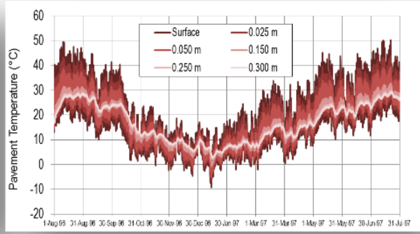
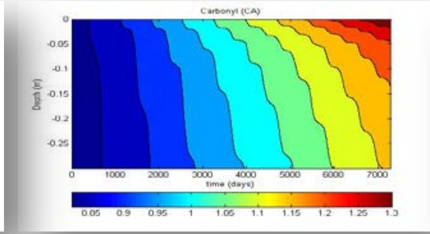
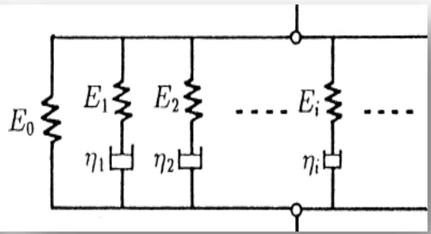
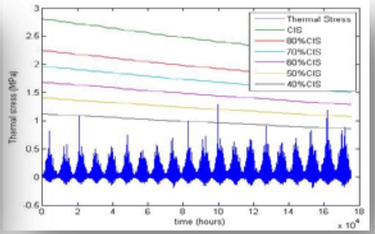




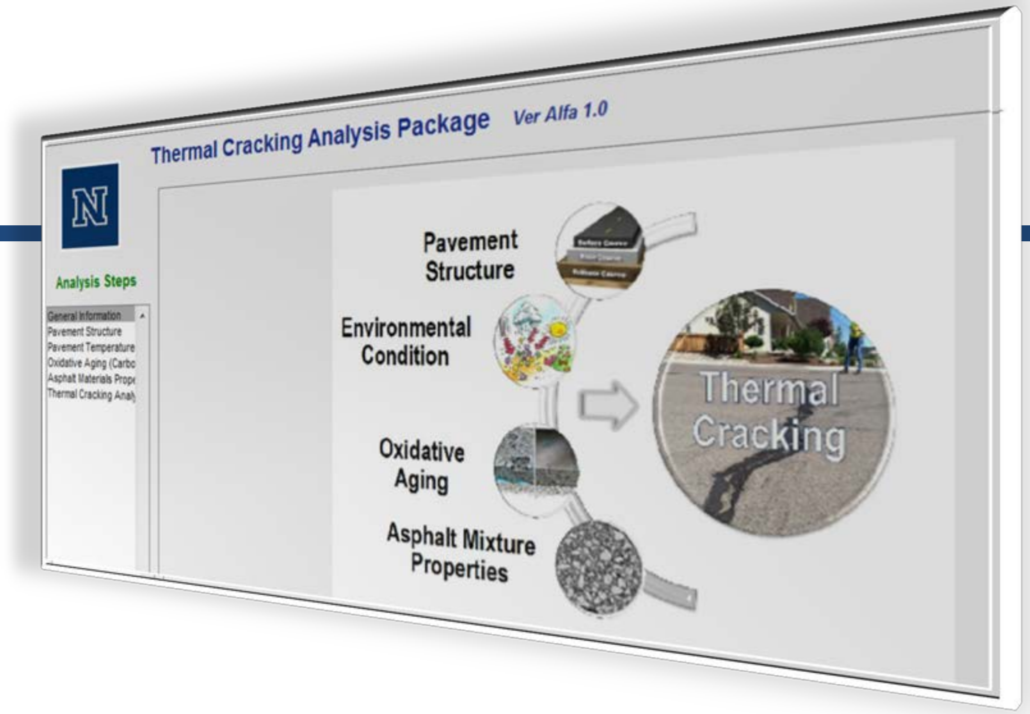




Thermal Cracking Analysis Model AND Pavement Temperature Profile Prediction Model

Elie Y. Hajj, Assistant Professor, UNR
M. Zia Alavi, Ph.D., Postdoctoral Scholar, UC Davis
Nathan Morian, Ph.D., Nevada DOT
S. Farzan Kazemi, Grad. Research Assistant, UNR
Peter E. Sebaaly, Professor, UNR

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

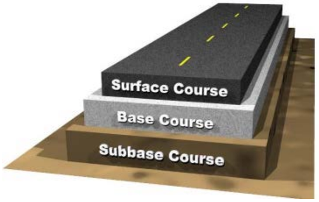


Comprehensive Evaluation of Thermal Cracking in Asphalt Pavements

THERMAL CRACKING ANALYSIS PACKAGE (TCAP)

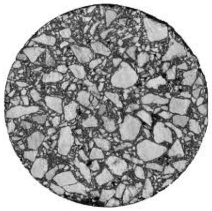
Influential Factors

- 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.

- **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

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)*

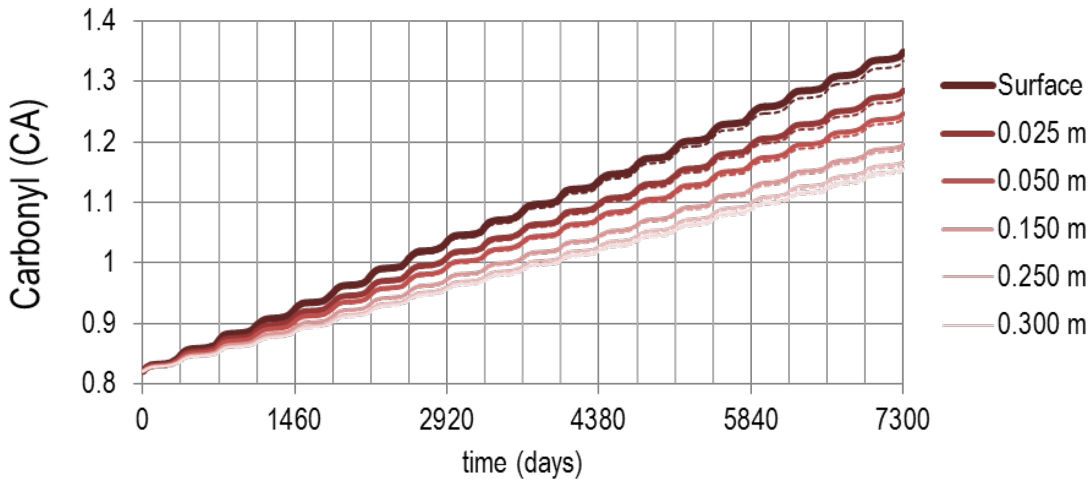
HS = 2.7 (1/CA)

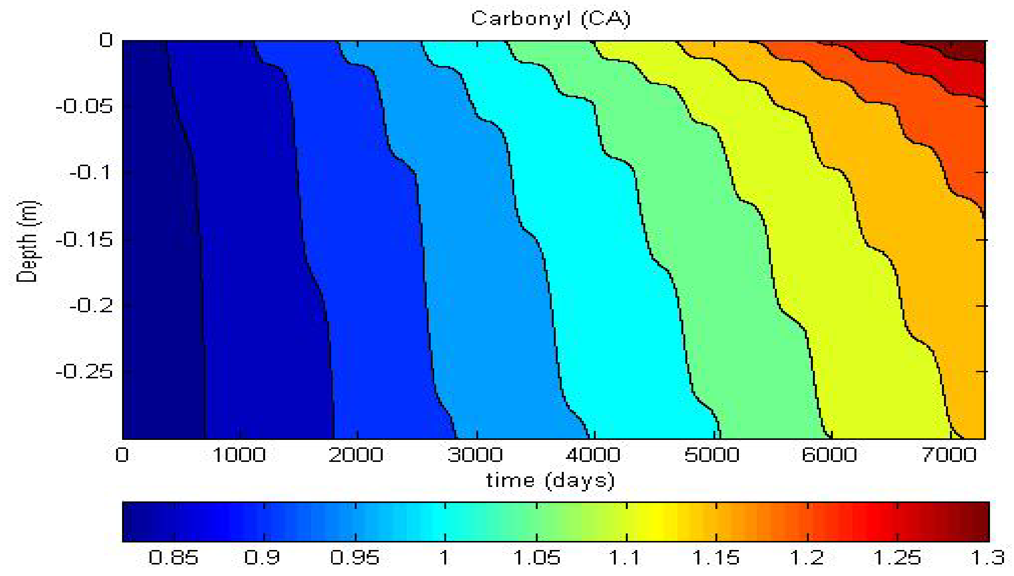
m = 9.24 (poise)

Air void diameter = 0.5 mm

Eff. aging zone = 1.0 mm

(film thickness)



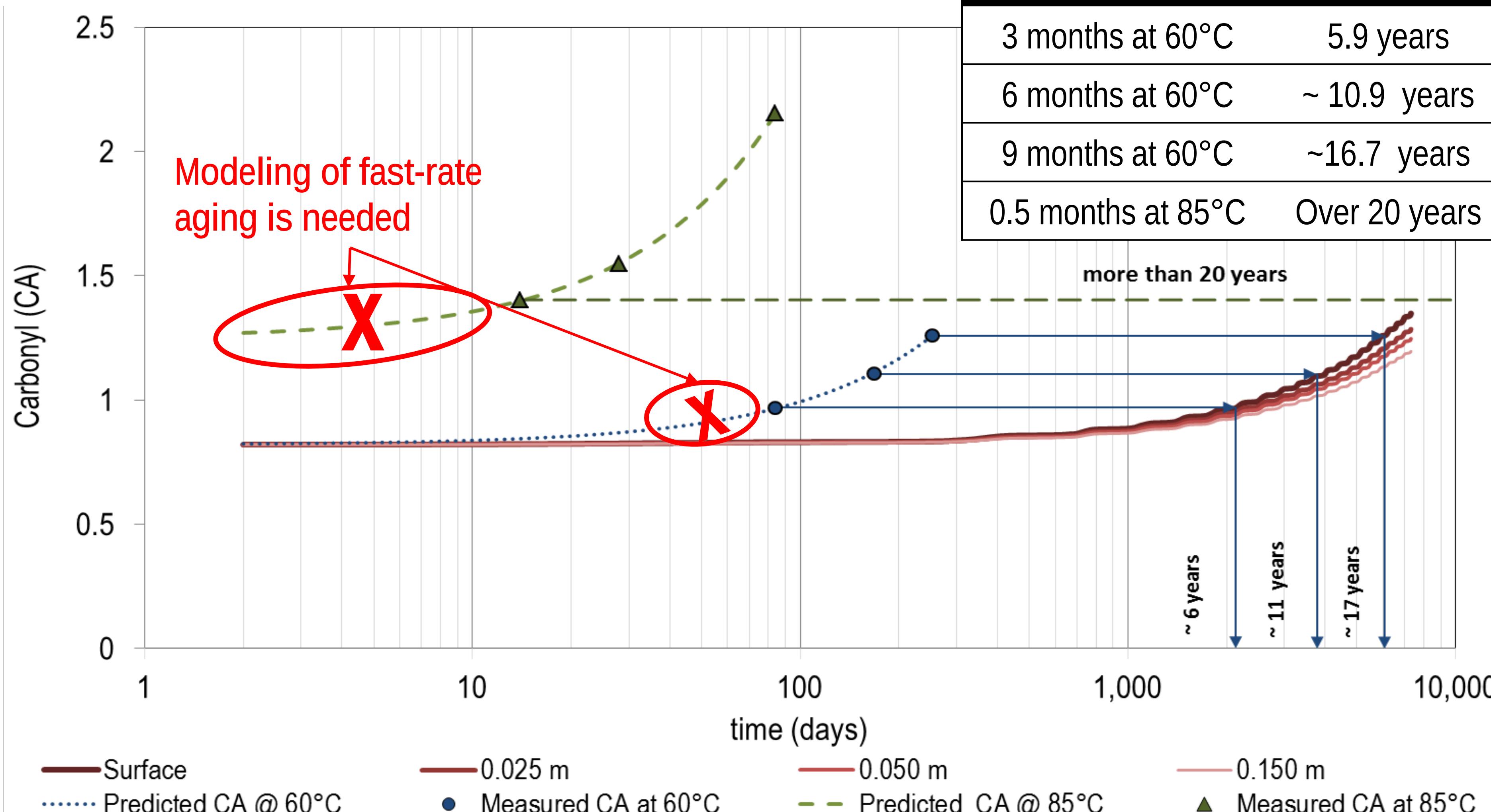


Thermal Cracking Analysis

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

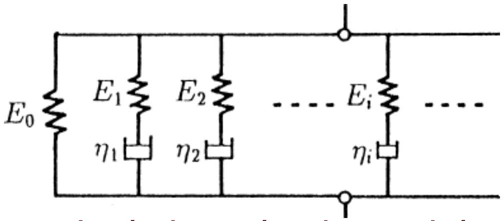
Age-Dependent Relaxation Modulus

- 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)*.

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

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

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

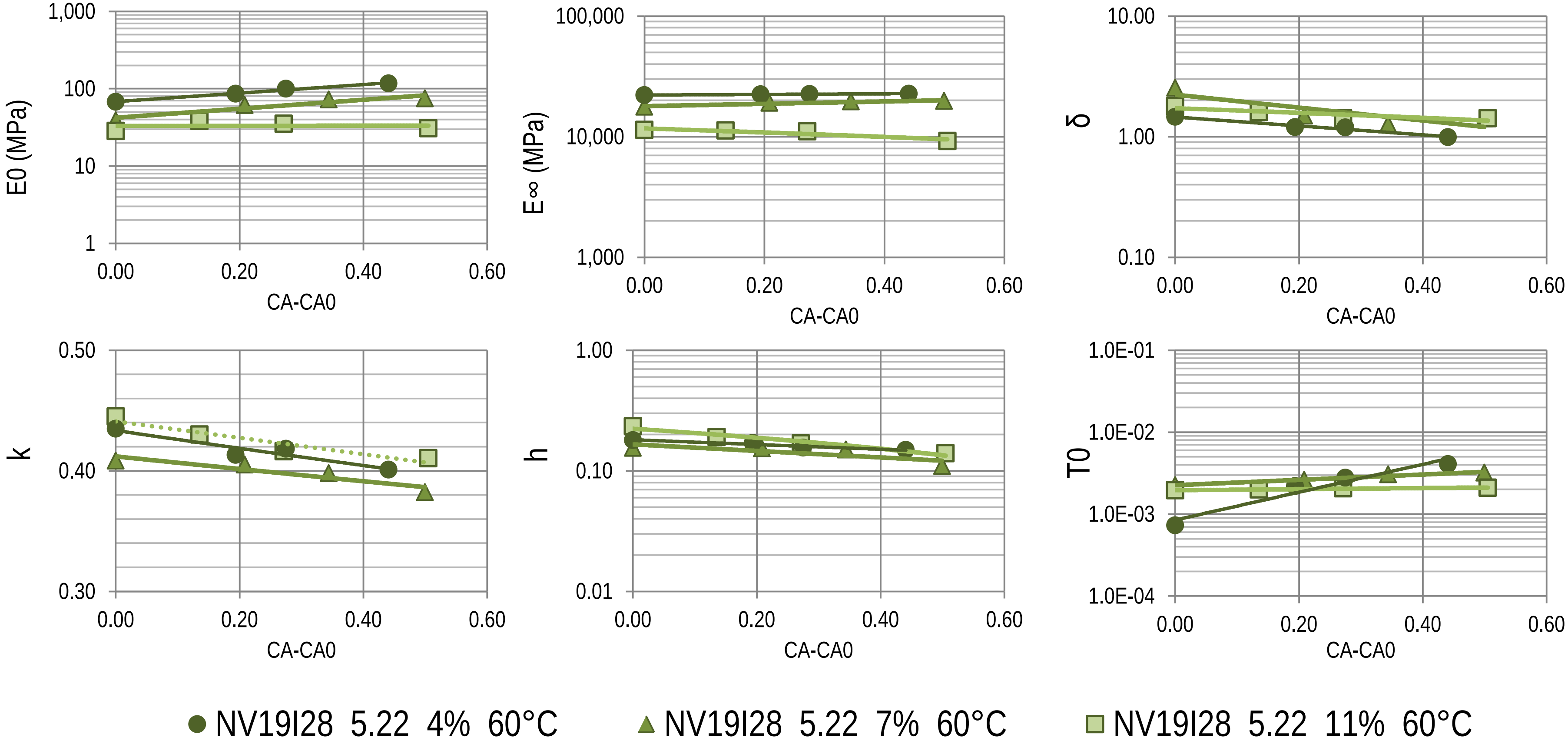


Ideal viscoelastic model

- ω: 2π*frequency, the pulsation
- E_0 : static modulus when $\omega \to 0$
- E_∞ : limit of complex modulus when $\omega \to \infty$,
- h, k : exponents such as 1>h>k>0,
- δ : dimensionless constant.
- β: dimensionless constant, $\beta = \eta . \tau^{-1} / (E_\infty - E_0)$; when $\omega \to 0$, 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!

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

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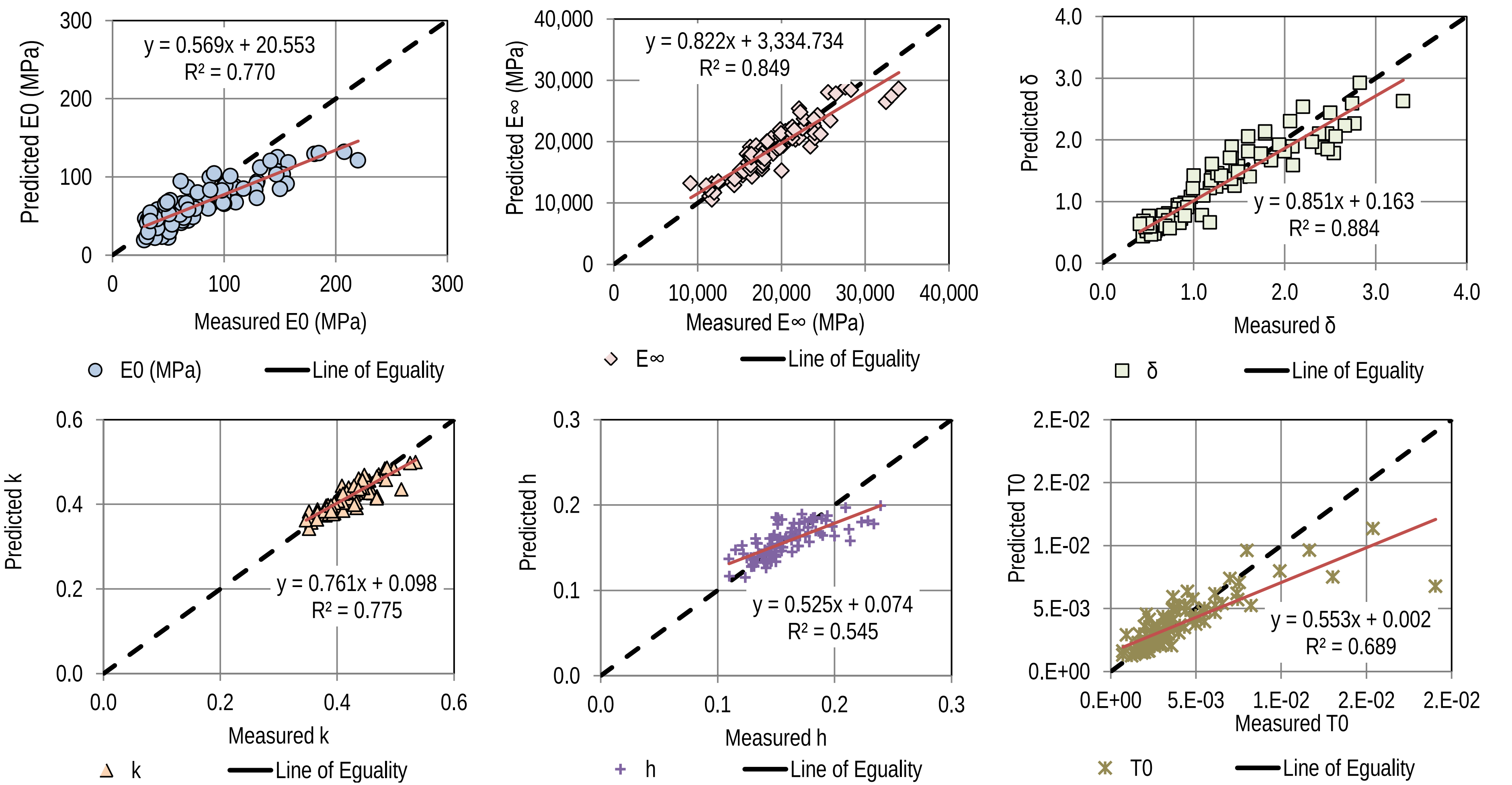
Evolution of 2S2P1D Coefficient with Aging

	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	√		√				√

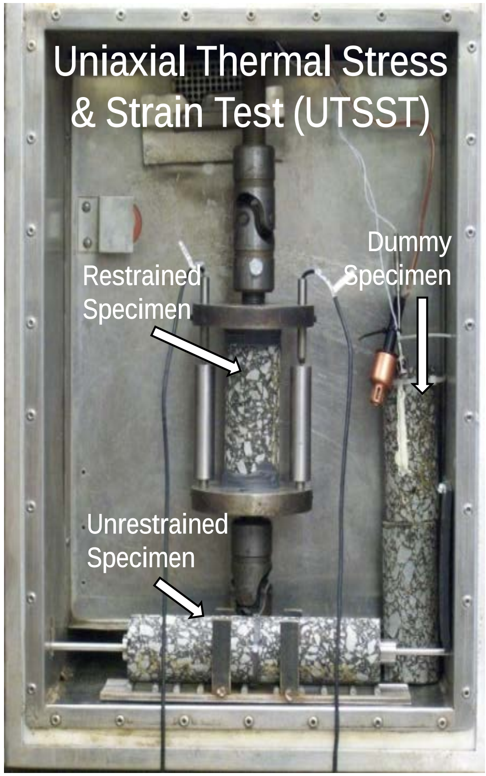
Thermal Cracking Analysis

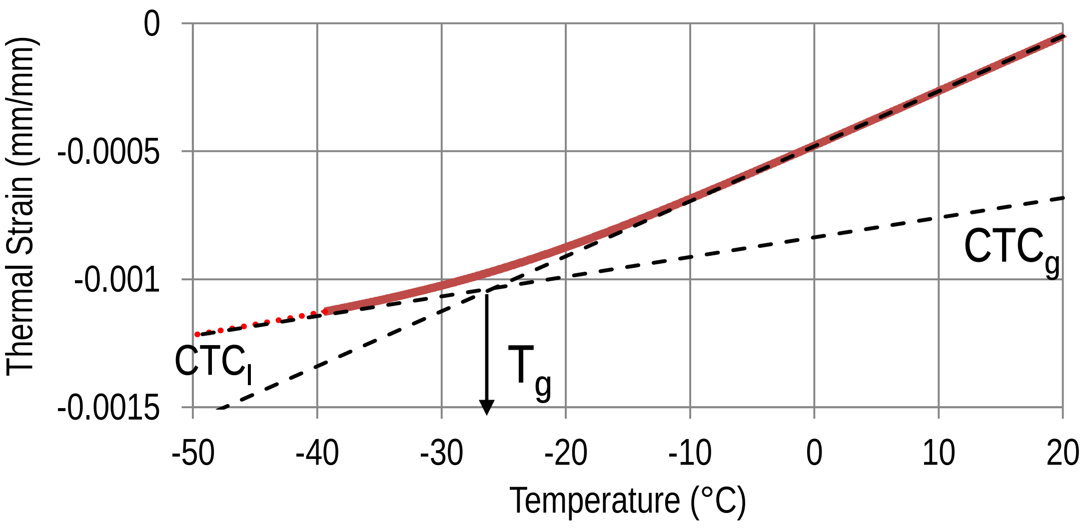
Evolution of 2S2P1D Coefficient with Aging



Thermal Cracking Analysis

Temperature and Age-Dependent CTC





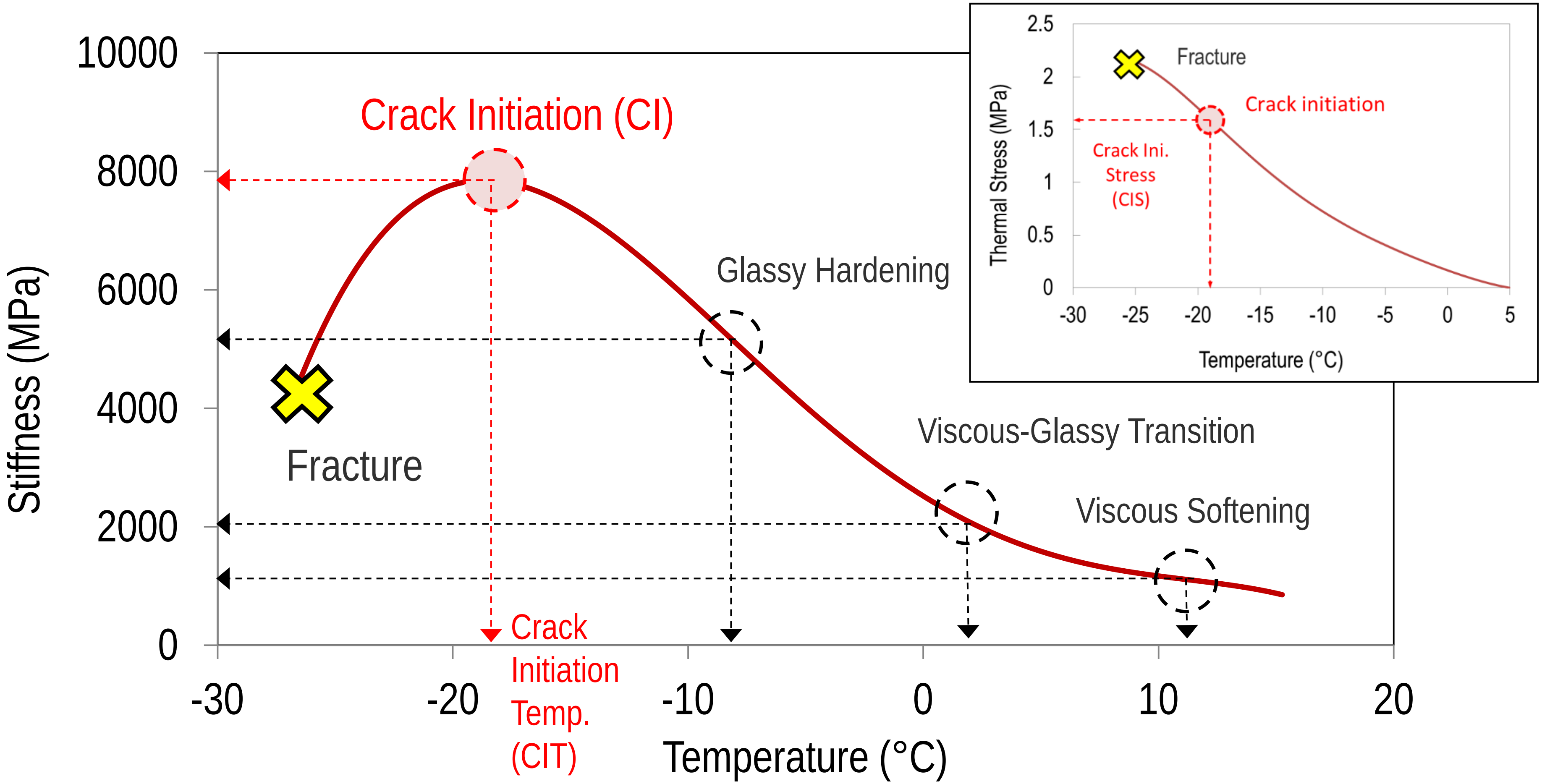
$$\varepsilon_{th} = \frac{\Delta l}{l_0} = C + CTC_g(T - T_g) + ln\left\{\left[1 + e^{\frac{(T-T_g)}{R}}\right]^{R(CTC_l - CTC_g)}\right\}$$

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

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

Thermal Cracking Analysis

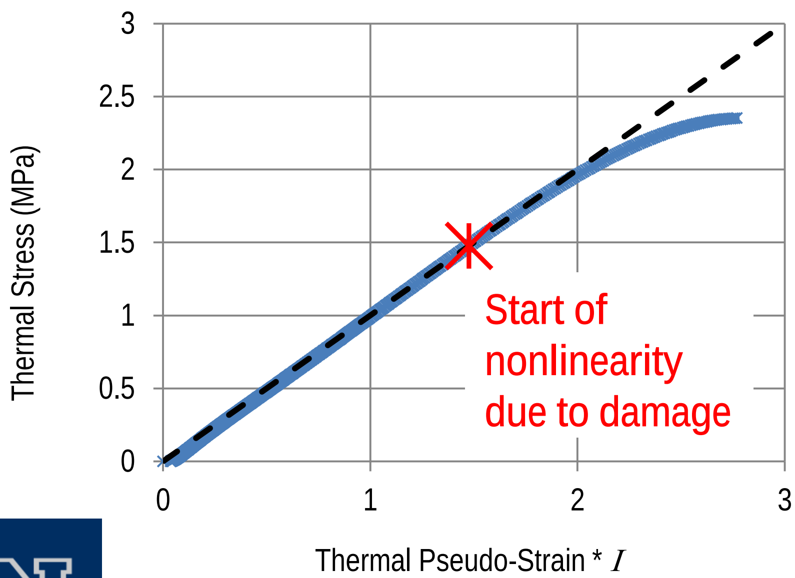
Age-Dependent Crack Initiation Stress (CIS)

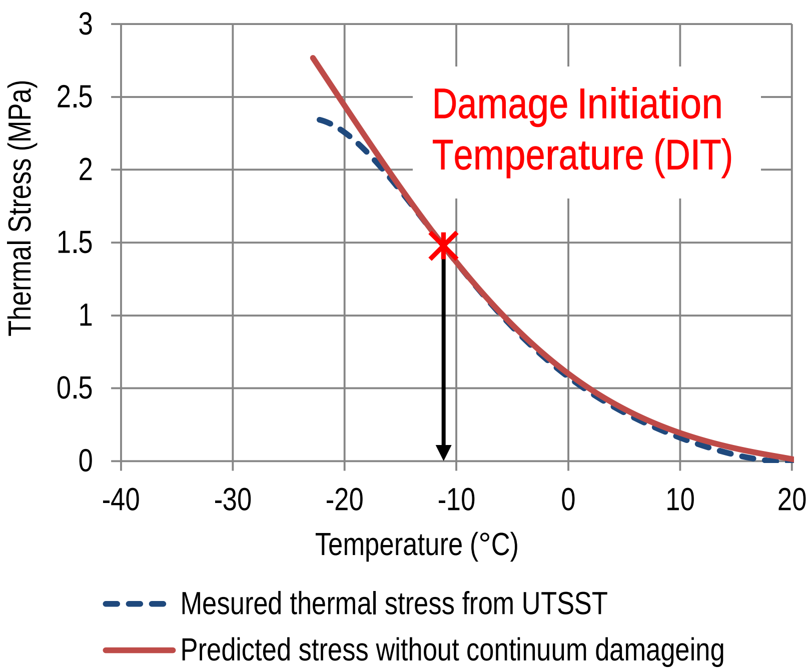


Age-Dependent Crack Initiation Stress (CIS)

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

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

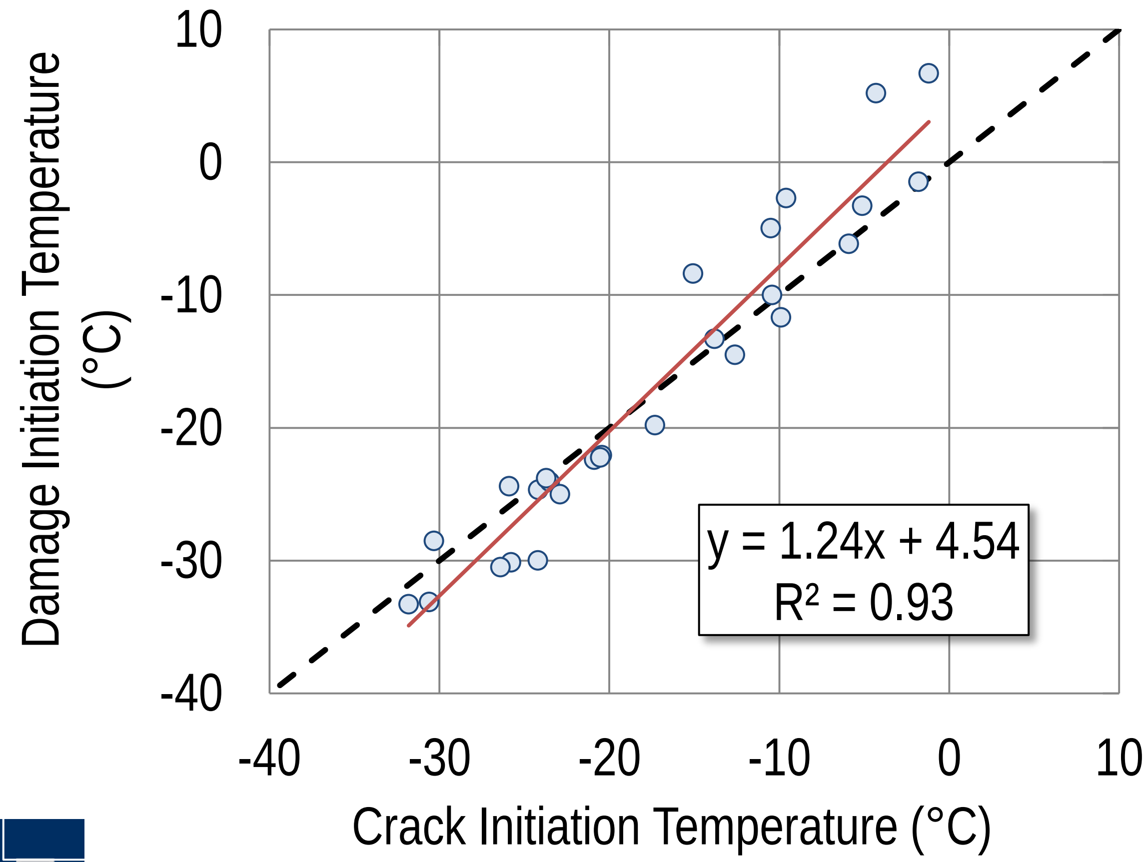




Thermal Cracking Analysis

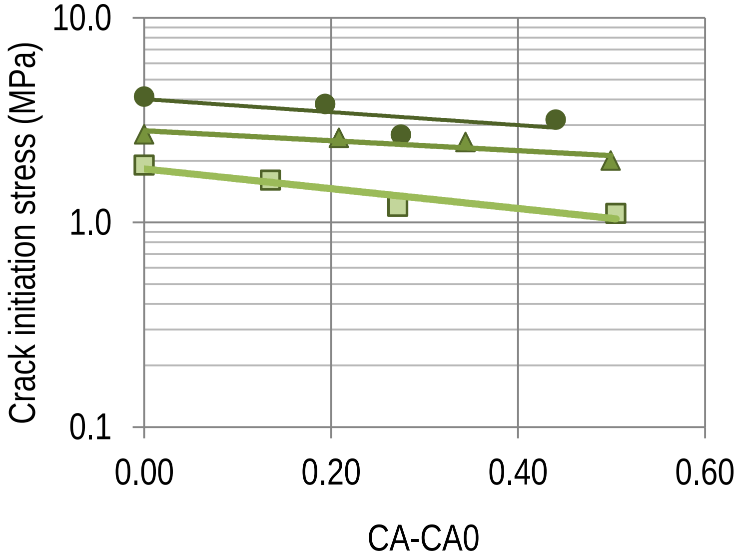
Age-Dependent Crack Initiation Stress (CIS)

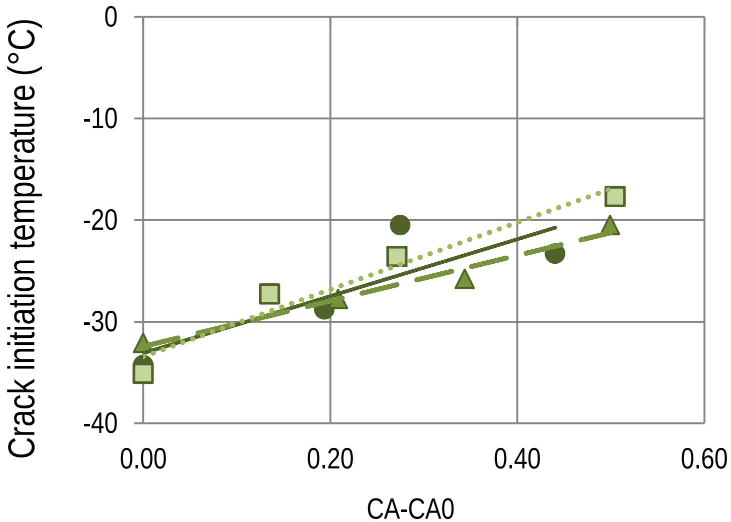
- Validation of CIS with VECD.



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

Age-Dependent Crack Initiation Stress (CIS)





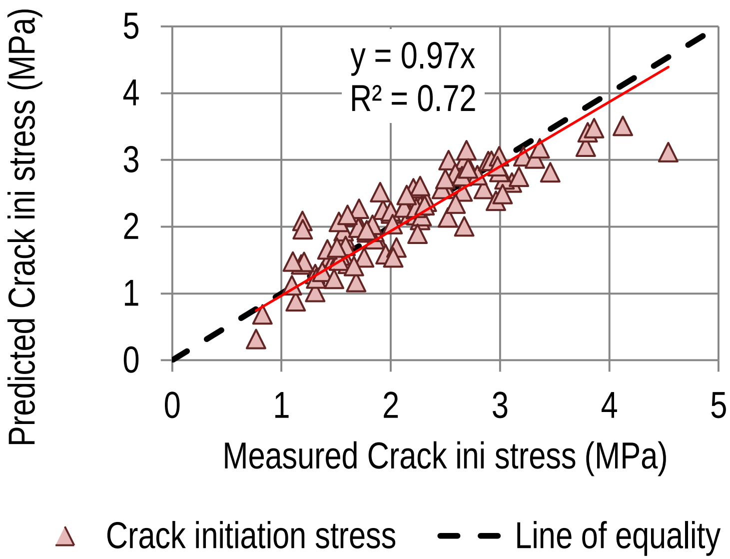
Similar trends were observed for all evaluated mixtures!

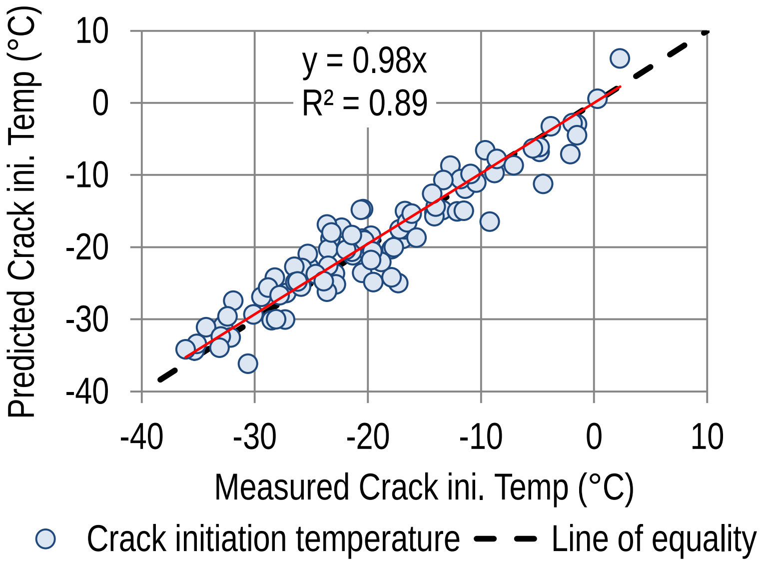
$$CIS = E \times e^{F(CA-CA_0)}$$

Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

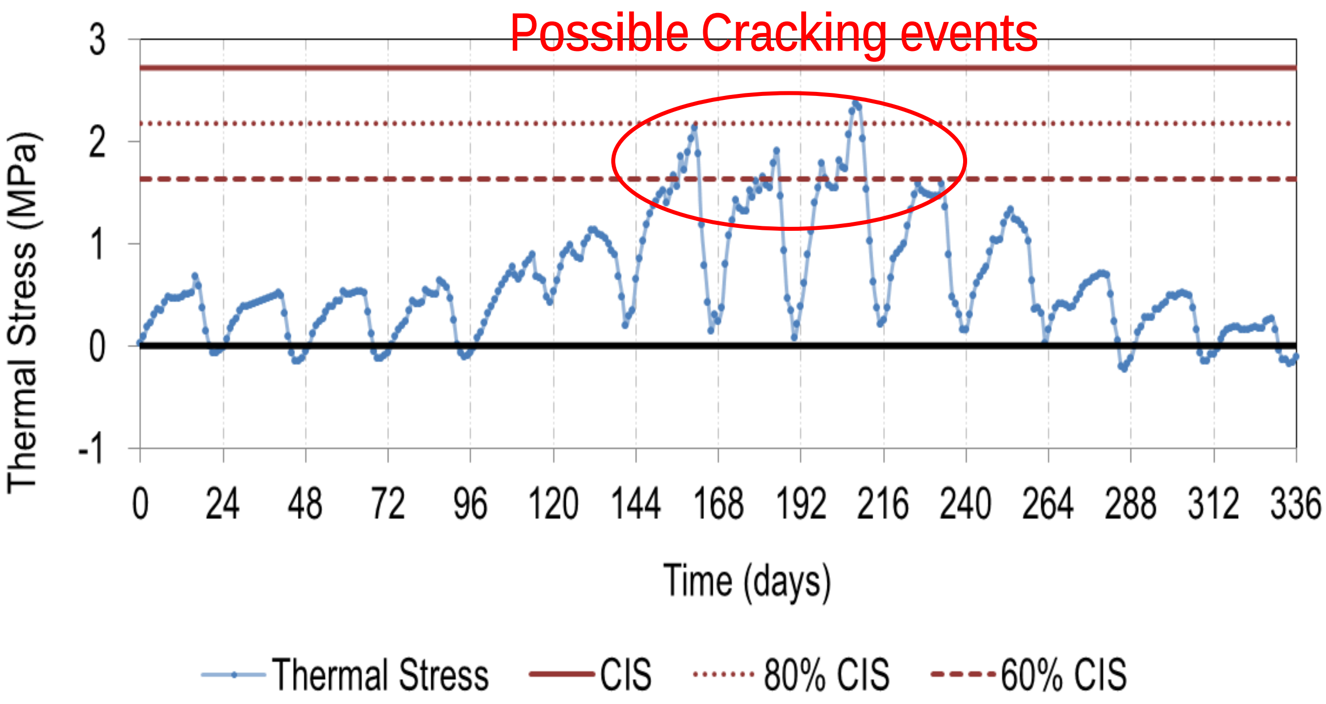
	Mixture variable						
	CA	Va (%)	Abs. (%)	LSV_{Tank} (poise)	B.C. (%)	Retained # 8	Passing # 200
CIS	√	√	√	√			√
CIT	√	√		√	√	√	√





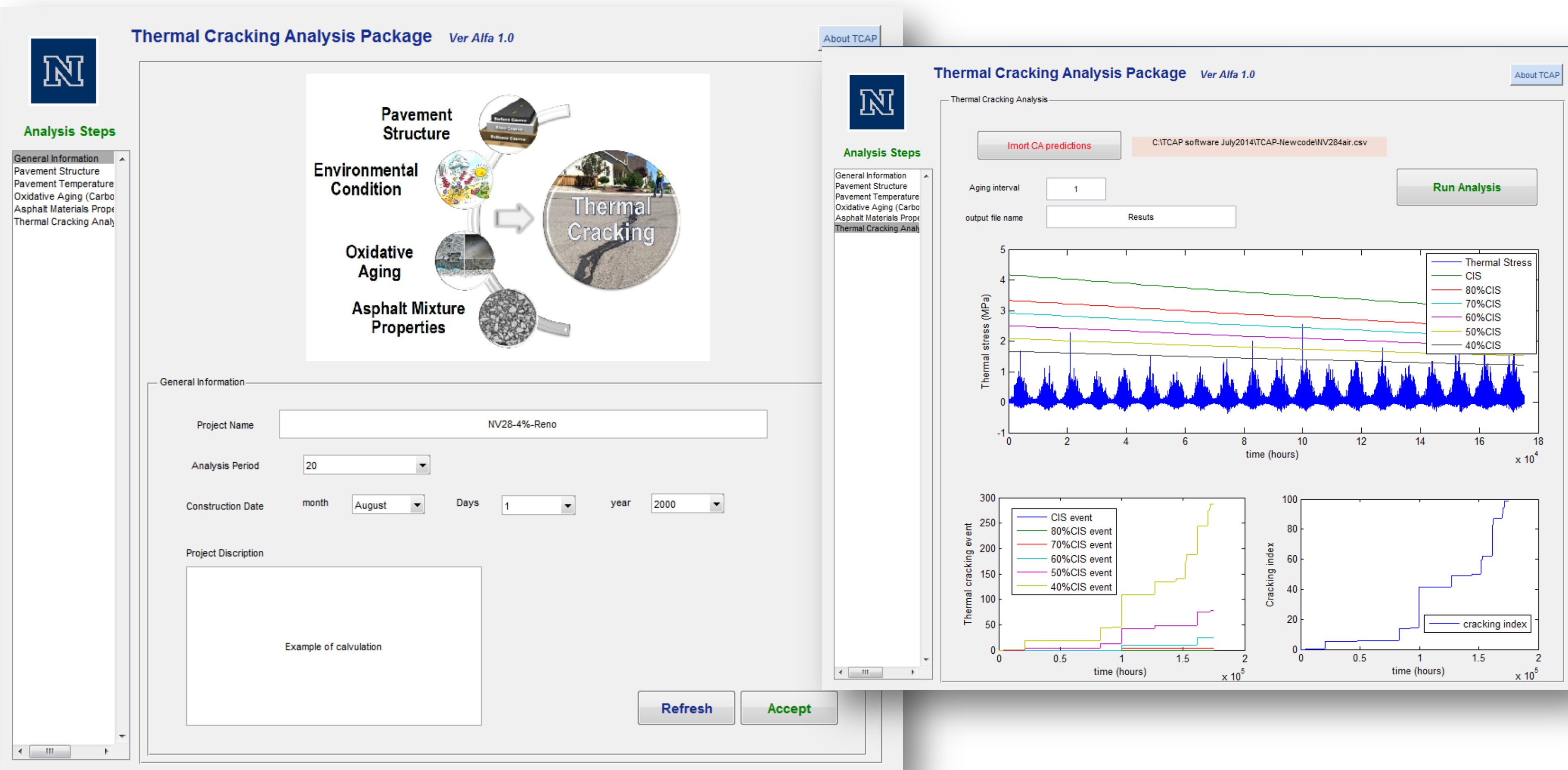
Thermal Cracking Event Probability

- 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)



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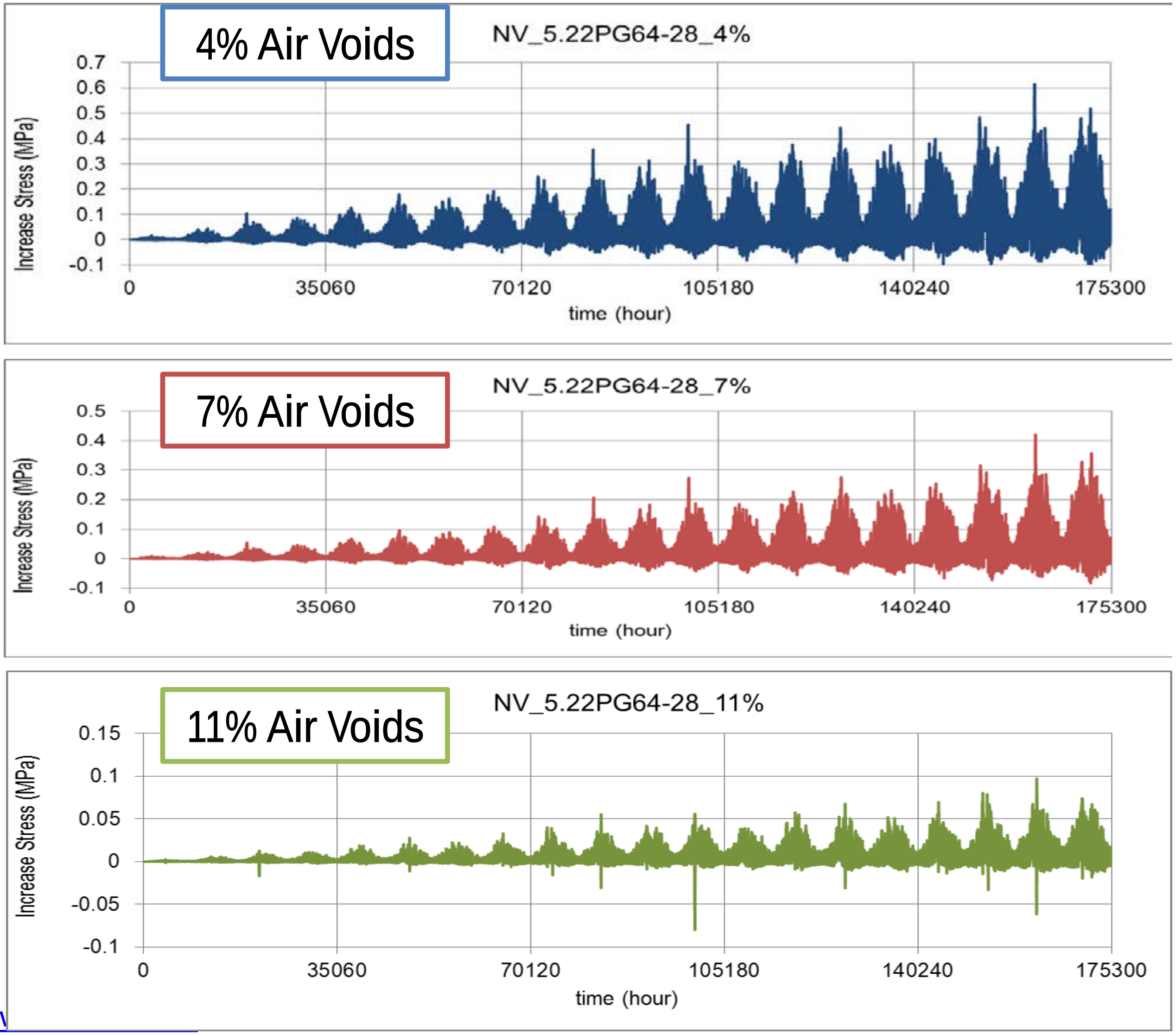
Examples: TCAP Analysis

- 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

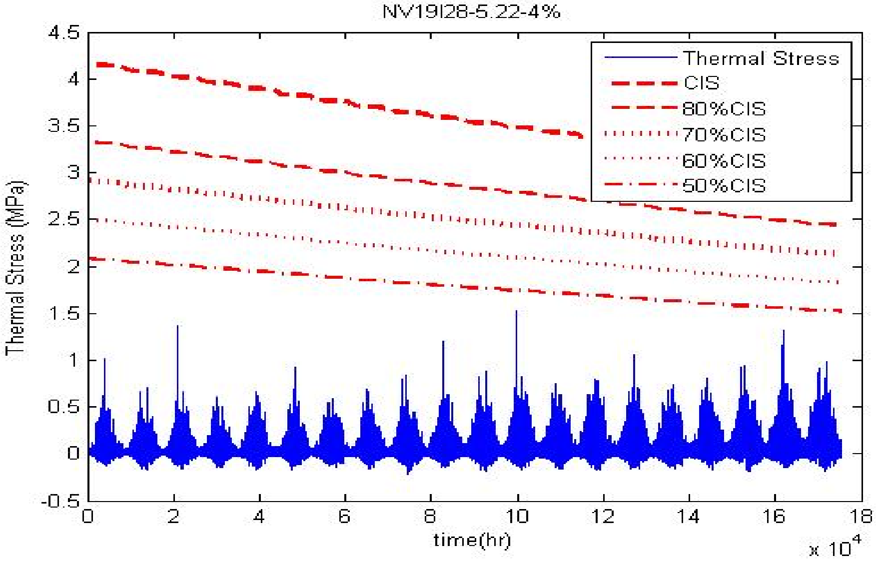
Effect of Oxidative Aging on Thermal Stresses

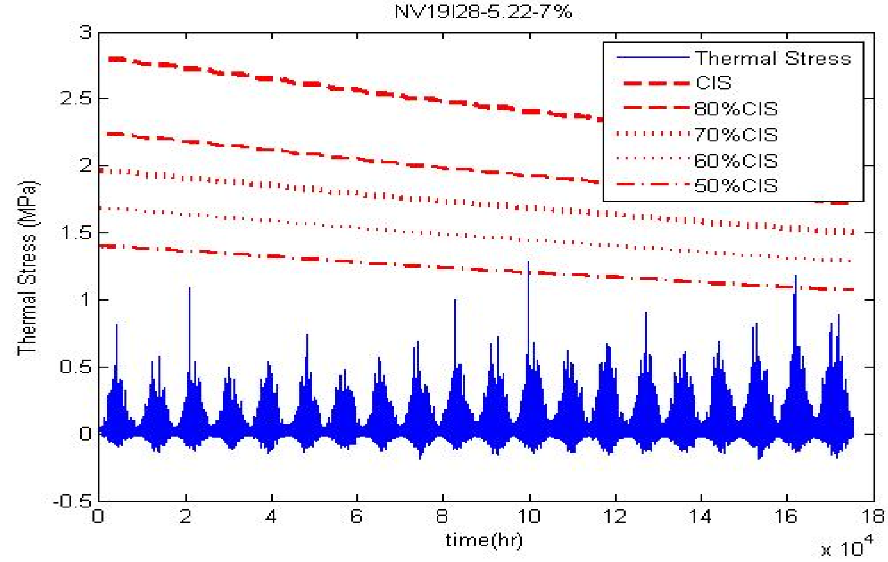
Difference in predicted thermal stresses between aging and no-aging effect analyses.

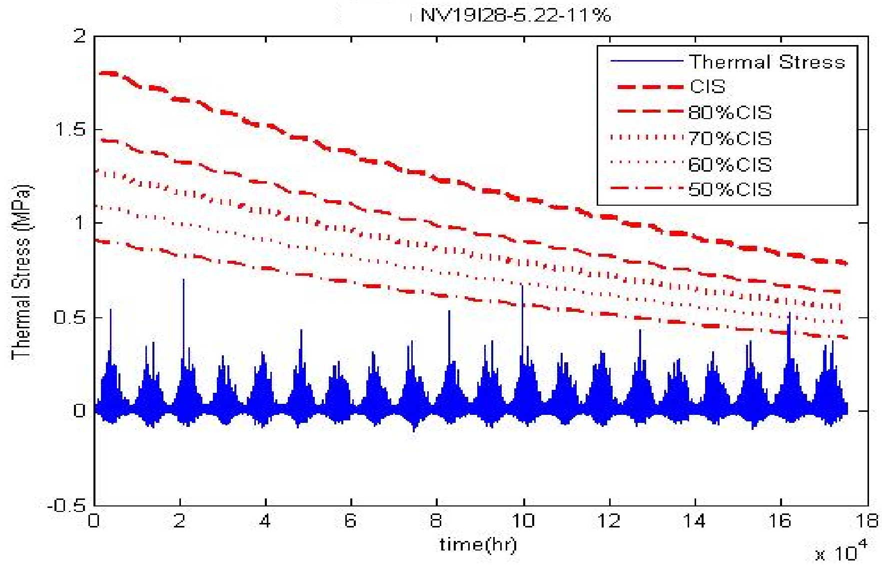


Examples: TCAP analysis

Thermal Stress vs. Crack Initiation Stress (CIS)

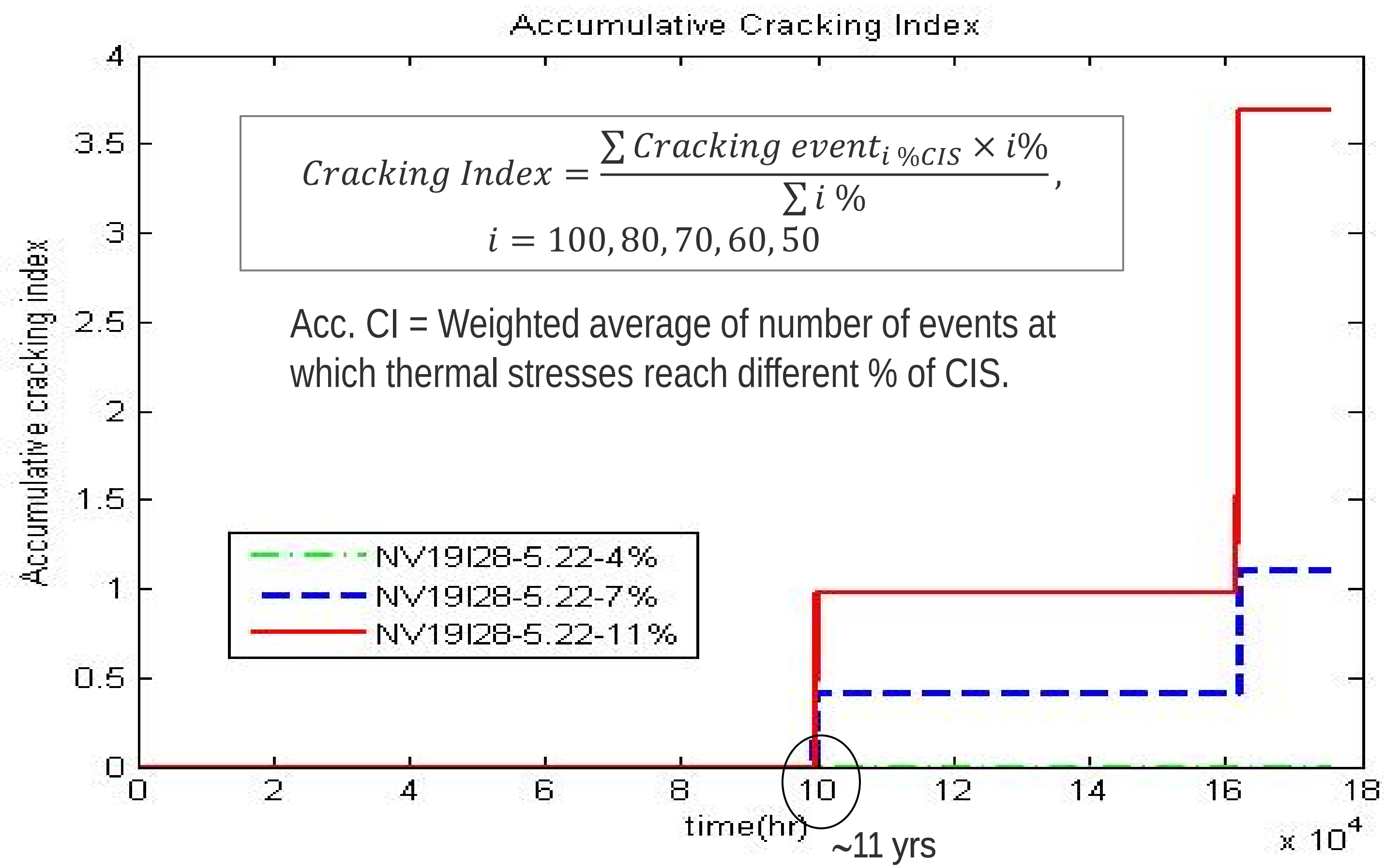






Examples: TCAP analysis

Effect of Mixtures Air Voids



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

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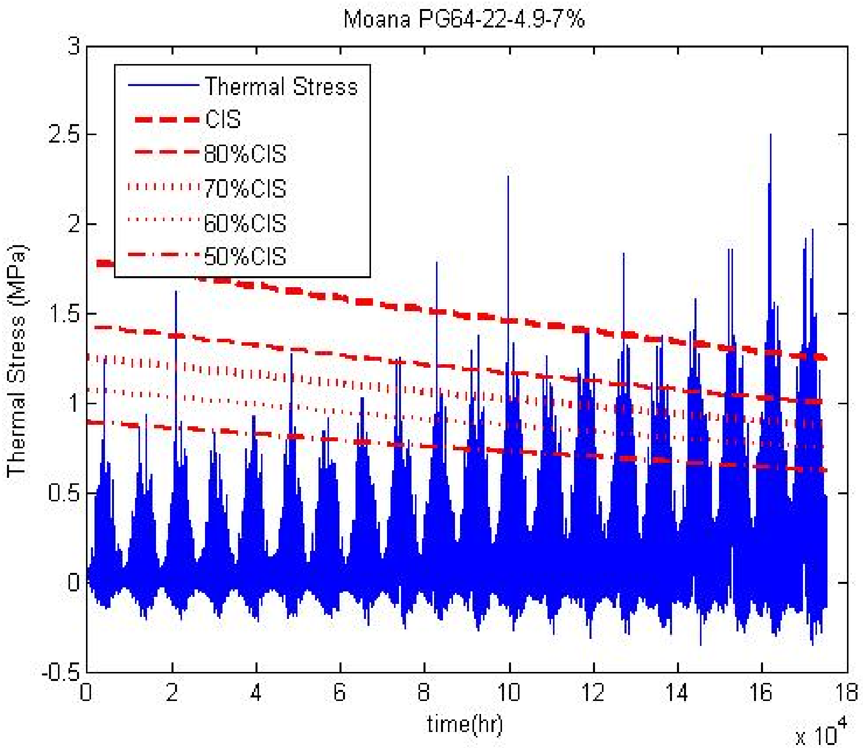
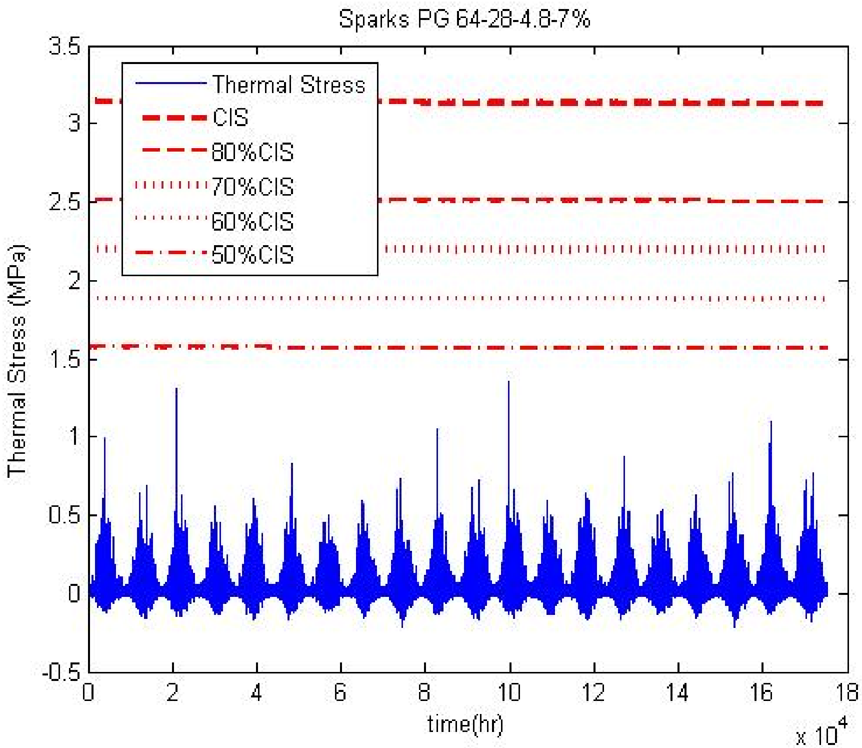
Examples: TCAP analysis

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

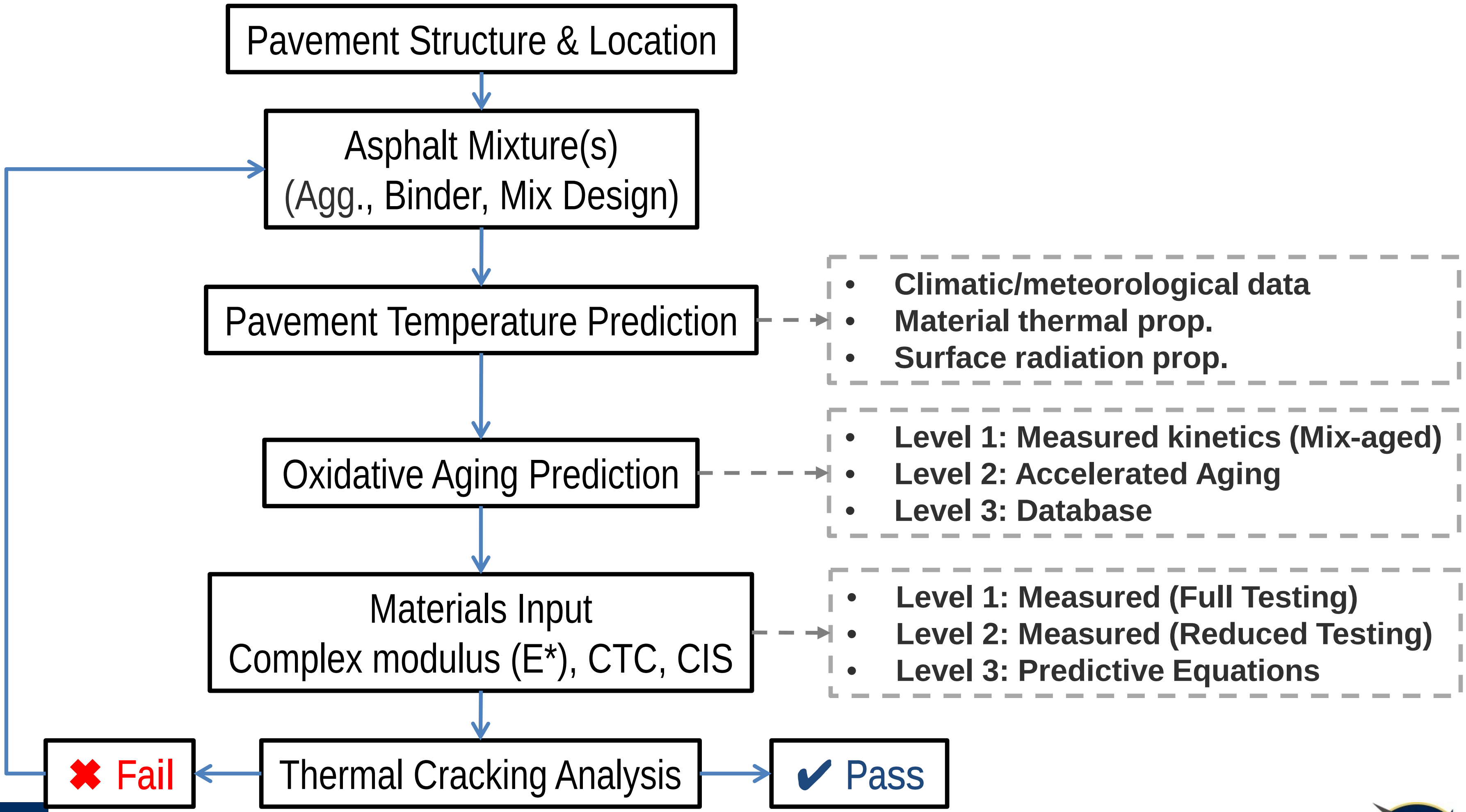


Un-modified
PG64-22 (Moana, 2006)



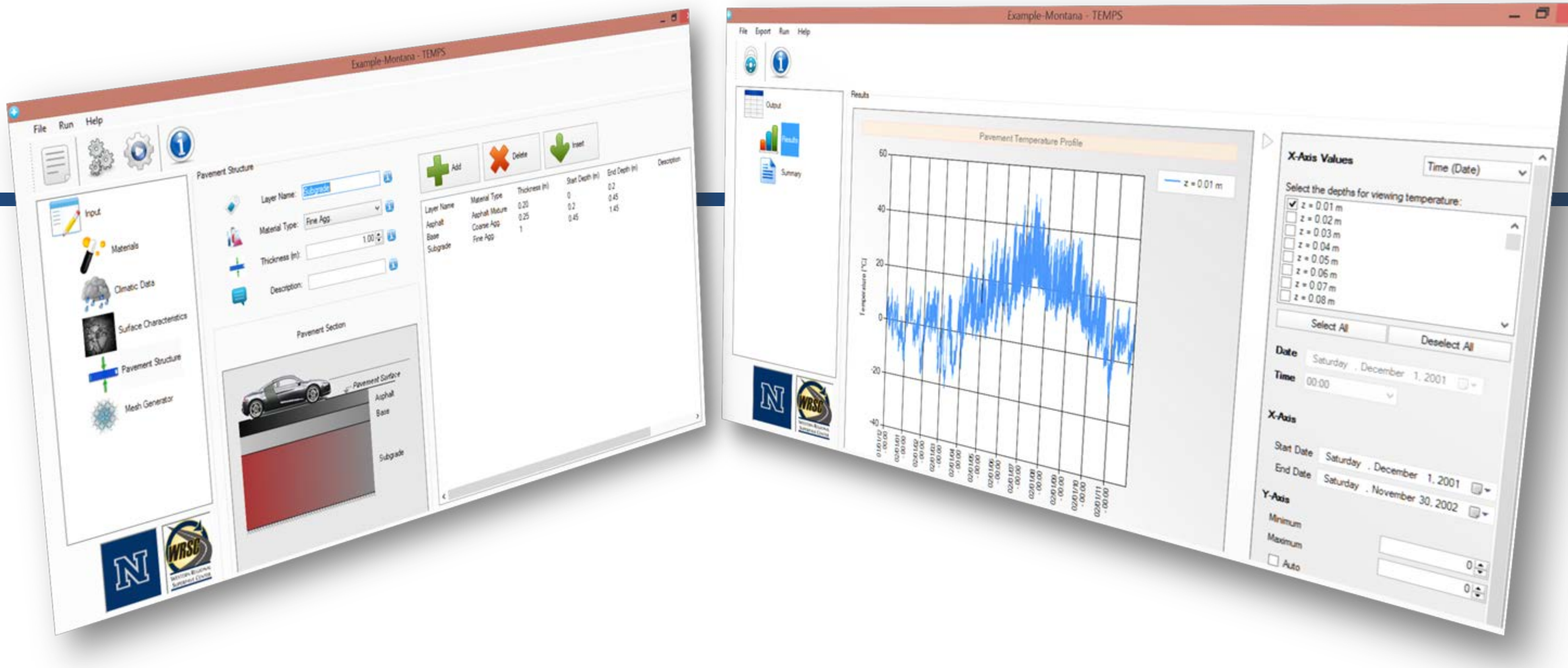
SBS polymer-modified
PG64-28 (Sparks, 2008)

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

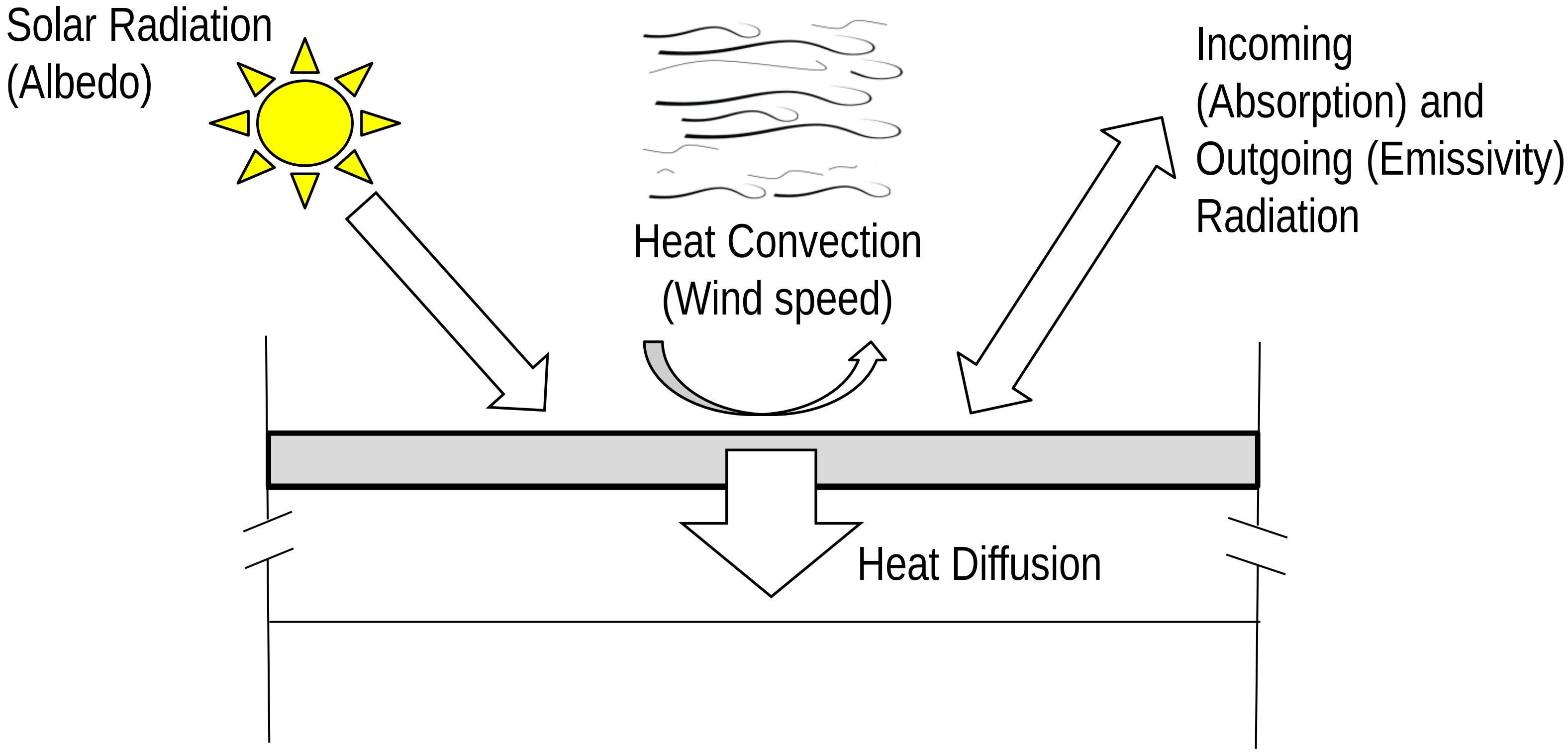
TEMPERATURE ESTIMATE MODEL FOR PAVEMENT STRUCTURES (TEMPS)

Pavement Temperature Profile Prediction

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

Heat Transfer Model Concept

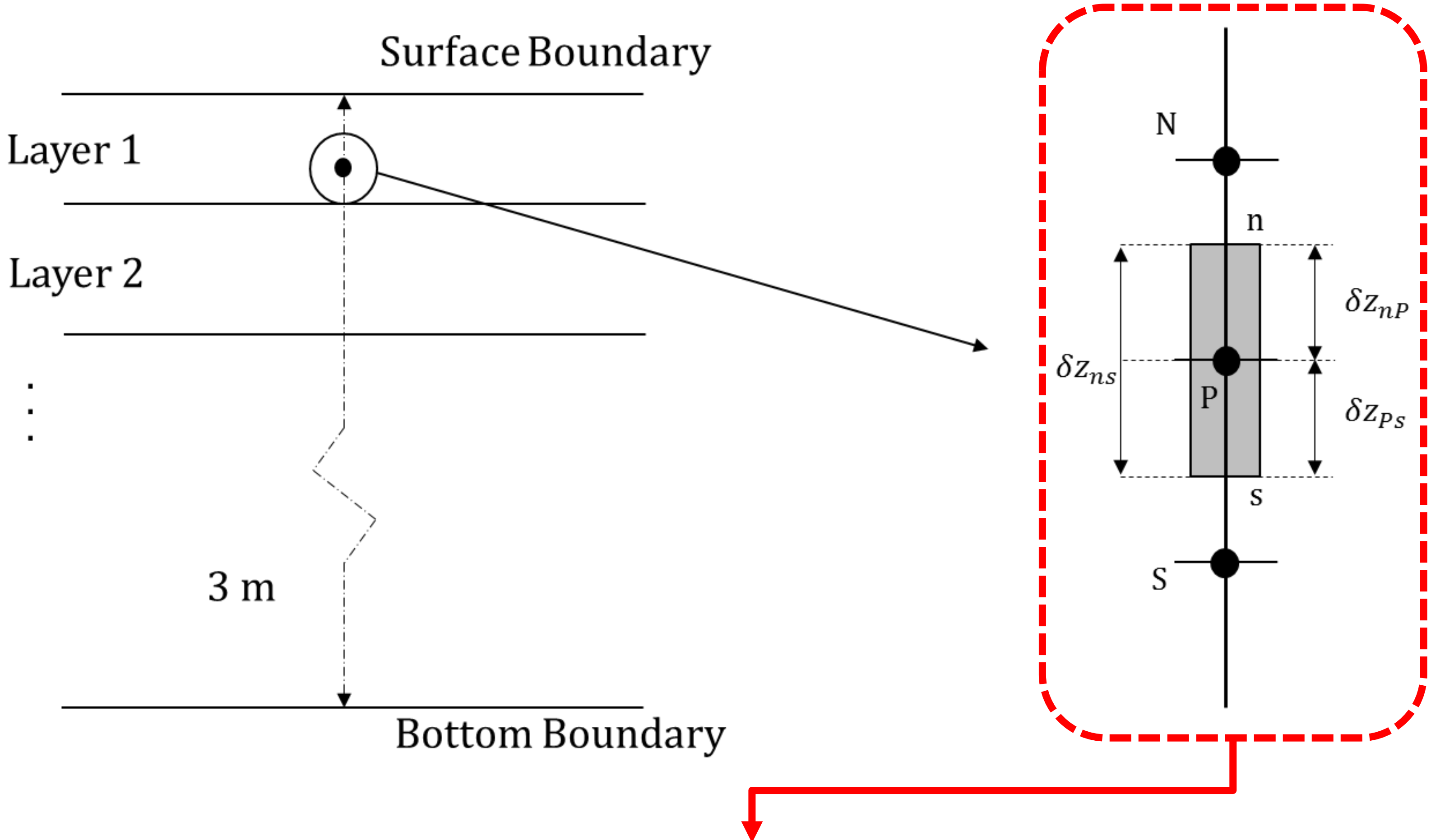


Heat Transfer Balance Between Pavement Structure & Surrounding Environment

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

Pavement Temperature Profile Prediction

Numerical Computation: Finite Control Volume Method (FCVM)



Energy Balance in Each of Control Elements

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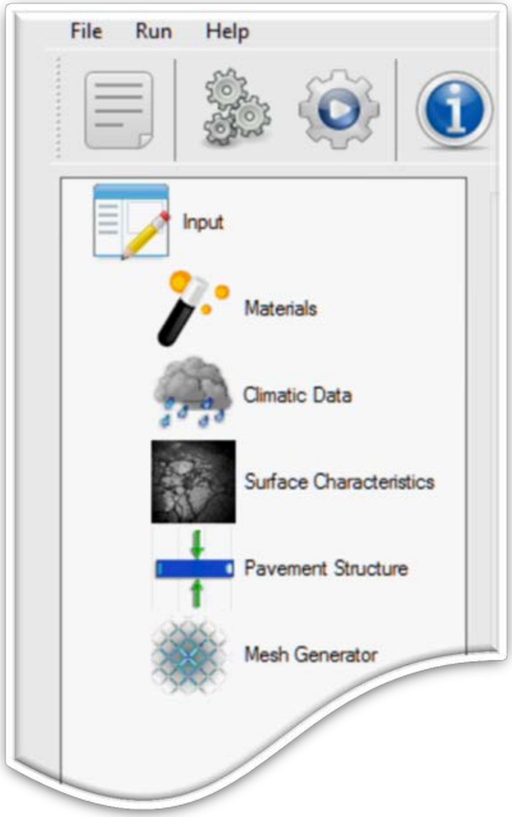
Standalone Software: TEMPS (Alpha Version)

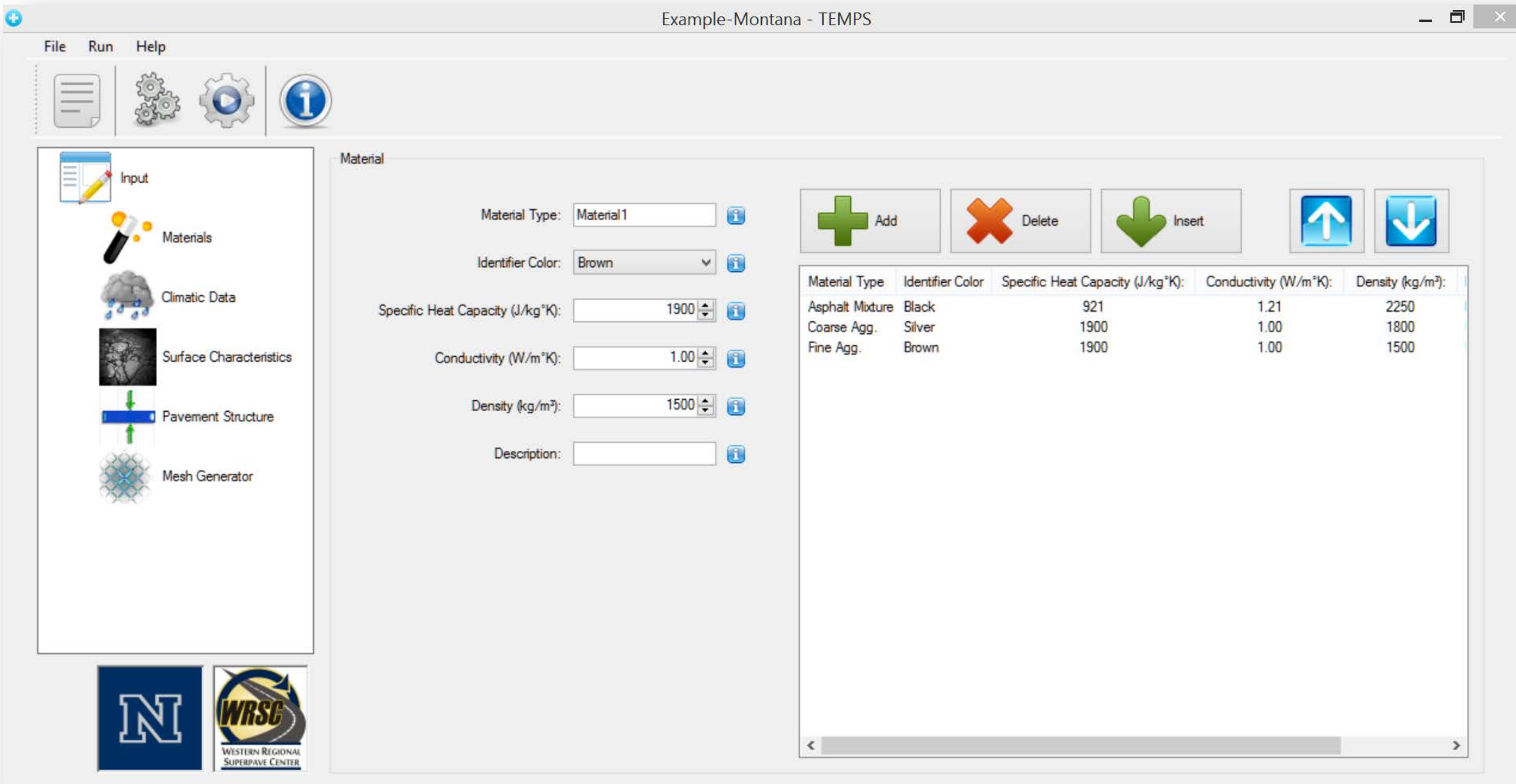
Temperature Estimate Model for Pavement Structures (TEMPS)



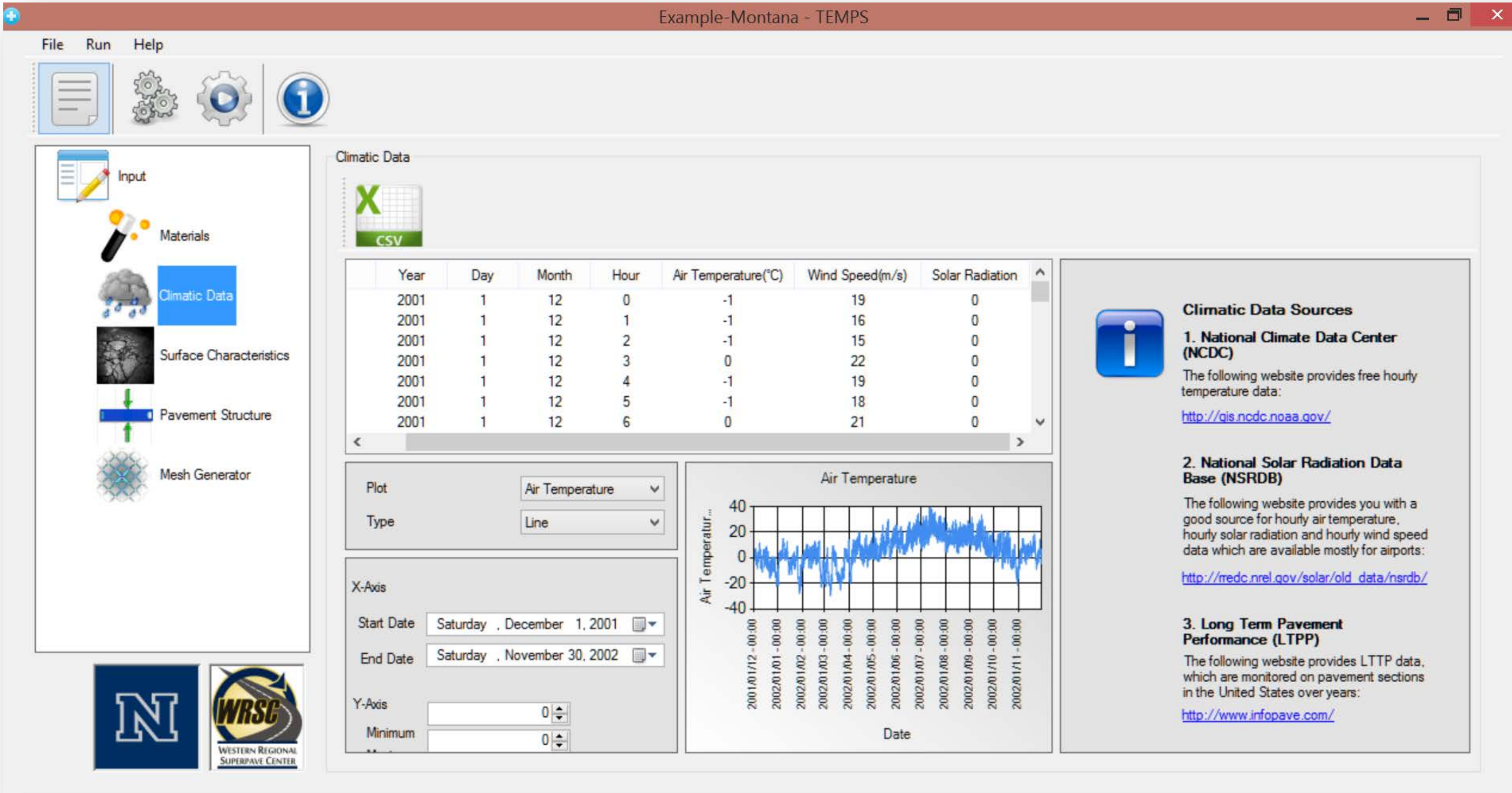
INPUT MODULES:

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

Pavement Temperature Profile Prediction
TEMPS – Materials Input

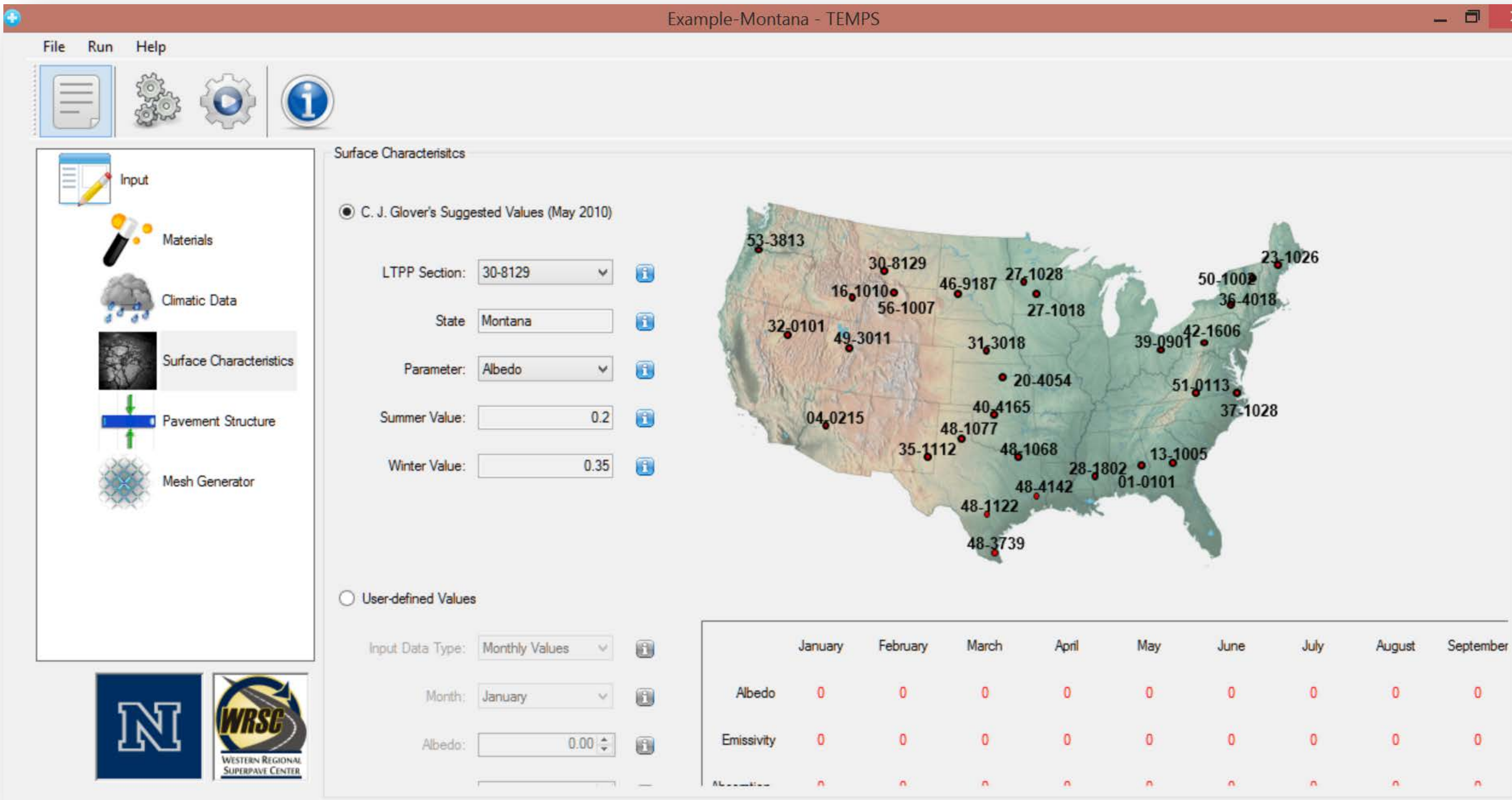


Pavement Temperature Profile Prediction
TEMPS – Climatic Data Input



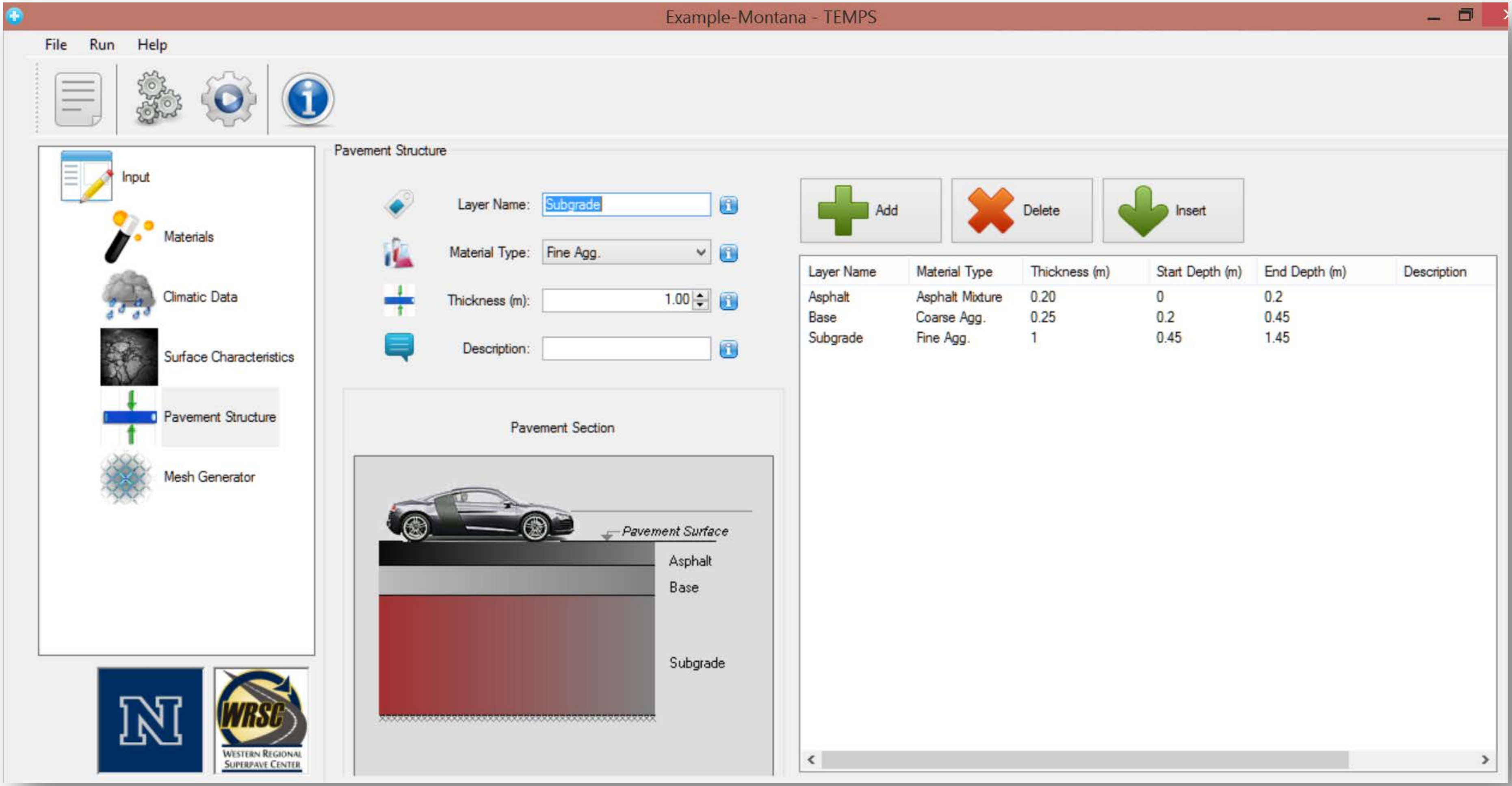
Pavement Temperature Profile Prediction

TEMPS – Surface Characteristics Input



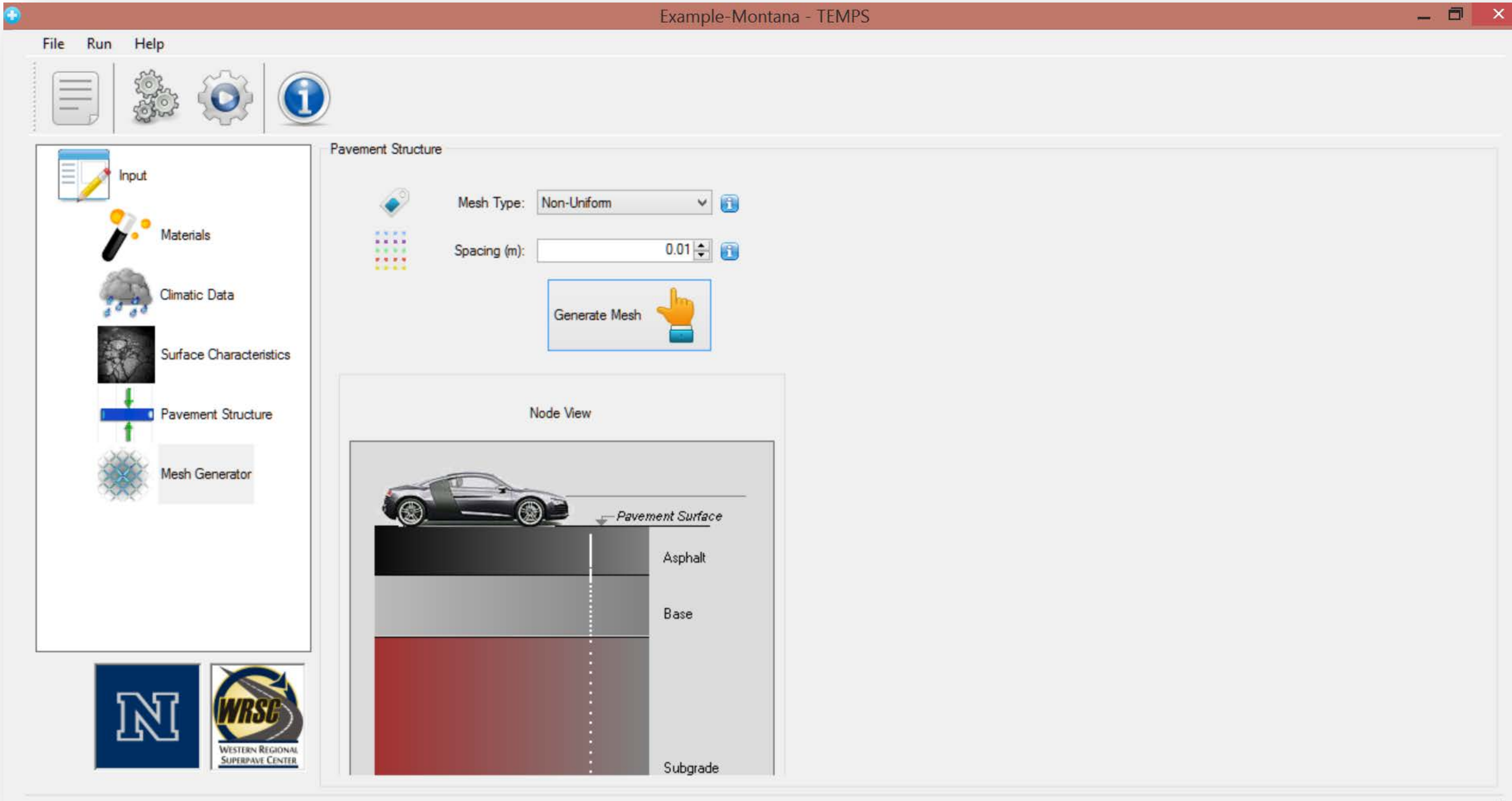
Pavement Temperature Profile Prediction

TEMPS – Pavement Structure



Pavement Temperature Profile Prediction

TEMPS – Mesh Generator



TEMPS – Run Analysis

Time Efficiency of Computation: Implicit Scheme

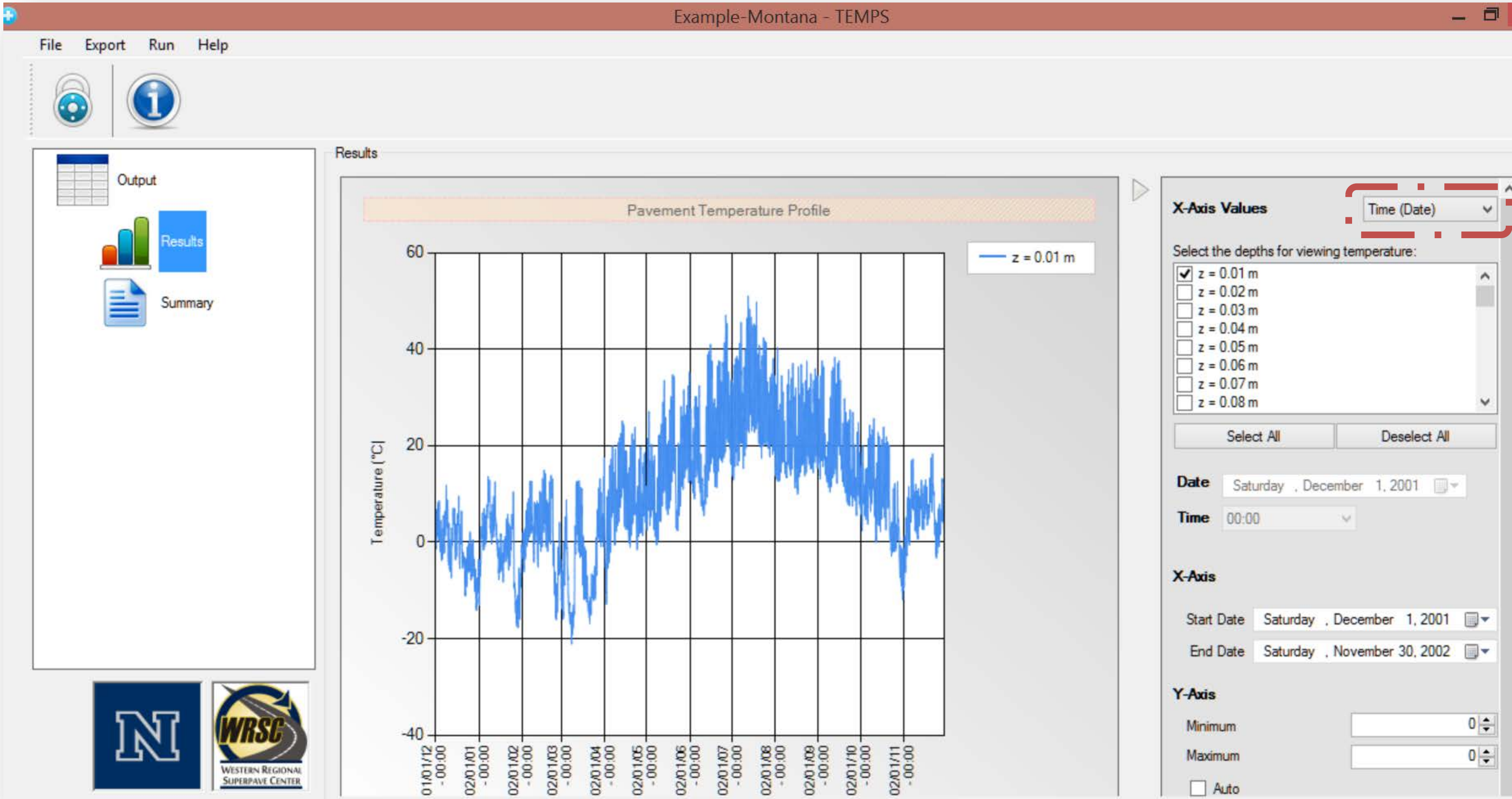
Run time for 1 years analysis period
(3.10 GHz proc. and 4.00 GB RAM)

< 10 seconds using 1 hour time step*

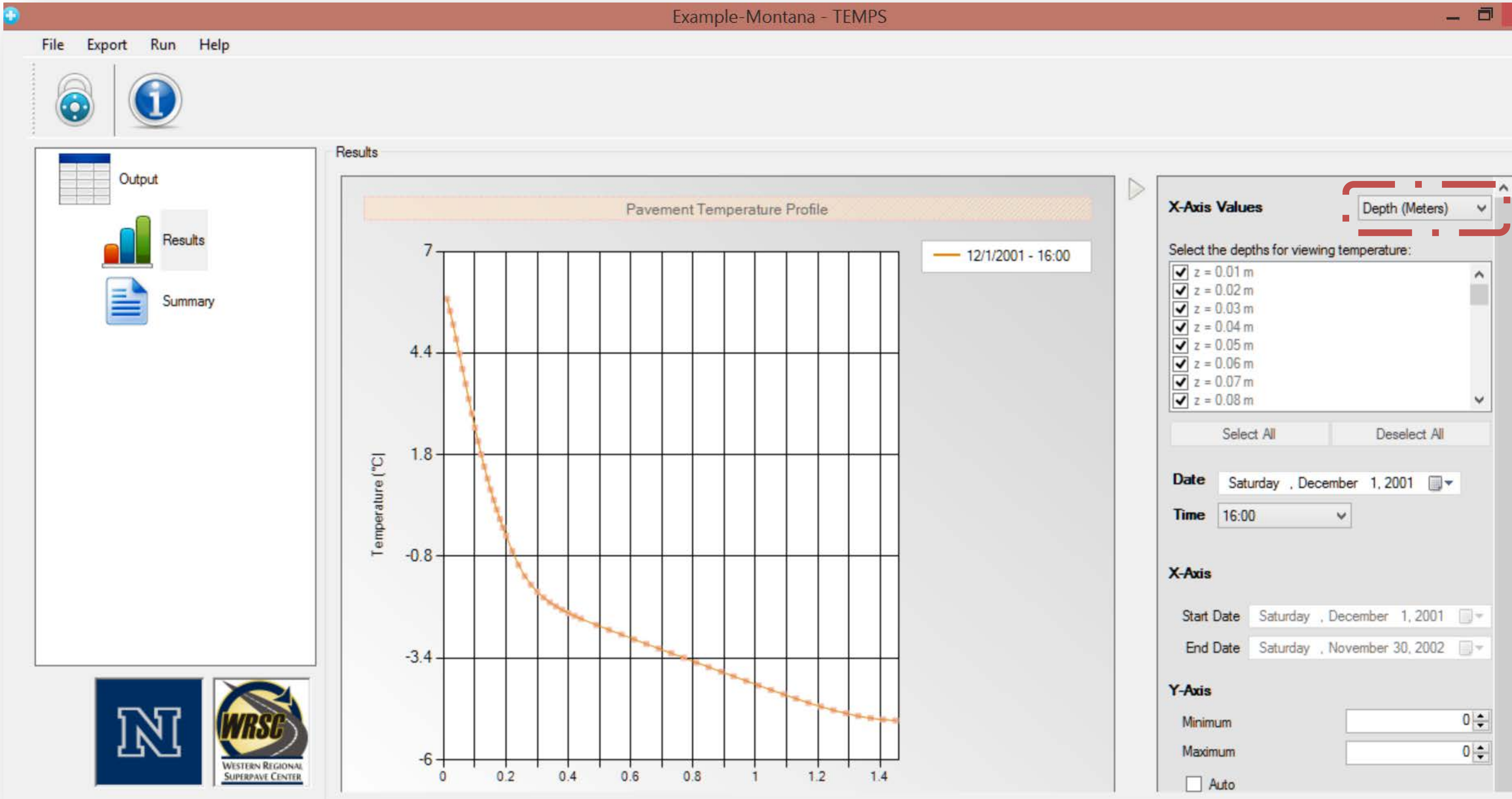
* Note: *1 hour time step was chosen without jeopardizing the model accuracy for prediction.*

Pavement Temperature Profile Prediction

TEMPS – Output Results

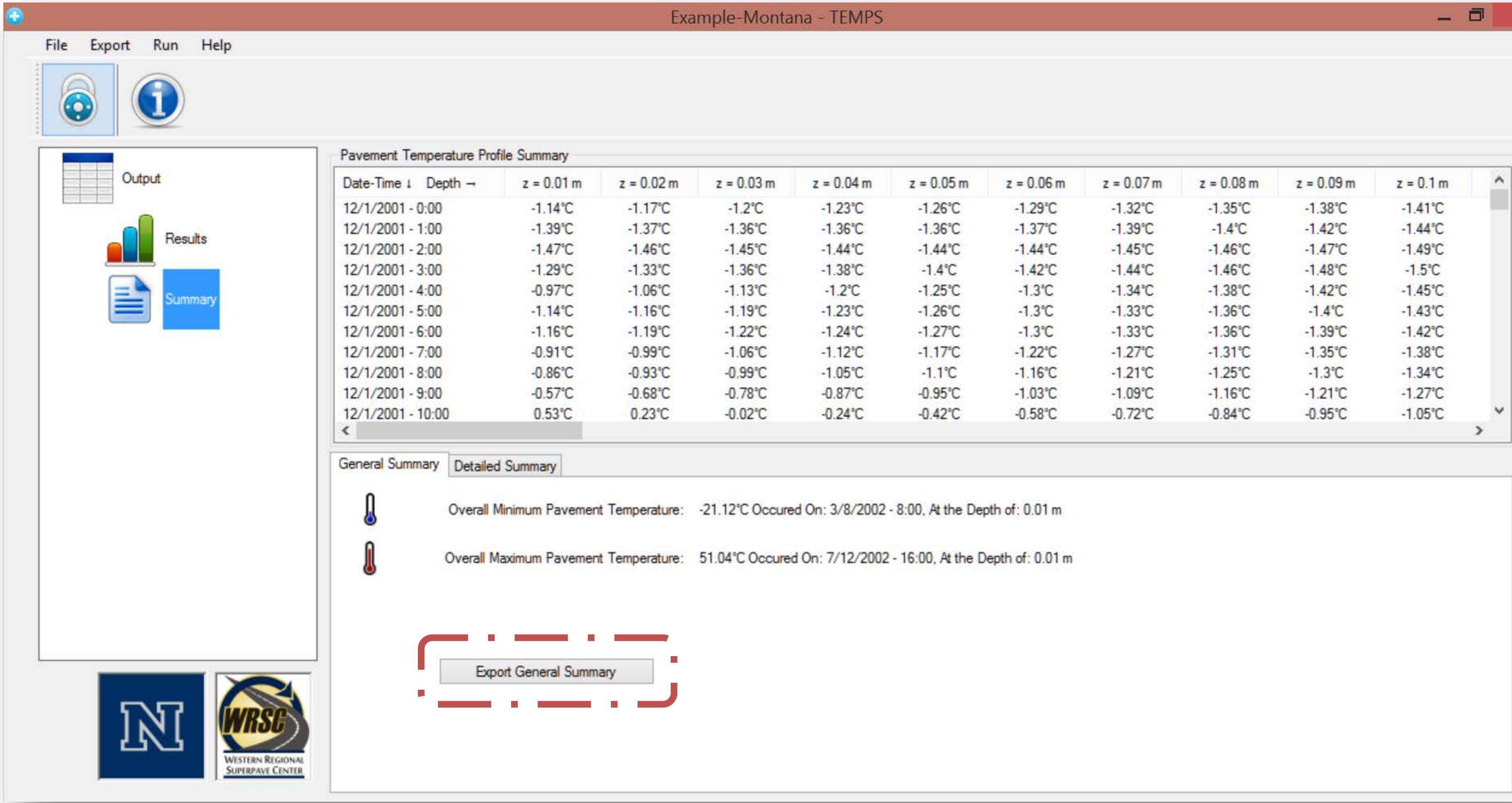


TEMPS – Output Results



Pavement Temperature Profile Prediction

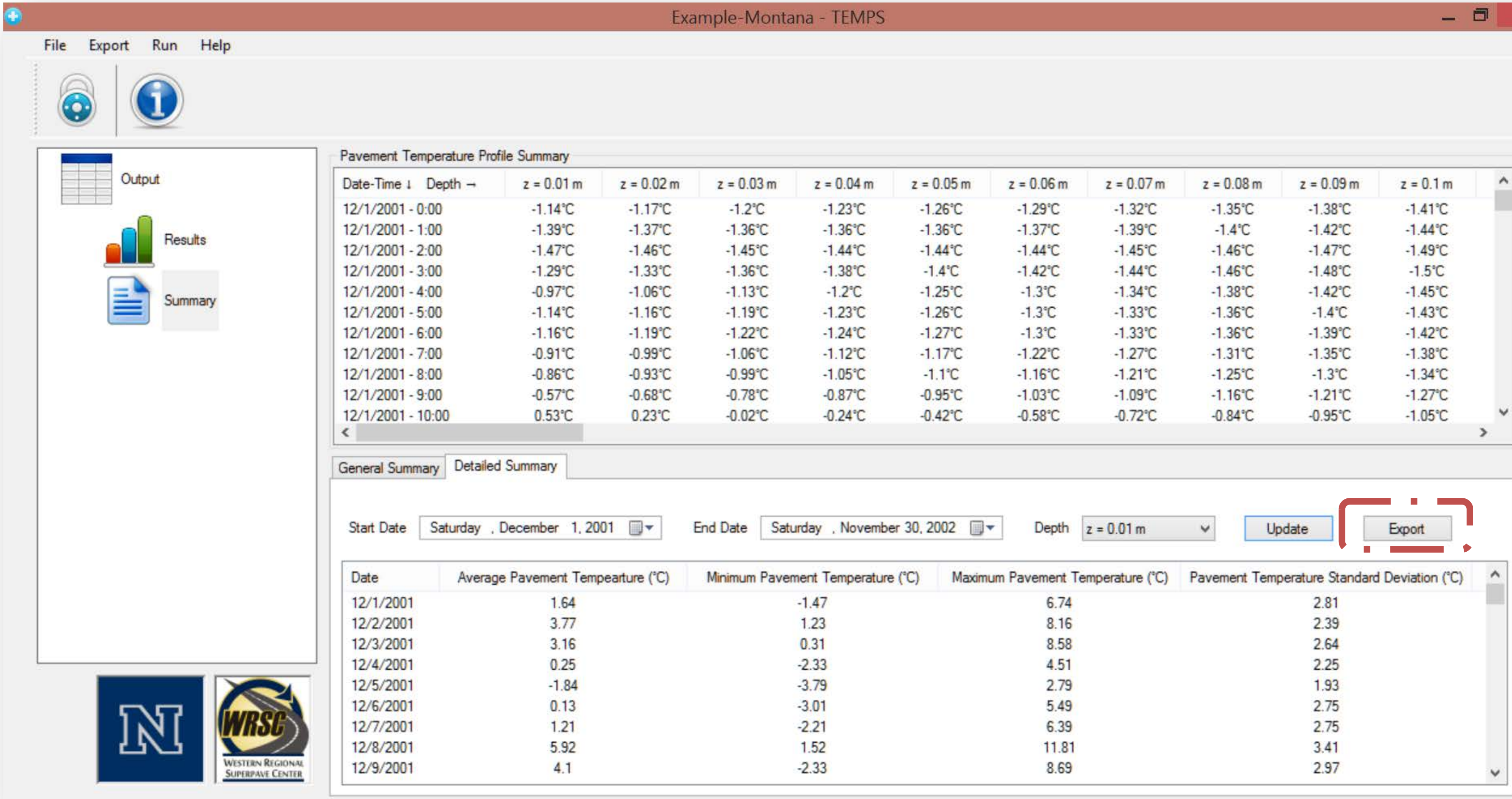
TEMPS – Output Summary



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	-1.14°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

Pavement Temperature Profile Prediction

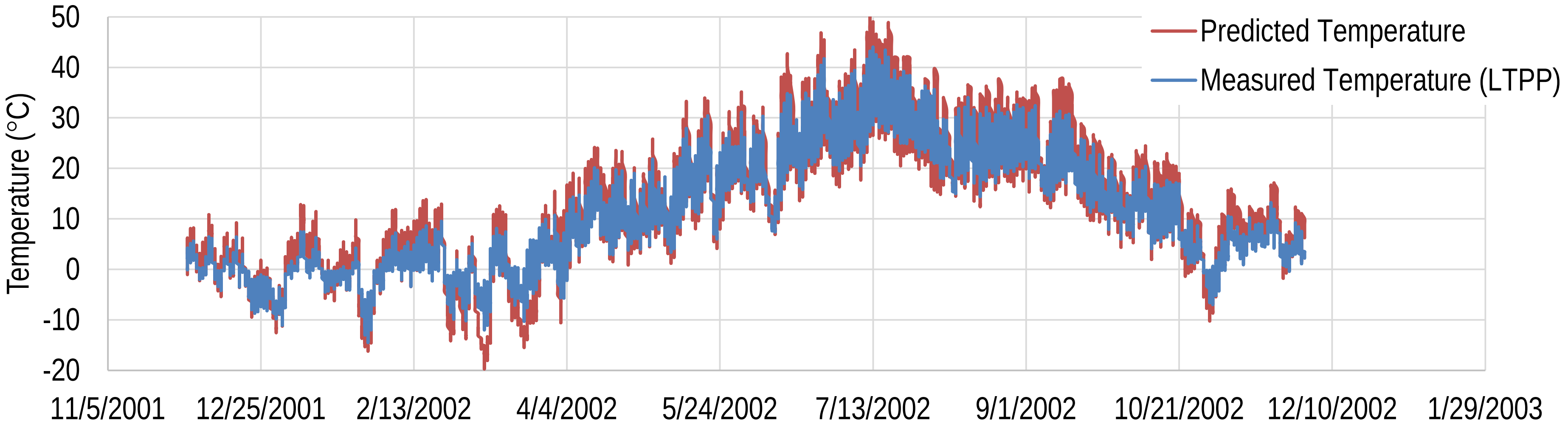
TEMPS – Output Summary

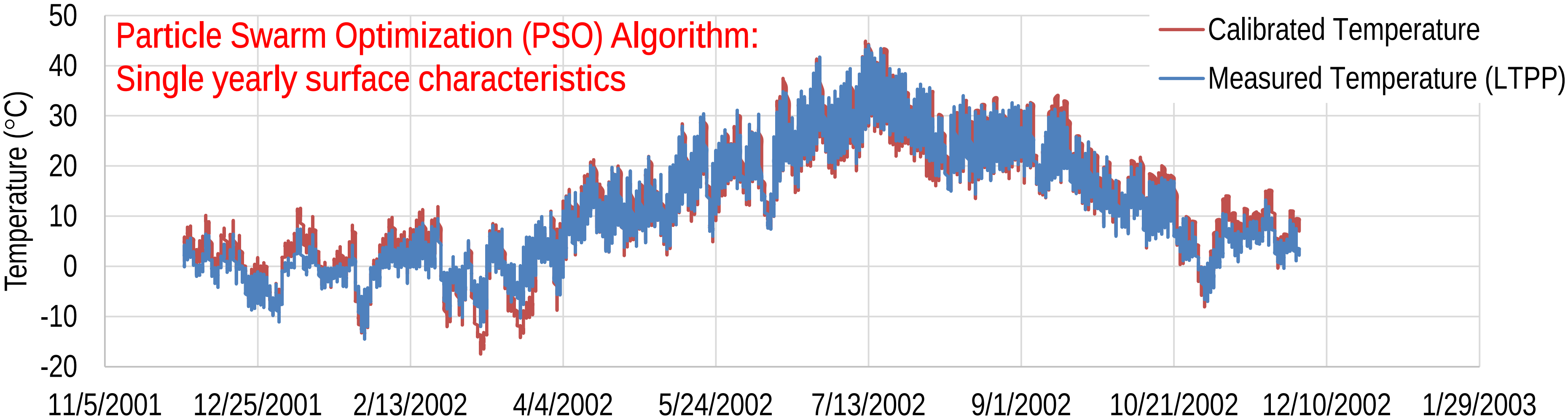


Pavement Temperature Profile Prediction

TEMPS – Predicted versus Measured

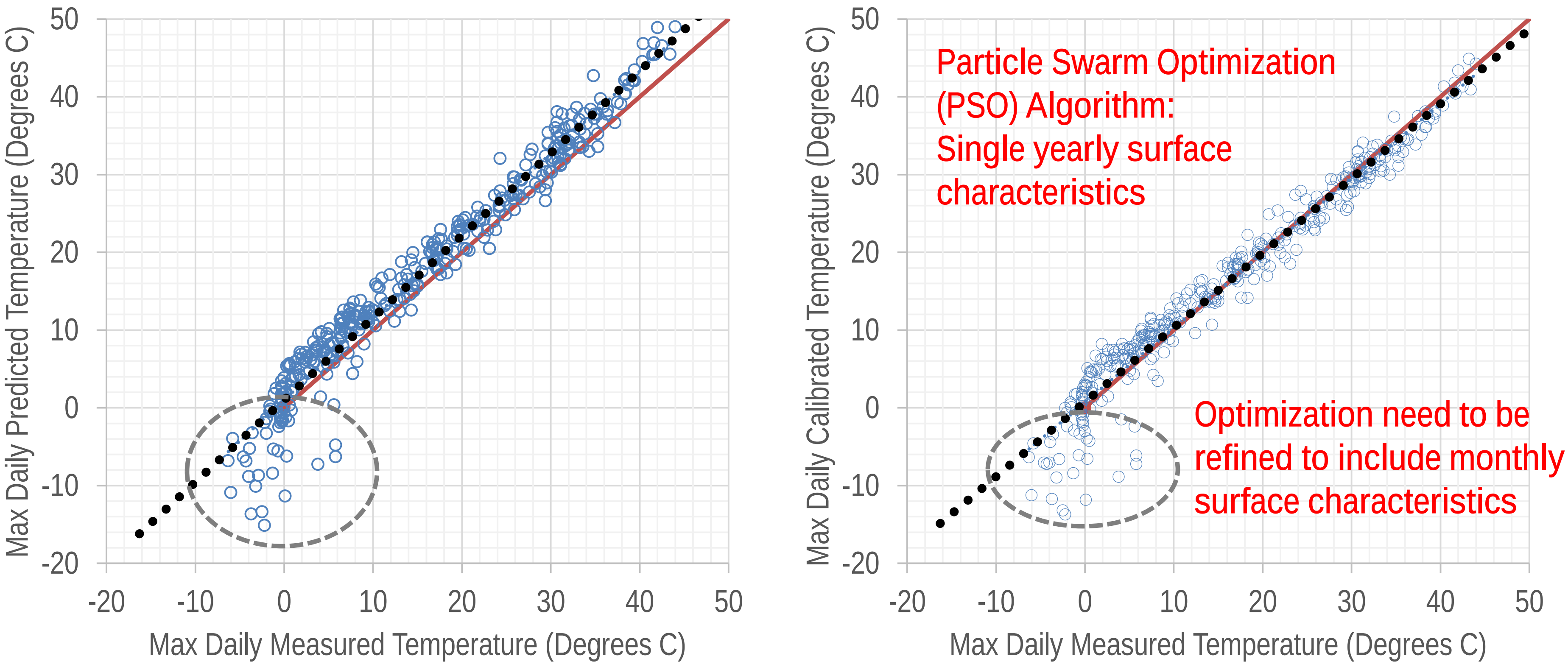
Great Falls, MT at depth of 0.09 m (3.5 inch)





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!