
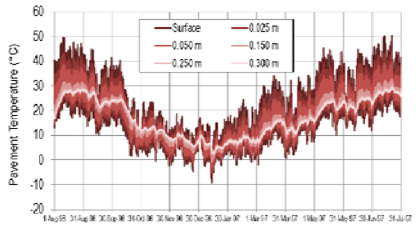
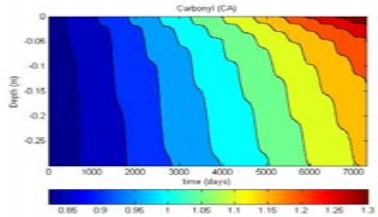
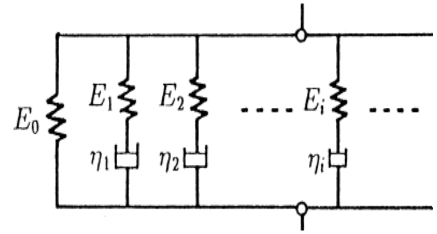
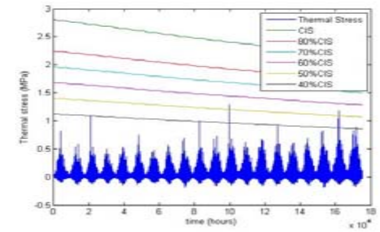

Thermal Cracking Analysis Model
AND
Pavement Temperature Profile Prediction Model

Elie Y. Hajj, Assistant Professor, UNR

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Nathan Morian, Ph.D., Nevada DOT

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Peter E. Sebaaly, Professor, UNR

FHWA Asphalt Mixture Expert Task Group

Baton Rouge, Louisiana – September 17-19, 2014

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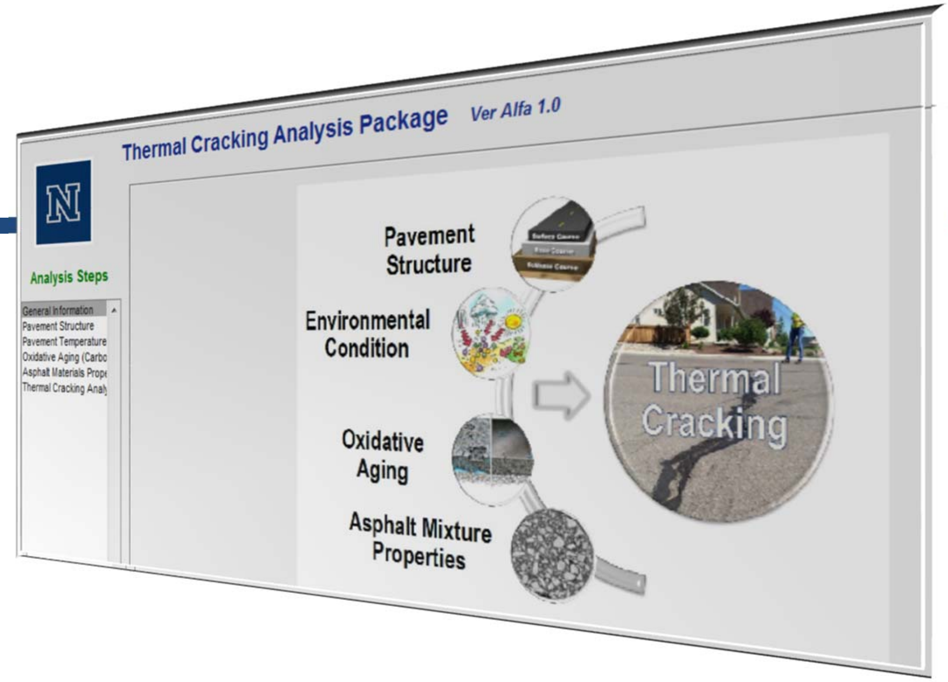


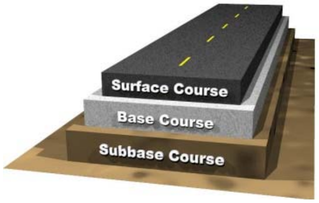
Comprehensive Evaluation of Thermal Cracking in Asphalt Pavements

THERMAL CRACKING ANALYSIS PACKAGE (TCAP)

Thermal Cracking Analysis

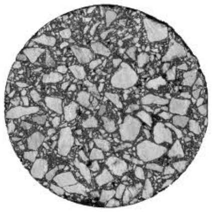
Influential Factors

- **Pavement Structure**
  - Asphalt layer thickness.
  - Interface condition.

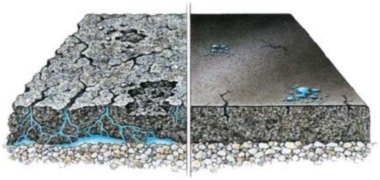


- **Environmental Conditions**
  - Pavement temperatures.
  - Cooling/warming rates.

- **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

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)*

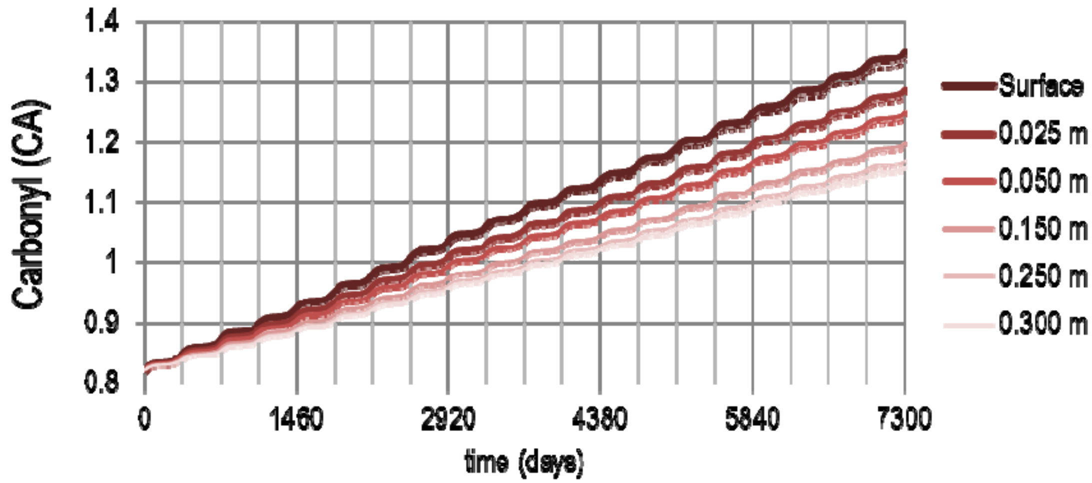
HS = 2.7 *(1/CA)*

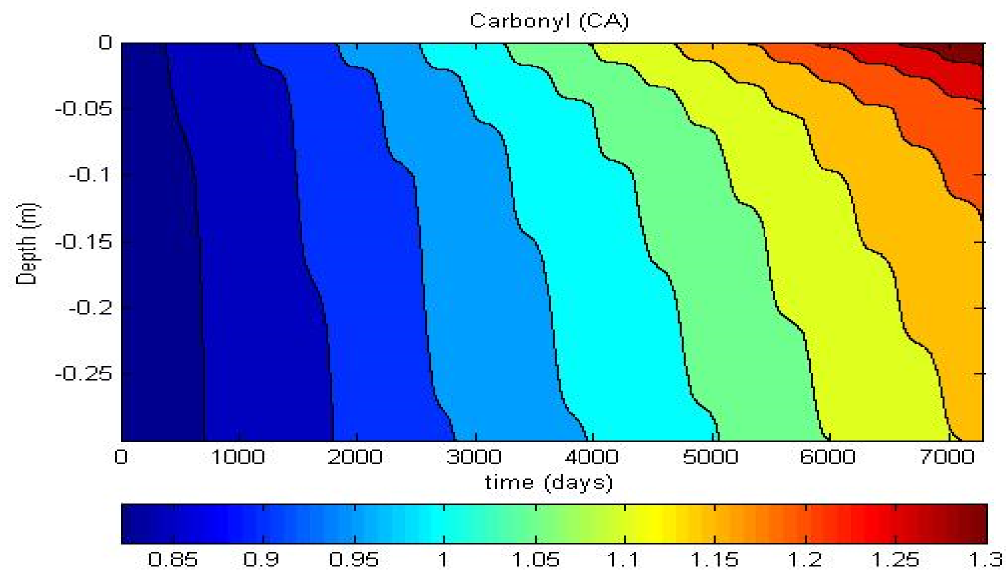
m = 9.24 *(poise)*

Air void diameter = 0.5 *mm*

Eff. aging zone = 1.0 *mm*

(film thickness)





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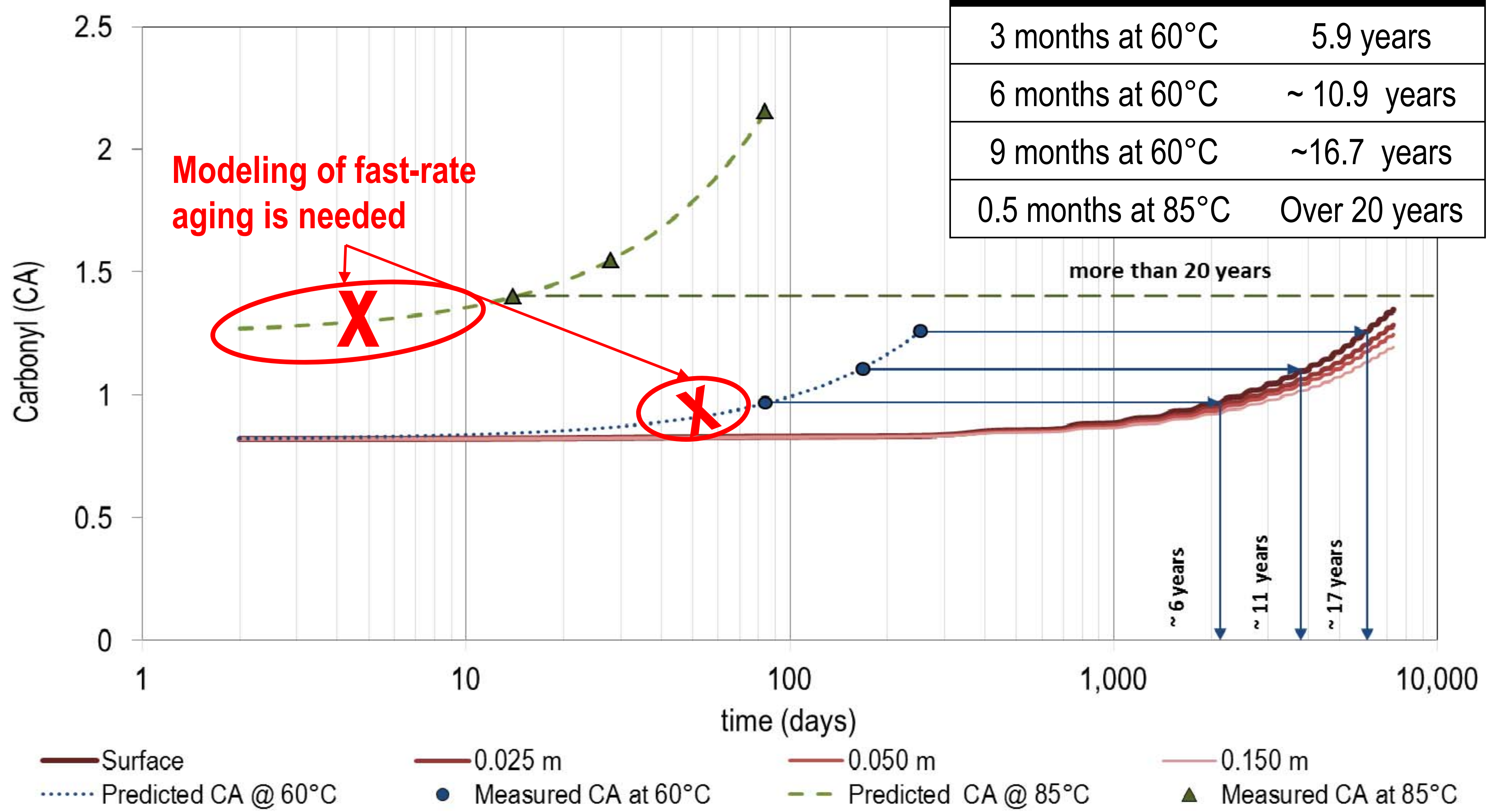
Thermal Cracking Analysis

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

Thermal Cracking Analysis

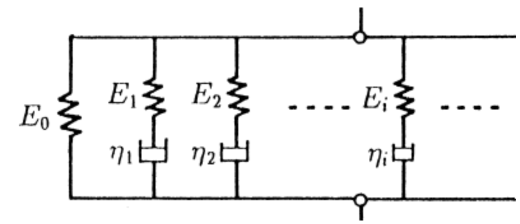
Age-Dependent Relaxation Modulus

- 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*).

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

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

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

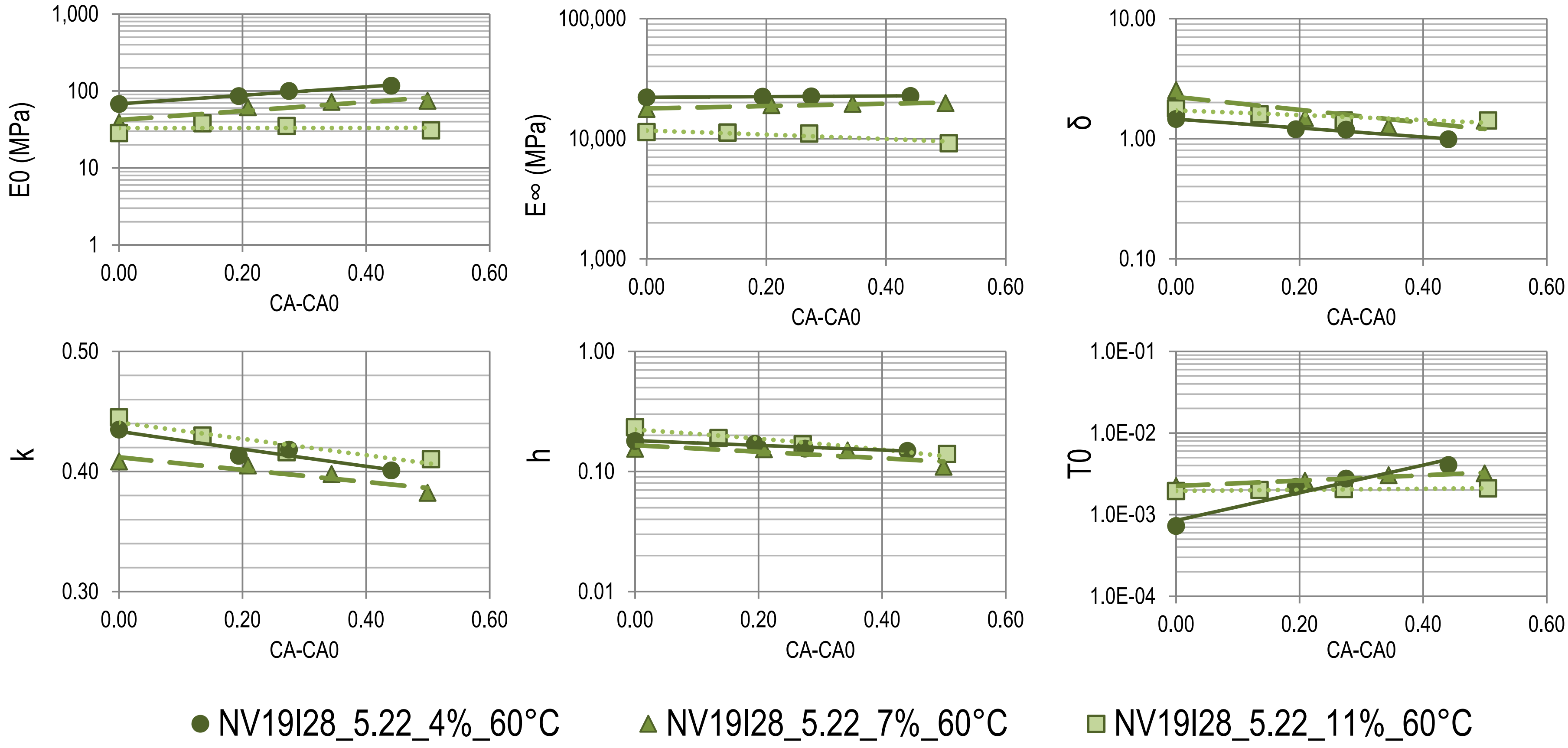


Ideal viscoelastic model

- ω: 2π*frequency, the pulsation
- E_0 : static modulus when $\omega \to 0$
- 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!

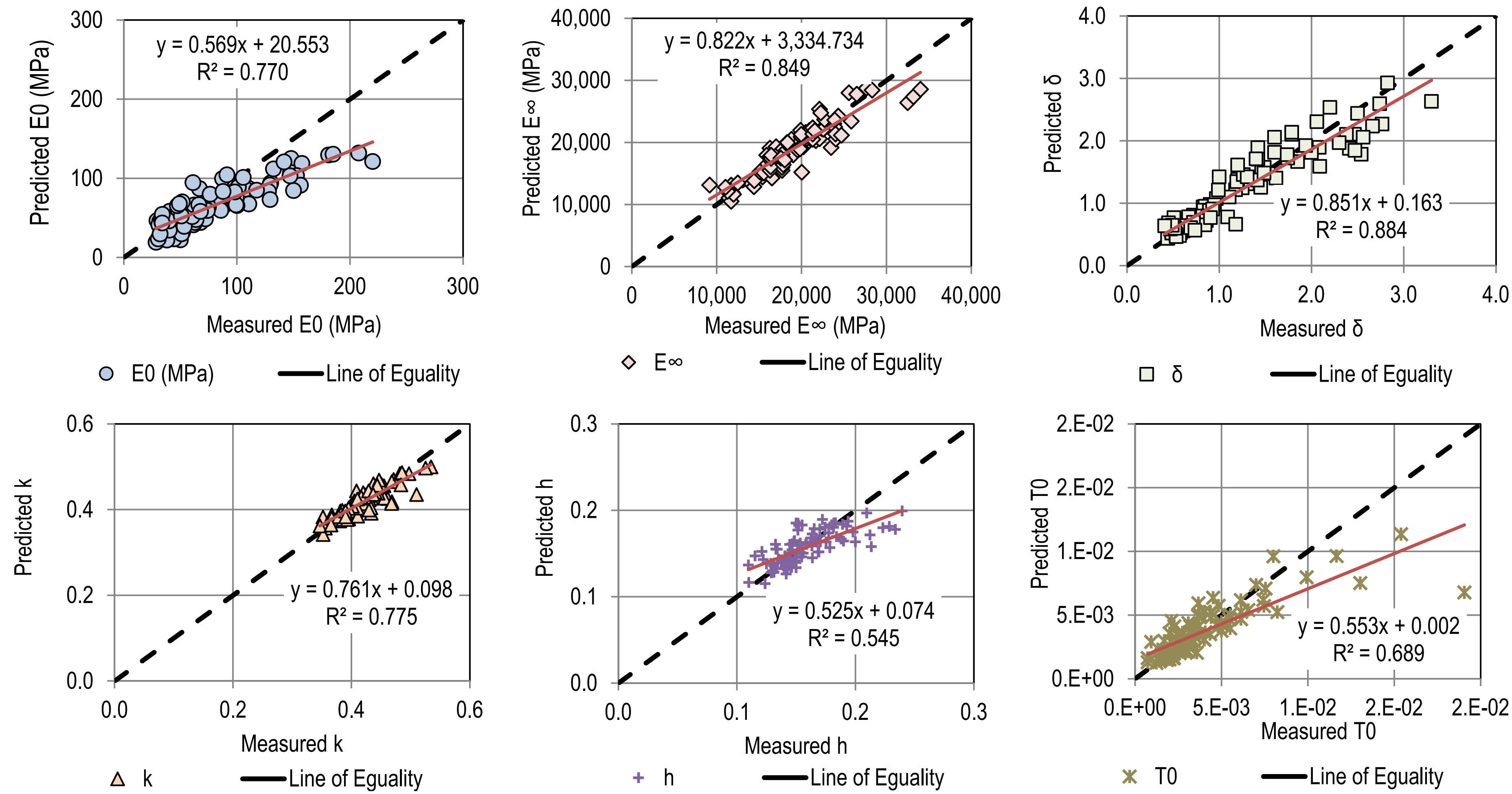
$$(2S2P1D\ coeff)_j = A_j \times e^{B_j(CA-CA_0)}$$

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	√		√				√

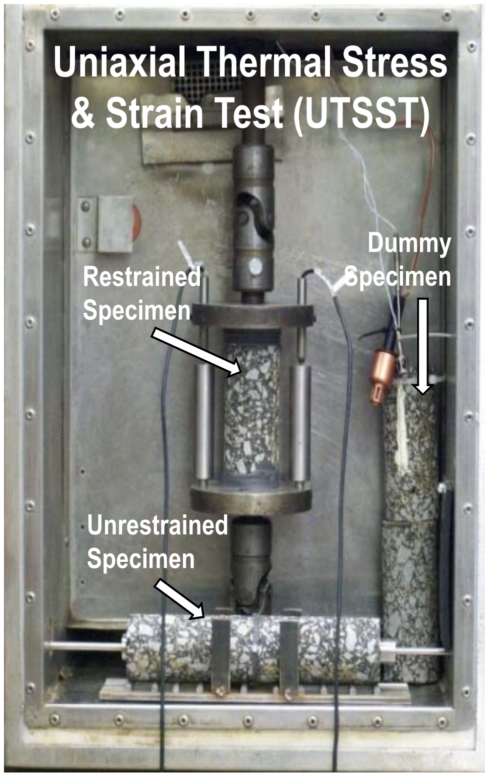
Thermal Cracking Analysis

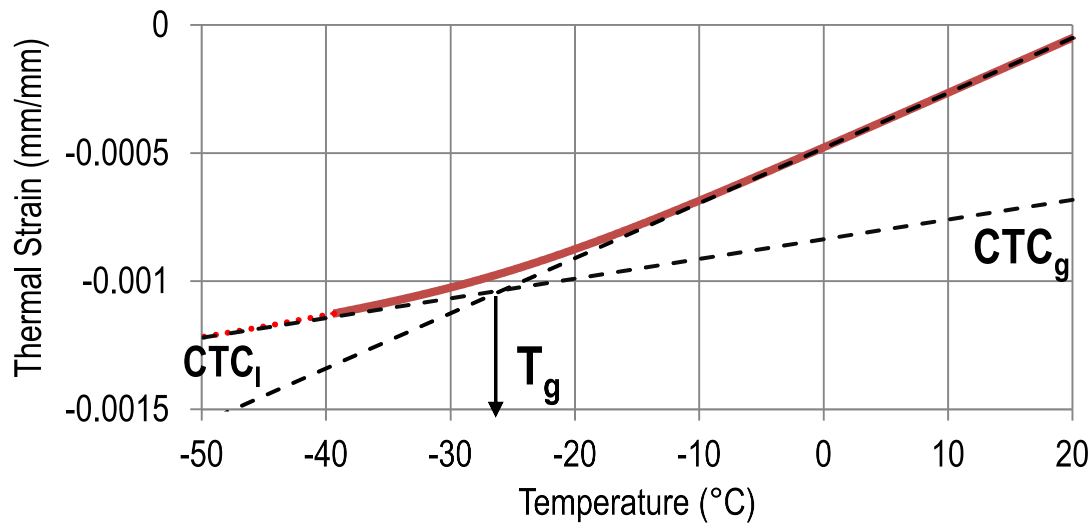
Evolution of 2S2P1D Coefficient with Aging



Thermal Cracking Analysis

Temperature and Age-Dependent CTC





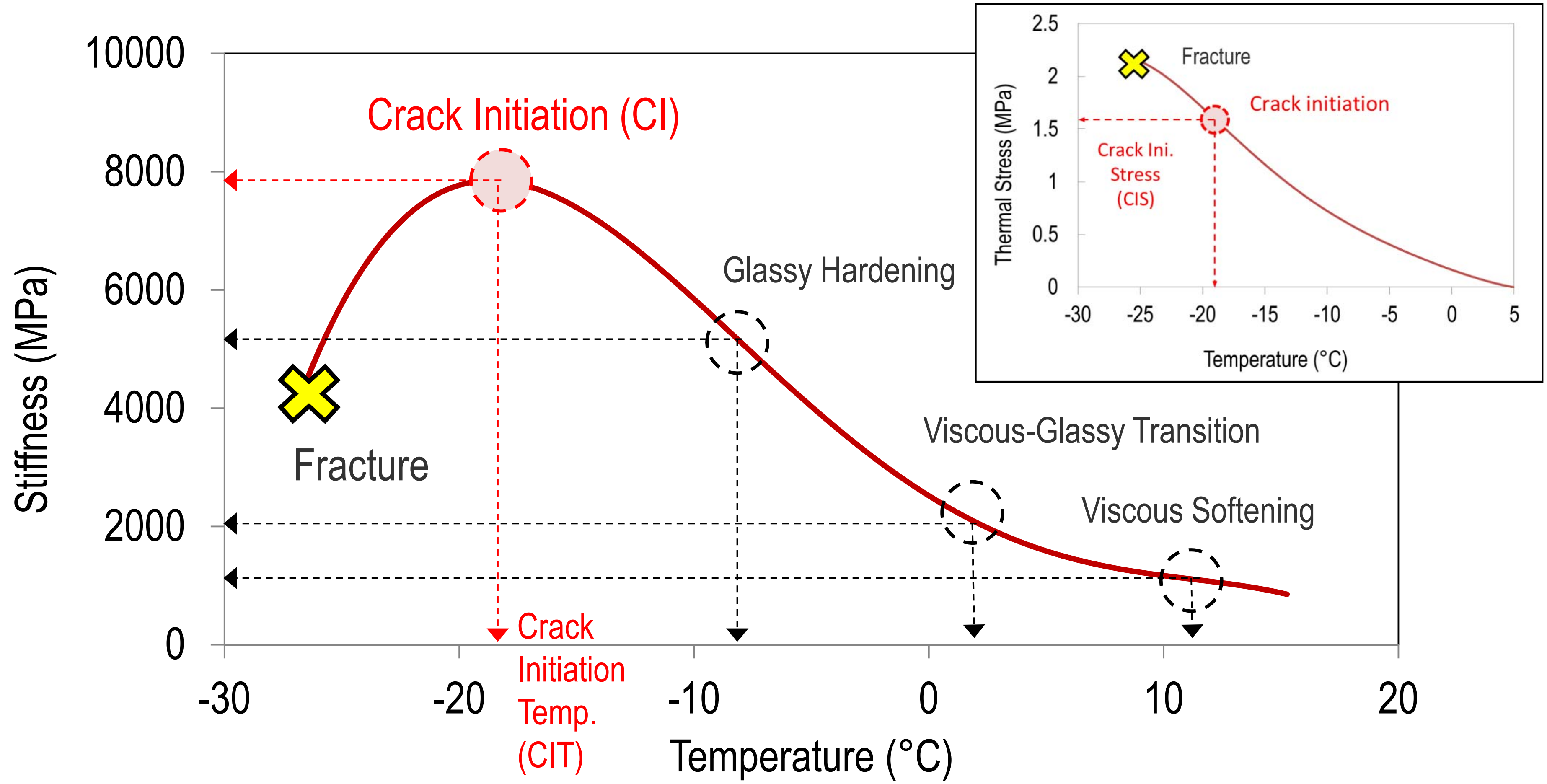
$$\varepsilon_{th} = \frac{\Delta l}{l_0} = C + CTC_g\left(T - T_g\right) + ln\left\{\left[1 + e^{\frac{(T-T_g)}{R}}\right]^{R(CTC_l - CTC_g)}\right\}$$

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

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

Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

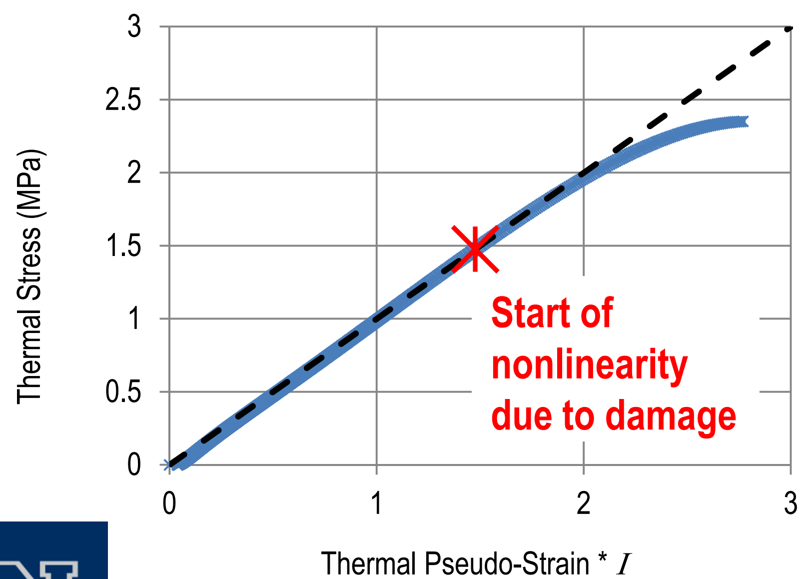


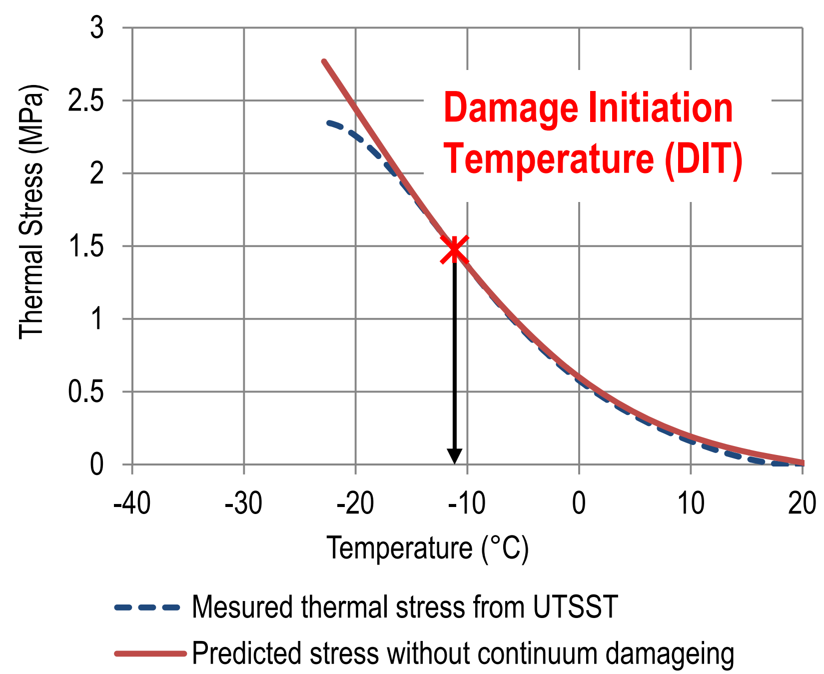
Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

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

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





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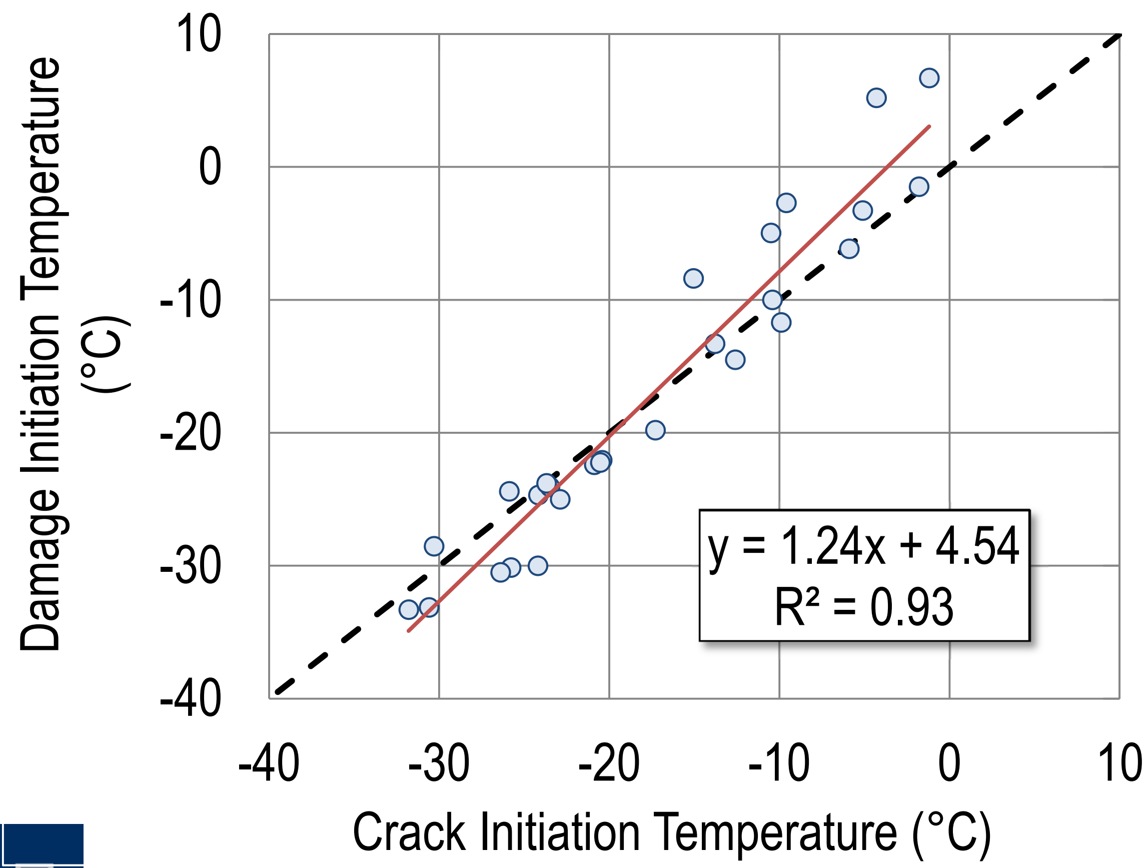
Thermal Cracking Analysis

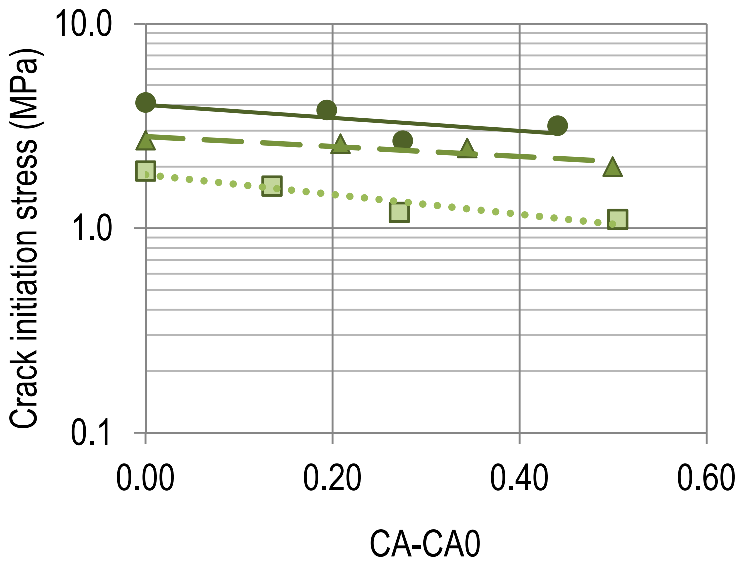
Age-Dependent Crack Initiation Stress (CIS)

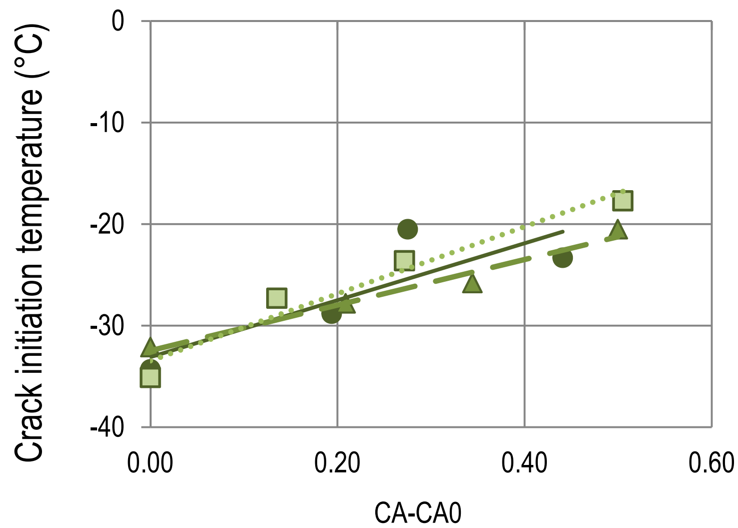
- Validation of CIS with VECD.



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

Age-Dependent Crack Initiation Stress (CIS)





Similar trends were observed for all evaluated mixtures!

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

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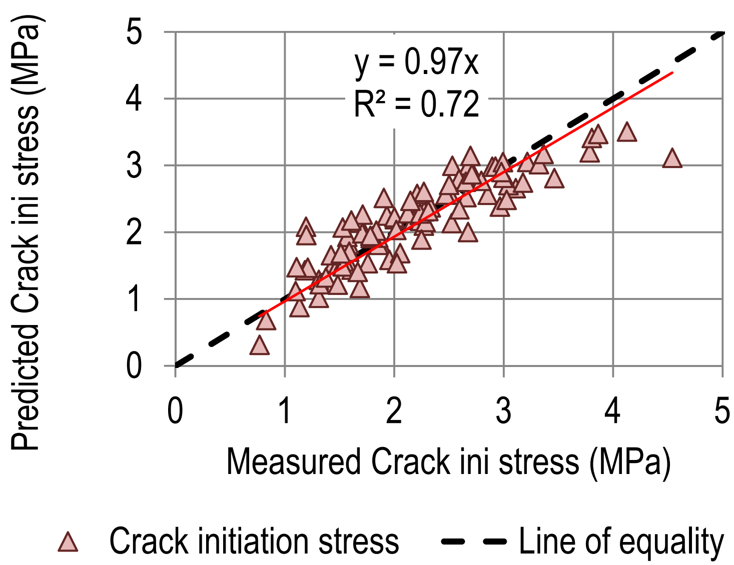
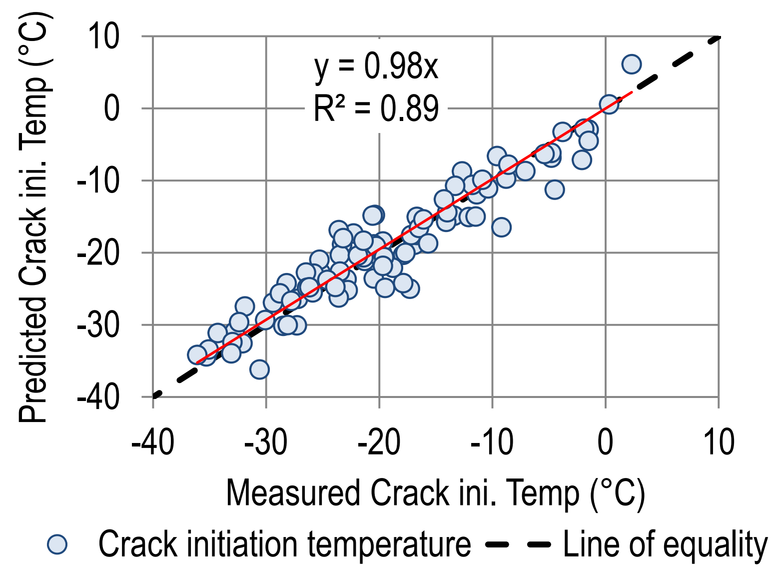
Thermal Cracking Analysis

Age-Dependent Crack Initiation Stress (CIS)

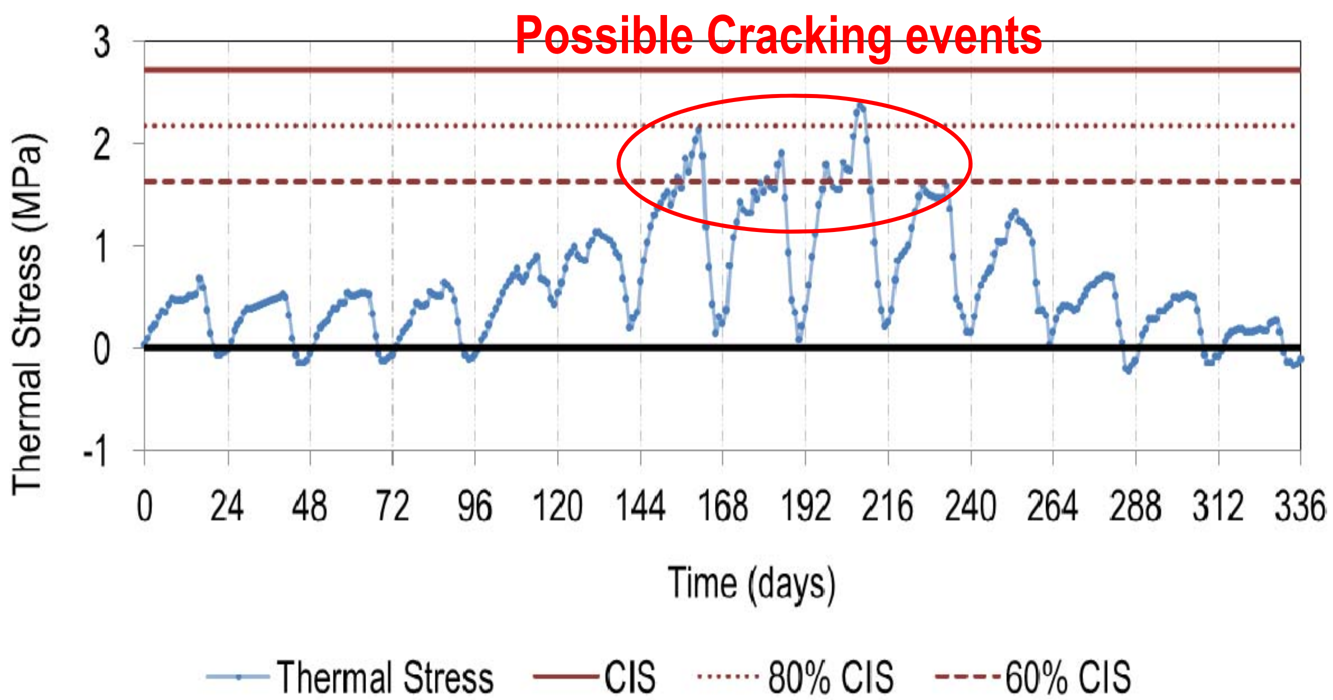
	Mixture variable						
	CA	Va (%)	Abs. (%)	LSV_{Tank} (poise)	B.C. (%)	Retained # 8	Passing # 200
CIS	√	√	√	√			√
CIT	√	√		√	√	√	√





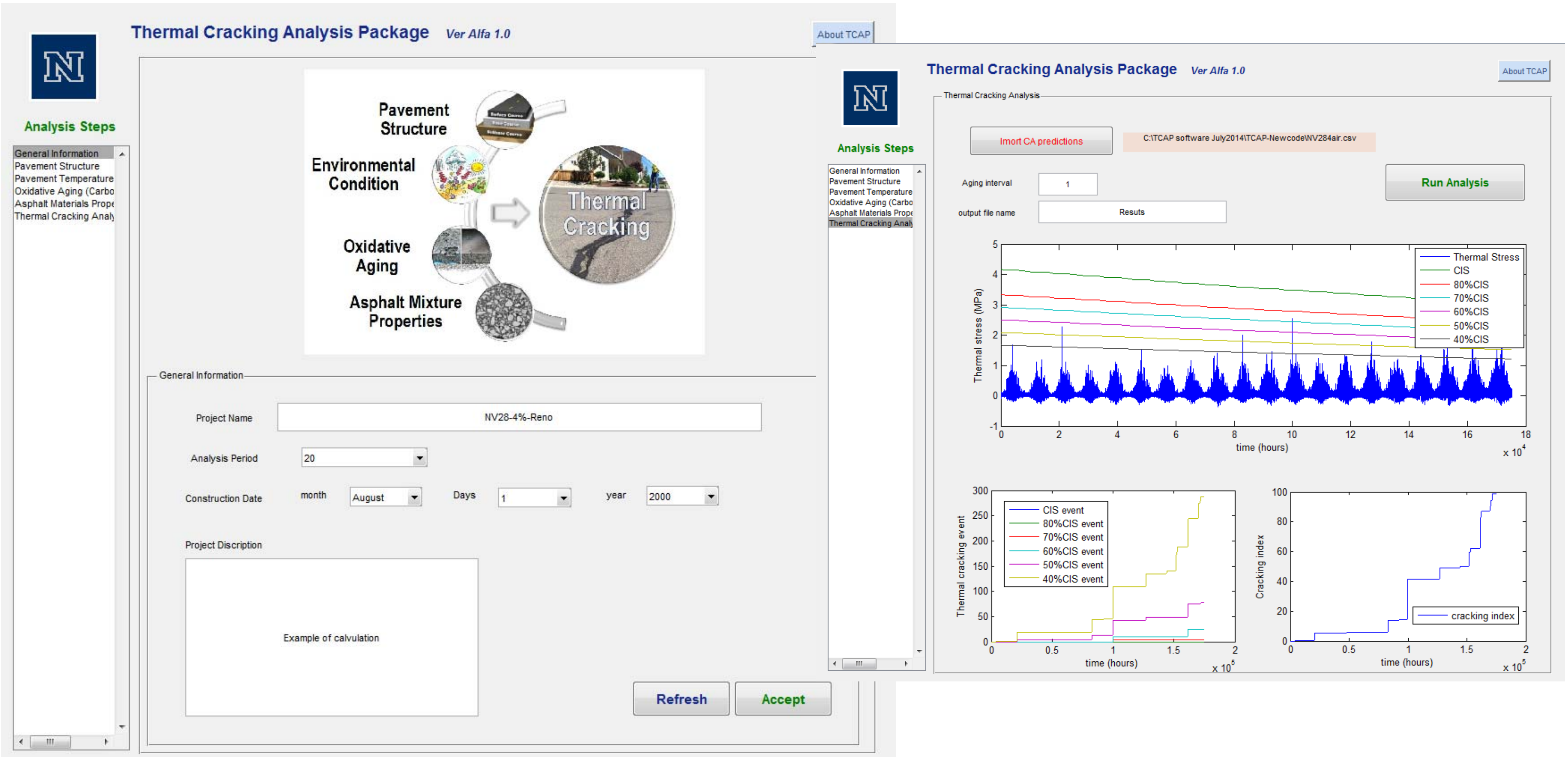
Thermal Cracking Event Probability

- 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)



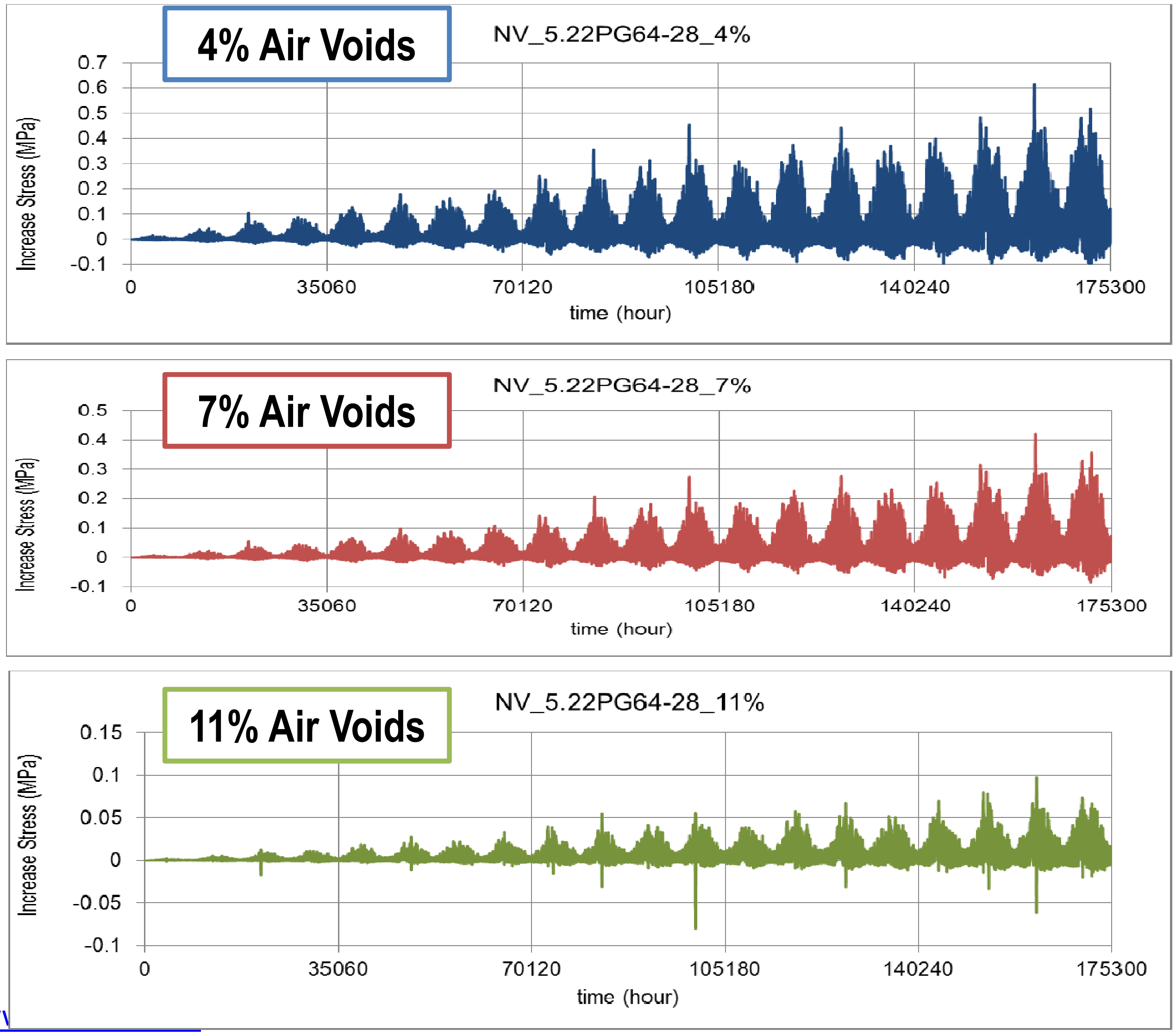
Examples: TCAP Analysis

- **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

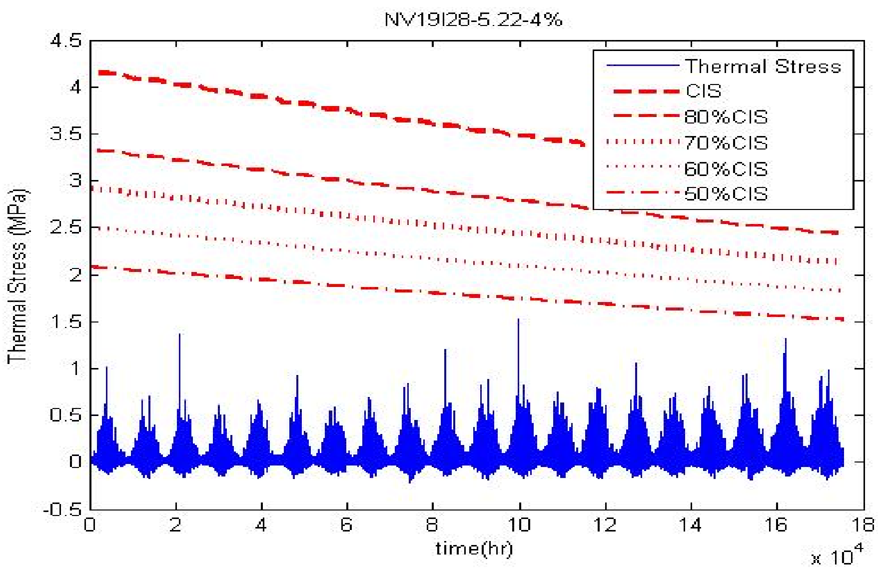
Effect of Oxidative Aging on Thermal Stresses

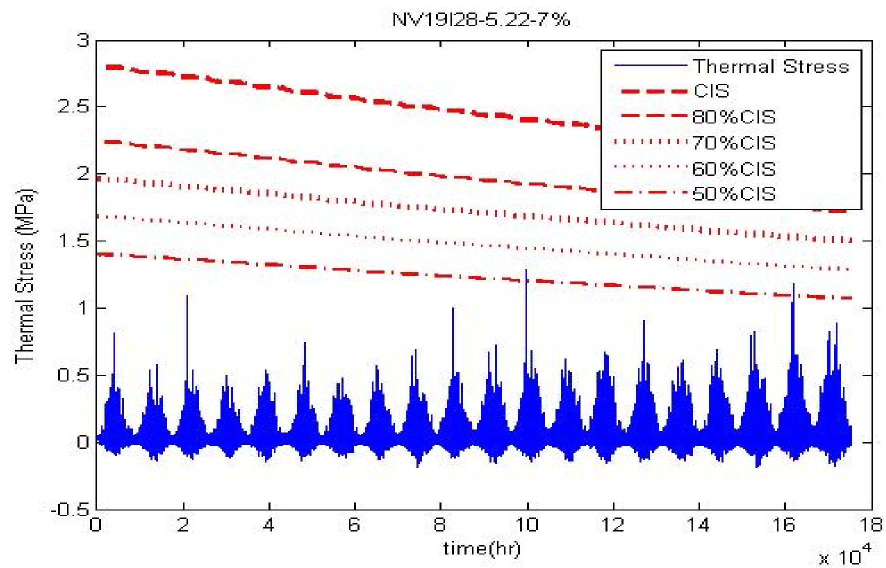
Difference in predicted thermal stresses between aging and no-aging effect analyses.

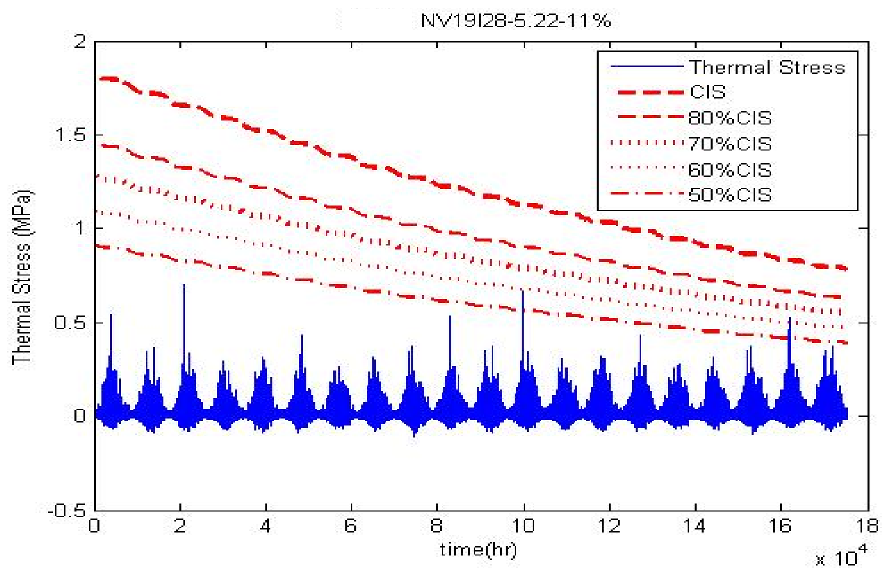


Examples: TCAP analysis

Thermal Stress vs. Crack Initiation Stress (CIS)

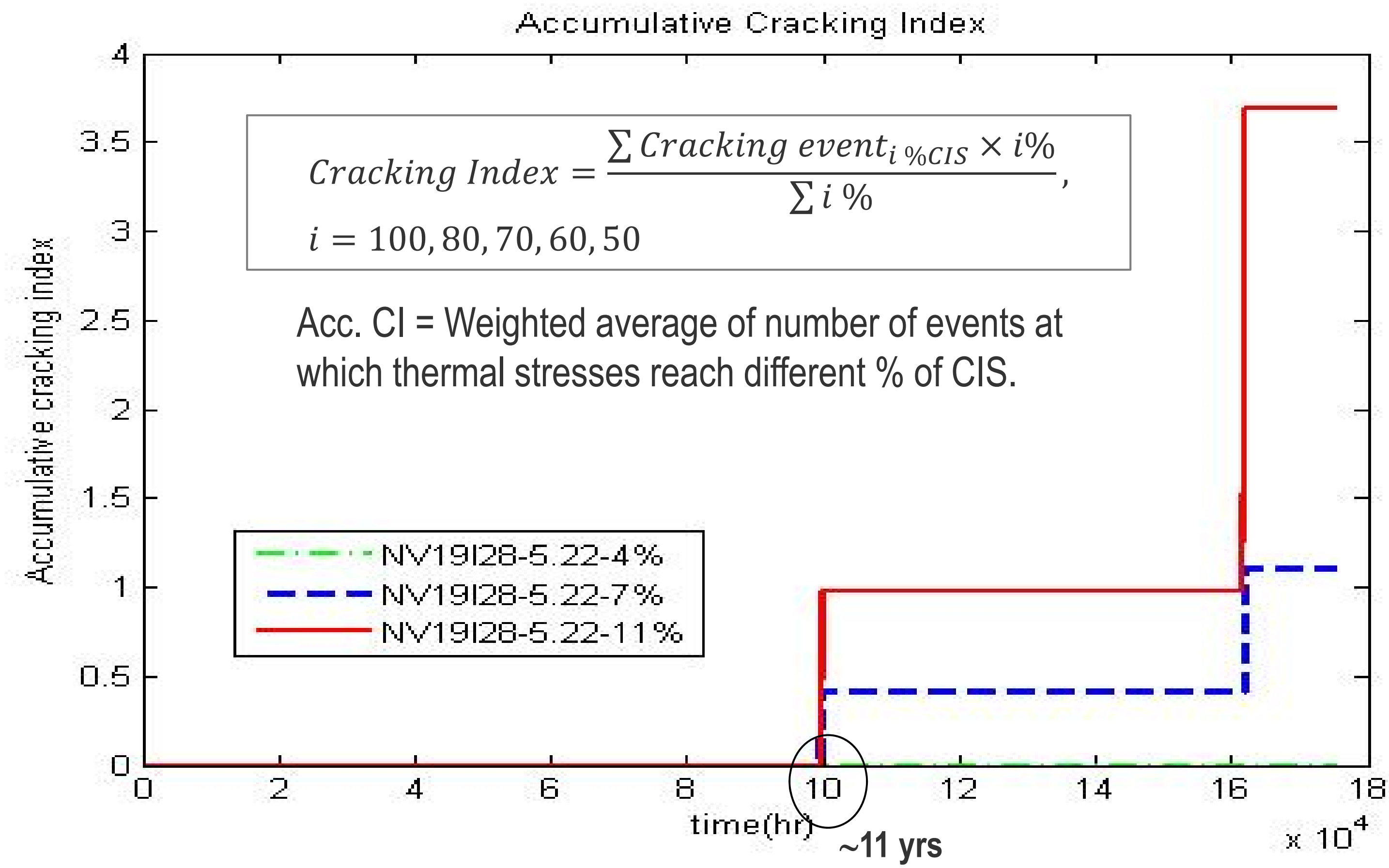






Examples: TCAP analysis

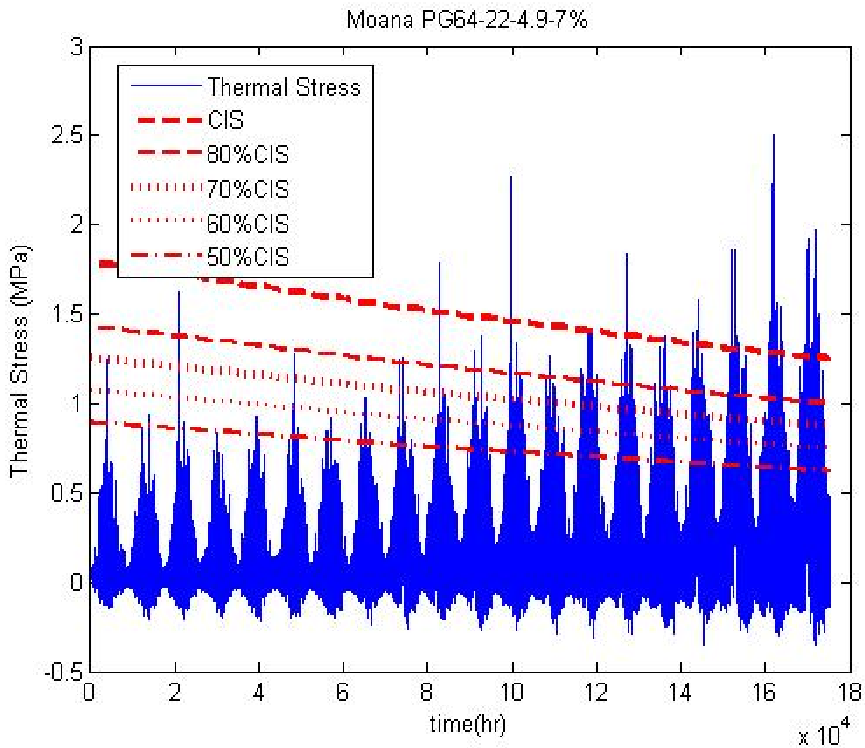
Effect of Mixtures Air Voids



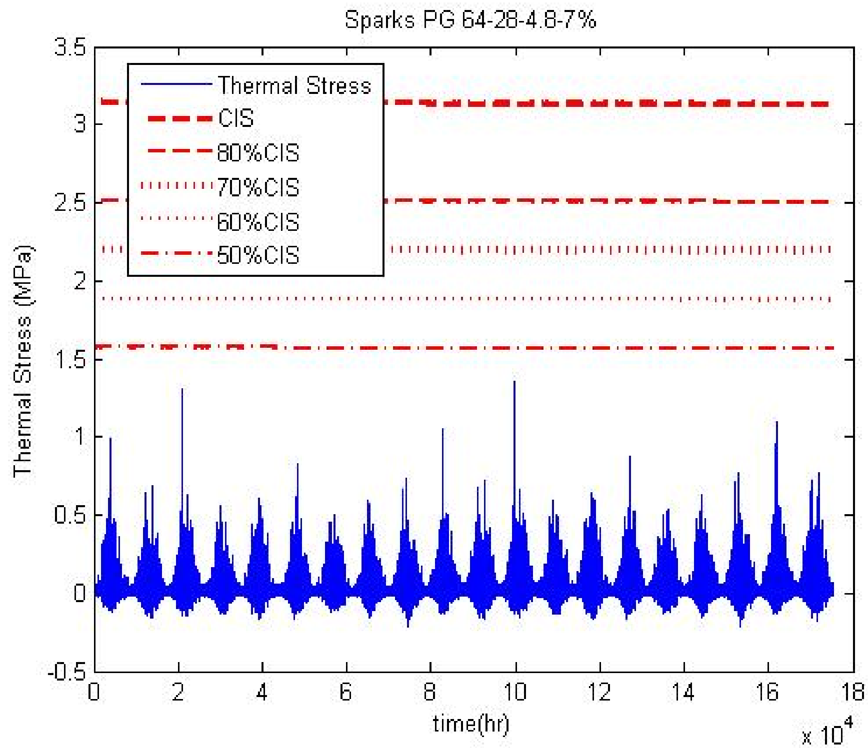
Cracking likelihoods increase for mixture with higher air voids level….

Examples: TCAP analysis

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

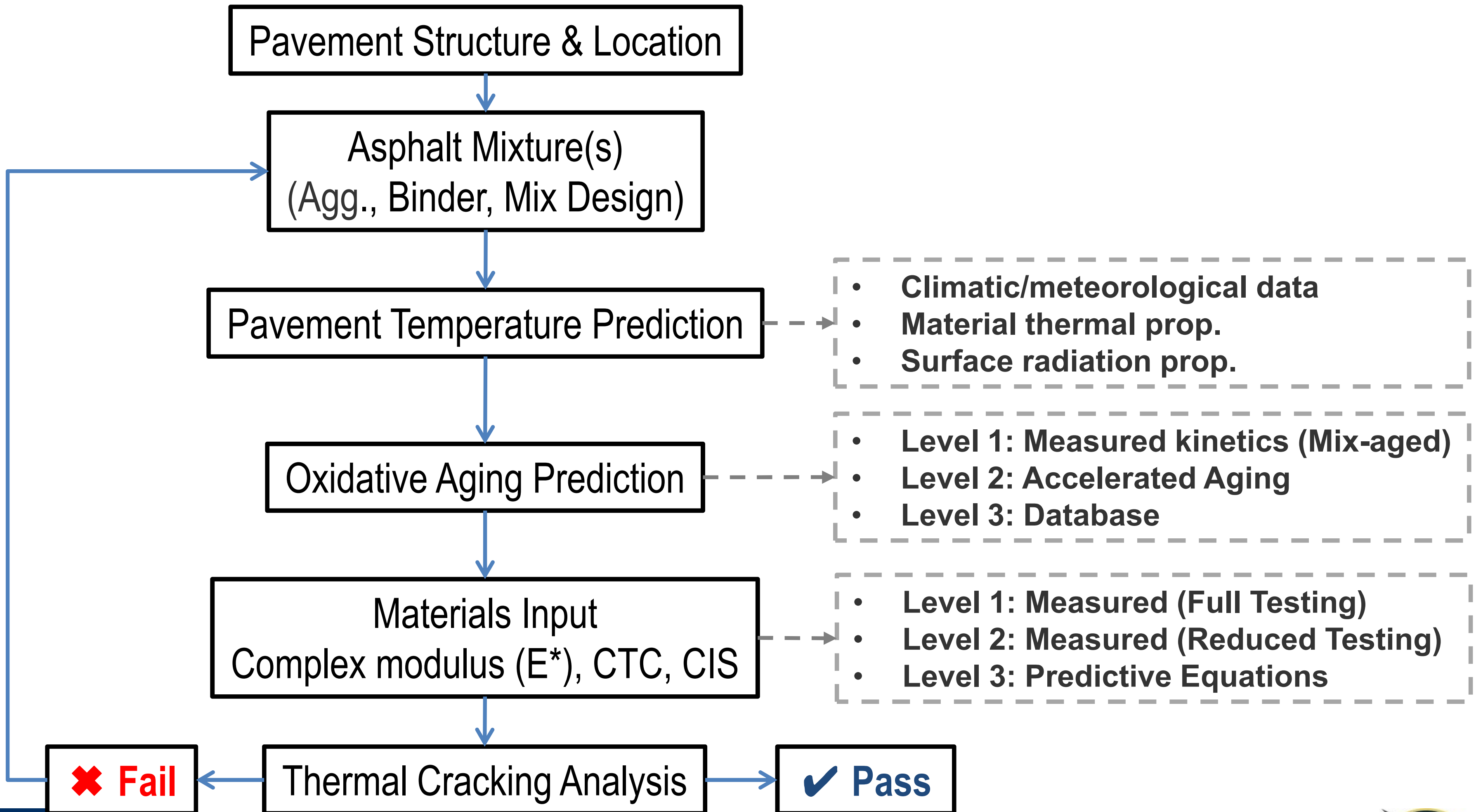


Un-modified PG64-22 (Moana, 2006)



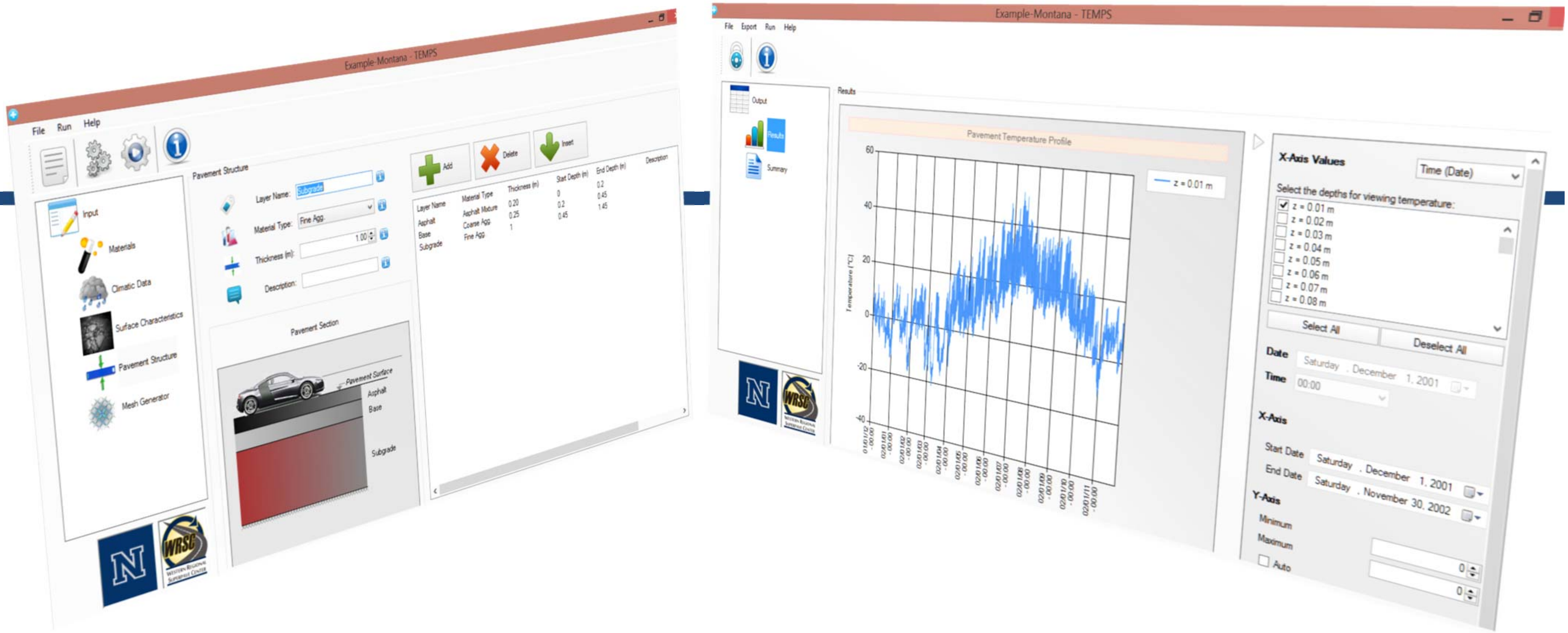
SBS polymer-modified PG64-28 (Sparks, 2008)

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)

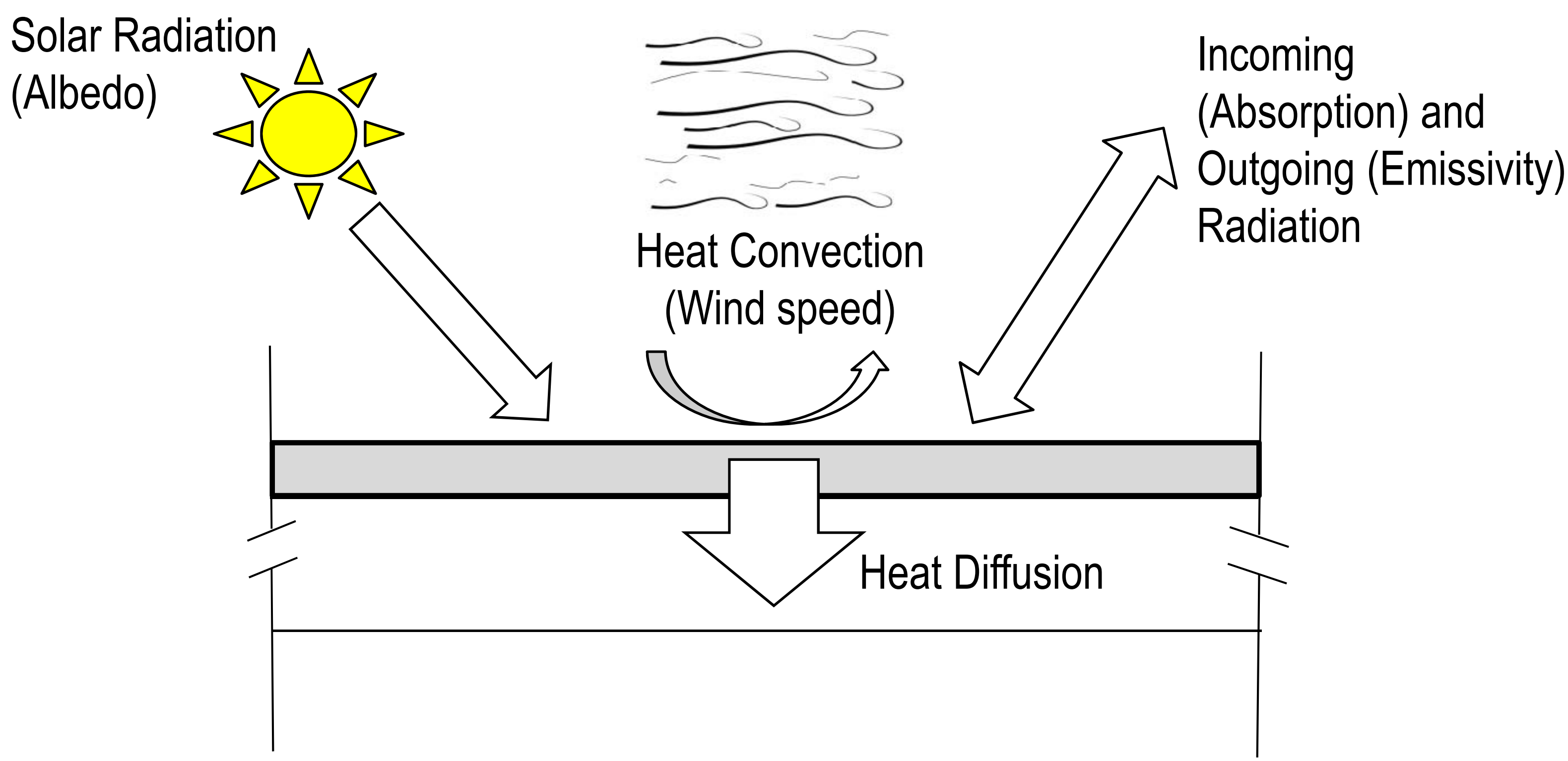
Pavement Temperature Profile Prediction

- **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 [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

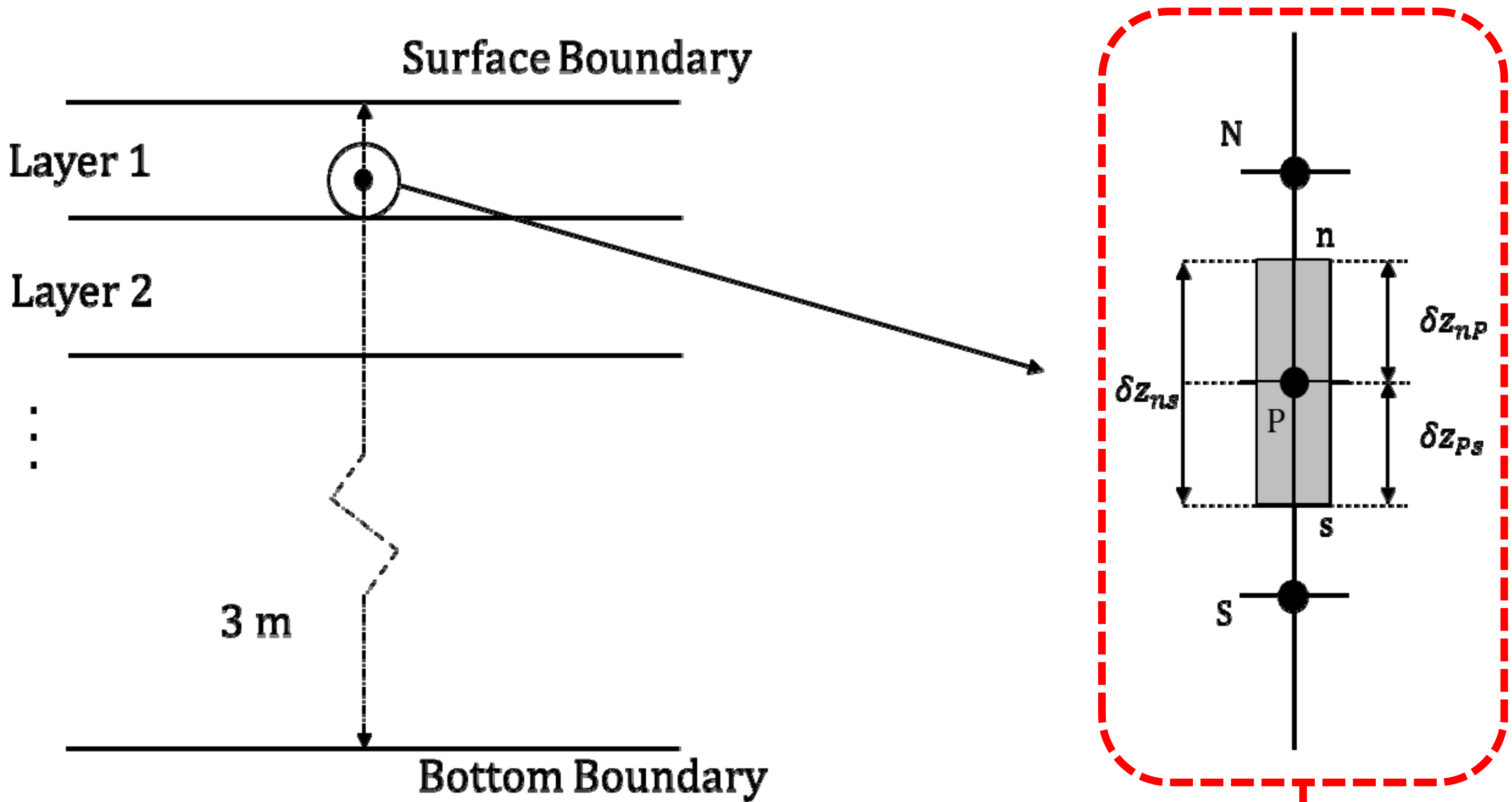


Heat Transfer Balance Between Pavement Structure & Surrounding Environment

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

Pavement Temperature Profile Prediction

Numerical Computation: Finite Control Volume Method (FCVM)

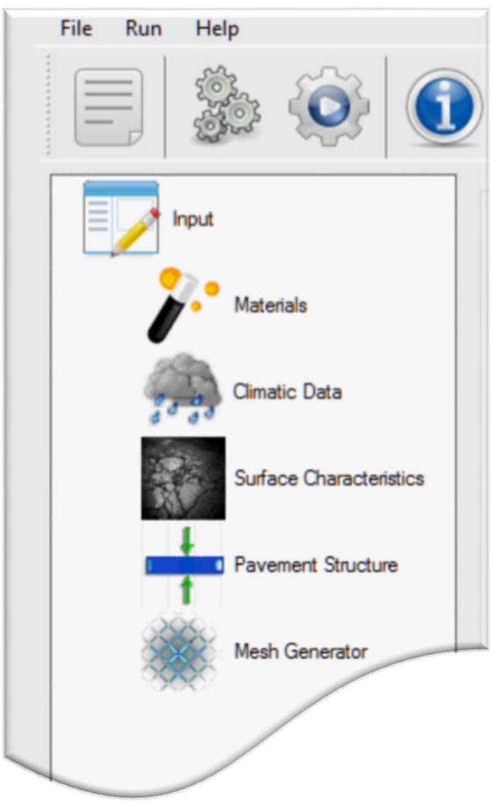


Energy Balance in Each of Control Elements

Pavement Temperature Profile Prediction

Standalone Software: TEMPS (Alpha Version)

Temperature Estimate Model for Pavement Structures (TEMPS)

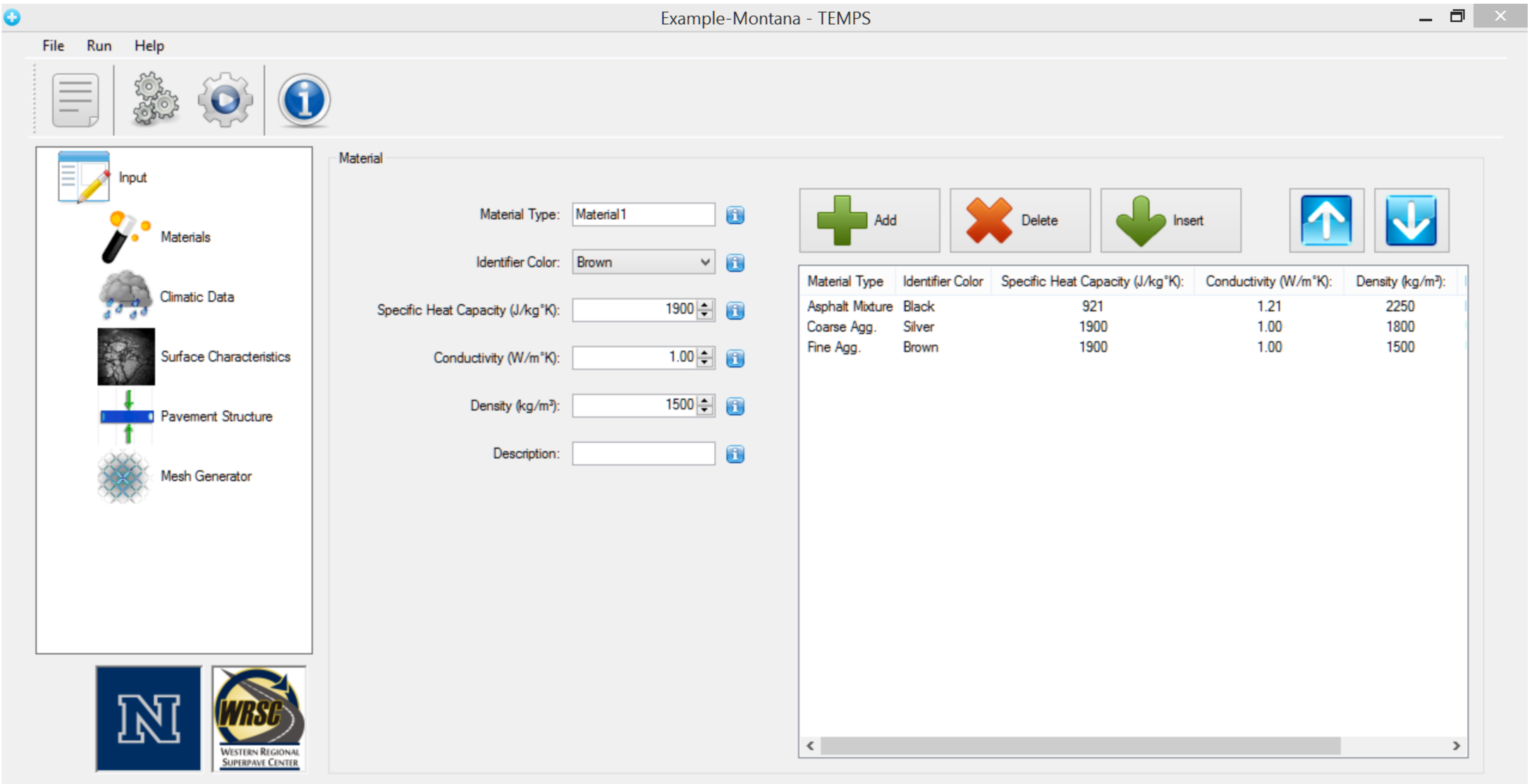


INPUT MODULES:

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

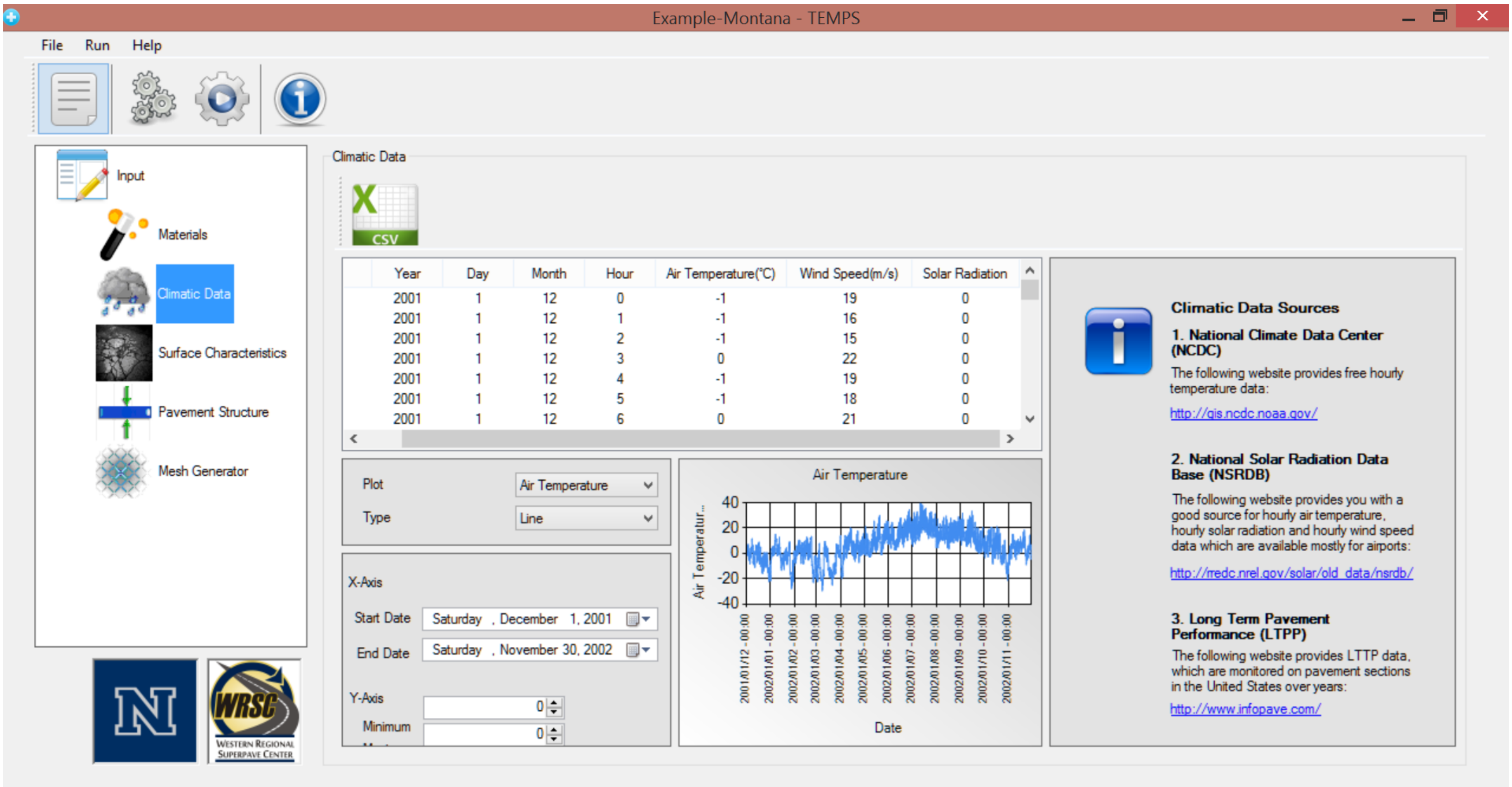
Pavement Temperature Profile Prediction

TEMPS – Materials Input



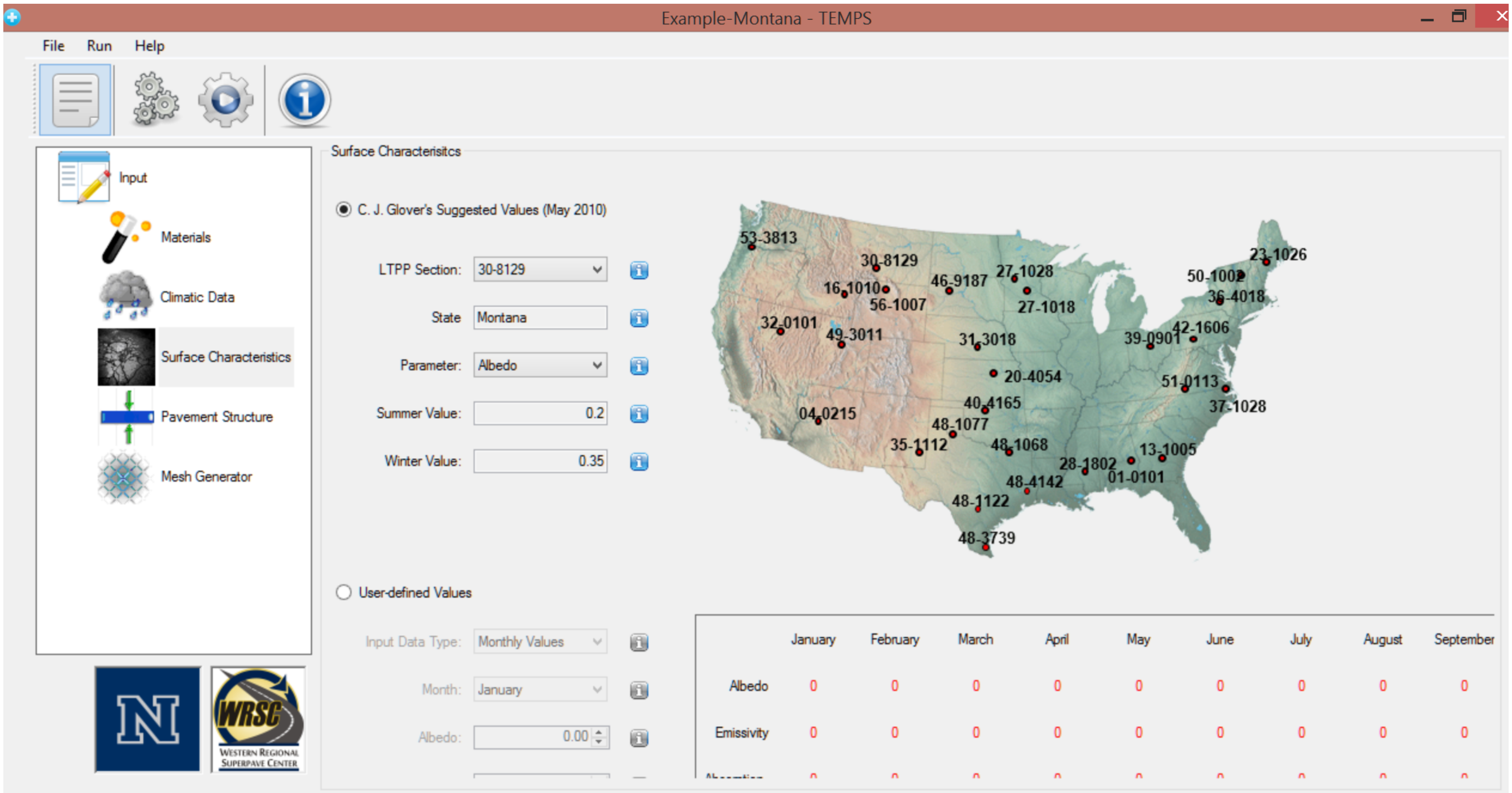
Pavement Temperature Profile Prediction

TEMPS – Climatic Data Input



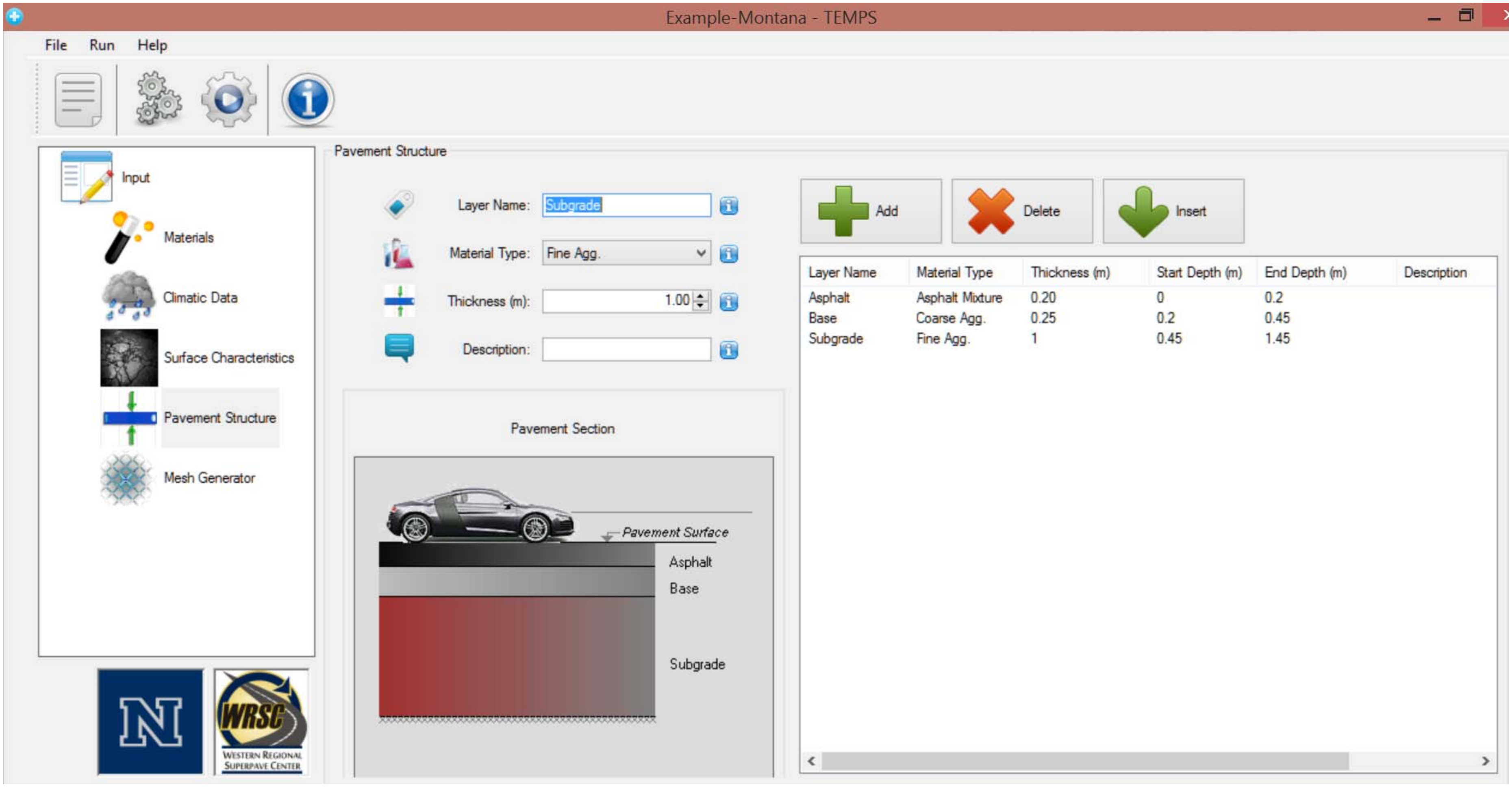
Pavement Temperature Profile Prediction

TEMPS – Surface Characteristics Input



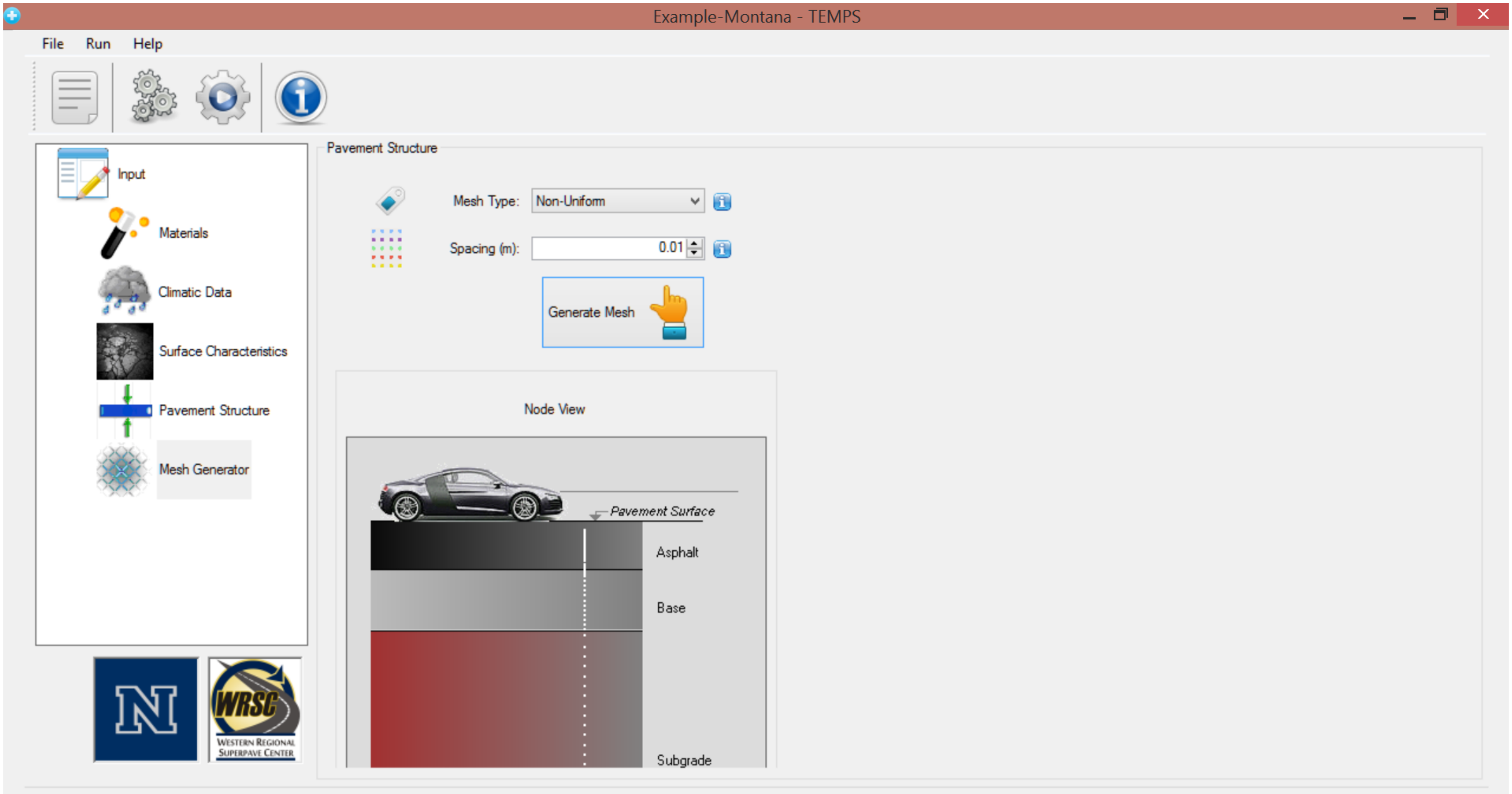
Pavement Temperature Profile Prediction

TEMPS – Pavement Structure



Pavement Temperature Profile Prediction

TEMPS – Mesh Generator



TEMPS – Run Analysis

Time Efficiency of Computation: Implicit Scheme

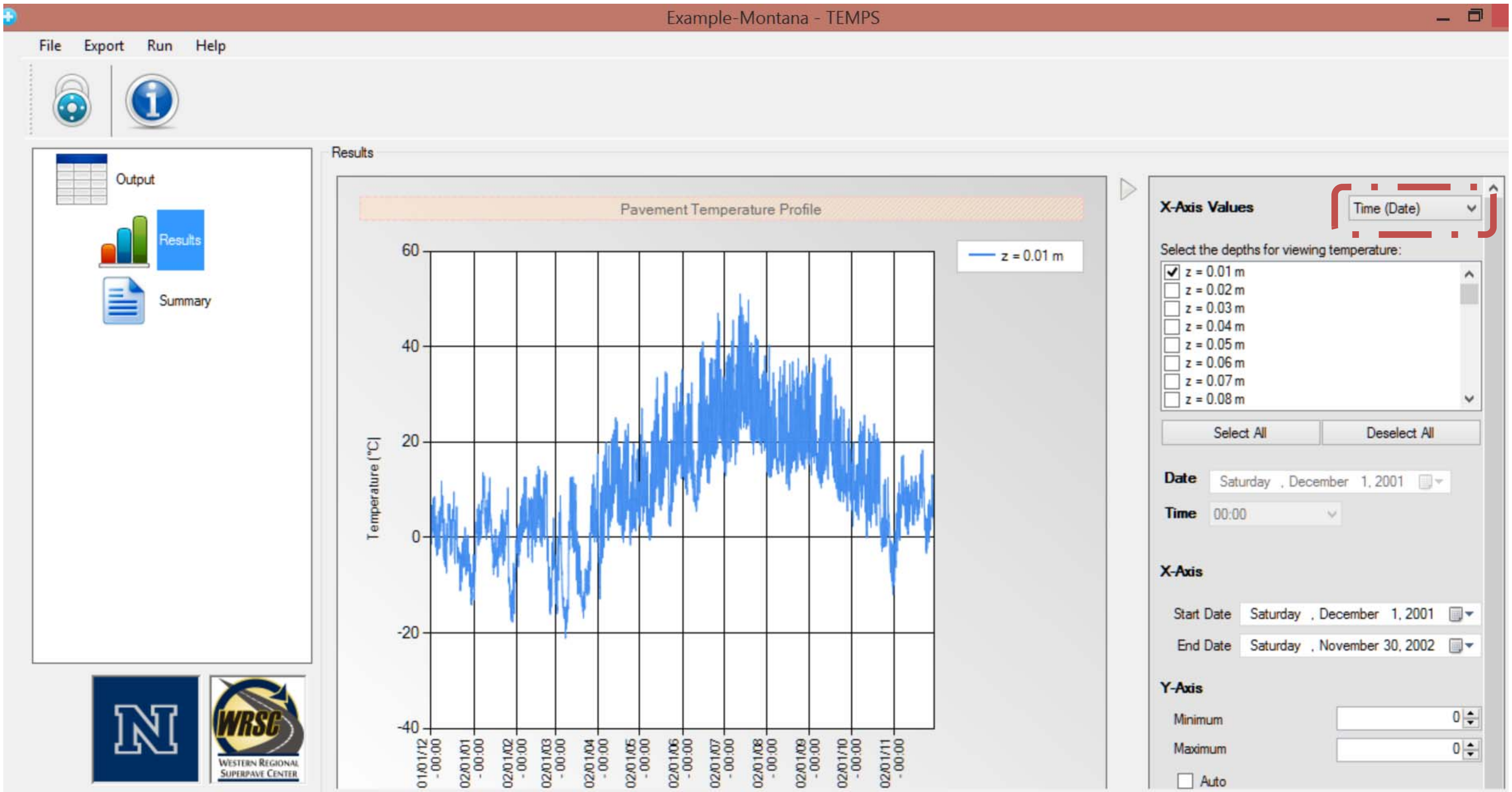
Run time for **1 years** analysis period
(3.10 GHz proc. and 4.00 GB RAM)

< 10 seconds using 1 hour time step*

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

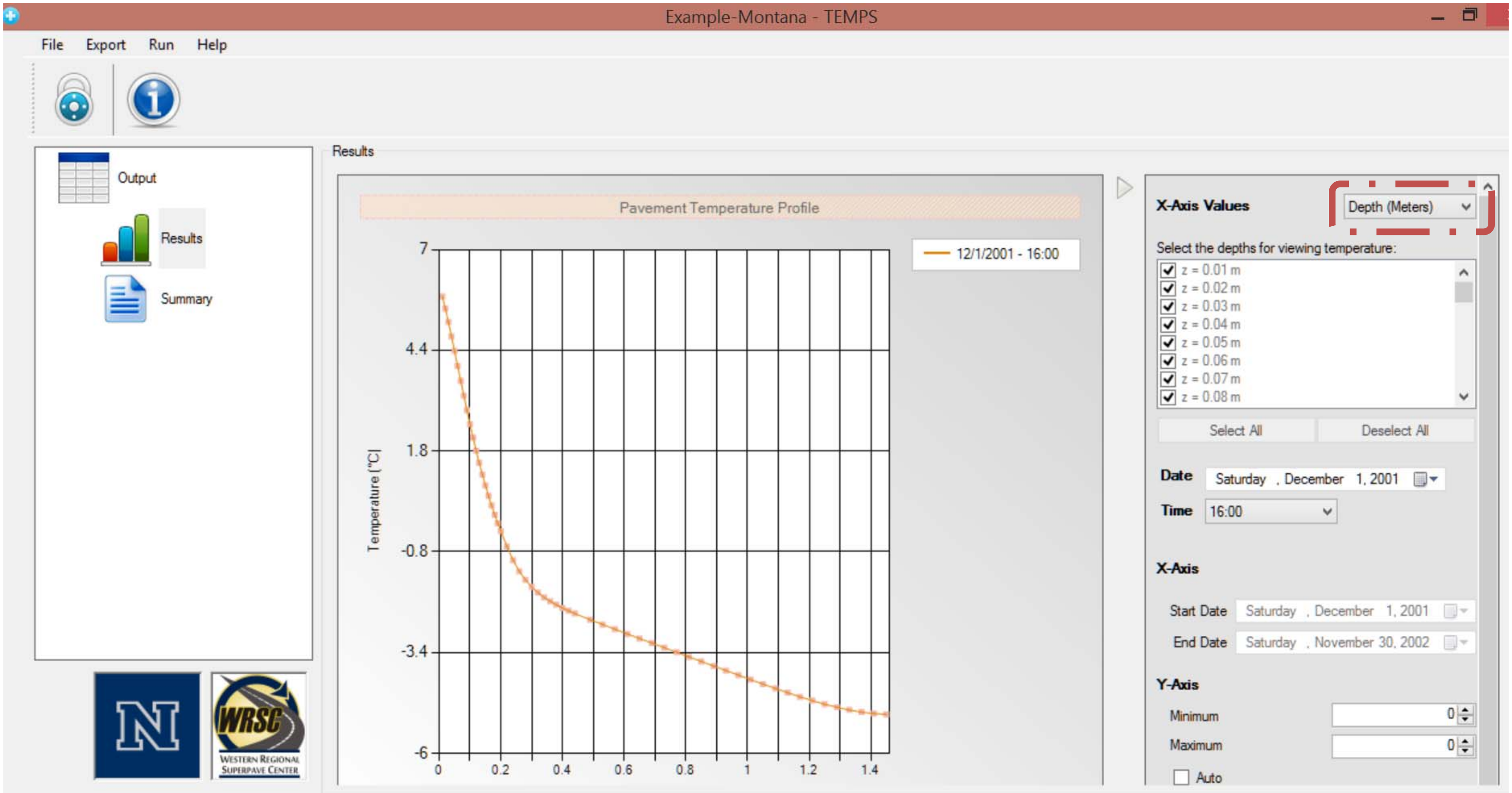
Pavement Temperature Profile Prediction

TEMPS – Output Results

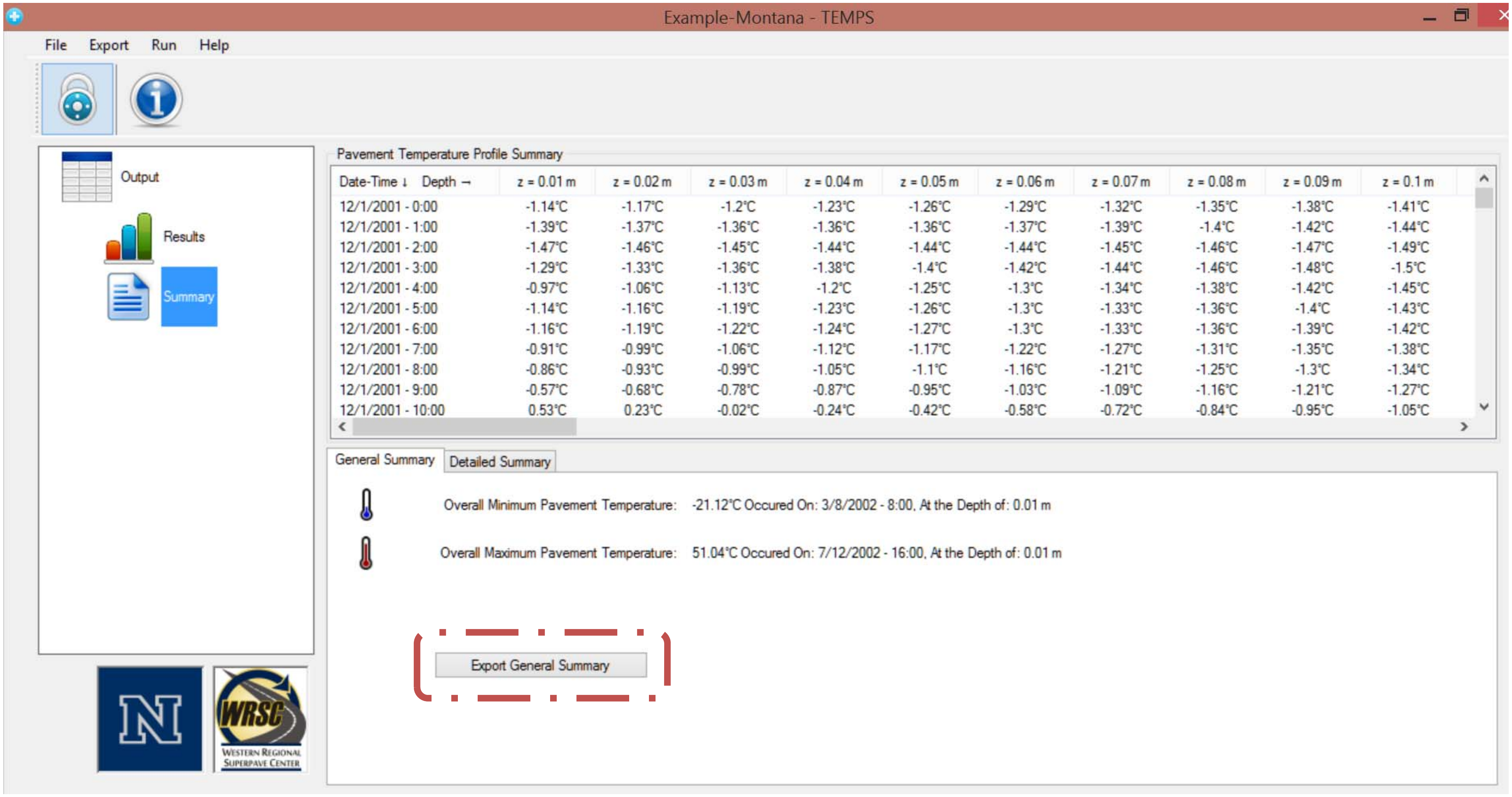


Pavement Temperature Profile Prediction

TEMPS – Output Results



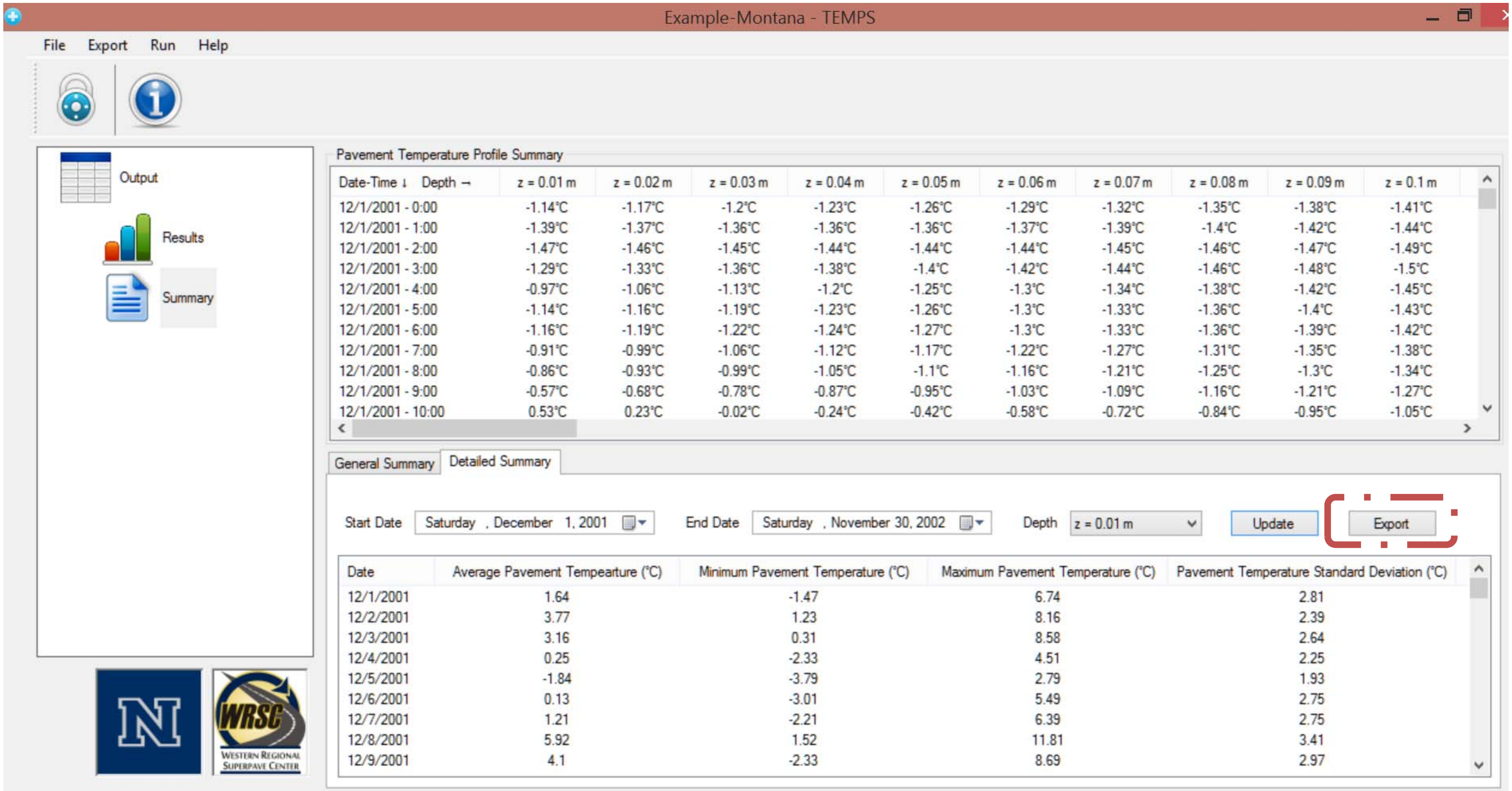
TEMPS – Output Summary



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

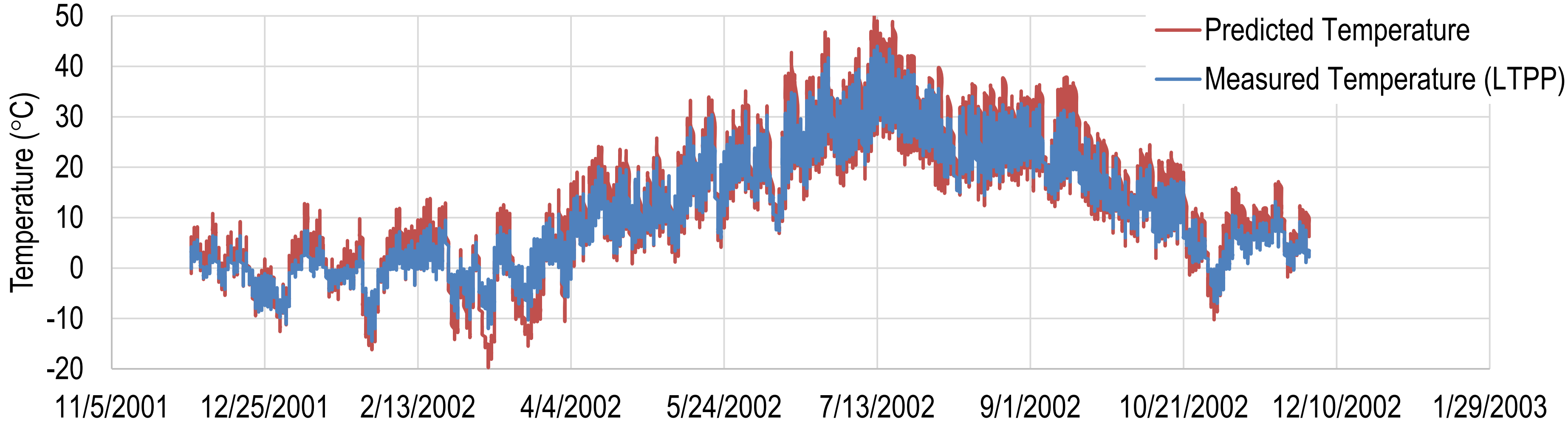
TEMPS – Output Summary

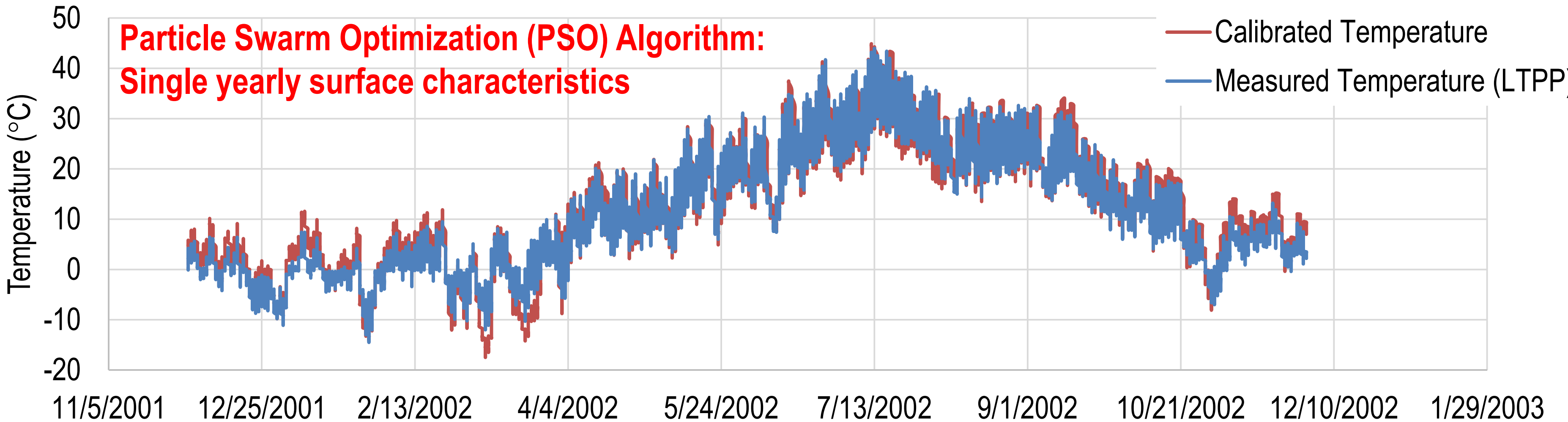


Pavement Temperature Profile Prediction

TEMPS – Predicted versus Measured

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

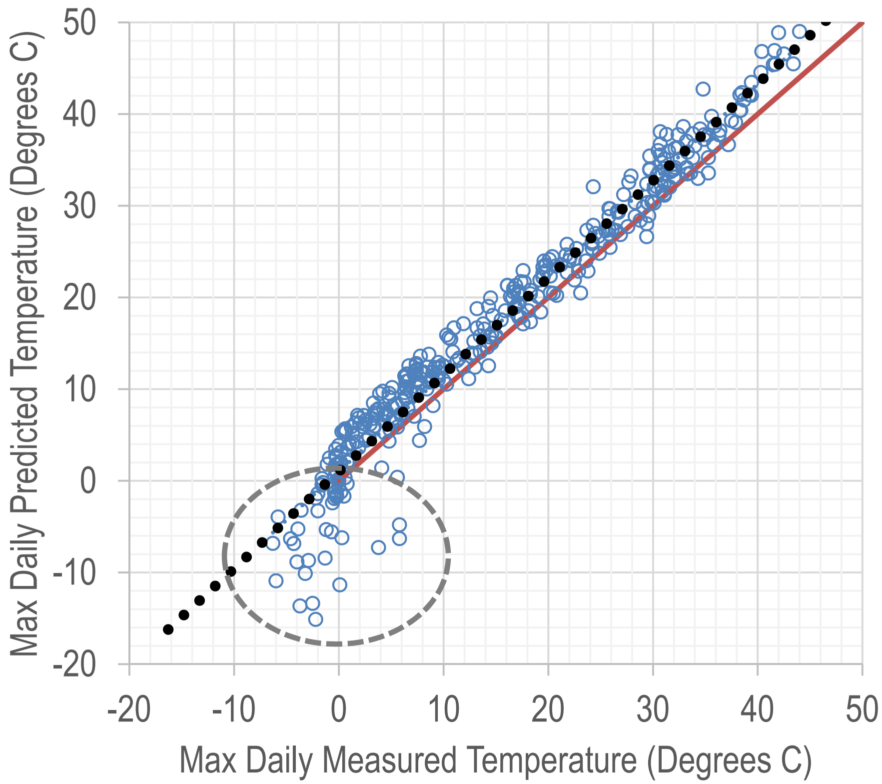


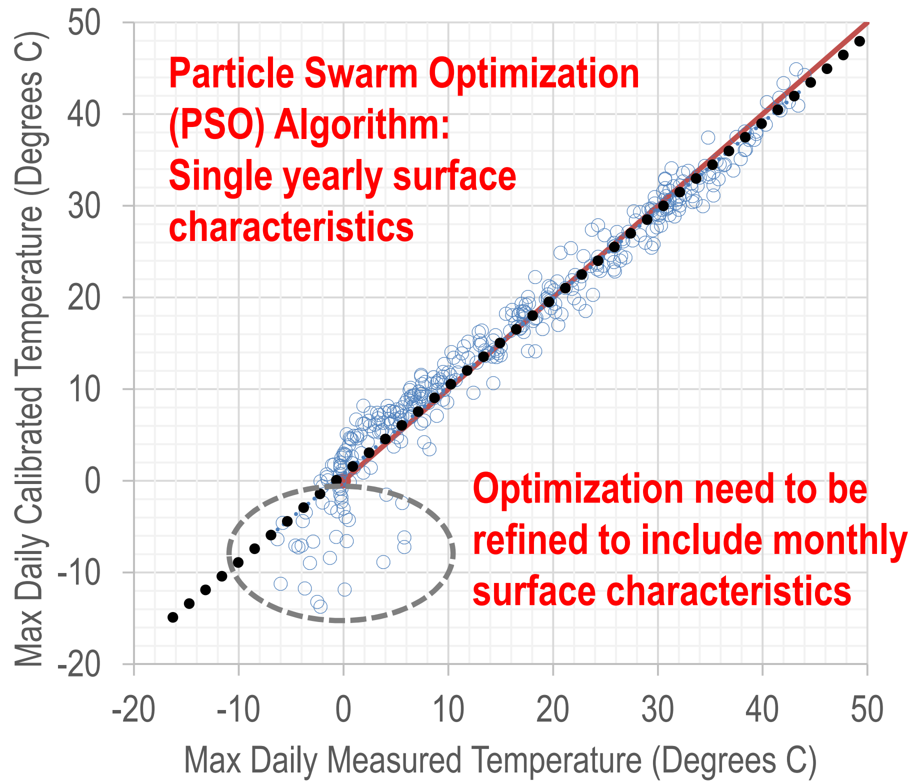


Pavement Temperature Profile Prediction

TEMPS – Predicted versus Measured

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





Pavement Temperature Profile Prediction

TEMPS – 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!