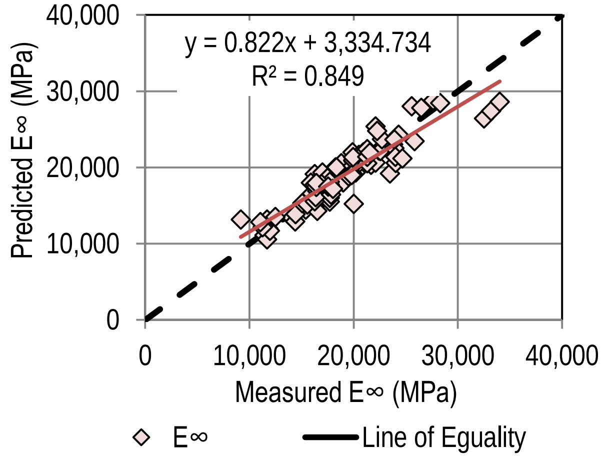
Evolution of 2S2P1D Coefficient with Aging

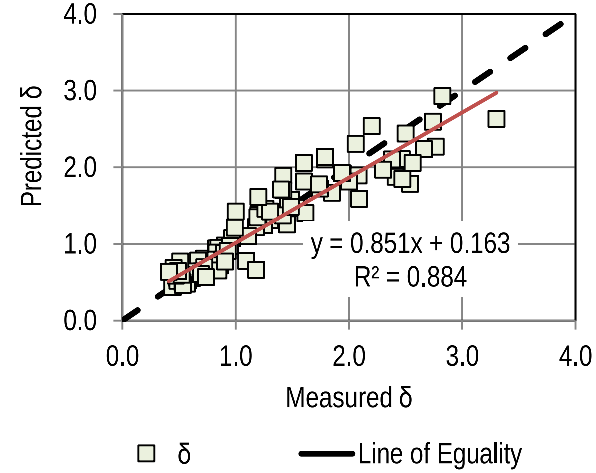
	Mixture variable						
2S2P1D coeff.	CA	V_a (%)	Abs. (%)	LSV_{Tank} (poise)	B.C. (%)	Retained # 8	Passing # 200
E_0	√	√	√	√	√		
E_∞	√	√	√	√	√	√	√
δ	√	√	√	√	√		√
k	√		√	√			√
h	√			√	√		
T_0	√		√				√

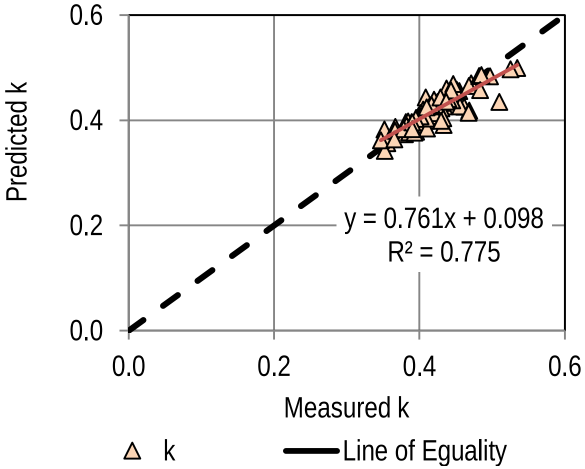
Thermal Cracking Analysis

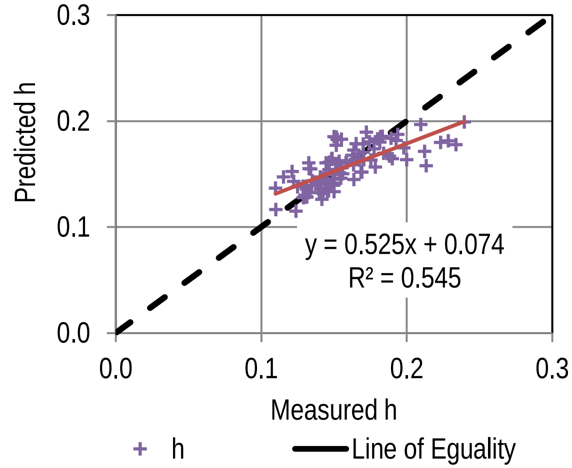
Evolution of 2S2P1D Coefficient with Aging

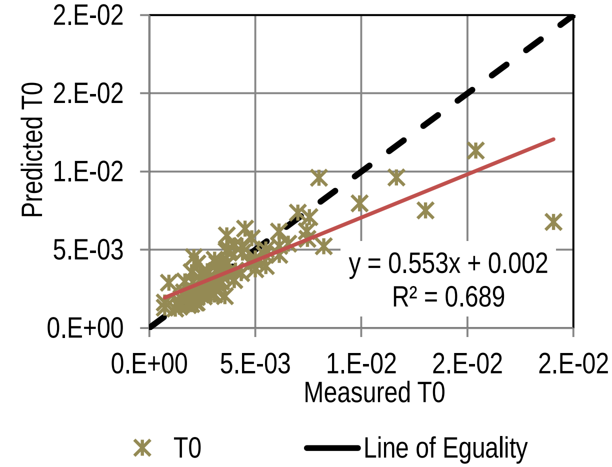












WESTERN REGIONAL SUPERPAVE CENTER

Age-Dependent Properties

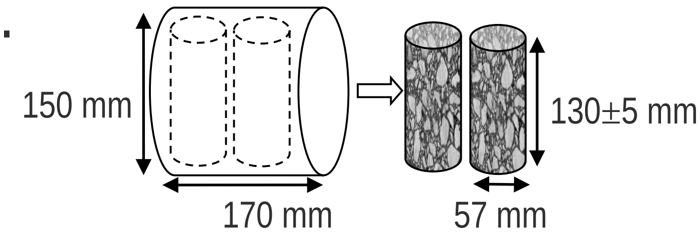
- Coefficient of thermal contraction (CTC)
- Crack initiation stress (CIS)

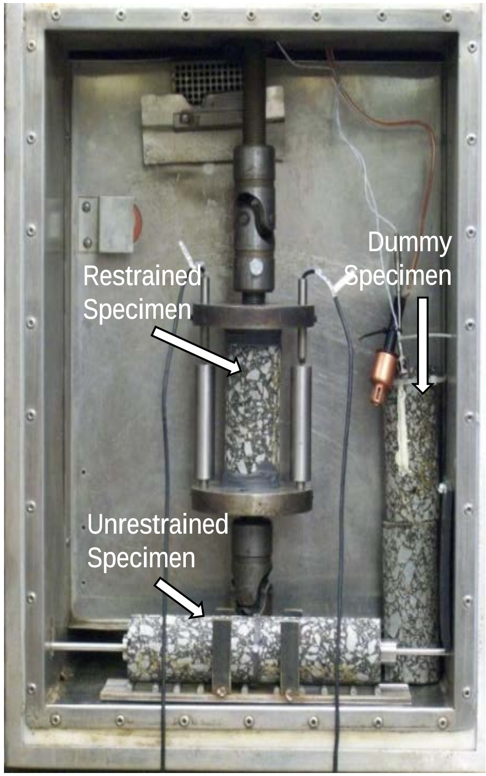
→ Uniaxial Thermal Stress and Strain Test (UTSST)

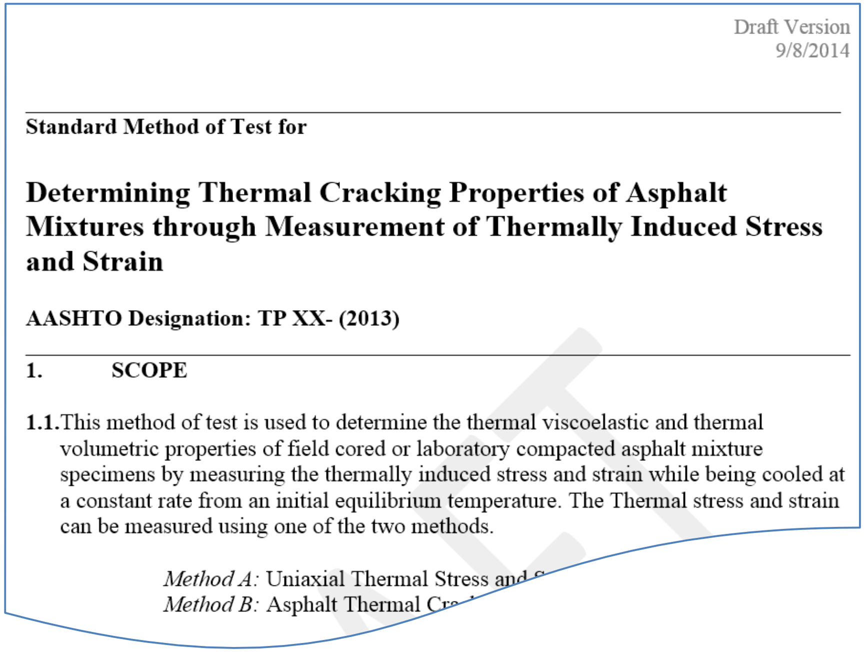
Age-Dependent Properties

Uniaxial Thermal Stress and Strain Test (UTSST)

- Samples are cored out of a SGC specimen.







Draft Version
9/8/2014

Standard Method of Test for

Determining Thermal Cracking Properties of Asphalt Mixtures through Measurement of Thermally Induced Stress and Strain

AASHTO Designation: TP XX- (2013)

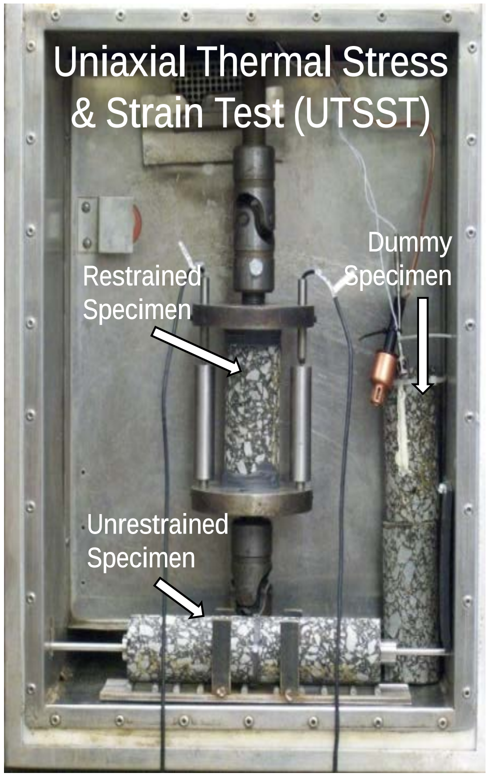
1. SCOPE

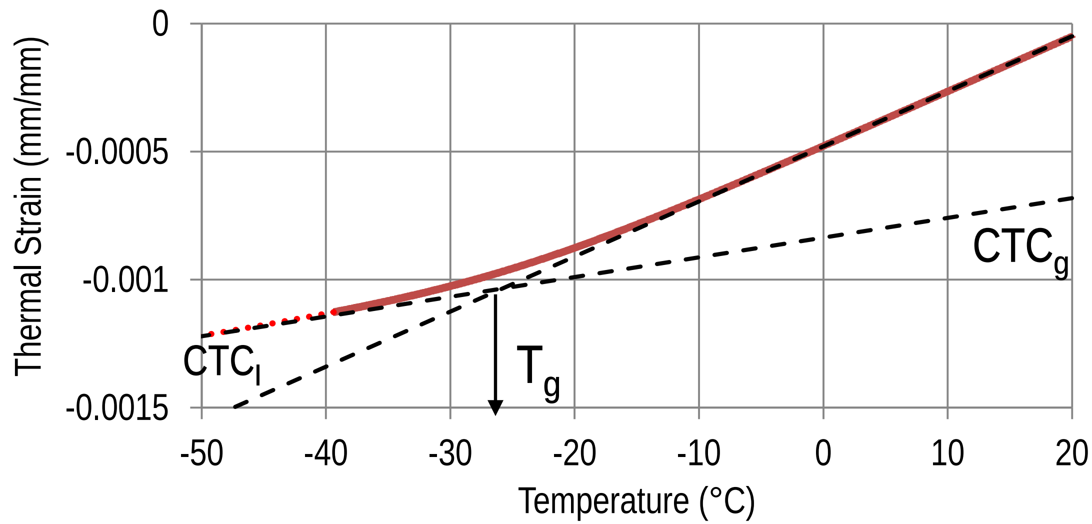
1.1. This method of test is used to determine the thermal viscoelastic and thermal volumetric properties of field cored or laboratory compacted asphalt mixture specimens by measuring the thermally induced stress and strain while being cooled at a constant rate from an initial equilibrium temperature. The Thermal stress and strain can be measured using one of the two methods.

Method A: Uniaxial Thermal Stress and S
Method B: Asphalt Thermal Cr

Thermal Cracking Analysis

Temperature and Age-Dependent CTC



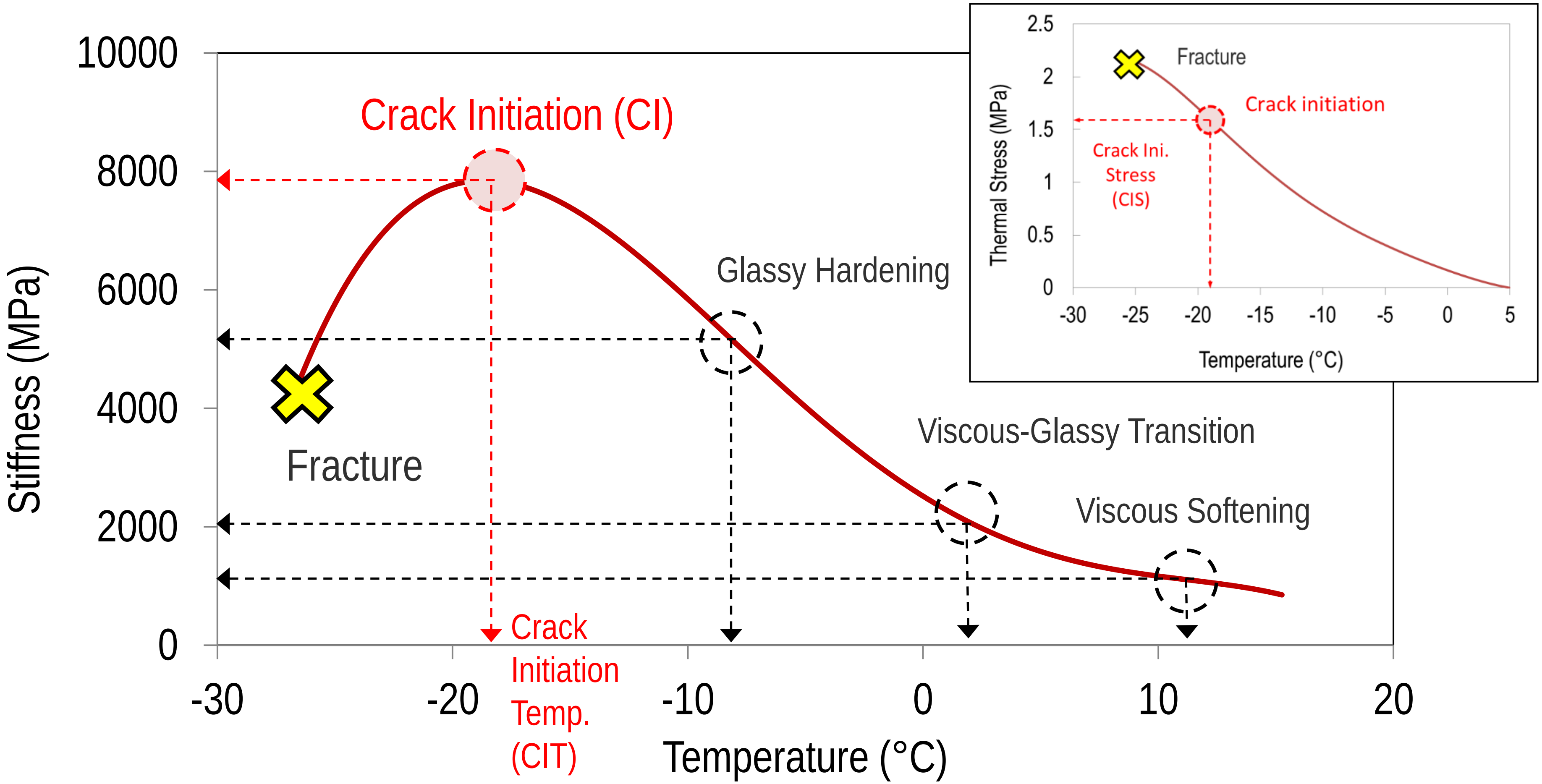


$$\varepsilon_{th} = \frac{\Delta l}{l_0} = C + CTC_g\left(T - T_g\right) + ln\left\{\left[1 + e^{\frac{(T-T_g)}{R}}\right]^{R(CTC_l - CTC_g)}\right\}$$

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

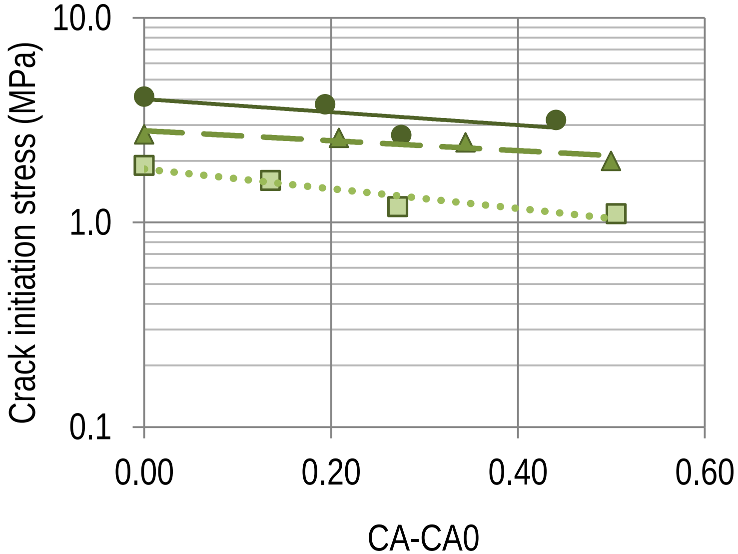
$$\varepsilon(T(t)) = \int_{T_0}^{T(t)} CTC(T(t)) \times dT'$$

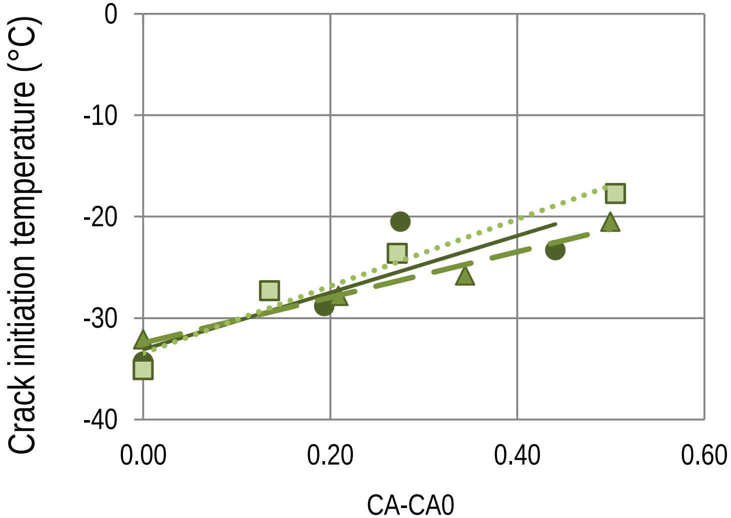
Age-Dependent Crack Initiation Stress (CIS)



Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)



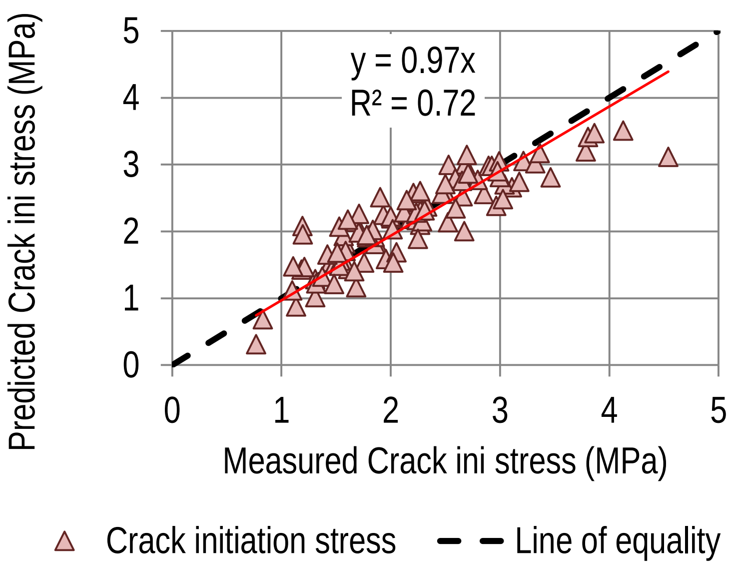


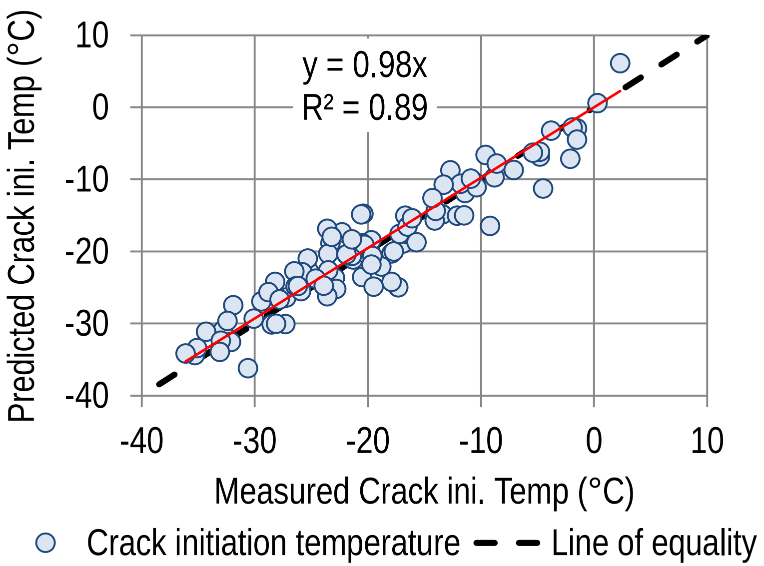
Similar trends were observed for all evaluated mixtures!

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

Age-Dependent Crack Initiation Stress (CIS)

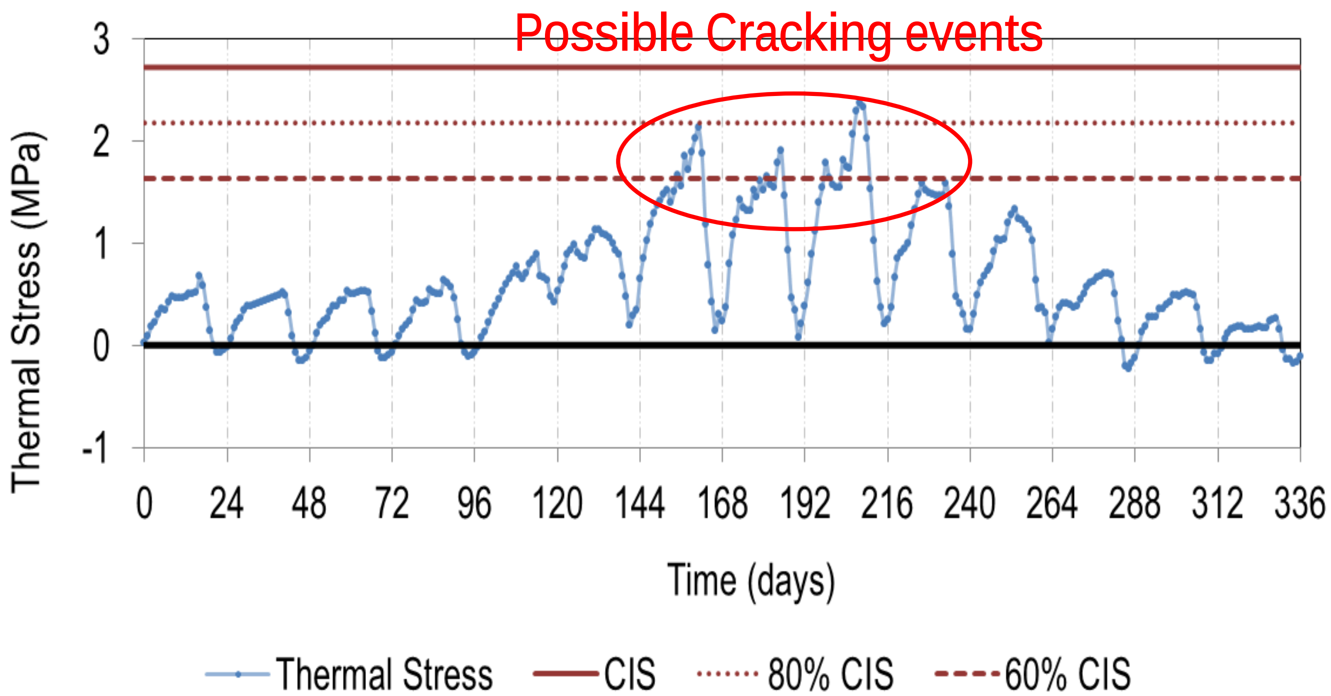
	Mixture variable						
	CA	Va (%)	Abs. (%)	LSV_{Tank} (poise)	B.C. (%)	Retained # 8	Passing # 200
CIS	√	√	√	√			√
CIT	√	√		√	√	√	√



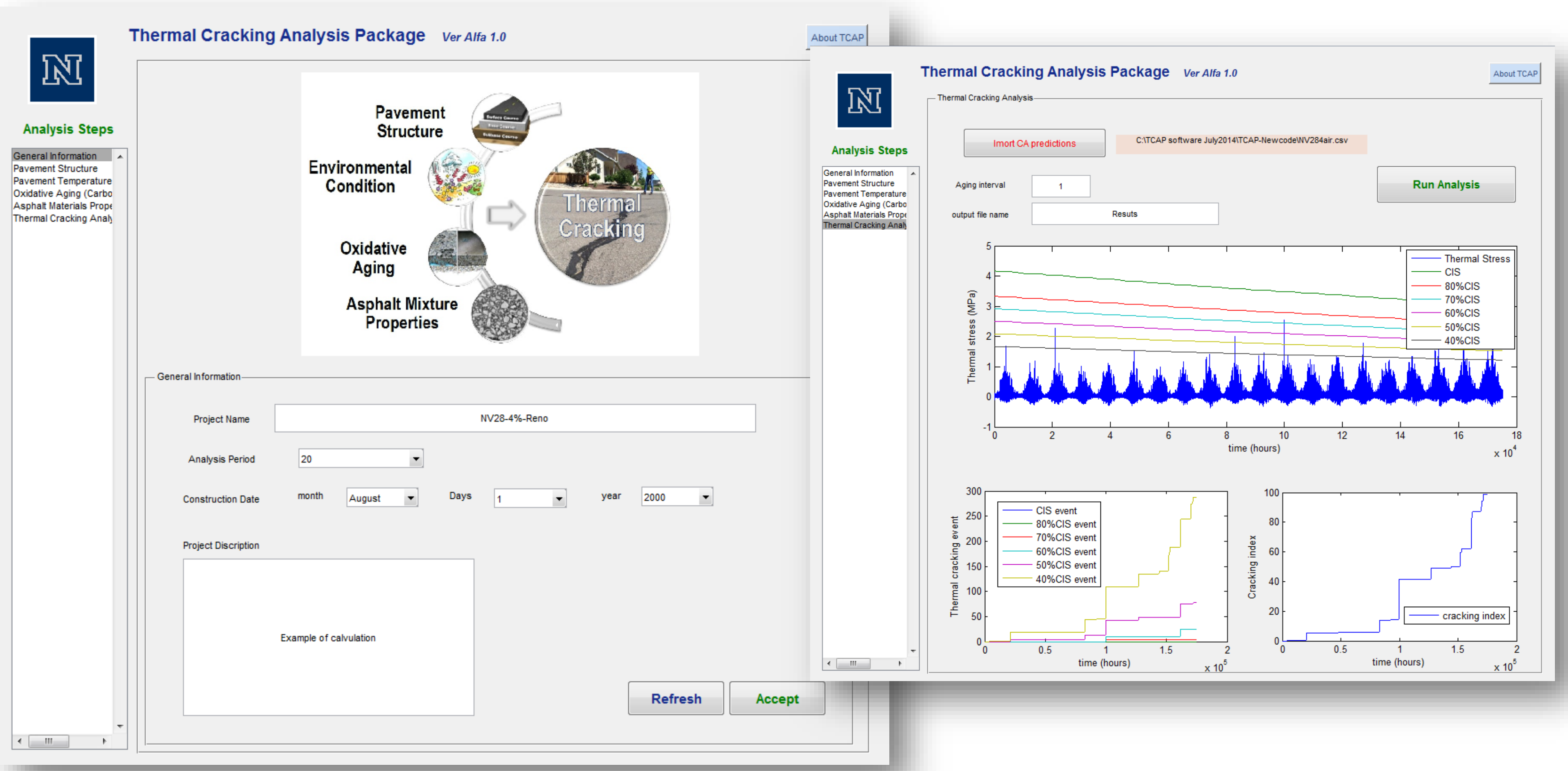


Thermal Cracking Event Probability

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



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



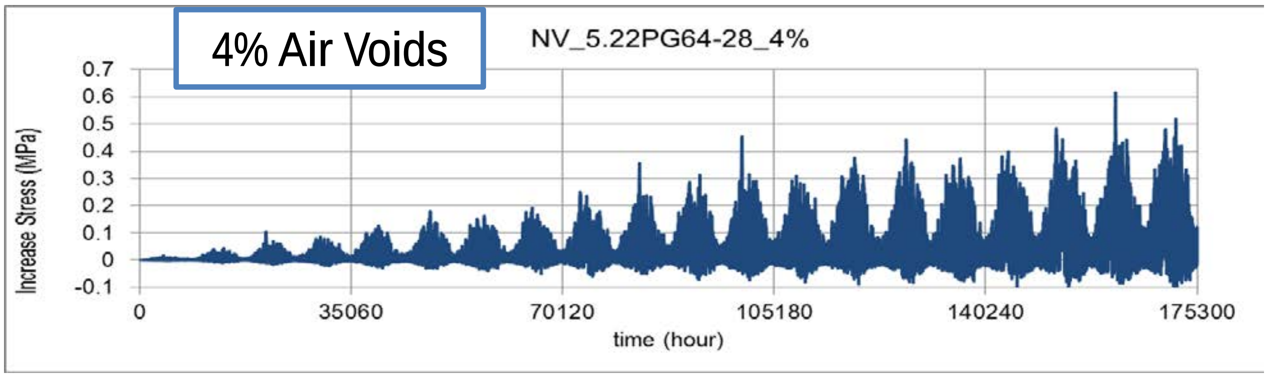
Examples: TCAP Analysis

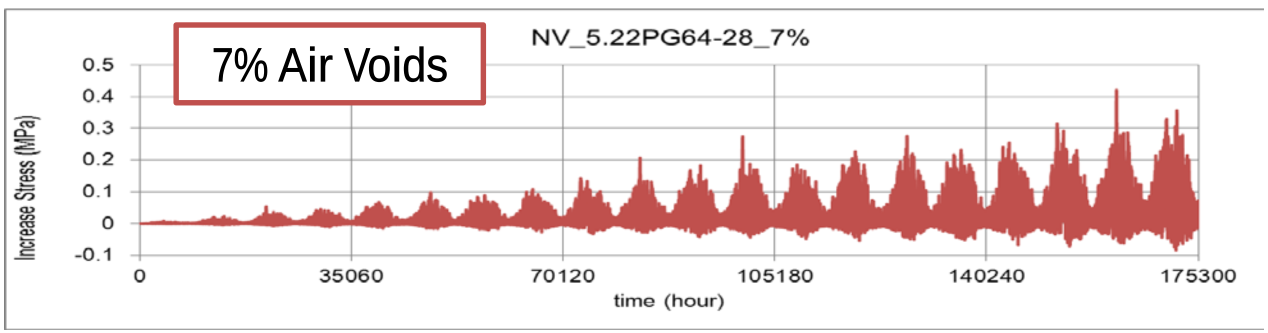
- Pavement Location
  - Reno, Nevada
- Asphalt Mixtures:
  - Polymer-modified PG64-28; 3 air void levels:
    - NV_5.22PG64-28_4%; NV_5.22PG64-28_7%; NV_5.22PG64-28_11%
- Design Period
  - 20 years

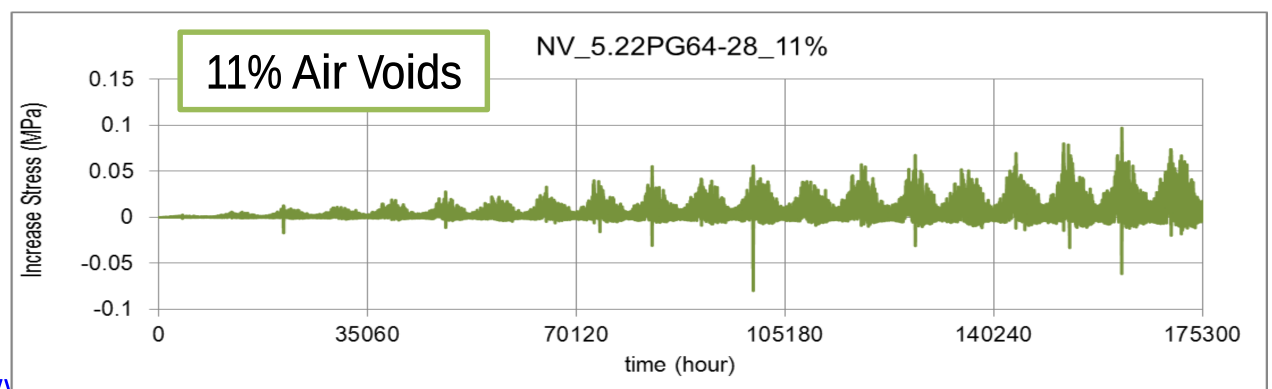
Examples: TCAP analysis

Effect of Oxidative Aging on Thermal Stresses

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

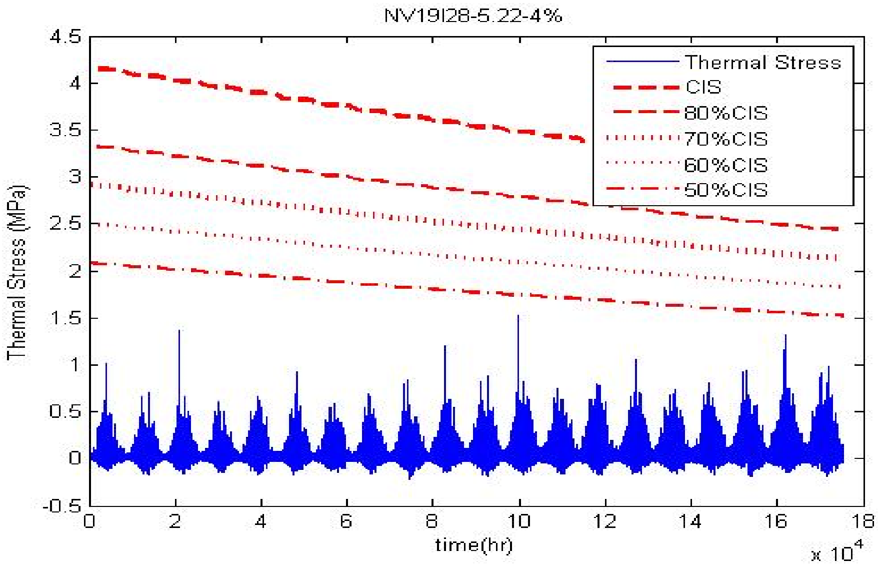


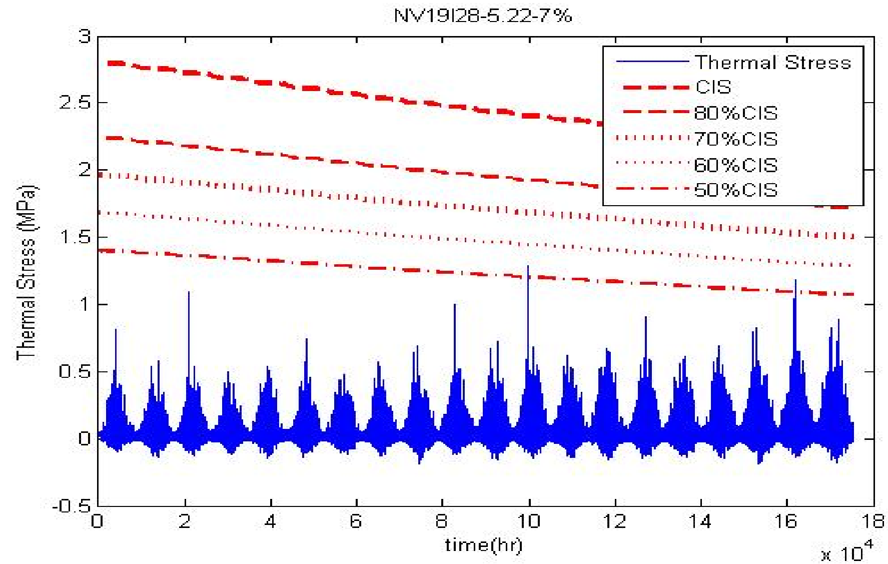


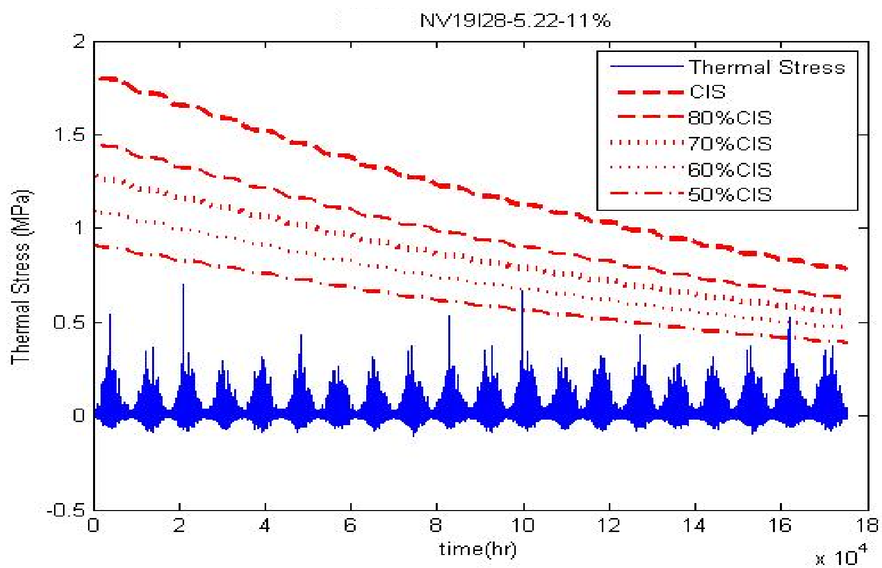


Examples: TCAP analysis

Thermal Stress vs. Crack Initiation Stress (CIS)

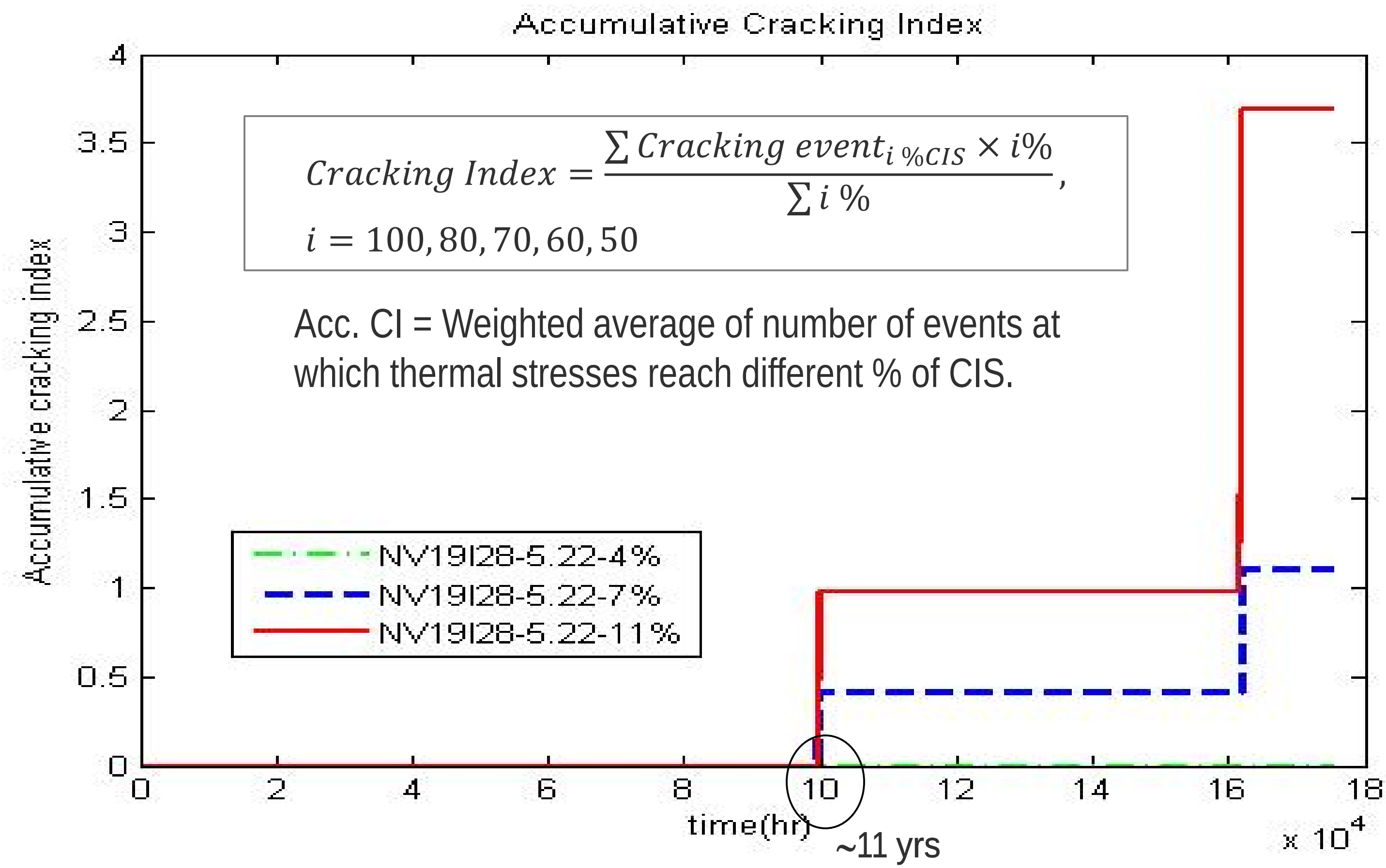






Examples: TCAP analysis

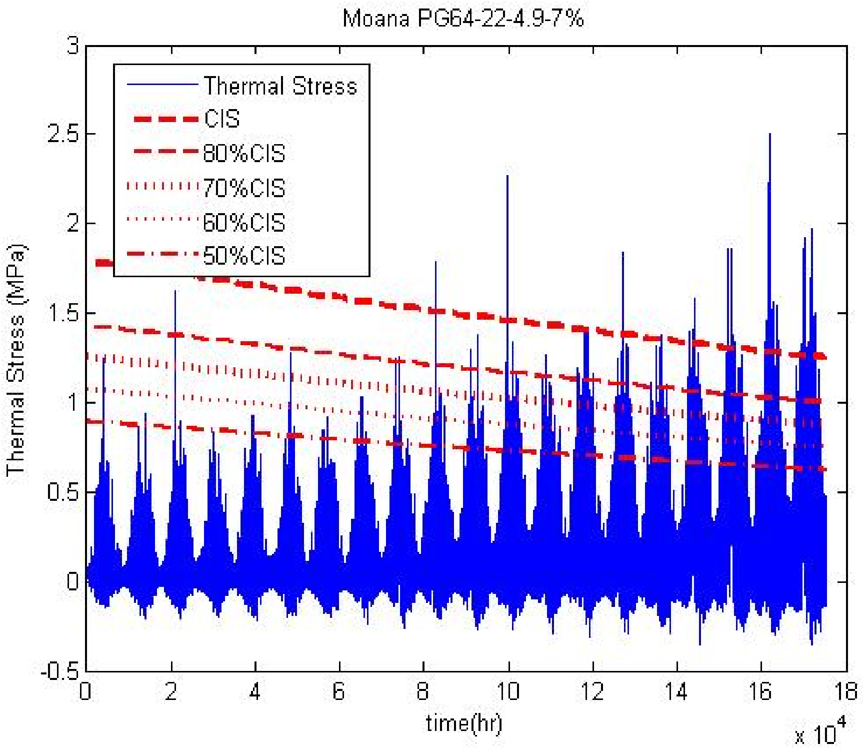
Effect of Mixtures Air Voids

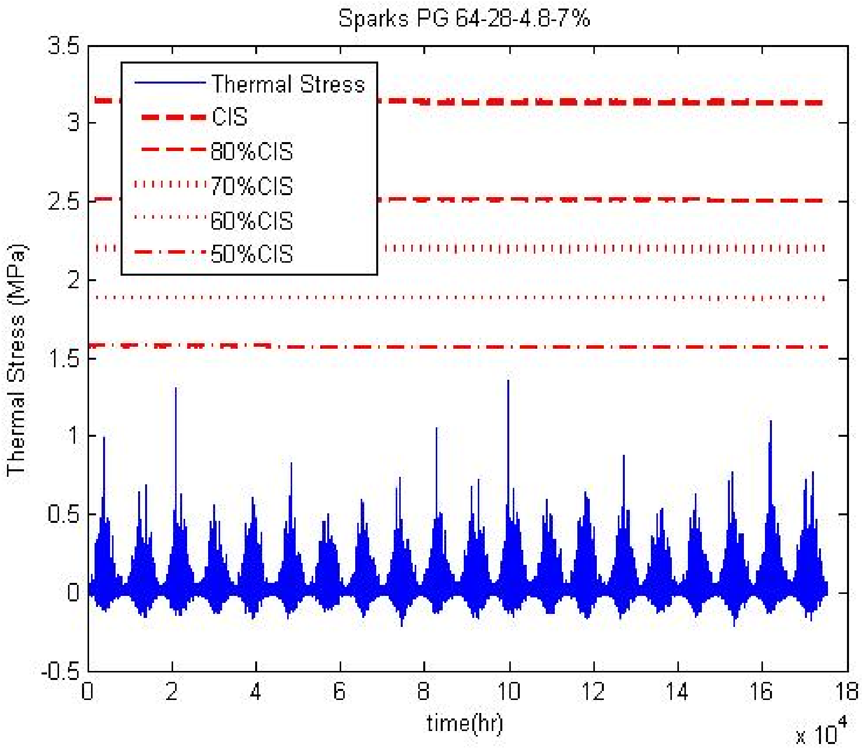


Cracking likelihoods increase for mixture with higher air voids level....

Examples: TCAP analysis

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

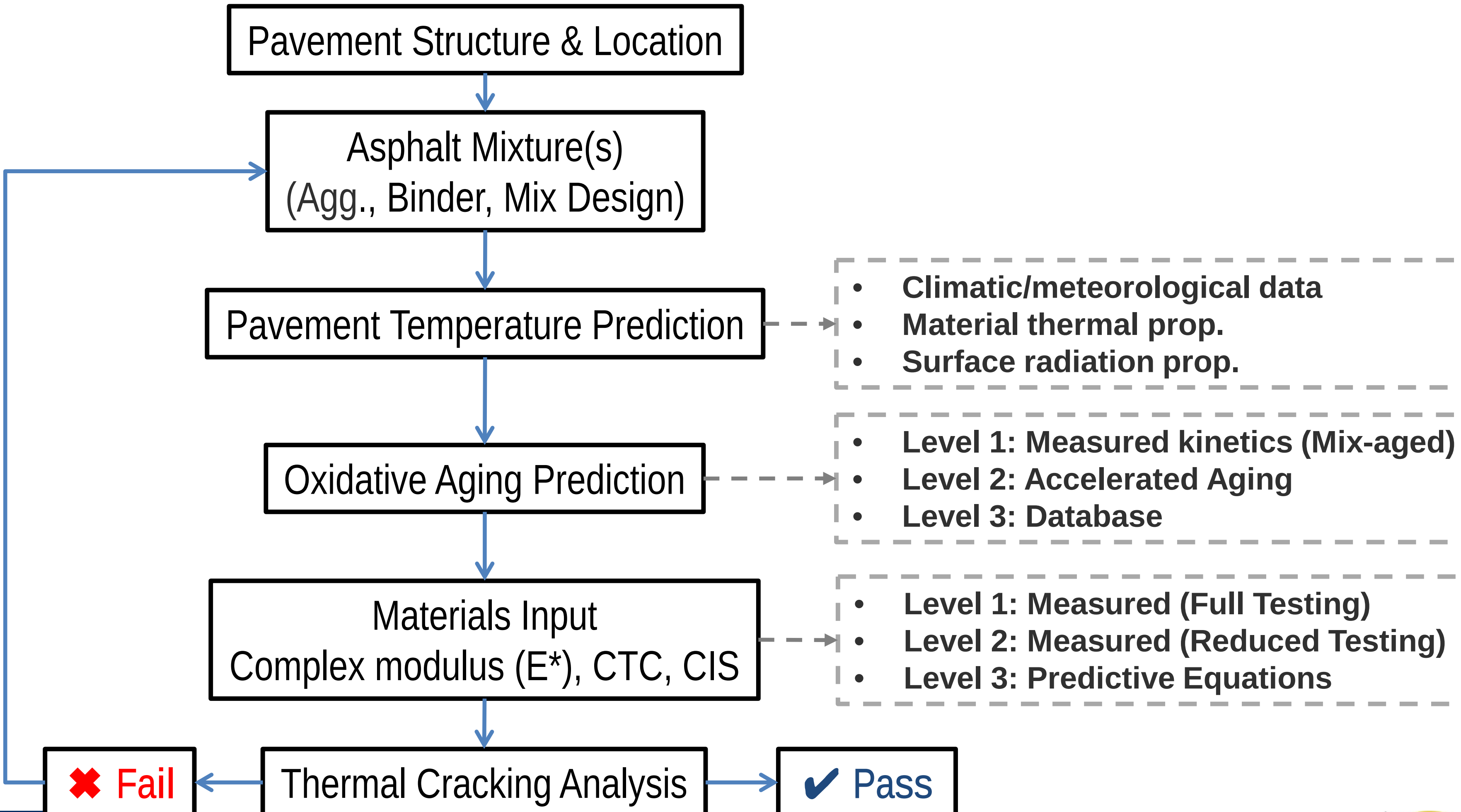




Un-modified
PG64-22 (Moana, 2006)

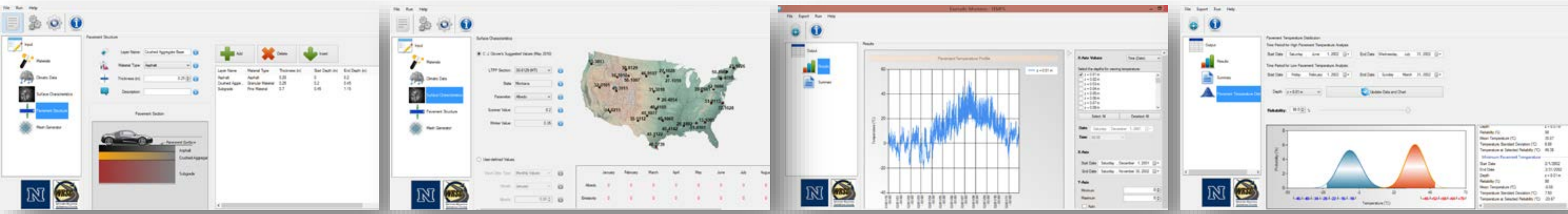
SBS polymer-modified
PG64-28 (Sparks, 2008)

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.

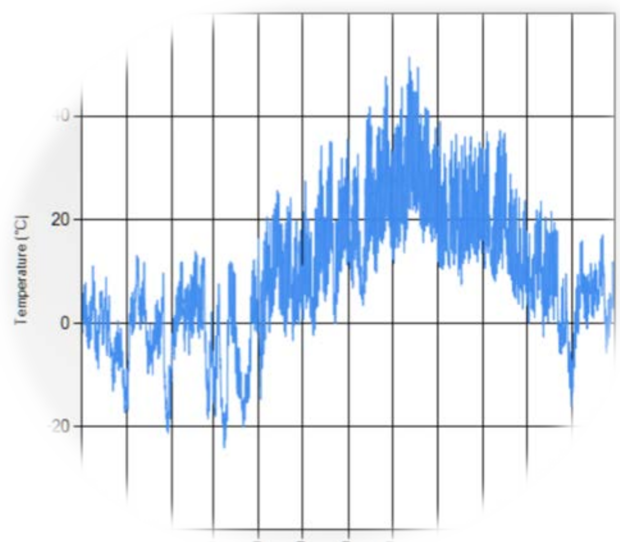


Pavement Temperature Profile Prediction

Temperature Estimate Model for Pavement Structures

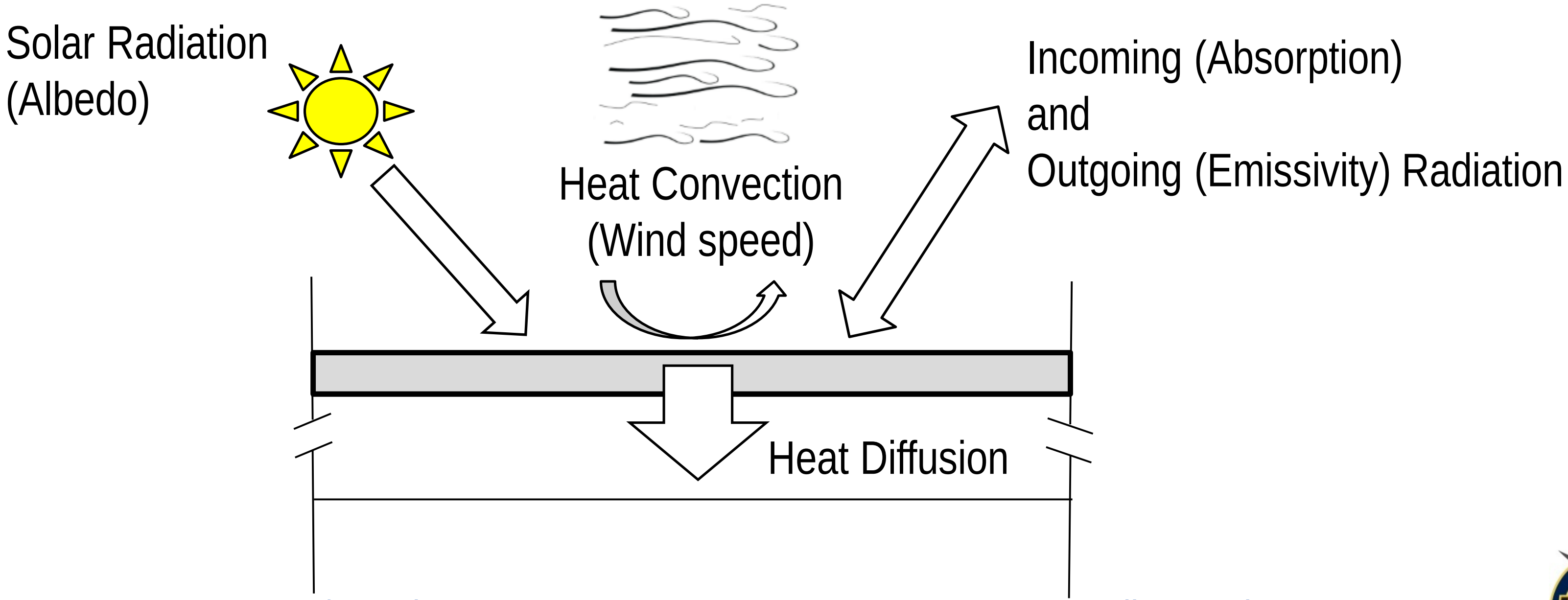
— TEMPS —

http://www.arc.unr.edu/Software.html



Pavement Temperature Profile Prediction

- Improvement of the *Heat Transfer* model [Han et al., 2011 (TAMU)]
  - Enhanced boundary conditions.
  - Variable pavement surface radiation properties.
- Application of Finite Control Volume method (FCV) with Implicit Scheme [Zia et al., 2014 (UNR)]



Heat Transfer Balance Between Pavement Structure & Surrounding Environment

Pavement Temperature Profile Prediction

Standalone Software: TEMPS (Alpha Version 0.0.1)

www.arc.unr.edu/Software.html

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Software

3D-Move Analysis
PANDA Model
TEMPS

Free Softwares

TEMPS Software (Version 0.0.1)
Release Date: December 2014

The research team at the University of Nevada, Reno has developed a new time-efficient software program that predicts the hourly temperature history at any depth in the asphalt pavement for any location in the United States. The software, called **Temperature Estimate Model for Pavement Structures (TEMPS)**, make use of the Finite Control Volume Method (FCVM) with the fully implicit scheme to remedy some of the known limitations in the current pavement temperature profile models. TEMPS suggests the use of meteorological data such as solar radiation and considers monthly variation in pavement surface radiation properties (albedo, emissivity, and absorption coefficients). The implemented improvements led to good agreement between the predicted pavement temperature profiles and selected LTPP SMP sites. The TEMPS model is a unique software and can have numerous applications in pavement engineering. For instance, accurate prediction of pavement temperatures, over time and with depth, is critical particularly in mechanistic modeling of thermal cracking.

To install the software:
1. *Download* the TEMPS Windows Installer Package;
2. Run Setup.exe file associated with the TEMPS program.

Simply follow the on-screen directions to install *TEMPS (Version 0.0.1)*. Click *Next* to start the installation on the Welcome screen.

Version

TEMPS
(Temperature Estimate Model for Pavement Structures)
Version 0.0.1 (Alpha Version)

Developed at:
University of Nevada, Reno

Contact

Homepage:
http://wrsc.unr.edu/

Email:
elieh@unr.edu

Disclaimer

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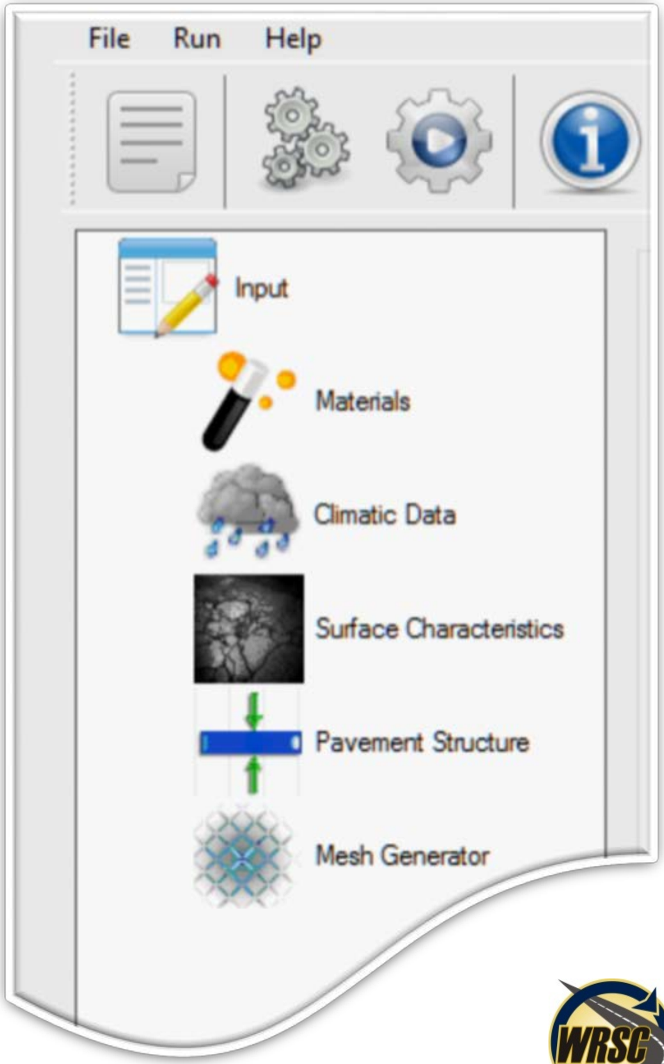
Pavement Temperature Profile Prediction

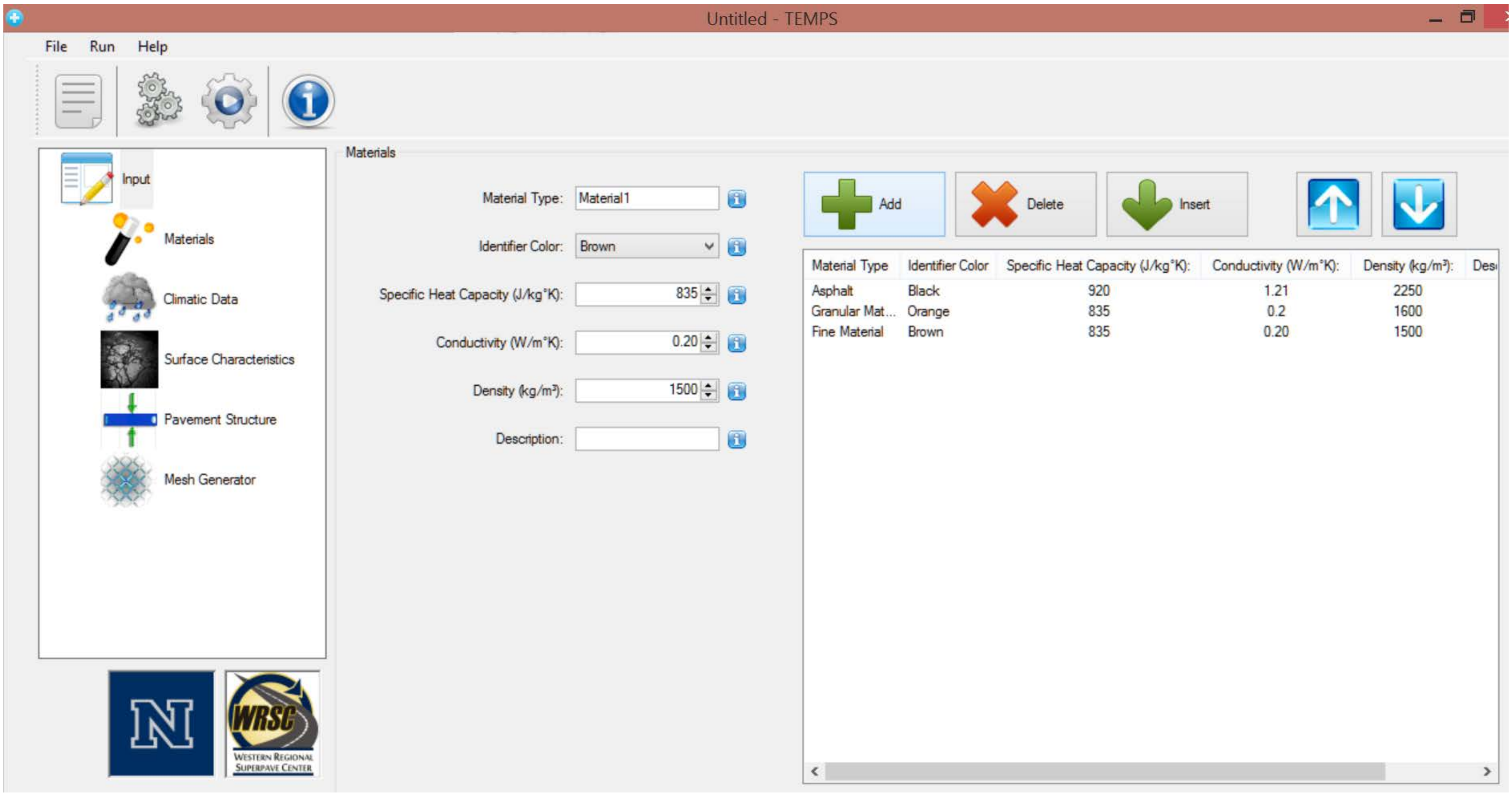
TEMPS – Input

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



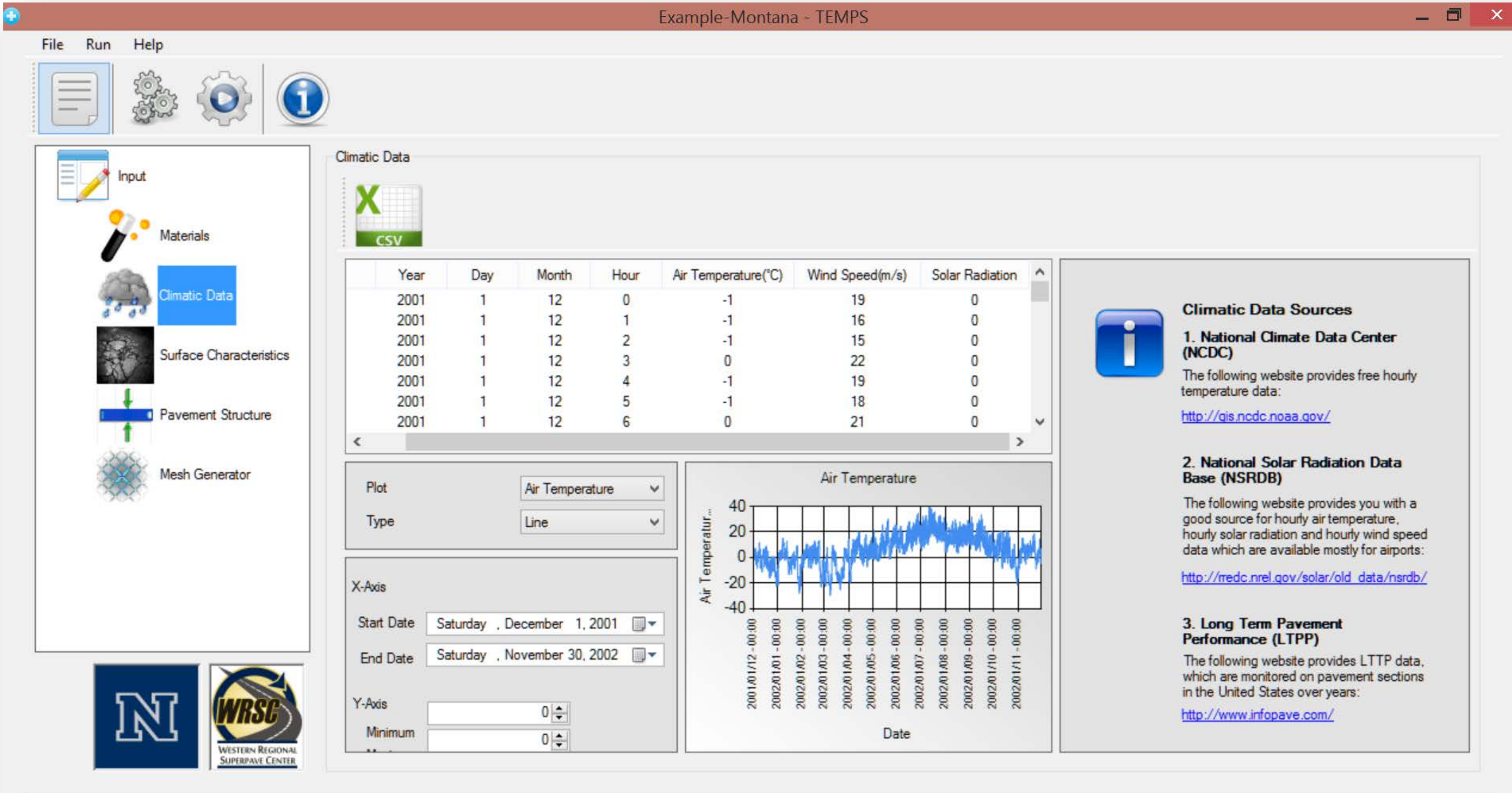
Pavement Temperature Profile Prediction

TEMPS – Materials



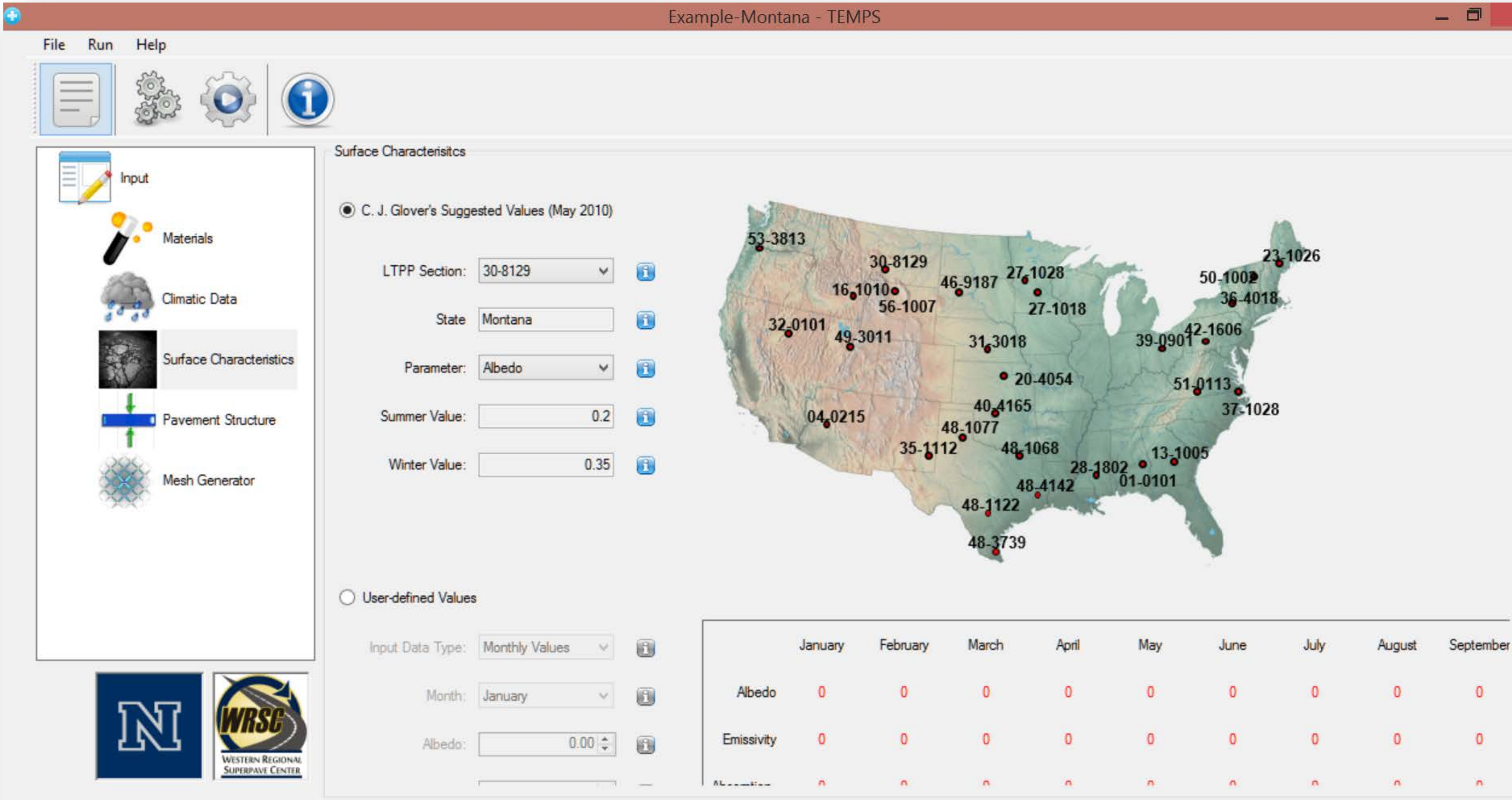
Pavement Temperature Profile Prediction

TEMPS – Climatic Data



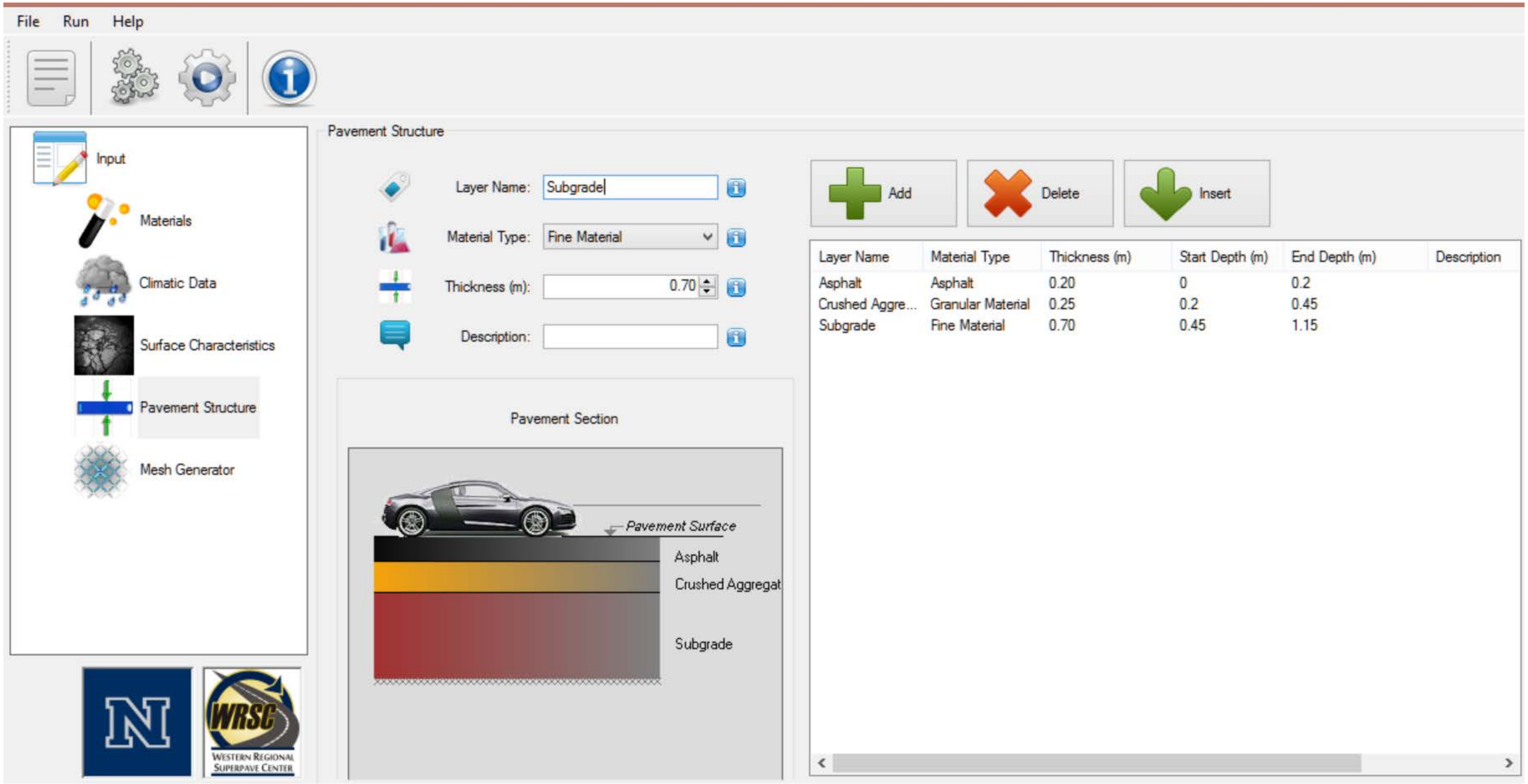
Pavement Temperature Profile Prediction

TEMPS – Surface Characteristics

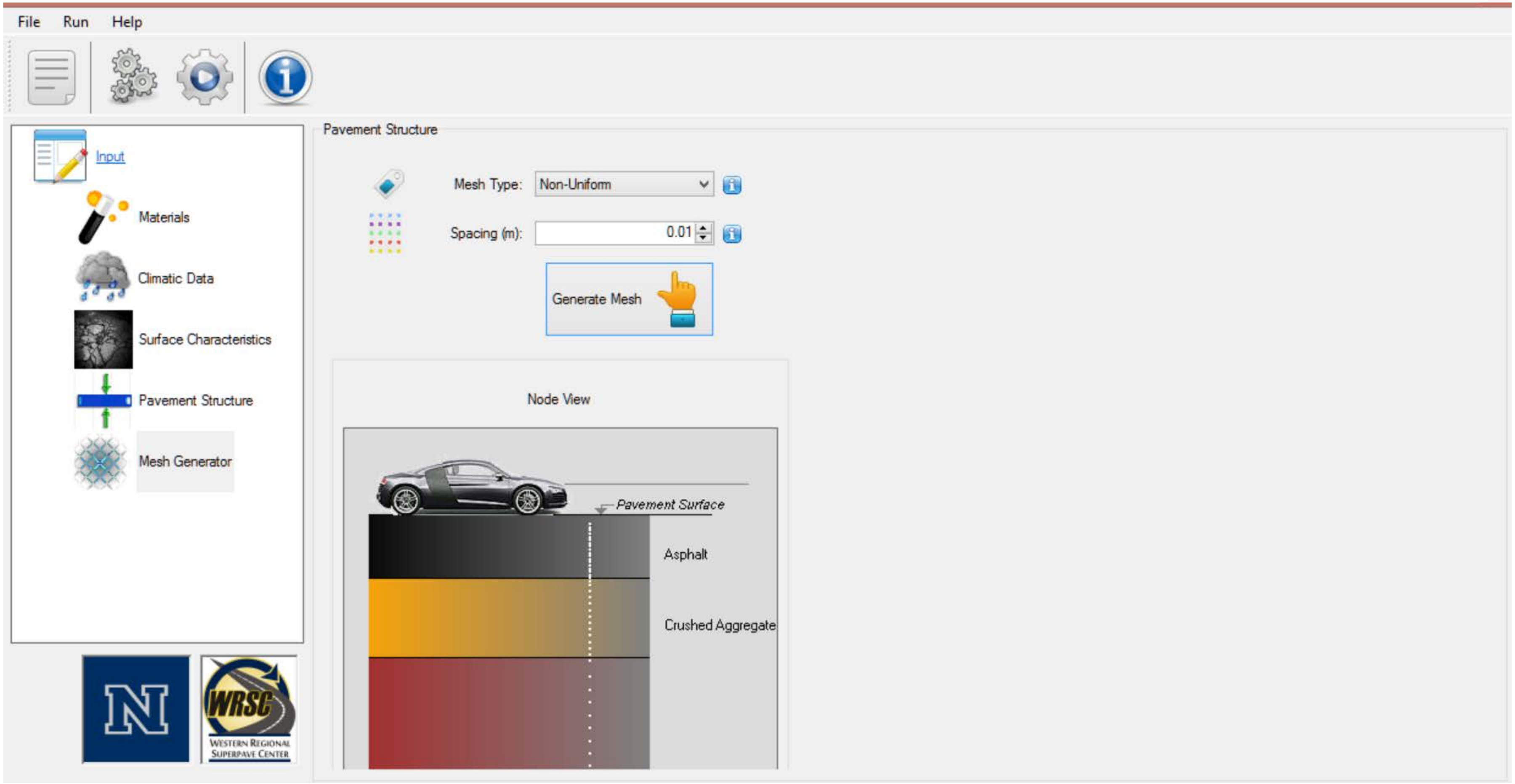


Pavement Temperature Profile Prediction

TEMPS – Pavement Structure

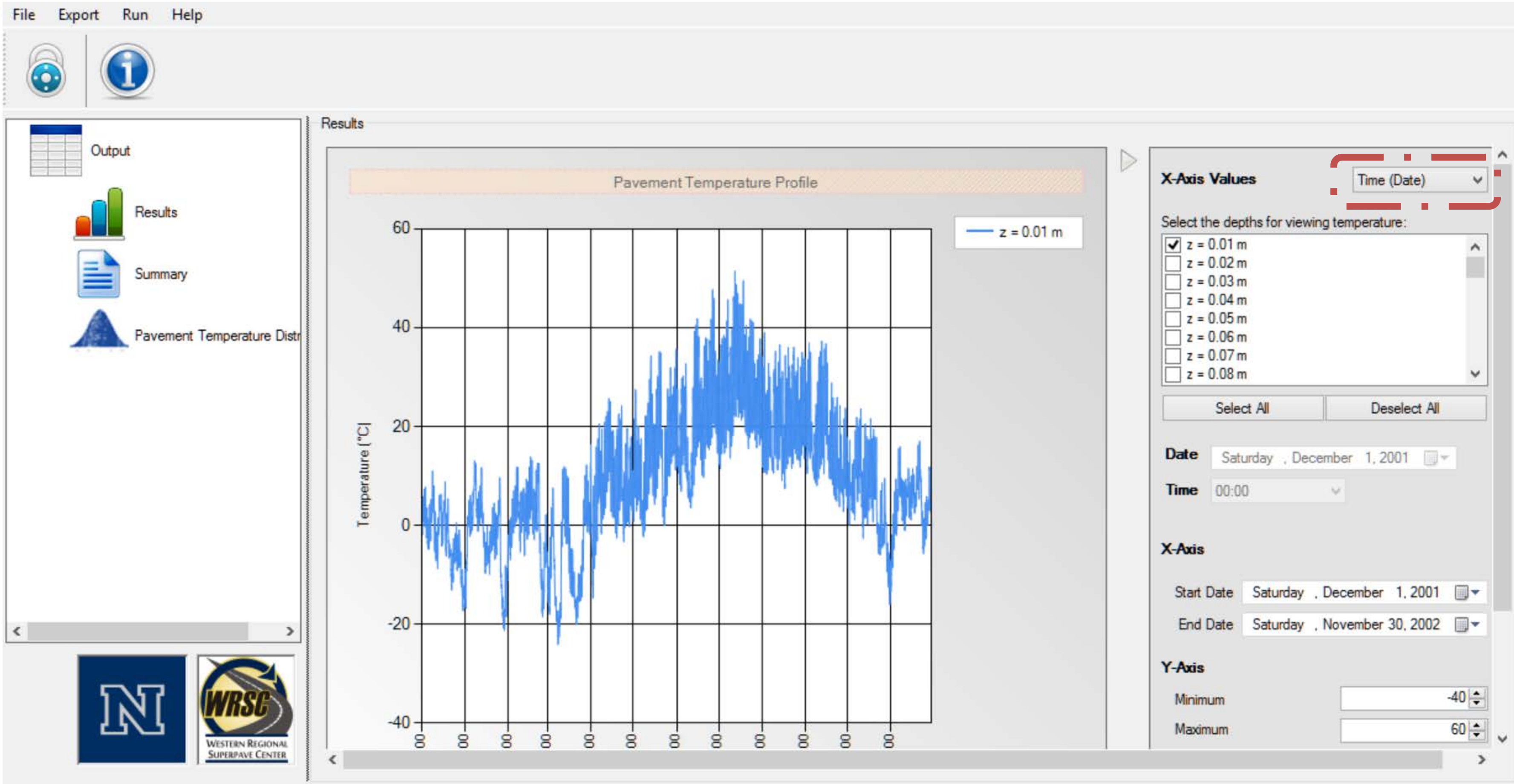


Pavement Temperature Profile Prediction
TEMPS – Mesh Generator



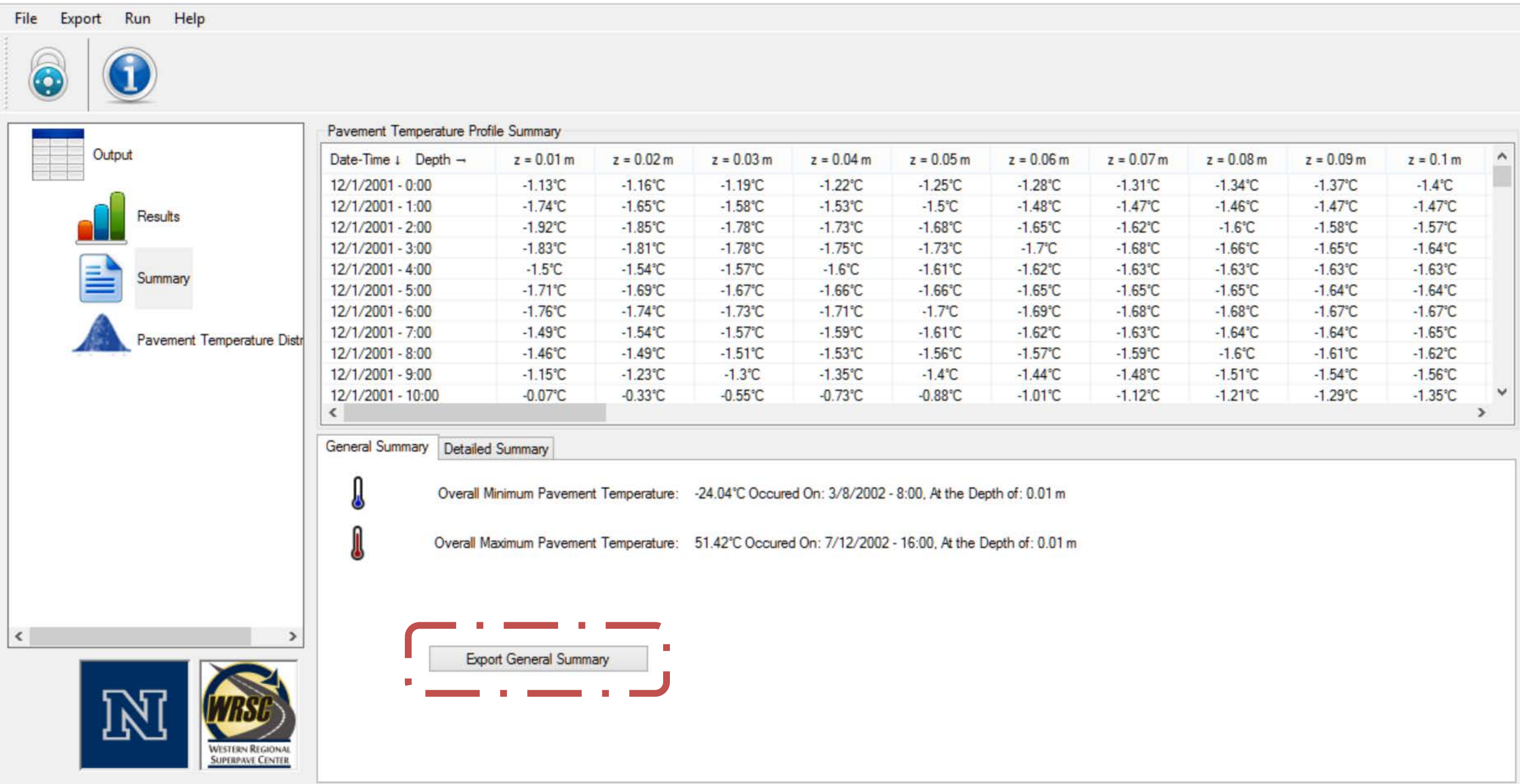
Pavement Temperature Profile Prediction

TEMPS – Output Results



Pavement Temperature Profile Prediction

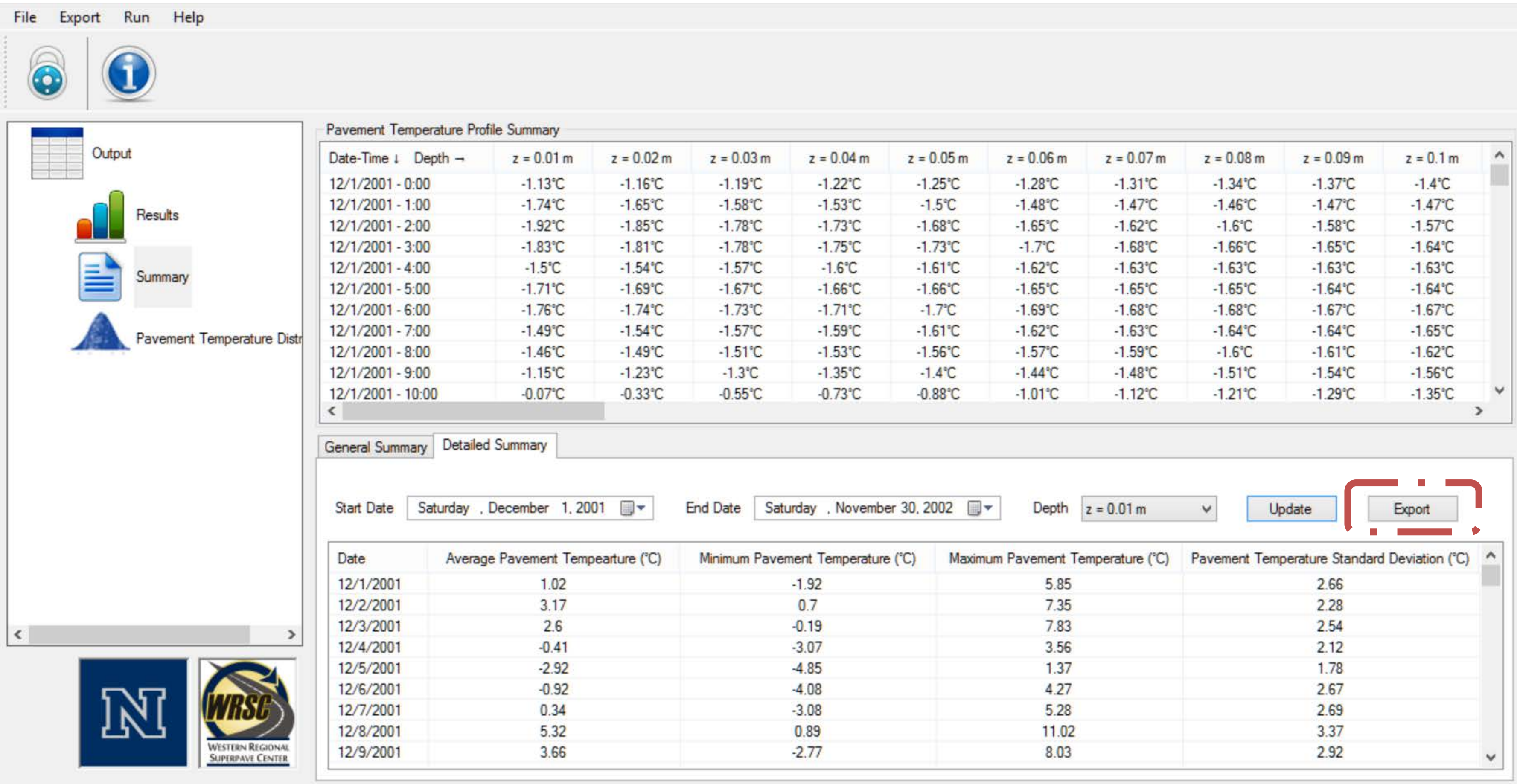
TEMPS – Output Summary



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	-1.13°C	-1.16°C	-1.19°C	-1.22°C	-1.25°C	-1.28°C	-1.31°C	-1.34°C	-1.37°C	-1.4°C
12/1/2001 - 1:00	-1.74°C	-1.65°C	-1.58°C	-1.53°C	-1.5°C	-1.48°C	-1.47°C	-1.46°C	-1.47°C	-1.47°C
12/1/2001 - 2:00	-1.92°C	-1.85°C	-1.78°C	-1.73°C	-1.68°C	-1.65°C	-1.62°C	-1.6°C	-1.58°C	-1.57°C
12/1/2001 - 3:00	-1.83°C	-1.81°C	-1.78°C	-1.75°C	-1.73°C	-1.7°C	-1.68°C	-1.66°C	-1.65°C	-1.64°C
12/1/2001 - 4:00	-1.5°C	-1.54°C	-1.57°C	-1.6°C	-1.61°C	-1.62°C	-1.63°C	-1.63°C	-1.63°C	-1.63°C
12/1/2001 - 5:00	-1.71°C	-1.69°C	-1.67°C	-1.66°C	-1.66°C	-1.65°C	-1.65°C	-1.65°C	-1.64°C	-1.64°C
12/1/2001 - 6:00	-1.76°C	-1.74°C	-1.73°C	-1.71°C	-1.7°C	-1.69°C	-1.68°C	-1.68°C	-1.67°C	-1.67°C
12/1/2001 - 7:00	-1.49°C	-1.54°C	-1.57°C	-1.59°C	-1.61°C	-1.62°C	-1.63°C	-1.64°C	-1.64°C	-1.65°C
12/1/2001 - 8:00	-1.46°C	-1.49°C	-1.51°C	-1.53°C	-1.56°C	-1.57°C	-1.59°C	-1.6°C	-1.61°C	-1.62°C
12/1/2001 - 9:00	-1.15°C	-1.23°C	-1.3°C	-1.35°C	-1.4°C	-1.44°C	-1.48°C	-1.51°C	-1.54°C	-1.56°C
12/1/2001 - 10:00	-0.07°C	-0.33°C	-0.55°C	-0.73°C	-0.88°C	-1.01°C	-1.12°C	-1.21°C	-1.29°C	-1.35°C

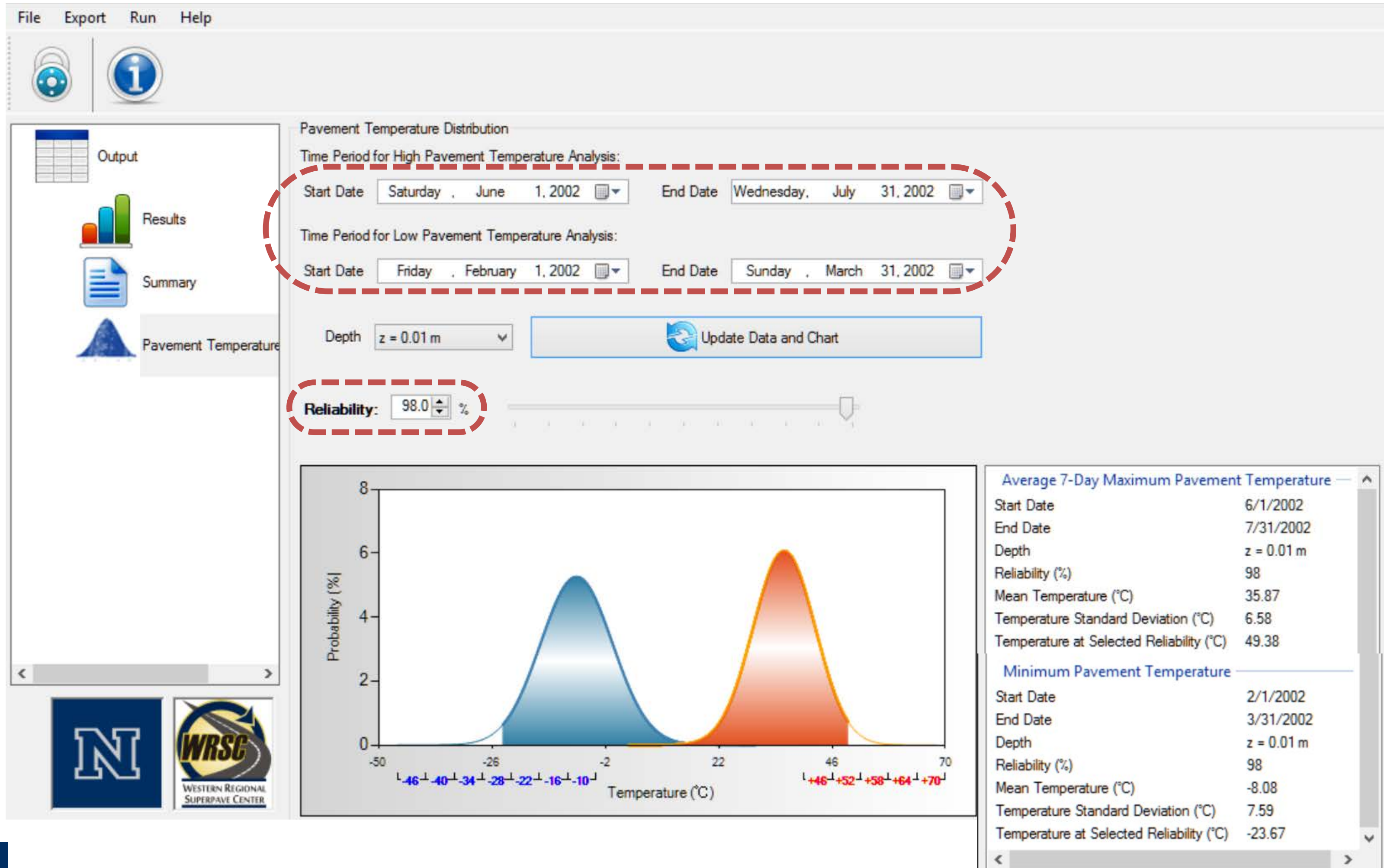
Pavement Temperature Profile Prediction

TEMPS – Output Summary



Pavement Temperature Profile Prediction

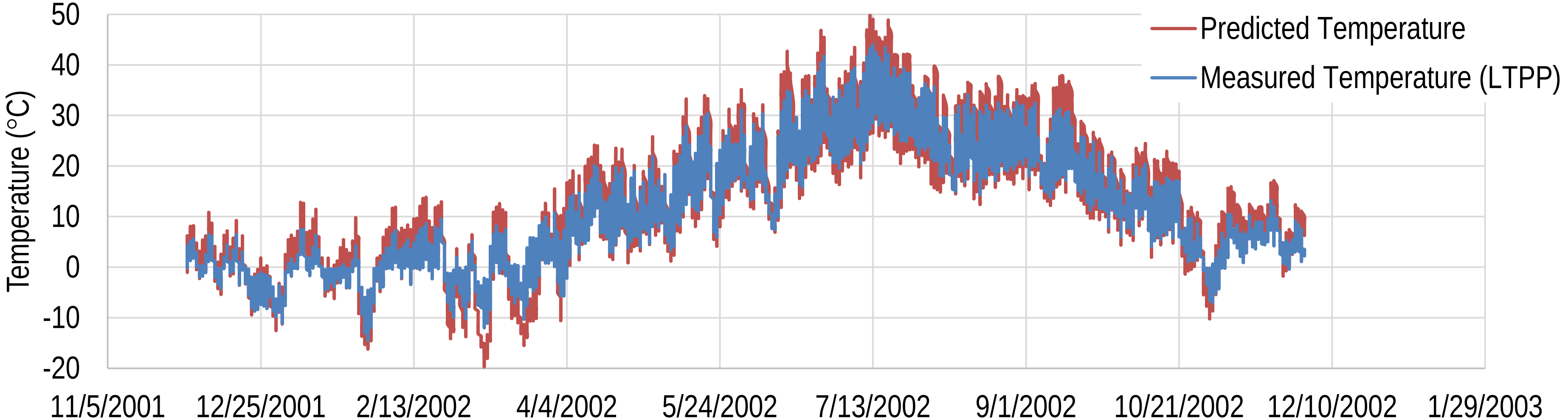
TEMPS – Pavement Temperature Distribution

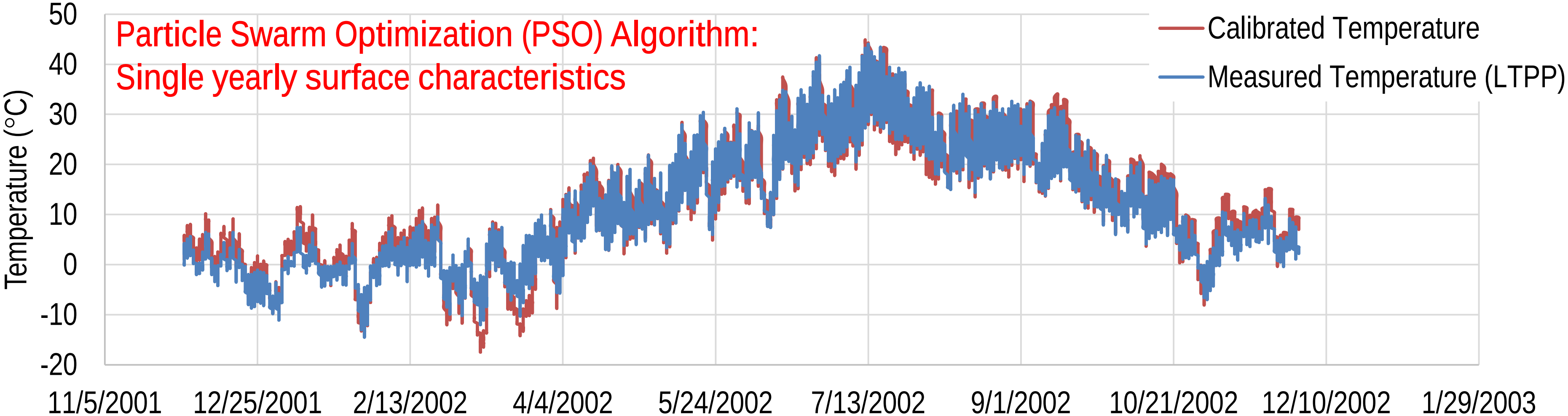


Pavement Temperature Profile Prediction

TEMPS – Predicted versus Measured

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





TEMPS – Additional Improvements

- Calibration: Optimize the surface characteristics (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 pavement cooling/warming rates

Thank You!

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Thank You!