


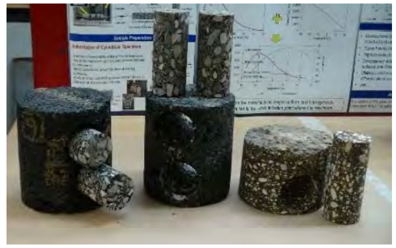
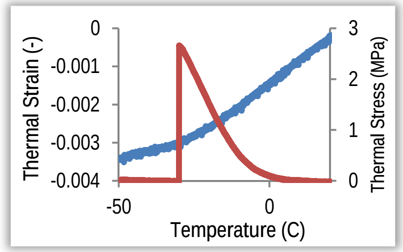

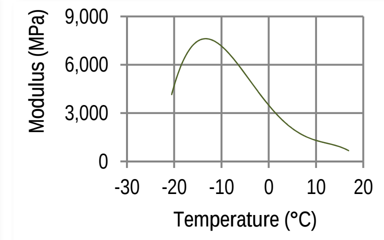

Uniaxial Thermal Stress and Strain Test (UTSST)

2016 Pacific Coast Committee on Asphalt Specifications
Seattle, May 11, 2016

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Director

Western Regional Superpave Center

University of Nevada Reno (UNR)

Acknowledgement and Disclaimer

- The contents of this research effort are part of the overall effort in the Asphalt Research Consortium (ARC).

- The contents do not necessarily reflect the official views and policies of the Federal Highway Administration (FHWA).

Thermal Cracking in AC Pavements (Cont'd)

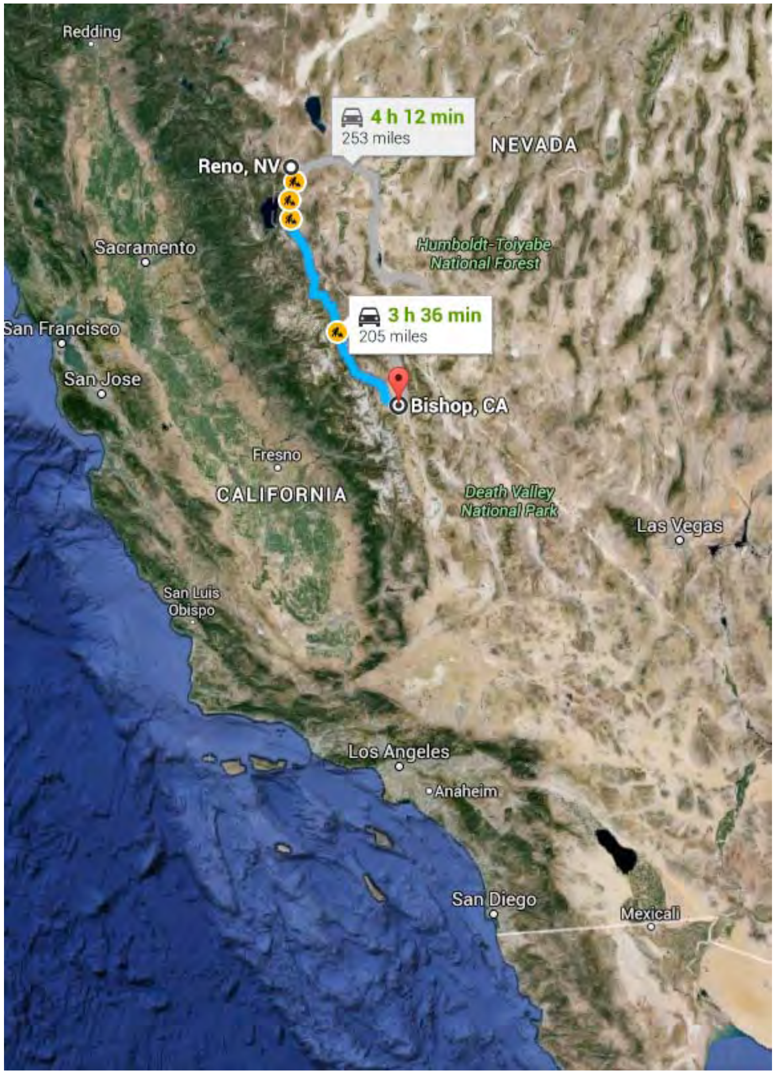
Northern Nevada

Courtesy: Nevada DOT

	Jan.	Jul.
Average Max. Temp (°C)	7.6	33.8
Average Min. Temp (°C)	-2.5	16.4

Thermal Cracking in AC Pavements (Cont'd)

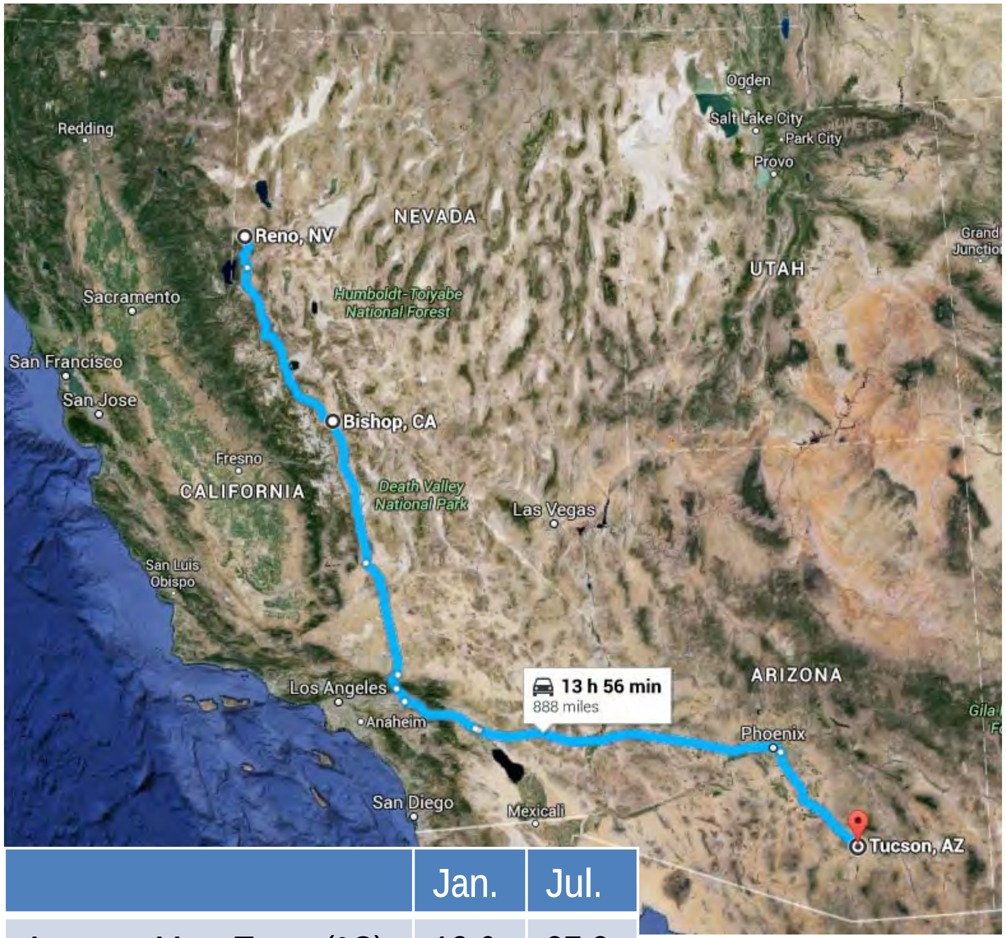
Bishop, CA



	Jan.	Jul.
Average Max. Temp (°C)	11.7	36.5
Average Min. Temp (°C)	-5.7	13.4

Thermal Cracking in AC Pavements (Cont'd)

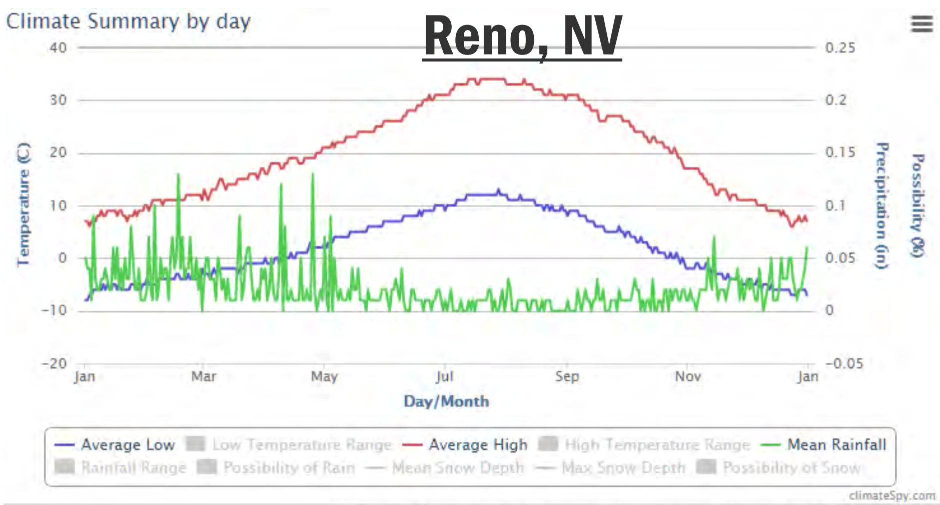
Tucson, AZ



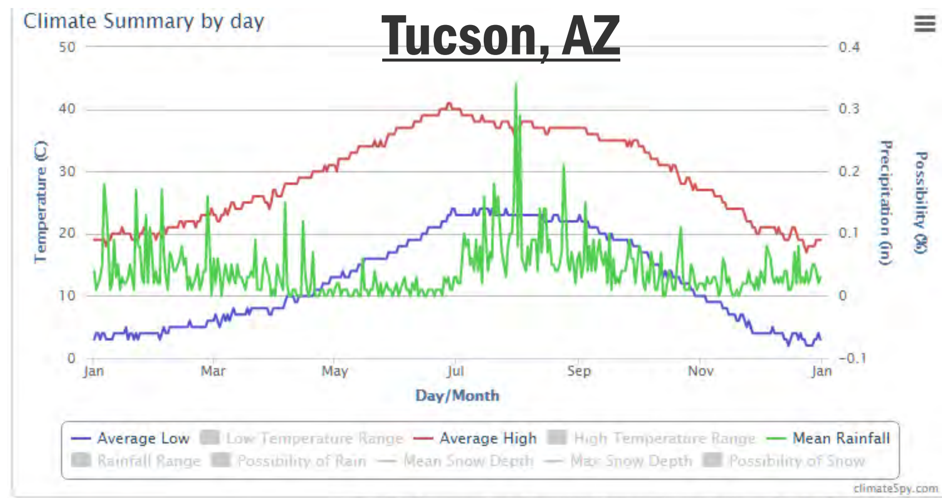
	Jan.	Jul.
Average Max. Temp (°C)	18.6	37.8
Average Min. Temp (°C)	3.1	23.3

Thermal Cracking in AC Pavements (Cont'd)

Average Temperature Ranges: Reno vs. Tucson



Graph of average and extreme temperature ranges by day for Reno, NV



Graph of average and extreme temperature ranges by day for Tucson, AZ

RENO WFO, NEVADA (266791)

Period of Record Monthly Climate Summary

Period of Record : 05/01/1996 to 01/20/2015

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	45.7	48.3	56.6	61.2	72.4	82.3	92.9	90.7	82.2	67.6	54.4	44.8	66.6
Average Min. Temperature (F)	27.6	29.1	33.5	37.0	45.7	53.6	61.6	59.9	53.0	42.5	33.3	26.9	42.0
Average Total Precipitation (in.)	1.23	0.95	0.62	0.57	0.44	0.52	0.20	0.21	0.26	0.65	0.66	1.37	7.68
Average Total SnowFall (in.)	7.0	7.5	3.5	2.5	0.2	0.0	0.0	0.0	0.0	0.2	1.5	9.2	31.6
Average Snow Depth (in.)	1	0	0	0	0	0	0	0	0	0	0	1	0

TUCSON UNIV OF ARIZONA, ARIZONA (028815)

Period of Record Monthly Climate Summary

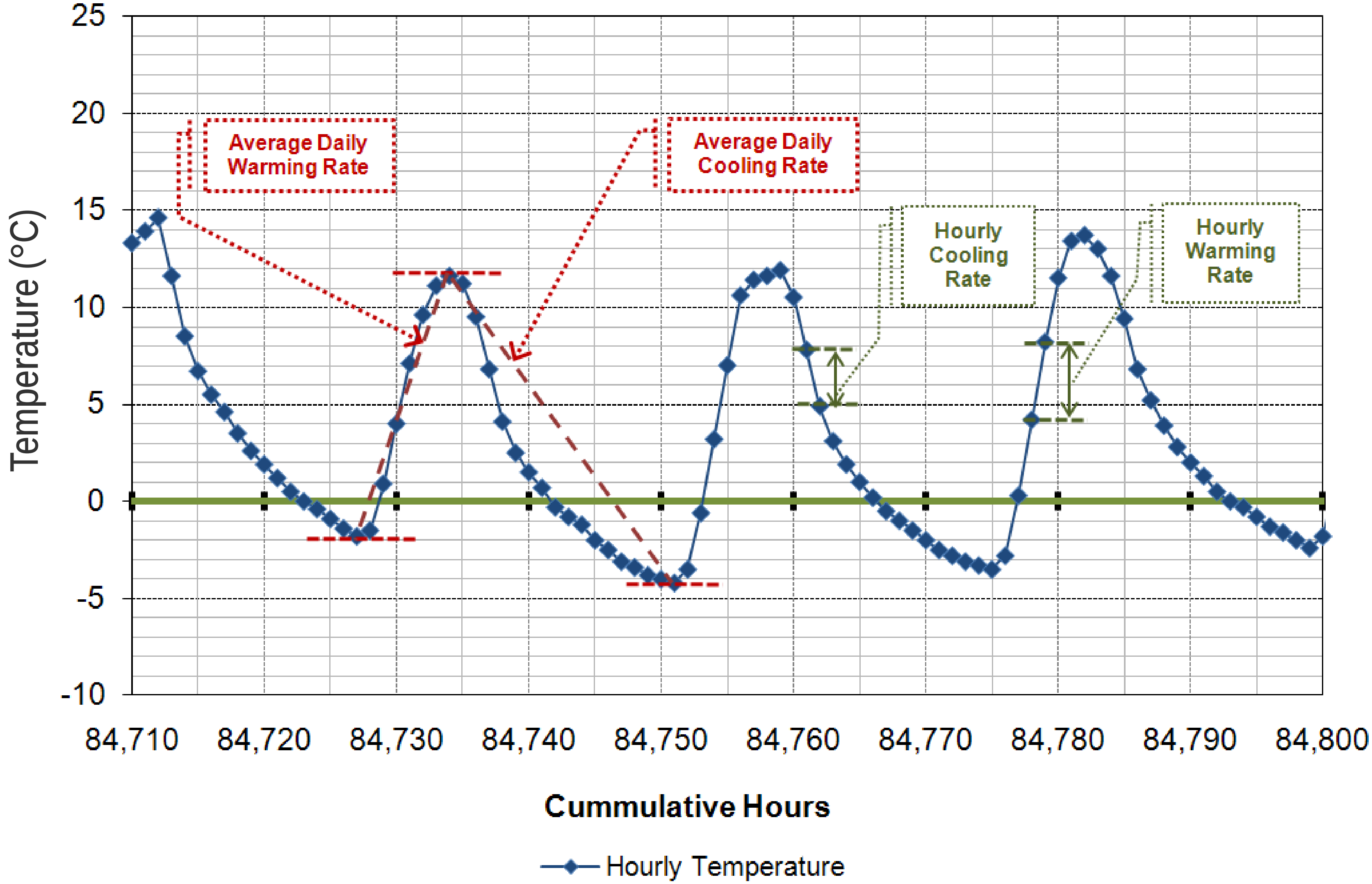
Period of Record : 9/ 1/1894 to 12/31/2005

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	65.5	68.9	74.3	82.1	90.7	99.8	100.1	97.9	95.2	85.9	74.3	66.2	83.4
Average Min. Temperature (F)	37.6	40.2	44.0	49.8	57.5	66.8	73.9	72.4	66.9	54.9	43.8	38.1	53.8
Average Total Precipitation (in.)	0.89	0.84	0.76	0.39	0.18	0.27	2.02	2.16	1.16	0.75	0.77	0.97	11.15
Average Total SnowFall (in.)	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.7
Average Snow Depth (in.)	0	0	0	0	0	0	0	0	0	0	0	0	0

Data Sources: climateSpy.com, and *Western Regional Climate Center*

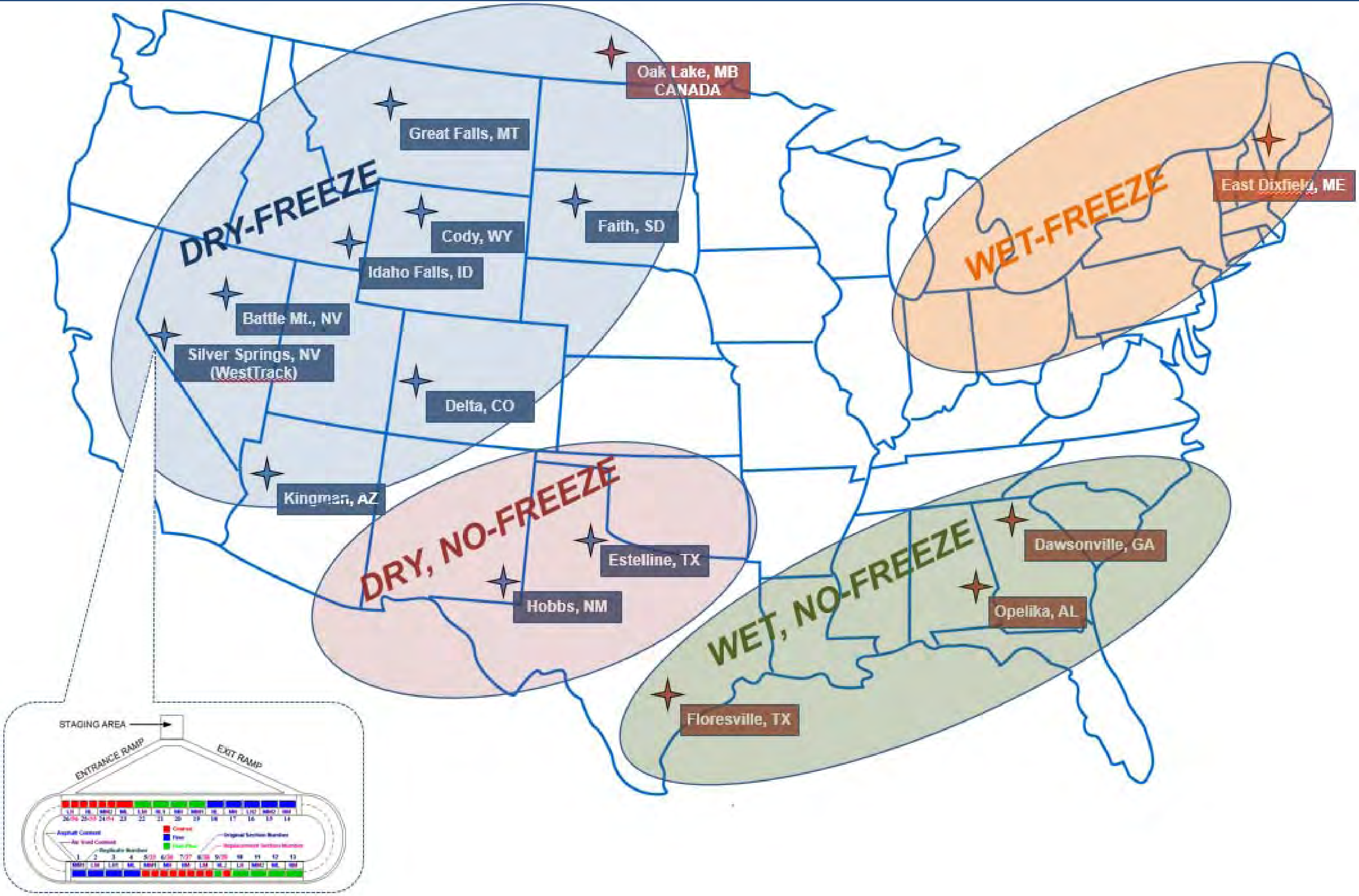
Pavement Temperature Rates

Average and Hourly Warming and Cooling Temperature Rates in AC



Pavement Temperature Rates (Cont'd)

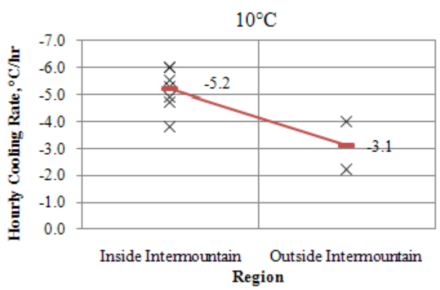
Average and Hourly Warming and Cooling Temperature Rates in AC

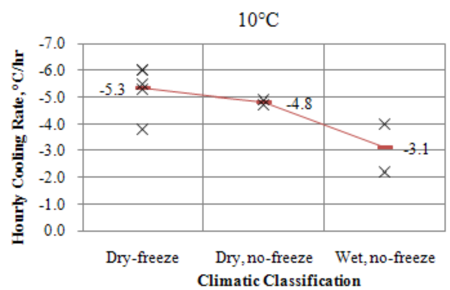


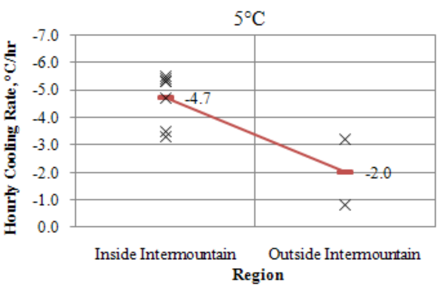
Pavement Temperature Rates (Cont'd)

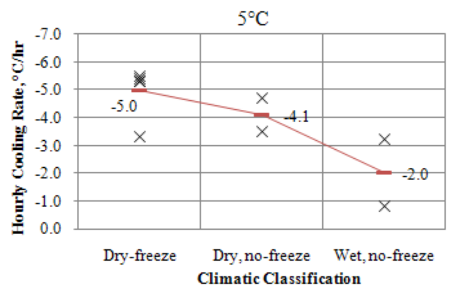
Measurements in AC at a Depth of 12.5 mm below pavement surface

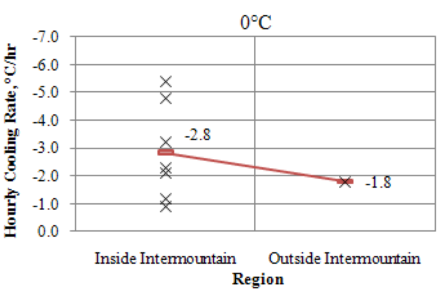
Cooling Rates

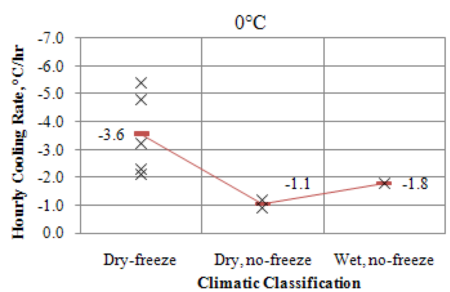




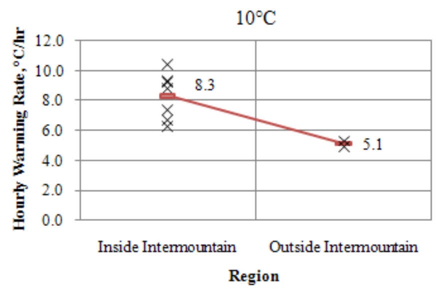


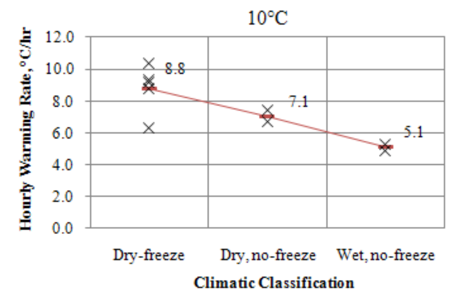


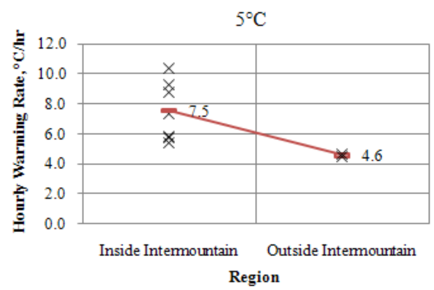


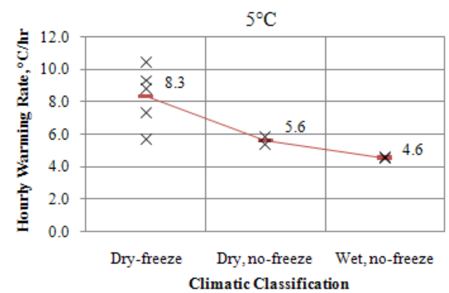


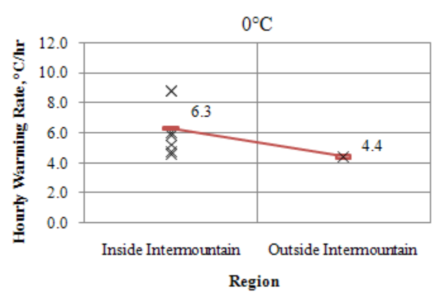
Warming Rates

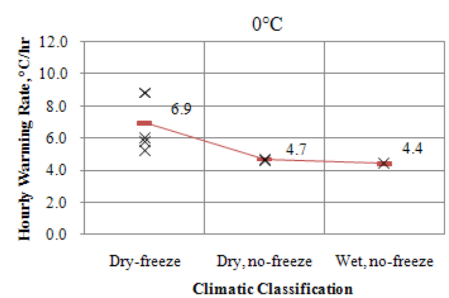




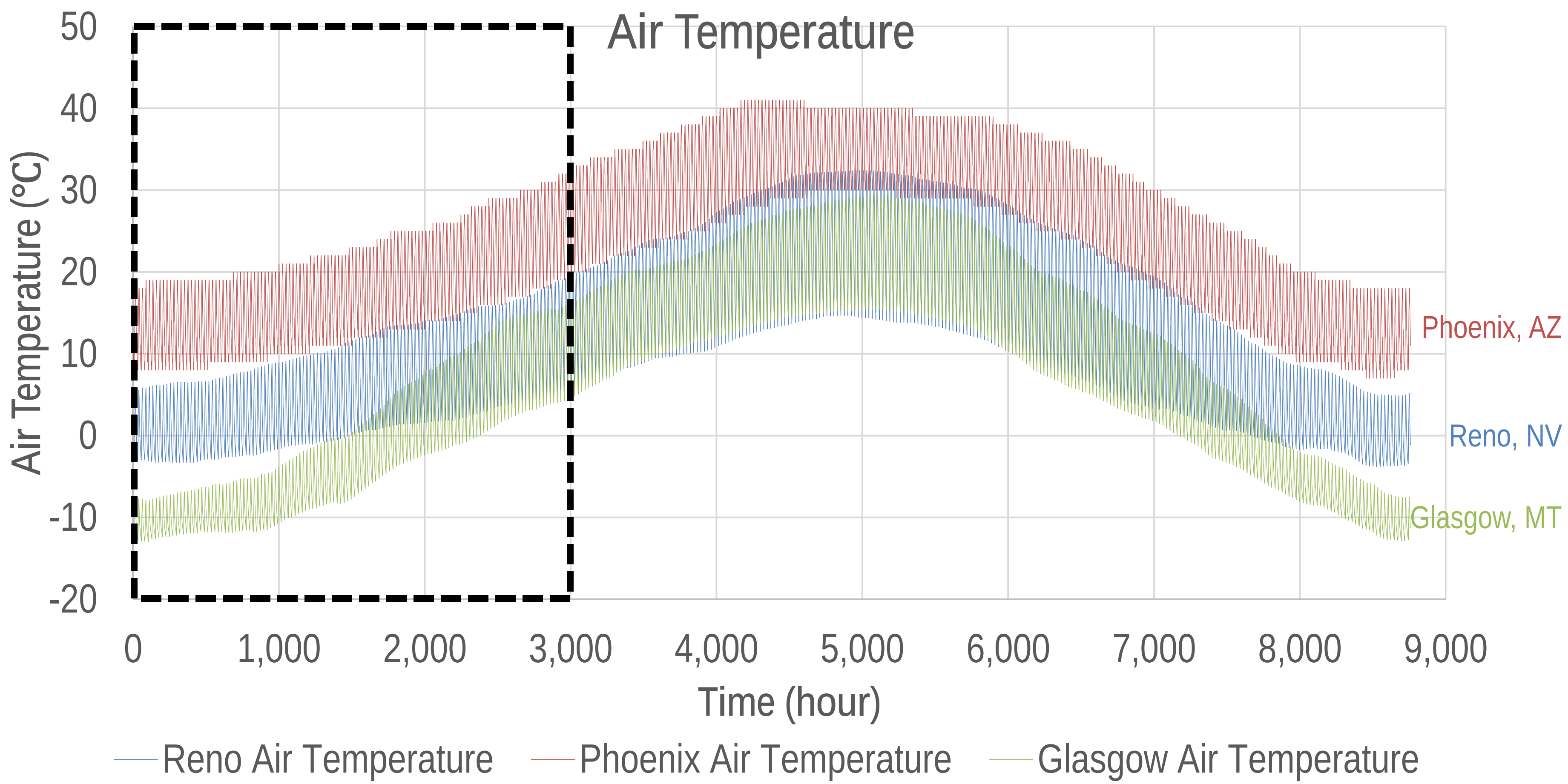




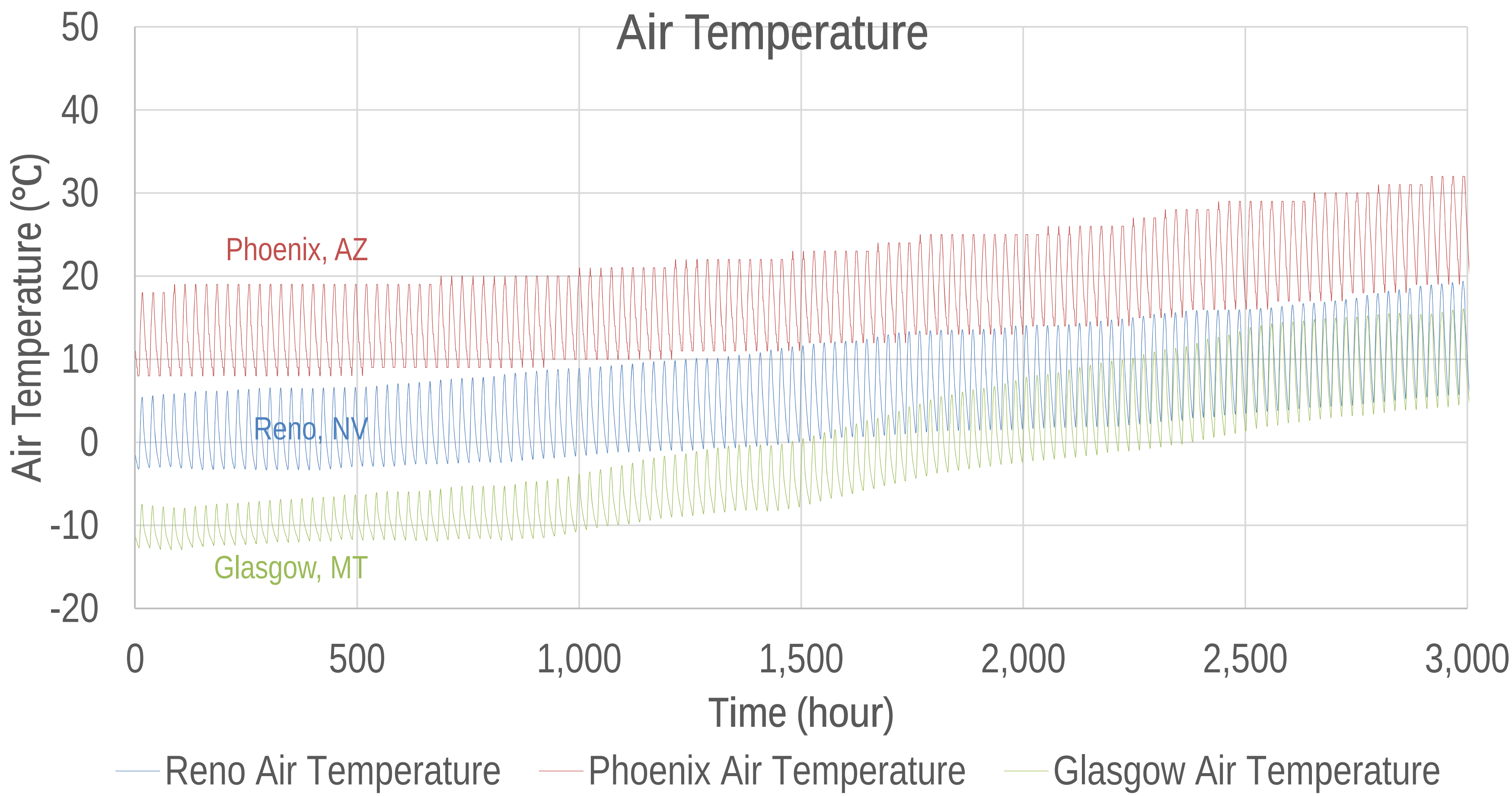




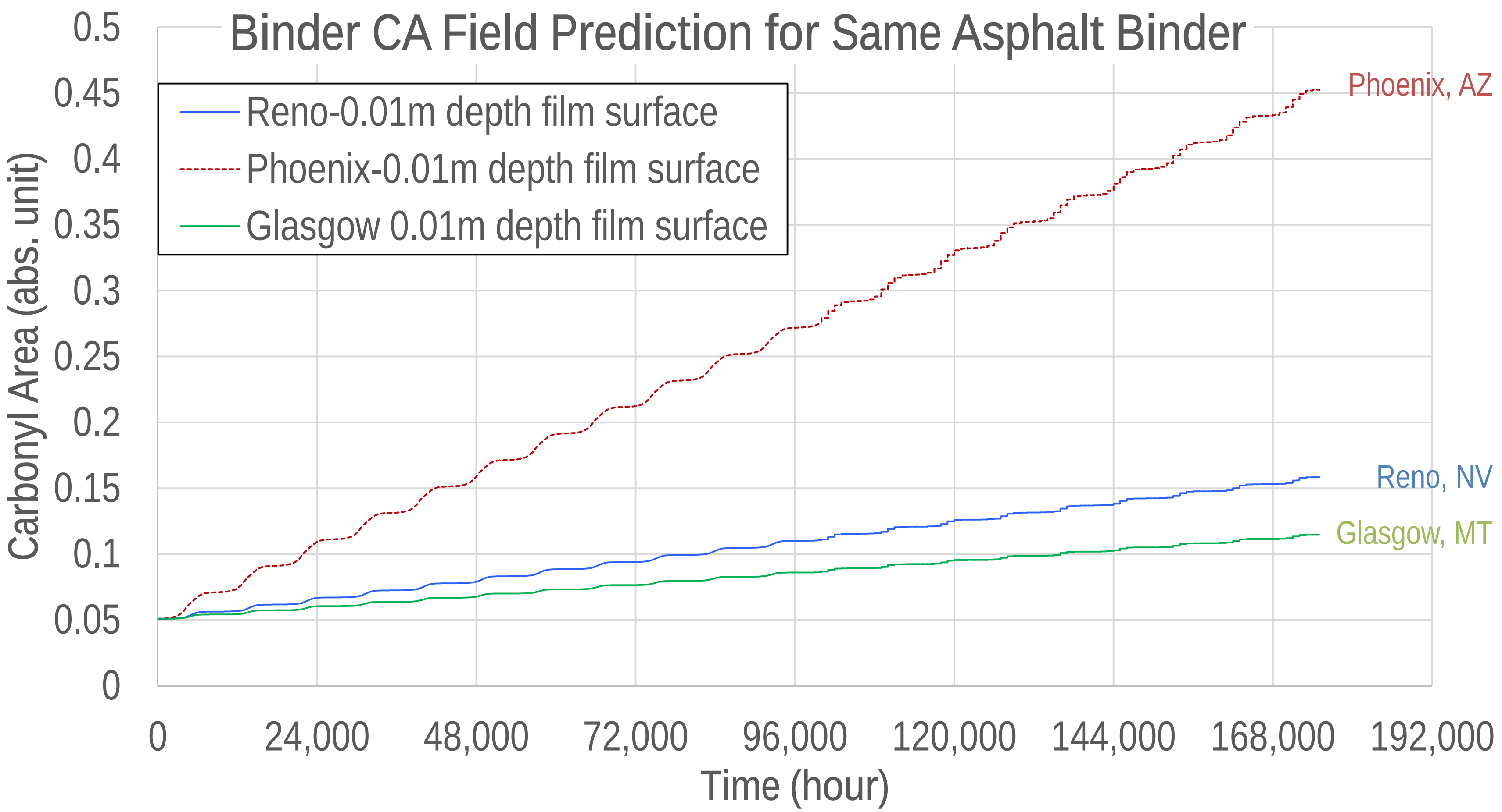
Impact of Temperature on Binder Aging



Impact of Temperature on Binder Aging (Cont'd)



Impact of Temperature on Binder Aging (Cont'd)



Thermal Cracking in AC Pavements

- Thermal cracking can be addressed by:
  - Selecting the appropriate asphalt binder grade coupled with the *proper rheological properties and aging characteristics*.
  - Selecting the appropriate aggregate properties and gradation.
  - Assuring the proper mixture volumetric and properties.

Thermal Stress Restrained Specimen Test (TSRST)

- Originally developed as a part of SHRP.
  - Mixture specimen is started at an initial temperature then subjected to a temperature drop until fracture while height of the specimen is kept constant.

- Has been successfully utilized in pavement research to evaluate low temperature cracking properties of asphalt mixtures.
  - Initially published as AASHTO TP10 (currently dropped from the AASHTO standards).
  - European standard EN12697-46 (2012) to characterize asphalt mixtures for thermal cracking resistance.

Thermal Stress Restrained Specimen Test (TSRST)

- Limitations/Potential Concerns
  - Compaction of prismatic specimens.
  - Variation in thermal stress build-up between replicate samples.
  - Variation in fracture stress and fracture temperature.

- Implemented Enhancements → UTSST
  - Sample geometry and preparation methods (cylindrical specimens/reduce edge effect).
  - Gluing technique (epoxy selection based on CTC and gluing jigs)
  - End platens and fixtures (reduce eccentricity)
  - Thermal strain measurements
  - Draft ASTM Standard (pending D04.26)

Test Procedure

Specimen Preparation

- Four 57mm (2 ¼ in.) diam. × 134mm (5 ¼ in.) height specimens
  - Cored 90° from the axis of compaction of a SGC sample or a field core sample.

Online Video: http://www.unr.edu/wrsc/research/facilities/asphalt

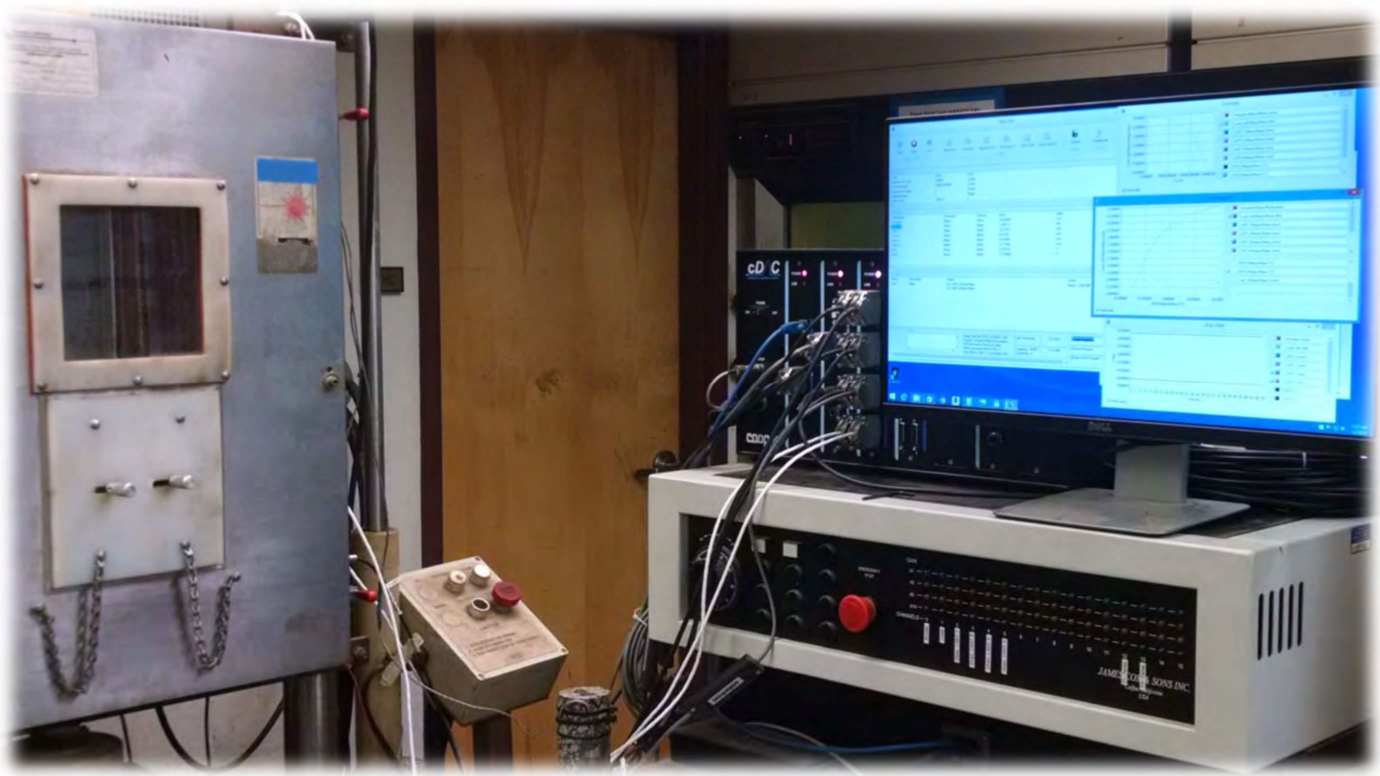
Test Procedure (Cont'd)

Loading Specimens into Testing Chamber

Test Procedure (Cont'd)

Running the Test

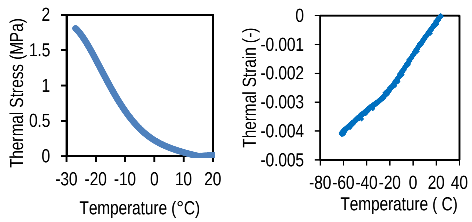
- Start test at room temperature (typically 20°C)
- Apply thermal loading at 10°C/hour or another predetermined cooling rate through -40°C.

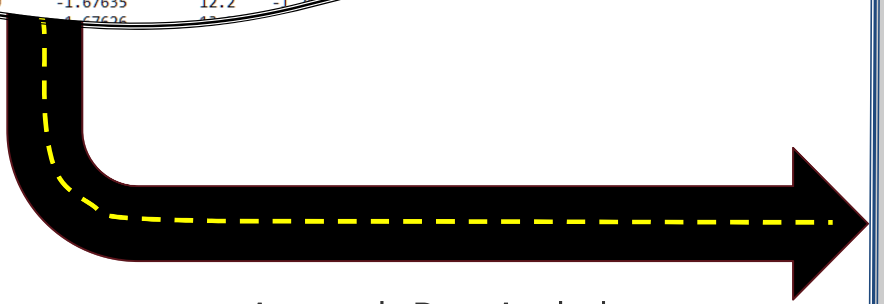


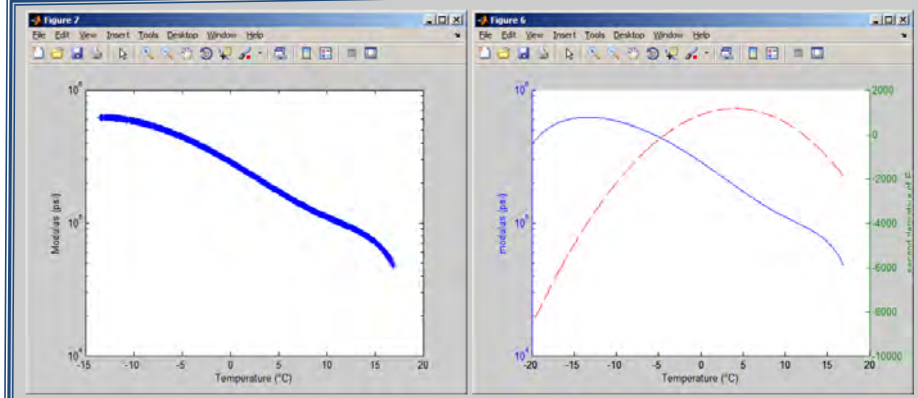
Test Procedure (Cont'd)

Data Collection and Analysis

```
Automatic_Testing_System_v.4.1

UTSST_RESULT


INFORMATION
File started on Fri Oct 24 07:00:37 2014
LW19IBI3_5day_85C_Ba
7.63%Va 2.255 Ave Dia.(inch)
CTC Aa-Ab 10.85 (inch)


RAW_ATS_DATA
CHANNELS=7

Time    cycle   Stroke      Load    LVDT_1      LVDT_2      LVDT_4      T1_TEMP
sec             inch        lb      in          in          in          C
30      2       -1.68984    16.7    -1.20E-02   -7.85E-05   -1.77E-02   20.051
60      3       -1.67913    14.5    -1.20E-02   -7.85E-05   -1.76E-02   20.026
90      4       -1.67874    16.1    -1.20E-02   -7.65E-05   -1.76E-02   19.96
120     5       -1.67932    13.3    -1.20E-02   -7.44E-05   -1.76E-02   19.935
150     6       -1.67874    15.6    -1.20E-02   -7.85E-05   -1.77E-02
180     7       -1.67865    12.2    -1.20E-02   -7.94E-05
210     8       -1.67836    15      -1.20E-02
240     9       -1.67807    13.3    -1.20E-02
        10      -1.67635    12.2
```



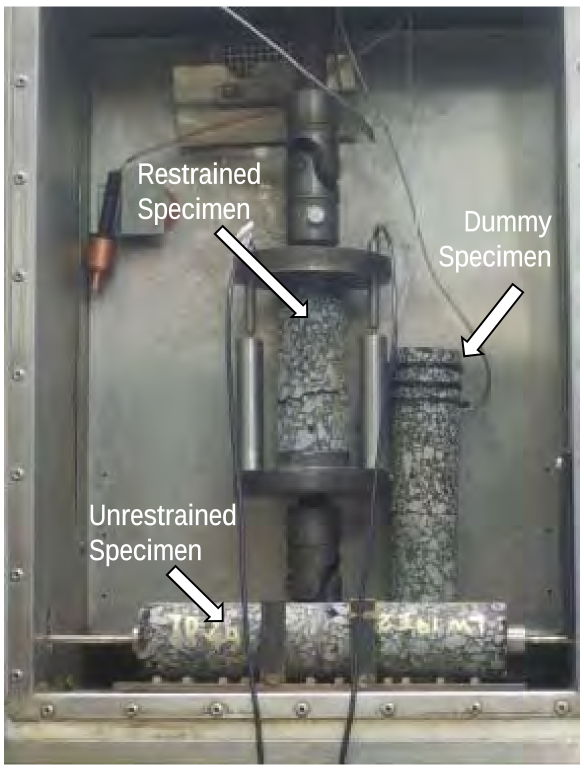


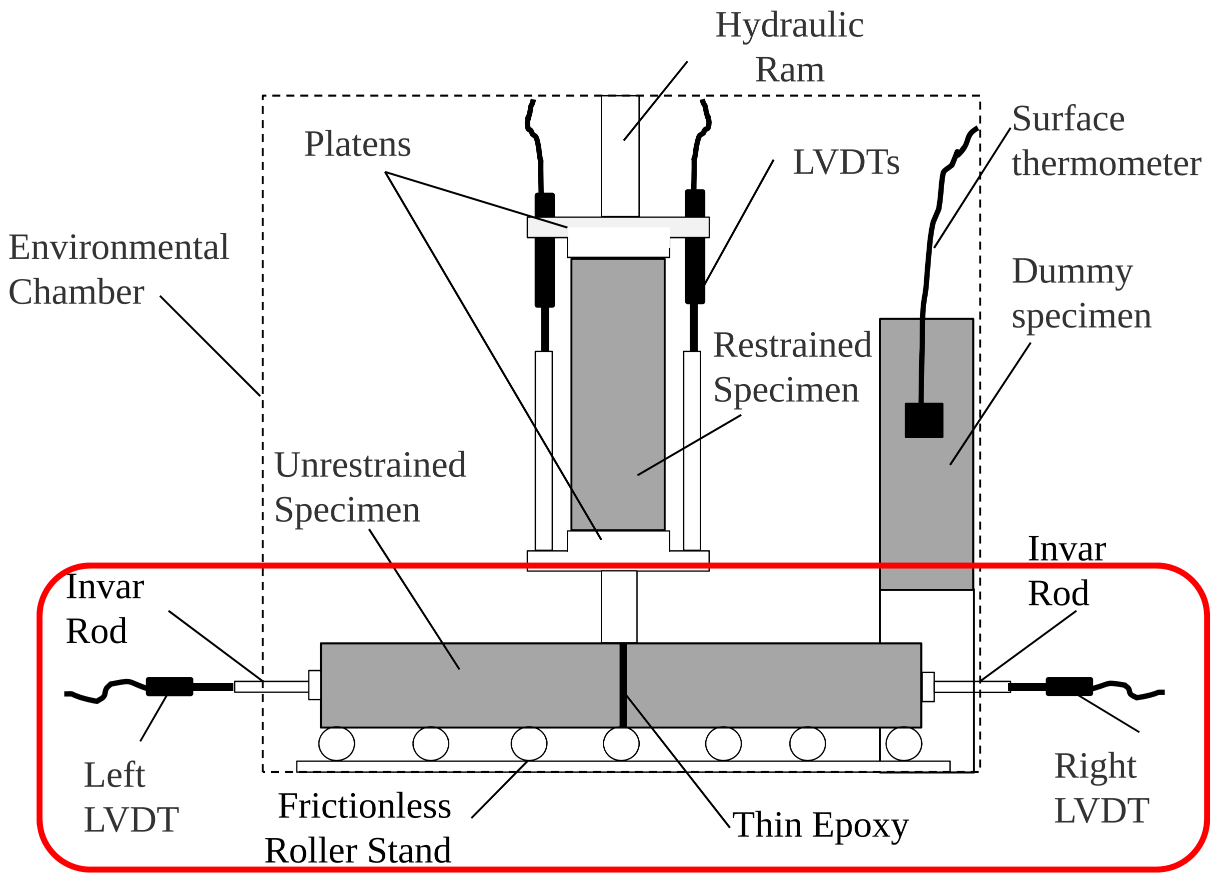


Temp(°C)	Modulus(	2nd derivative of Eth		Temp(°C)	Fitted Stre	Fitted Strain			Temp(°C)	Modulus (	Stress (psi)
10.68208	26506.23			21.17321	0	0		Fracture	-25.2043	0	310.4224
10.59881	35455.64			21.08995	-0.19216	1.57E-06		Crack Initi	-23.539	890843.5	278.7748
10.51555	35422.5			21.00668	-0.37805	3.15E-06		Glassy Har	-12.132	538465.1	91.24172
10.43229	35388.94	-30.7878		20.92342	-0.55777	4.72E-06		Vicous-Gl	-0.72495	124665.4	14.33868
10.34903	35355.28	-7.65858		20.84016	-0.73143	6.3E-06		Viscous Sc	10.34903	35355.28	0.238129
10.26576	35321.83	15.28573		20.75689	-0.89913	7.88E-06					
10.1825	35288.9	38.04537		20.67363	-1.06099	9.47E-06					
10.09924	35256.82	60.62059		20.59037	-1.2171	1.11E-05					
10.01597	35225.88	83.01162		20.50711	-1.36756	1.26E-05					
9.93271	35196.41	105.2187		20.42384	-1.51249	1.42E-05					
9.849448	35168.7	127.2421		20.34058	-1.65198	1.58E-05					
9.766185	35143.05	149.082		20.25732	-1.78613	1.74E-05					
9.682922	35119.78	170.7387		20.17405	-1.91504	1.9E-05					
9.599659	35099.16	192.2124		20.09079	-2.0388	2.06E-05					
9.516396	35081.51	213.5034		20.00753	-2.15752	2.22E-05					
9.433133	35067.12	234.6118		19.92427	-2.27129	2.38E-05					
9.34987	35056.26	255.5379		19.841	-2.3802	2.54E-05					
9.266607	35049.24	276.282		19.75774	-2.48434	2.7E-05					
9.183344	35046.33	296.8442		19.67448	-2.58382	2.87E-05					
9.100081	35047.82	317.2248		19.59121	-2.67871	3.03E-05					
9.016818	35053.99	337.4241		19.50795	-2.76912	3.19E-05					
8.933555	35065.11	357.4422		19.42469	-2.85513	3.35E-05					
8.850292	35081.47	377.2794		19.34142	-2.93682	3.51E-05					
8.767029	35103.33	396.9358		19.25816	-3.01429	3.67E-05					
8.683766	35130.96	416.4118		19.1749	-3.08762	3.84E-05					
8.600503	35164.64	435.7076		19.09164	-3.15689	4E-05					
8.51724	35204.62	454.8232		19.00837	-3.2222	4.16E-05					
8.433977	35251.17	473.7591		18.92511	-3.28362	4.33E-05					
8.350714	35304.55	492.5154		18.84185	-3.34123	[illegible]					
[illegible]	35365.01	511.0923		18.75858	[illegible]						

Test Description

Uniaxial Thermal Stress and Strain Test (UTSST)

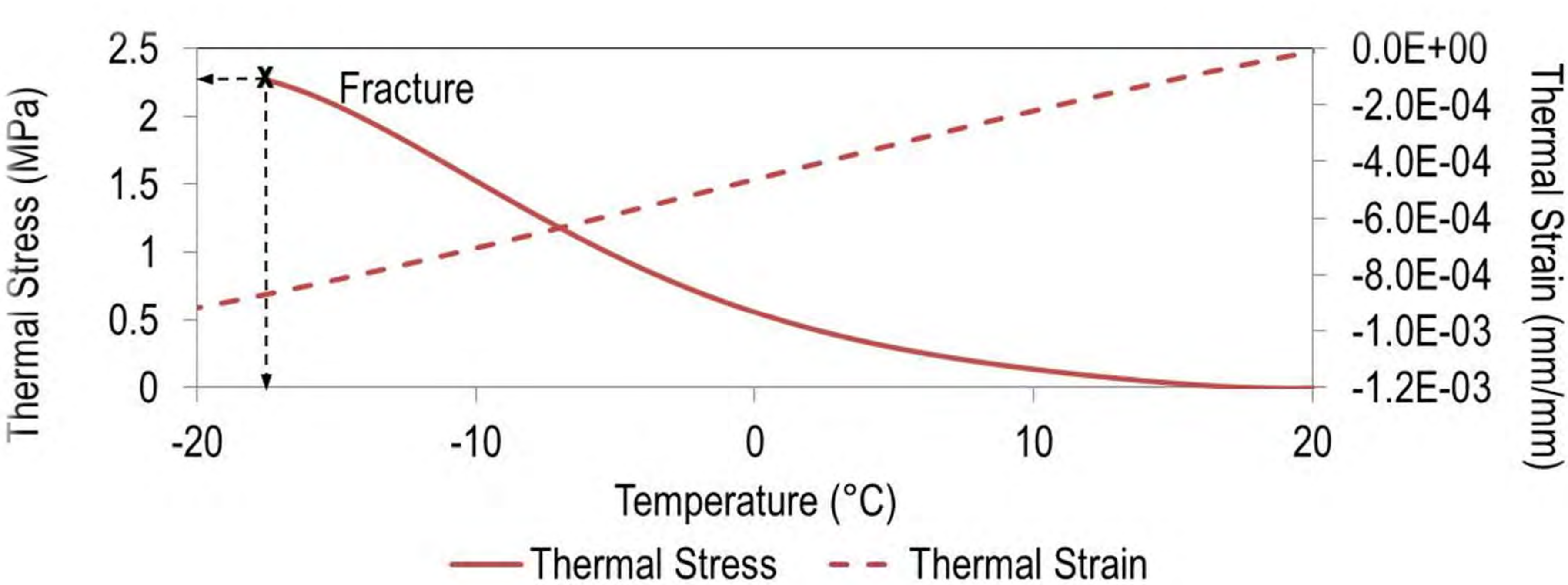


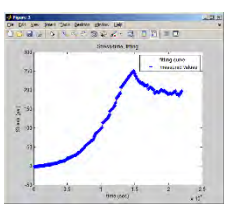


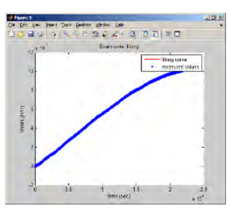
Test Description (Cont'd)

Uniaxial Thermal Stress and Strain Test Results

Thermal Stress Build-up and Thermal Strain



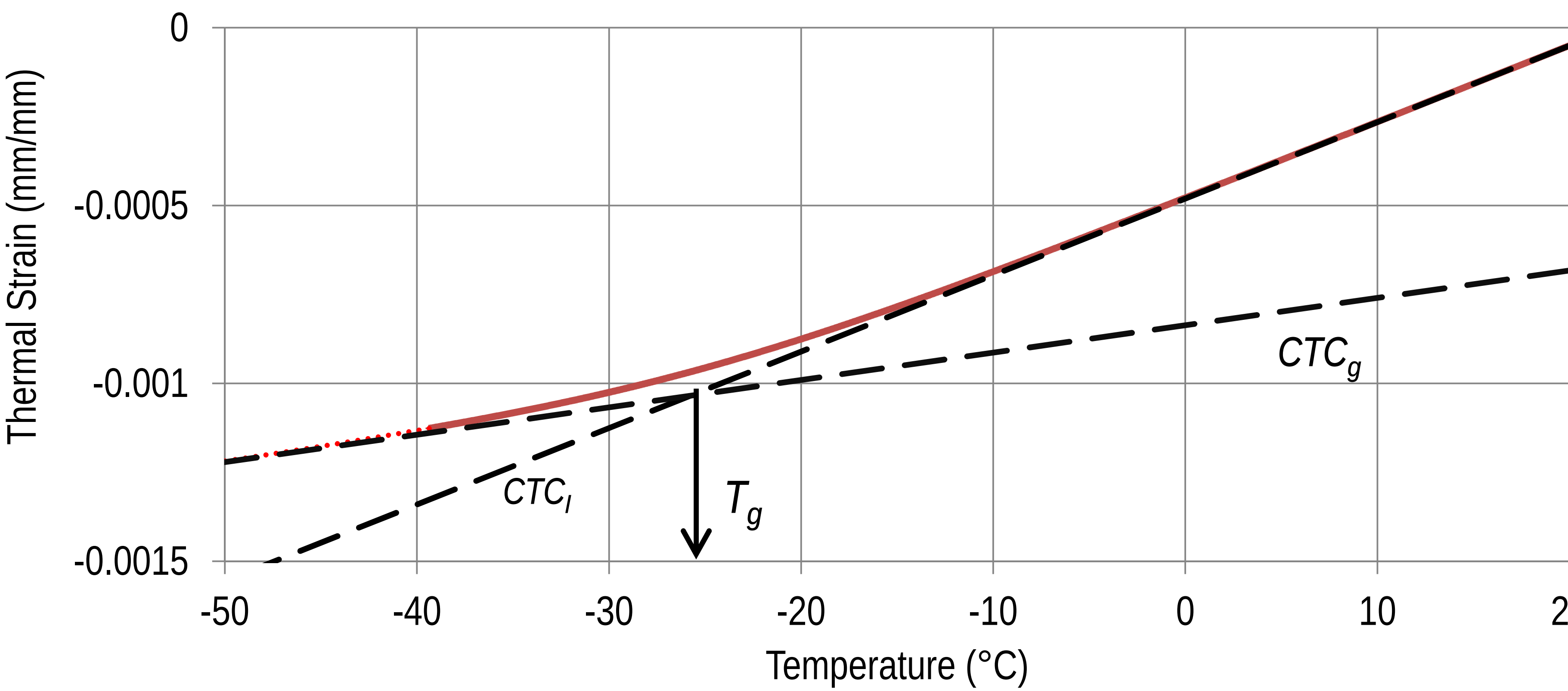




Test Description (Cont'd)

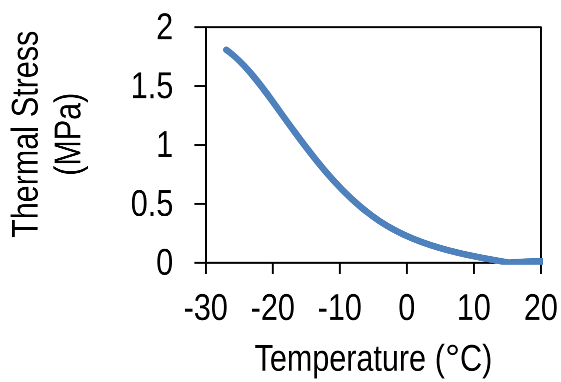
Data Analysis: Coeff. Of Thermal Contraction (CTC)

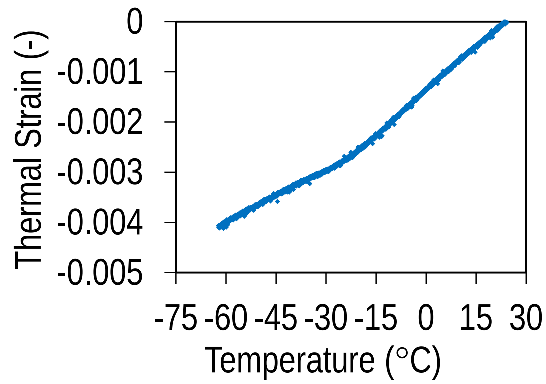
$$\varepsilon_{th} = \frac{\Delta l}{l_0} = C + CTC_g(T - T_g) + ln\left\{\left[1 + e^{\frac{(T-T_g)}{R}}\right]^{R(CTC_l - CTC_g)}\right\};\quad CTC(T) = CTC_g + \frac{(CTC_L - CTC_g) \times e^{\left(\frac{T-T_g}{R}\right)}}{\left(1 + e^{\frac{T-T_g}{R}}\right)}$$

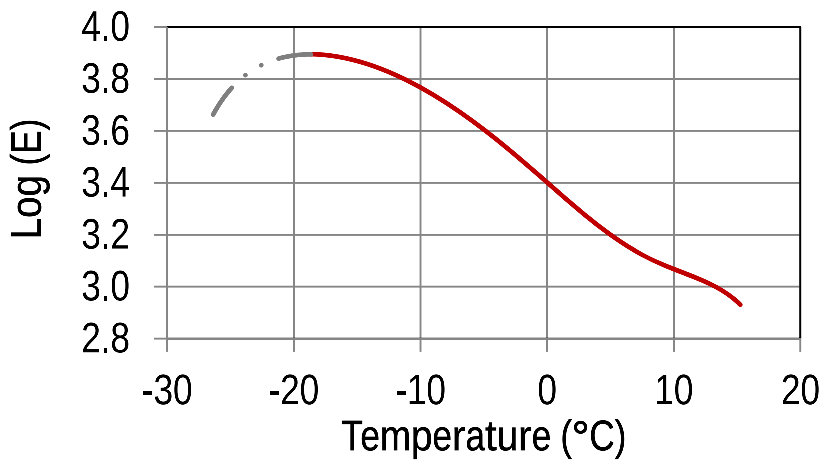


Test Description (Cont'd)

Data Analysis: Calculation of Modulus







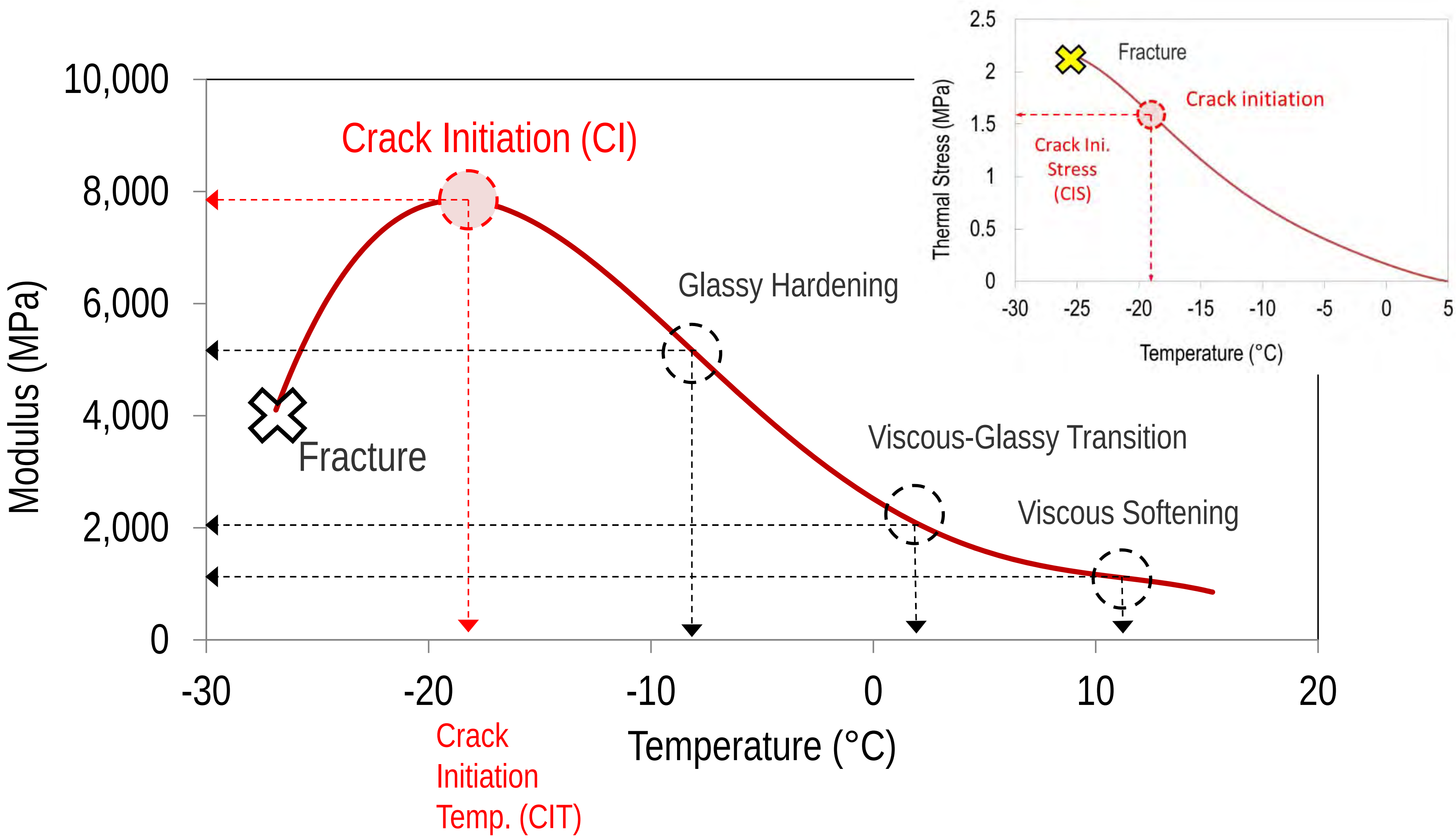
Boltzmann's Superposition Principle

$$\sigma(t) = \int_0^t E_r(t - t')\frac{\partial\varepsilon(t')}{\partial t'}dt'$$

$$E(T(t_n)) = \frac{\left(\sigma(t_{n+1}) - \sum_{i=2}^{n+1} E(t_{n+1} - t_i)\left(\varepsilon(t_i) - \varepsilon(t_{i-1})\right)\right)}{\varepsilon(t_1)}$$

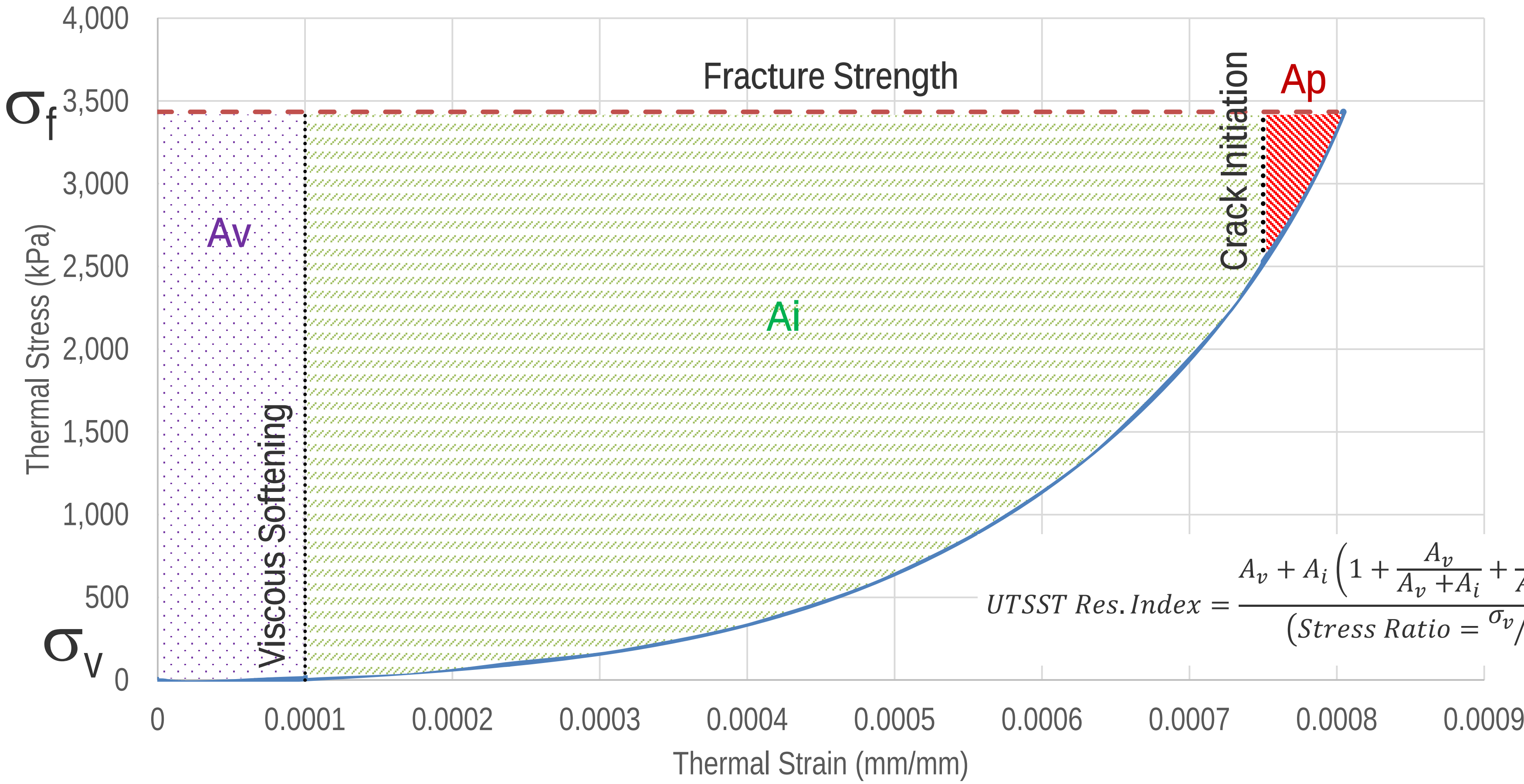
Test Description (Cont'd)

Data Analysis: Modulus as a Function of Temperature



Test Description (Cont'd)

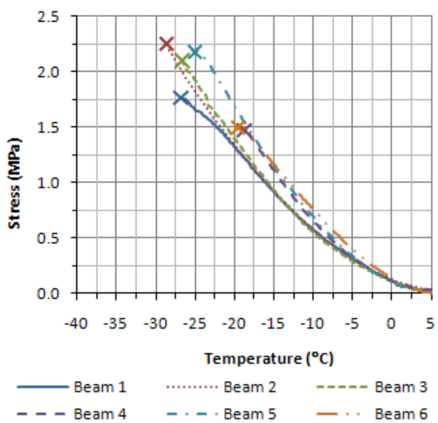
Data Analysis: UTSST Resistance Index



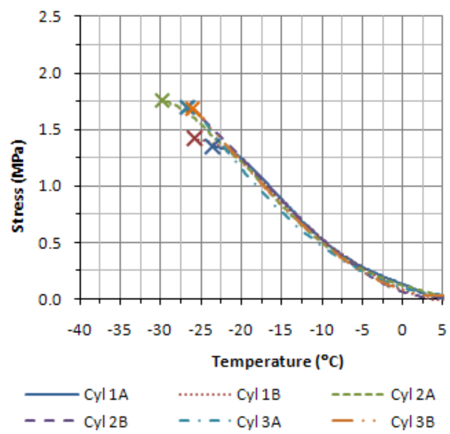
$$UTSST\ Res.Index = \frac{A_v + A_i\left(1 + \frac{A_v}{A_v + A_i} + \frac{A_p}{A_p + A_i}\right)}{\left(Stress\ Ratio = {}^{\sigma_v}/_{\sigma_F}\right)}$$

Test Variability

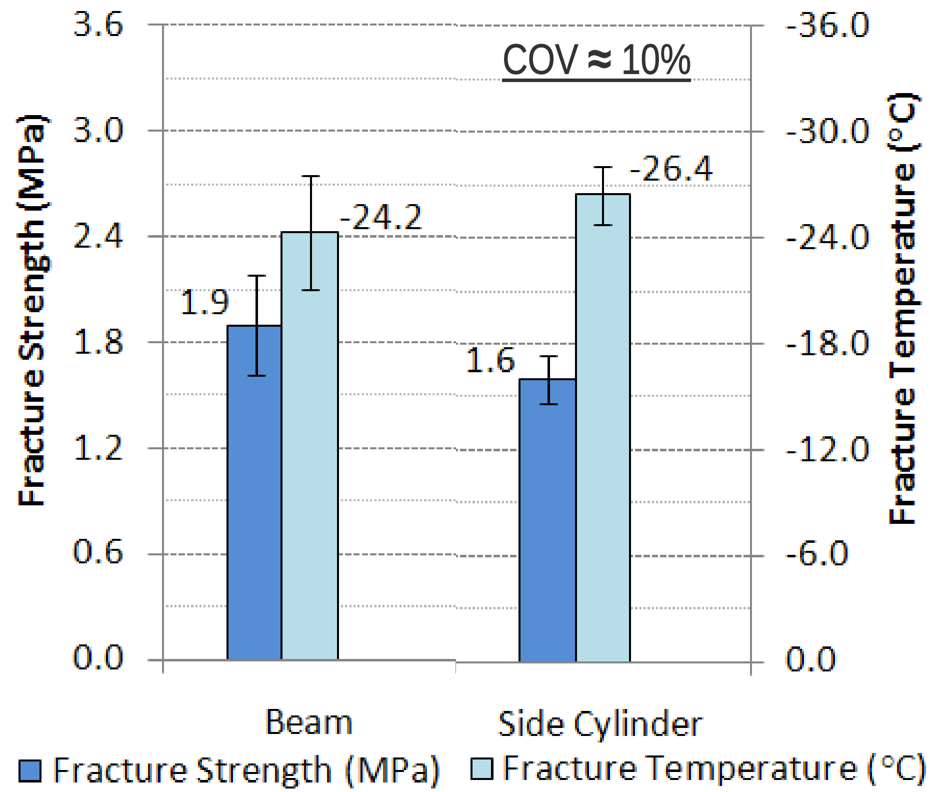
Prismatic versus Cylindrical Side Specimens



(a) Beam Specimens



(d) Side Cylinder Specimens



(Whiskers represent 95% confidence interval)

Test Variability
Fracture Location

- Failure Plane/Breakage Face
  - Specimen alignment is critical such as with any tension test.
  - The new gluing jig/technique reduced this issue significantly.

Lab-Mix Lab-Compacted

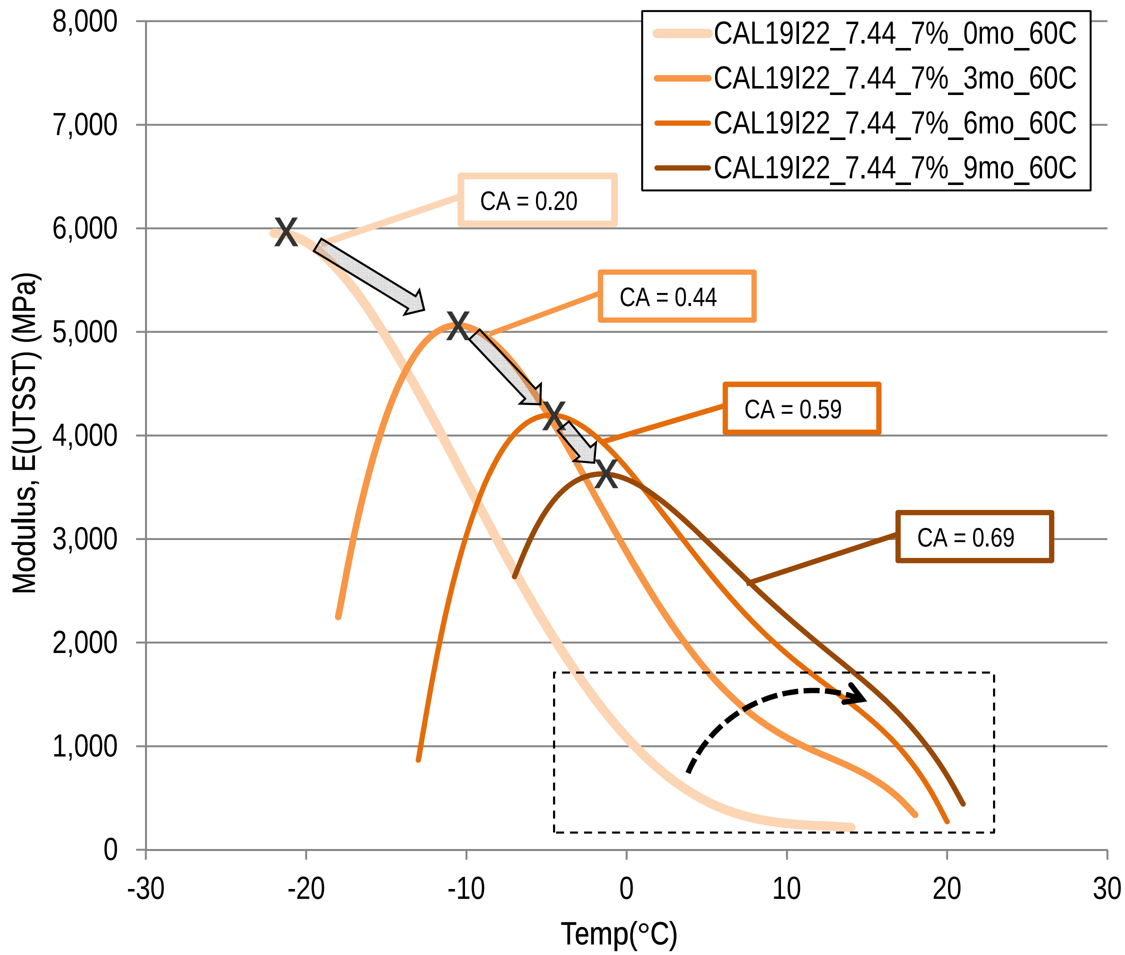
Field-Mix Field-Compacted/Cores

Test Sensitivity

- Examples highlighting the test sensitivity to:
  - Long-term aging;
  - Air void level;
  - Asphalt binder content;
  - Aggregate mineralogy;
  - Asphalt binder modification;
  - Recycled materials.

Test Sensitivity (Cont'd)

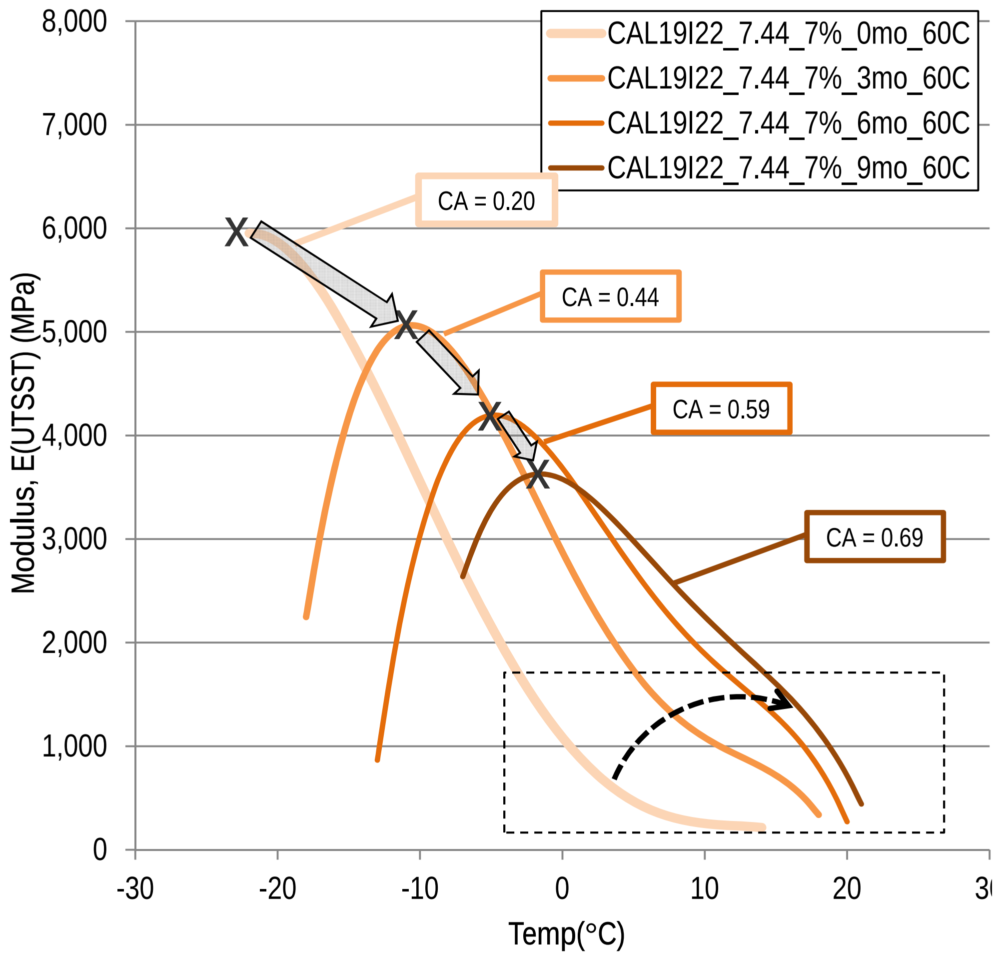
Effect of Aging

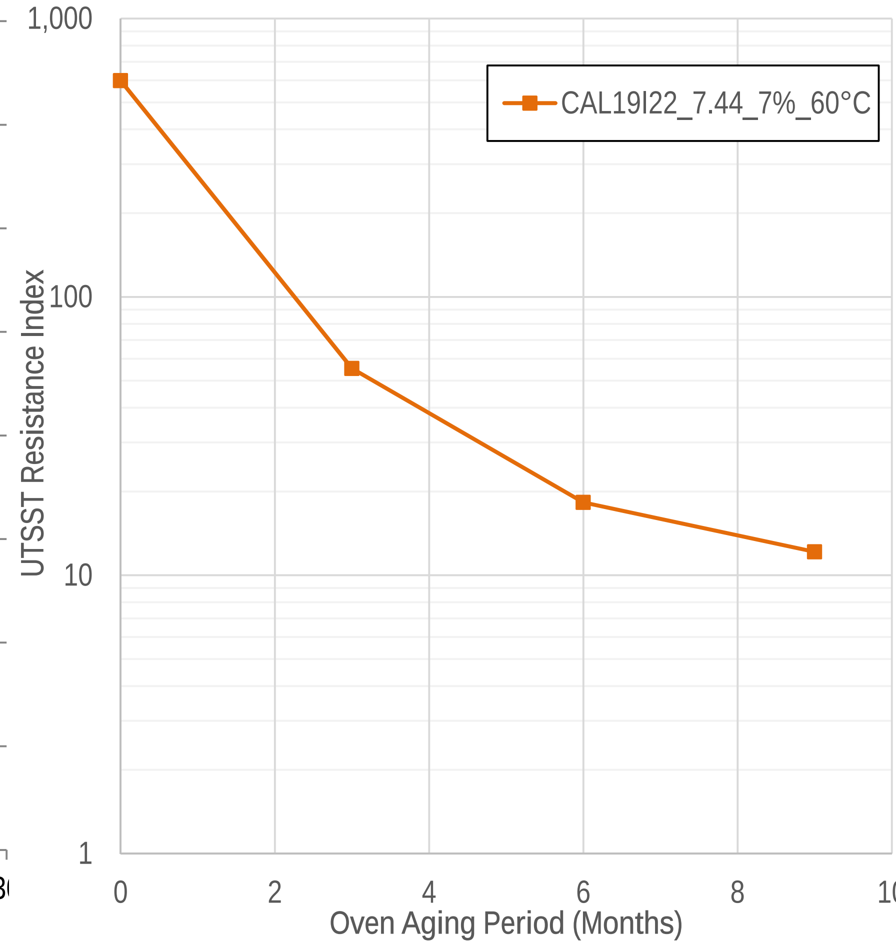


Property	PG64-22 (7% Va)			
	0 M	3 M	6 M	9 M
Fracture Temp (°C)	-23.3	-18.2	-13.2	-7.7
Fracture Stress (MPa)	2.4	2.4	2.2	1.6
Crack Initiation Temp, CIT (°C)	-22.3	-10.7	-4.8	-1.5
Crack Initiation Stress, CIS (MPa)	2.2	1.6	1.4	1.2
Glassy Hardening (°C)	-10.4	-2.0	+2.8	+7.5
Viscous-Glassy Transition (°C)	+1.2	+5.6	+8.1	+9.4
UTSST Resistance Index	599	55	18	12

Test Sensitivity (Cont'd)

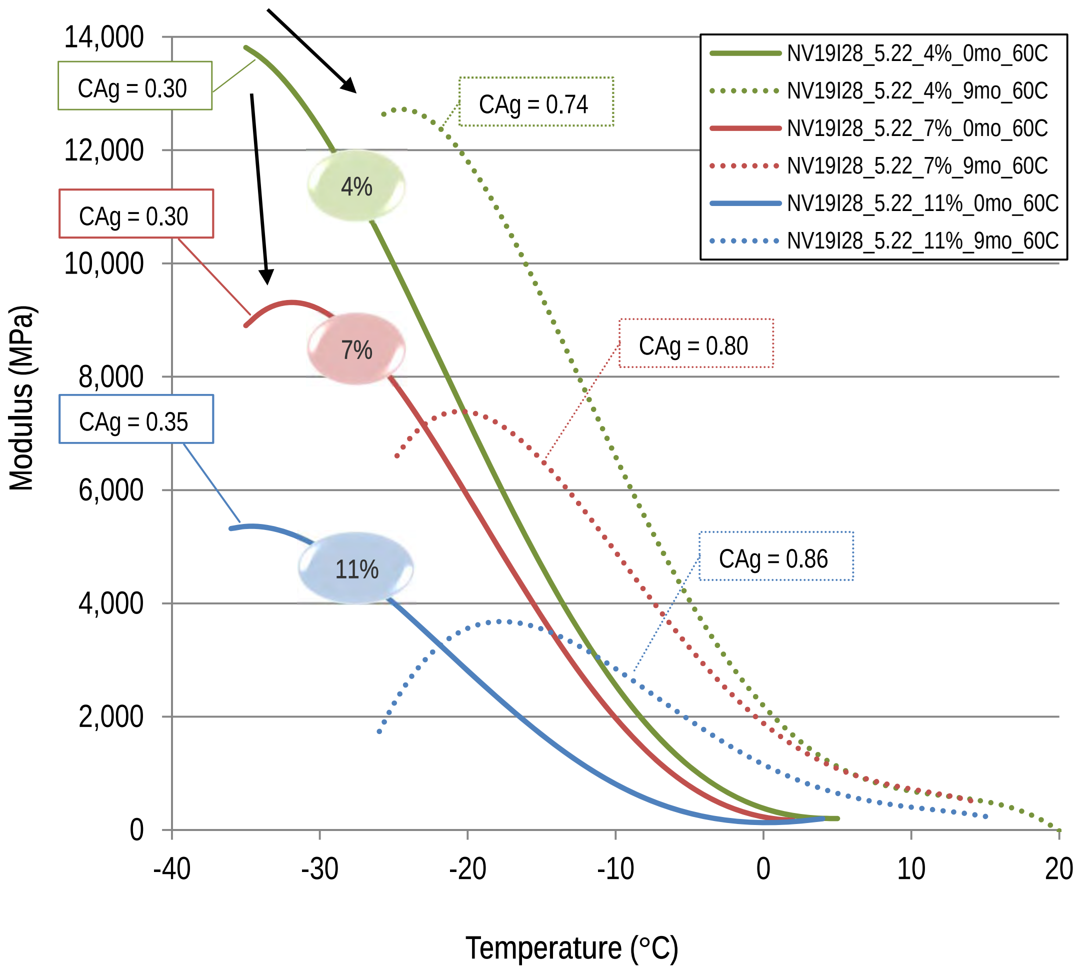
Effect of Aging





Test Sensitivity (Cont'd)

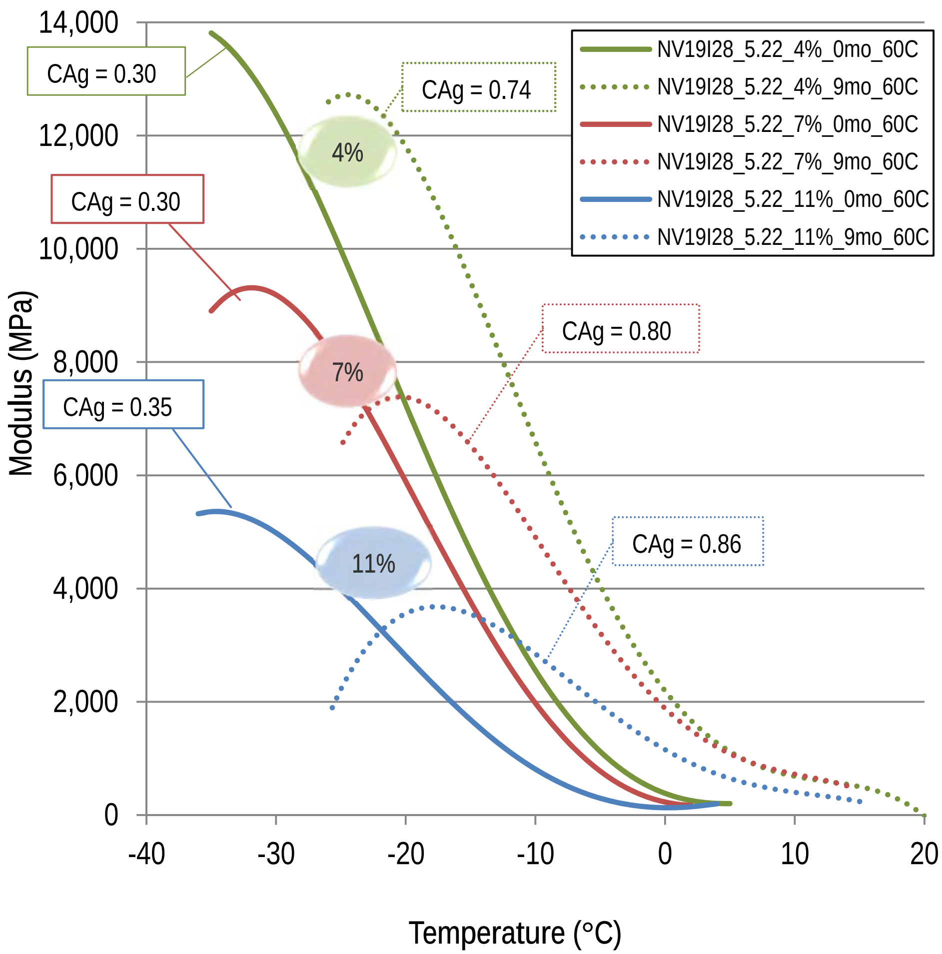
Effect of Air Void Level

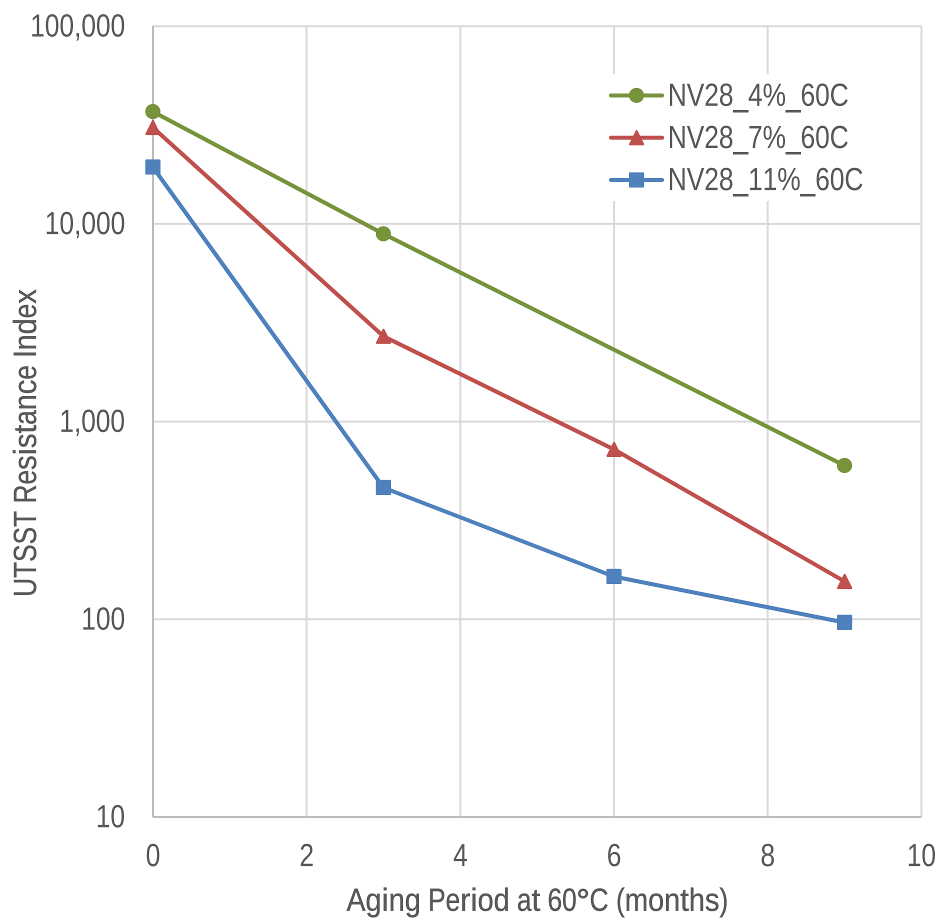


Property	4% Va		7% Va		11% Va	
	0 M	9 M	0 M	9 M	0 M	9 M
Fracture Temp (°C)	-34.4	-27.2	-35.4	-26.2	-36.5	-26.6
Fracture Stress (MPa)	4.2	4.0	3.2	2.7	2.1	1.6
Crack Initiation Temp, CIT (°C)	-34.3	-23.3	-32.1	-20.5	-35.1	-17.7
Crack Initiation Stress, CIS (MPa)	4.1	3.2	2.7	2.0	1.9	1.1
UTSST Resistance Index	36,973	599	30,728	156	19,358	96

Test Sensitivity (Cont'd)

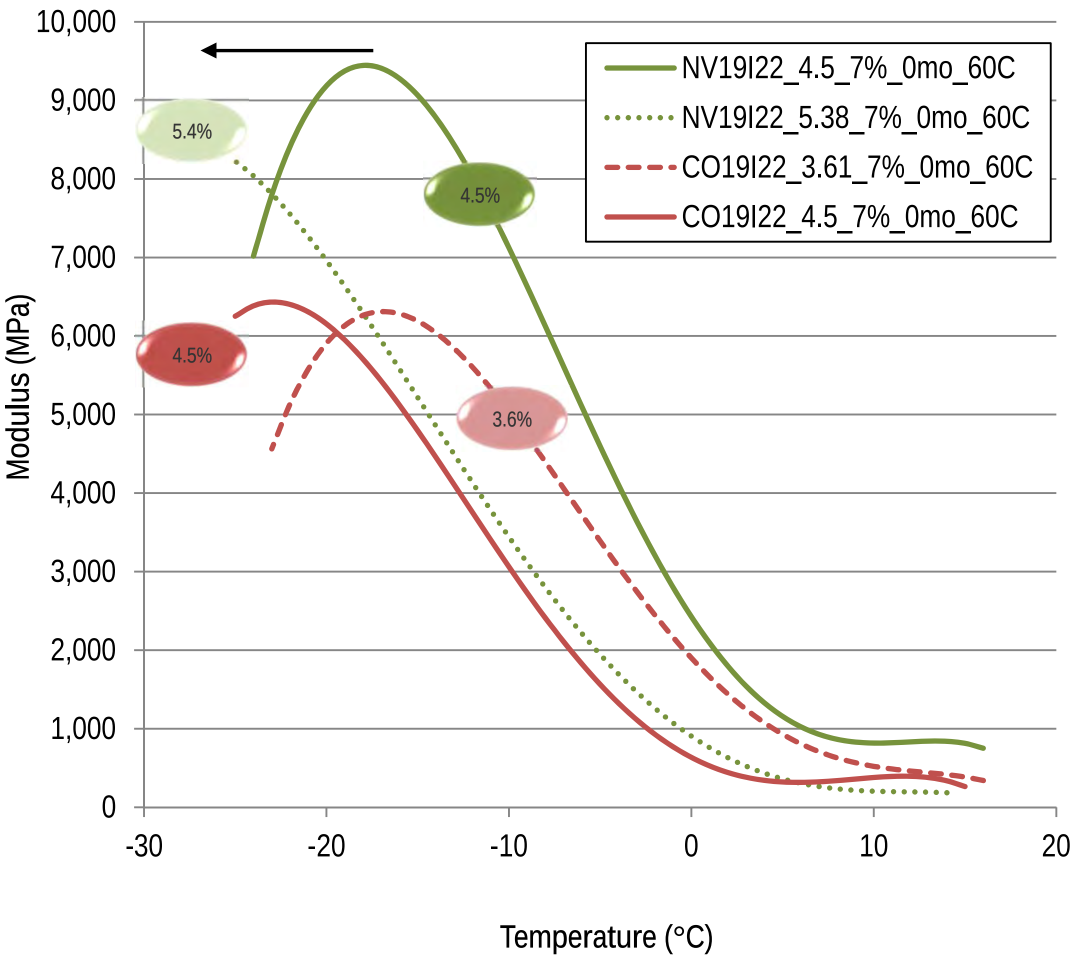
Effect of Air Void Level





Test Sensitivity (Cont'd)

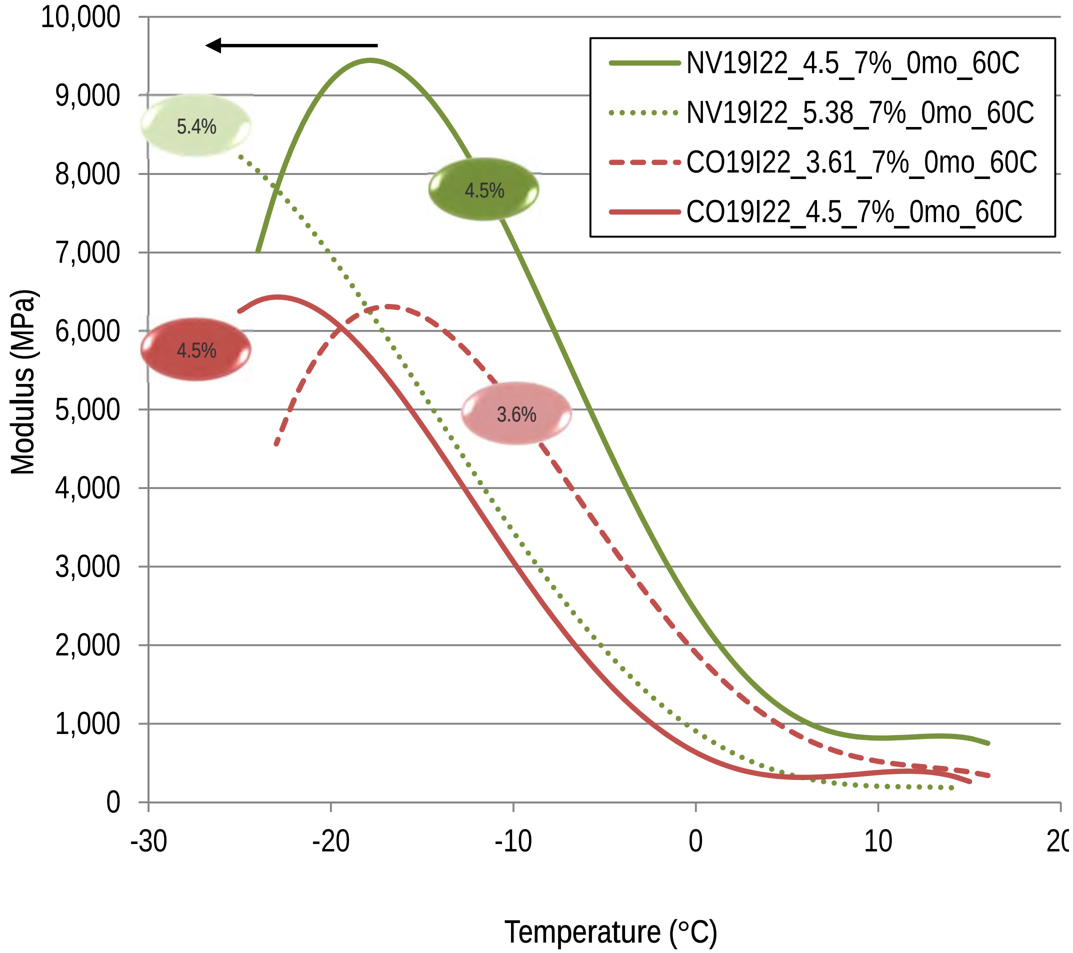
Effect of Asphalt Binder Content & Aggregate Mineralogy

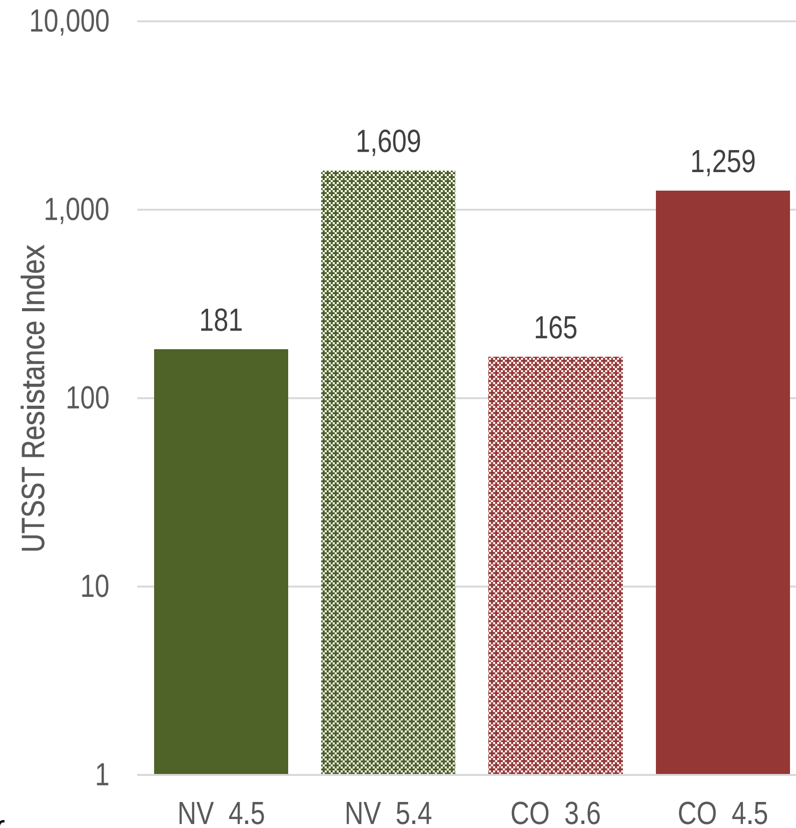


Property	Colorado		Nevada	
	3.6%	4.5%	4.5%	5.4%
Fracture Temp (°C)	-22.3	-25.1	-24.2	-25.4
Fracture Stress (MPa)	1.6	2.2	2.6	3.0
Crack Initiation Temp, CIT (°C)	-17.3	-22.9	-17.9	-25.3
Crack Initiation Stress, CIS (MPa)	1.2	1.9	1.7	3.0
UTSST Resistance Index	165	1,259	181	1,609

Test Sensitivity (Cont'd)

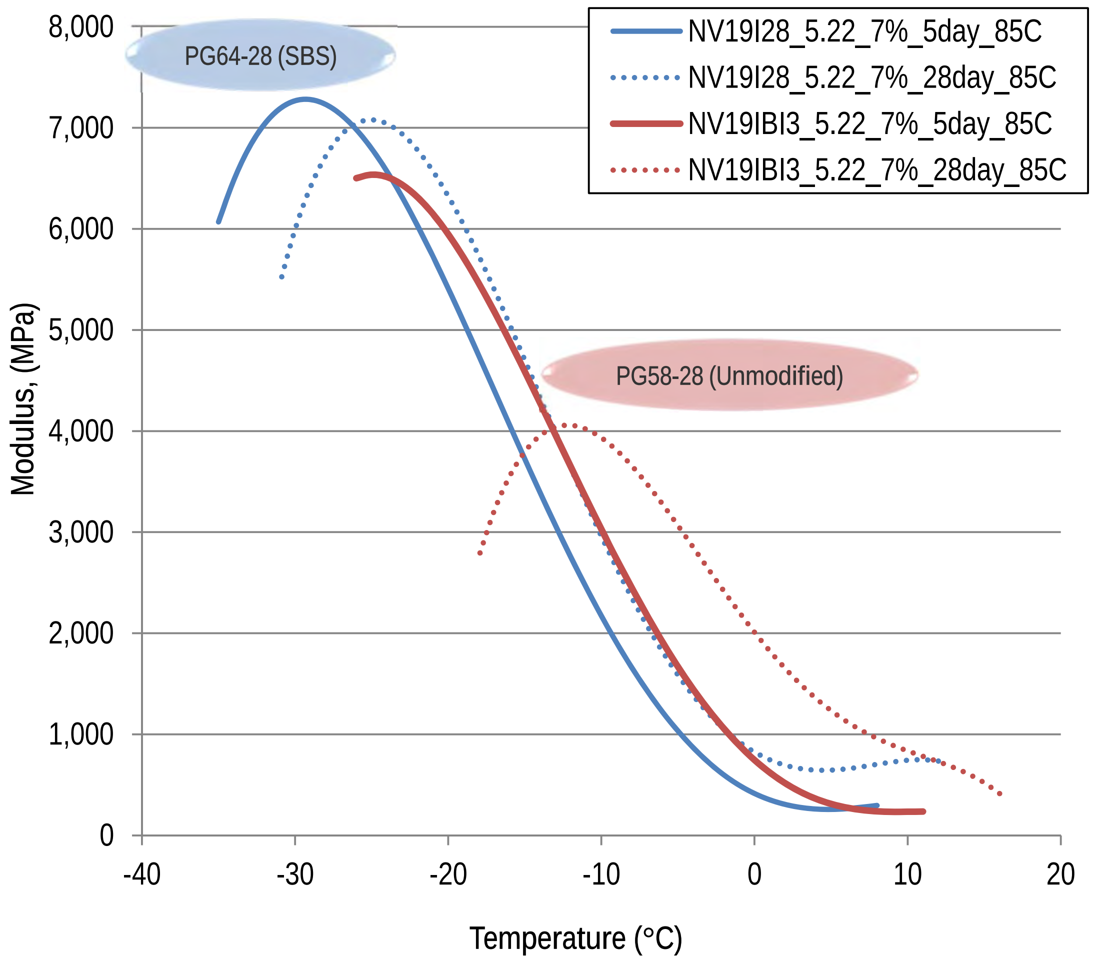
Effect of Asphalt Binder Content & Aggregate Mineralogy





Test Sensitivity (Cont'd)

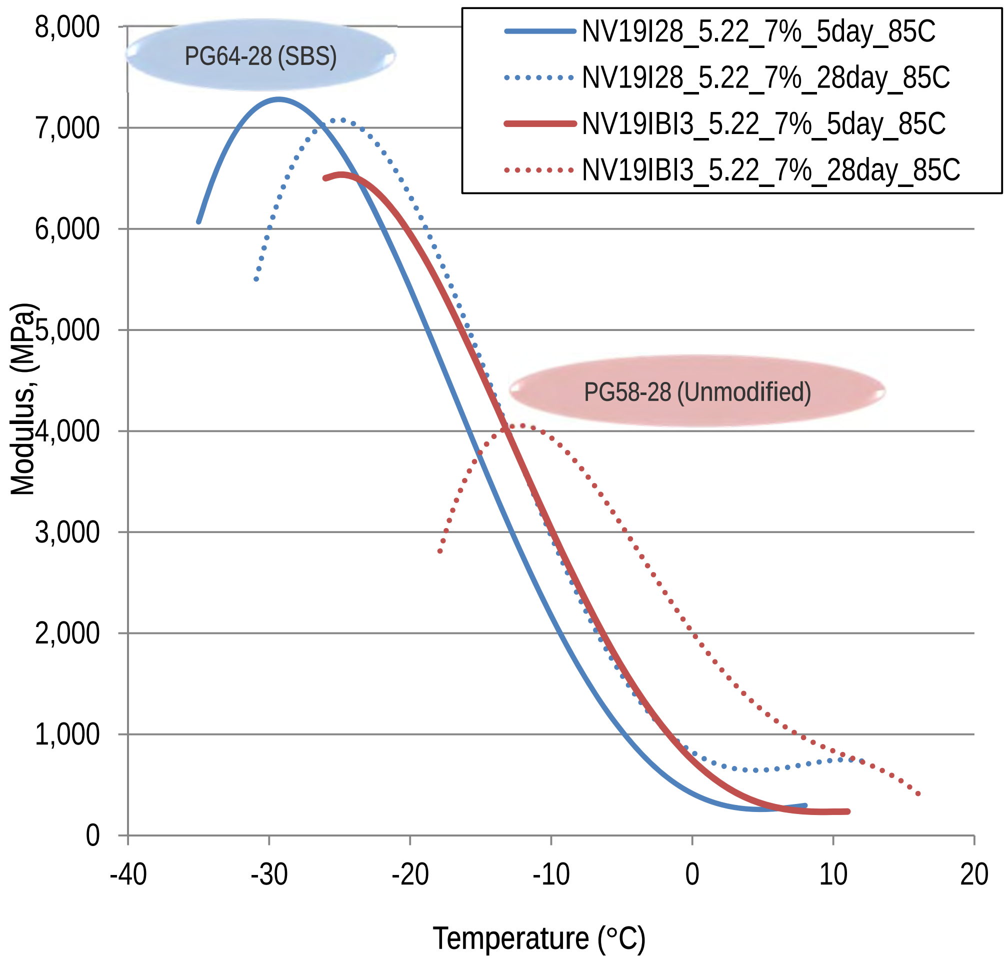
Effect of Asphalt Binder Modification

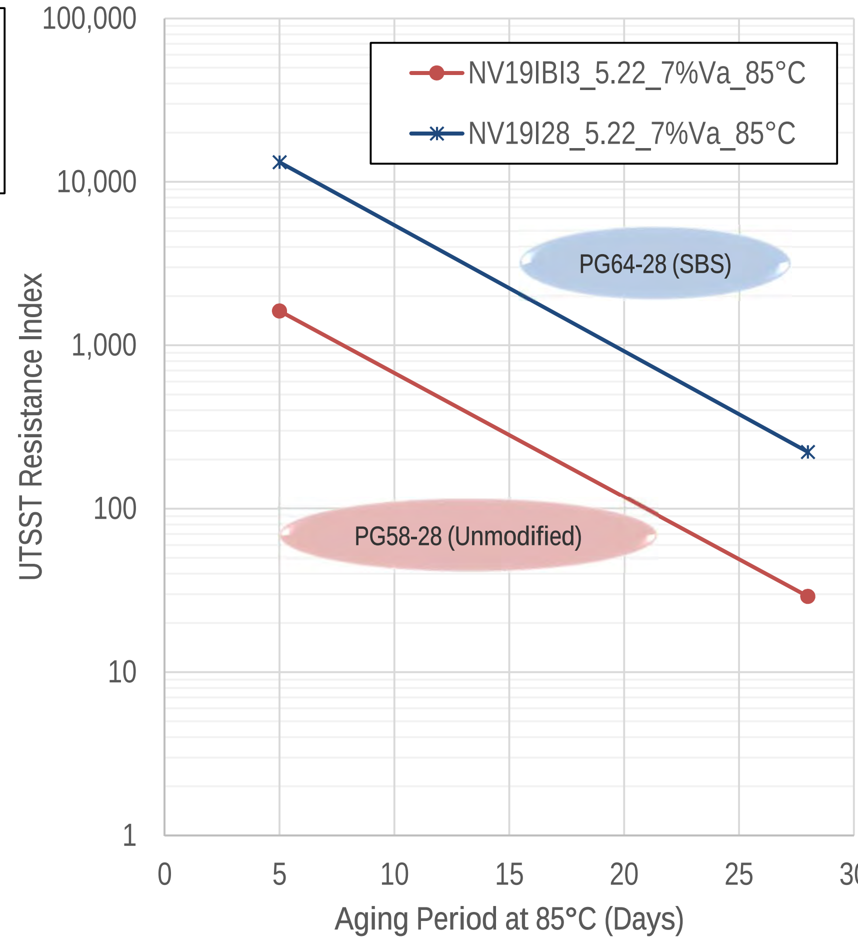


Property	PG64-28 (SBS)		PG58-28 (Unmodified)	
	5 day	28 day	5 day	28 day
Fracture Temp (°C)	-35.4	-31.8	-25.7	-18.8
Fracture Stress (MPa)	3.2	2.7	2.3	1.6
Strain at Fracture (me)	1,050	505	960	766
Crack Initiation Temp, CIT (°C)	-29.3	-25.1	-24.8	-12.4
Crack Initiation Stress, CIS (MPa)	2.3	1.9	2.1	1.1
UTSST Resistance Index	13,181	223	1,620	29

Test Sensitivity (Cont'd)

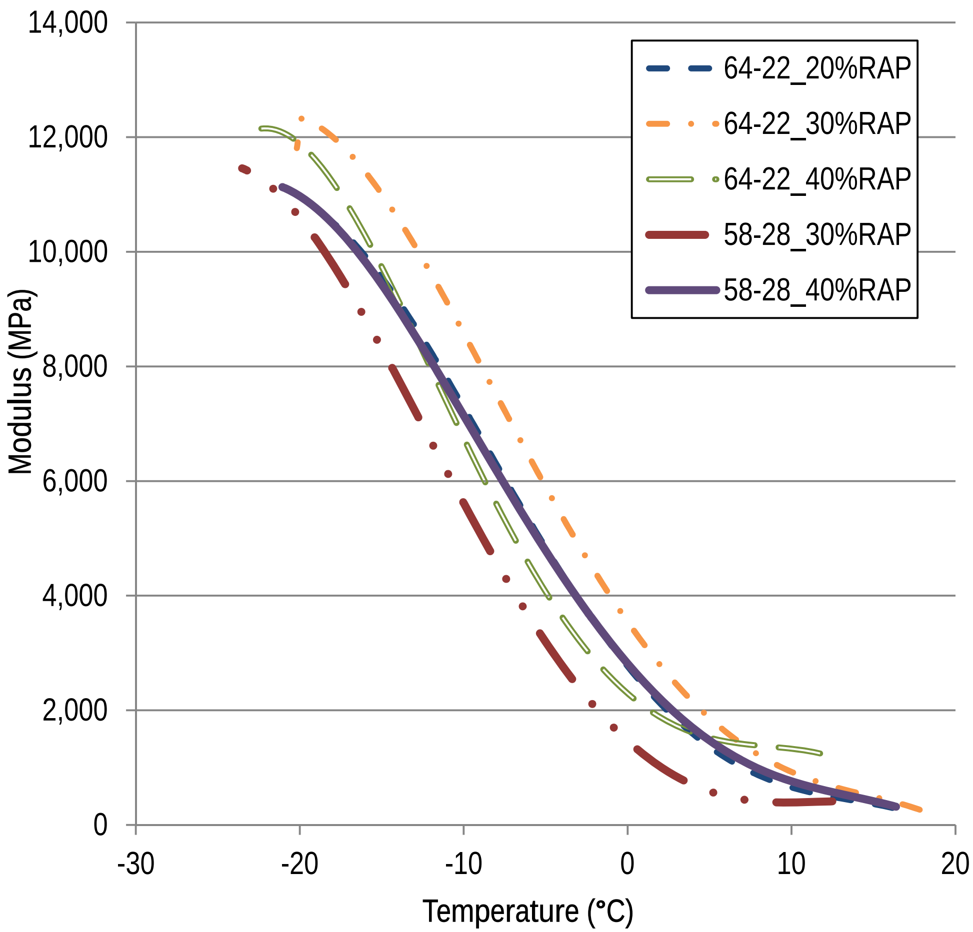
Effect of Asphalt Binder Modification

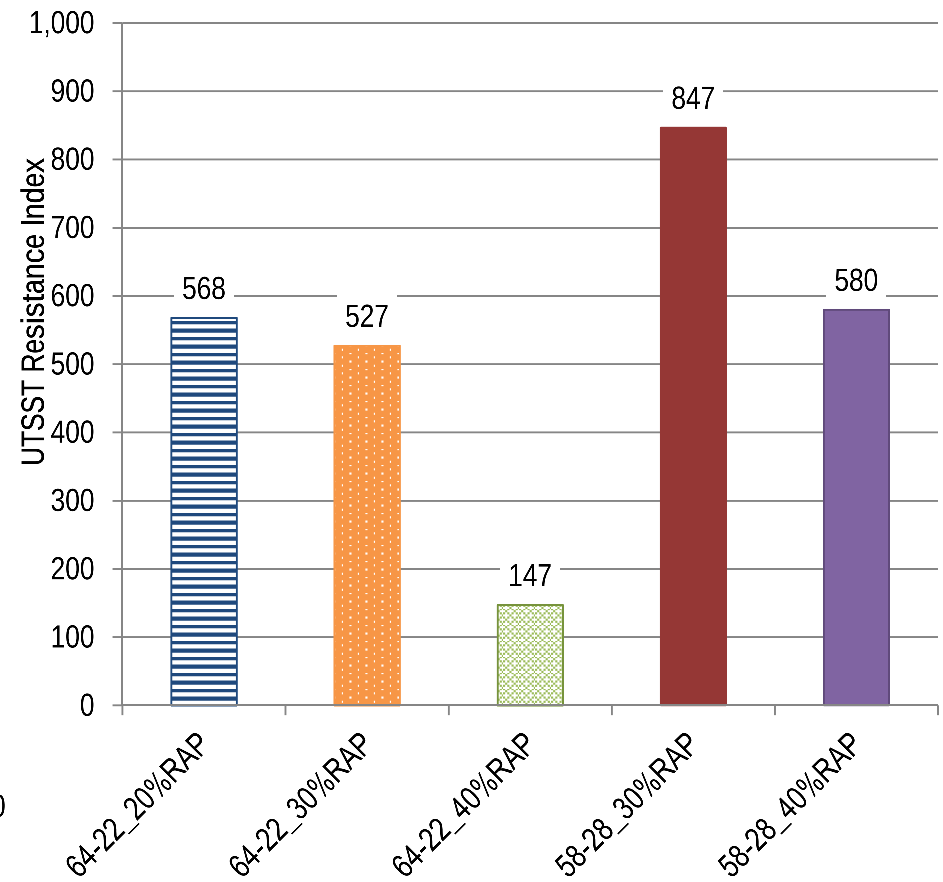




Test Sensitivity (Cont'd)

Effect of Recycled Materials

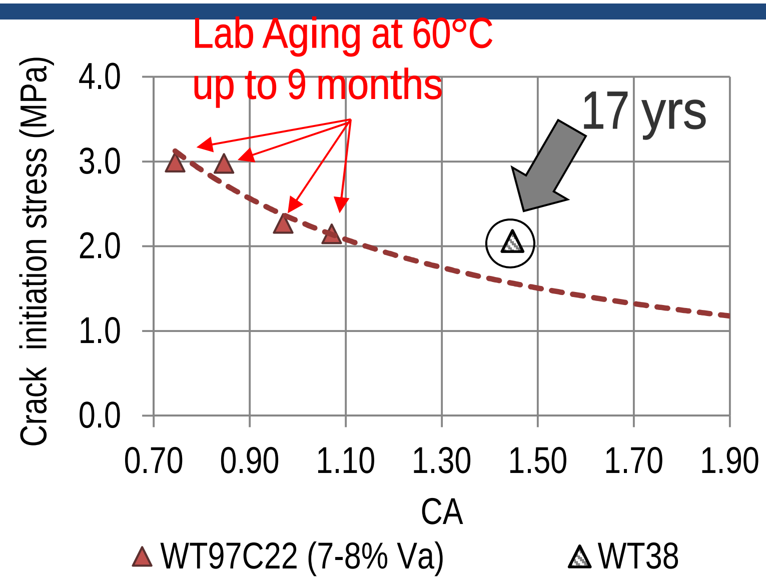


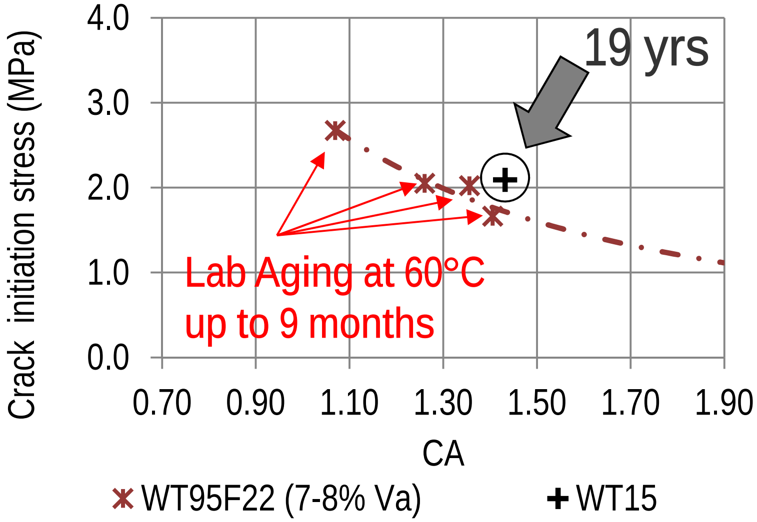


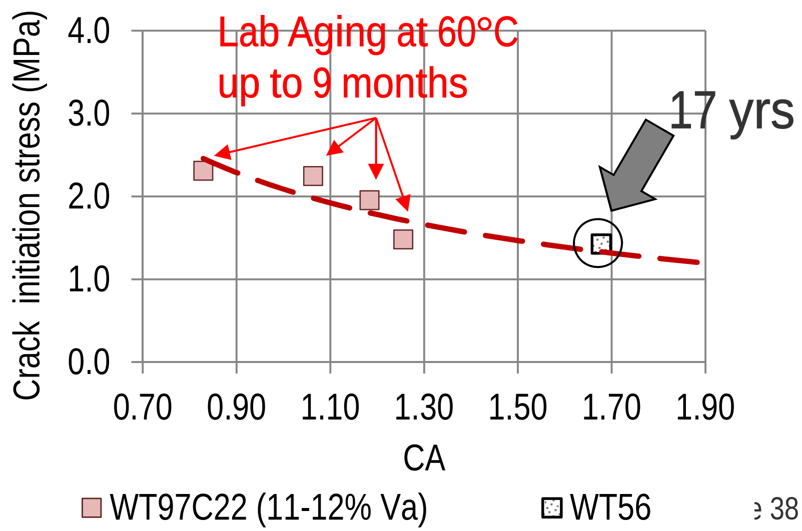
Lab to Field Correlation

WesTrack Mixes

- Consistencies observed between lab and field aging
  - Example: WesTrack Sections (Diff. Binder and Aggs.)
  - Section 15 – 1995 [19 yrs field aging]
  - Sections 38 & 56 – 1997 [17 yrs field aging]





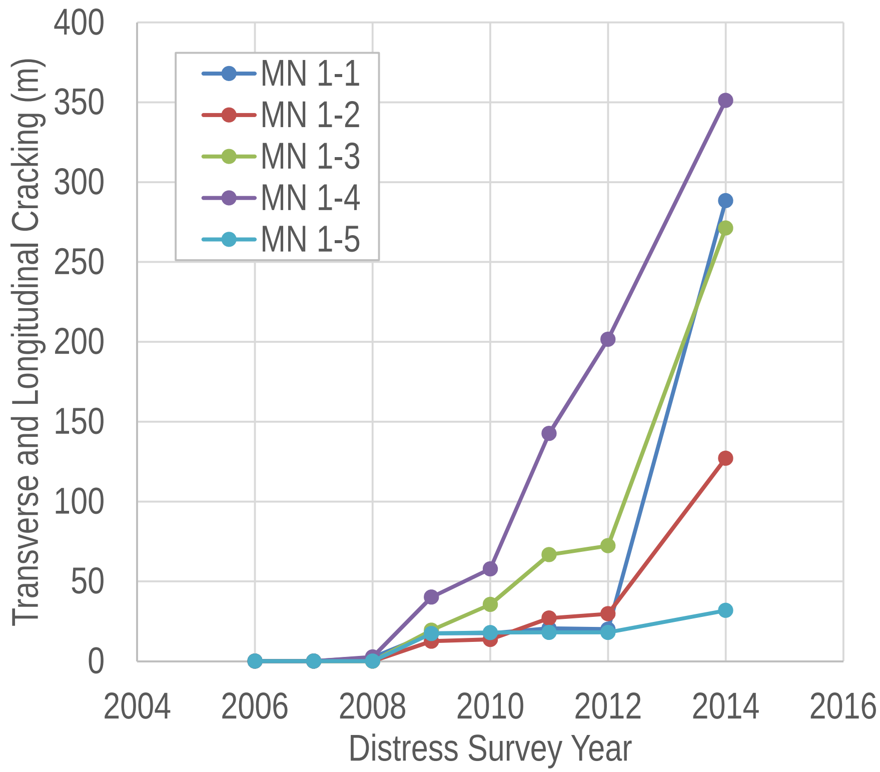


Lab to Field Correlation

CR 112 Olmsted County, Minnesota Sections

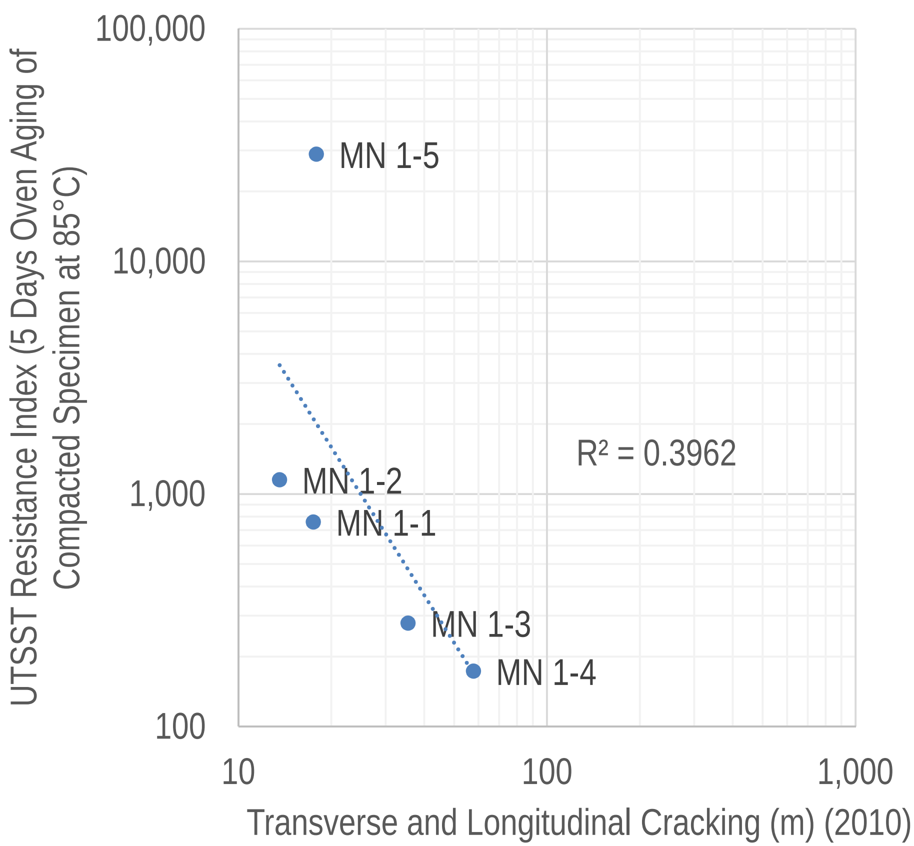
- Five test sections were constructed using same aggregate gradation and four binders from different sources.

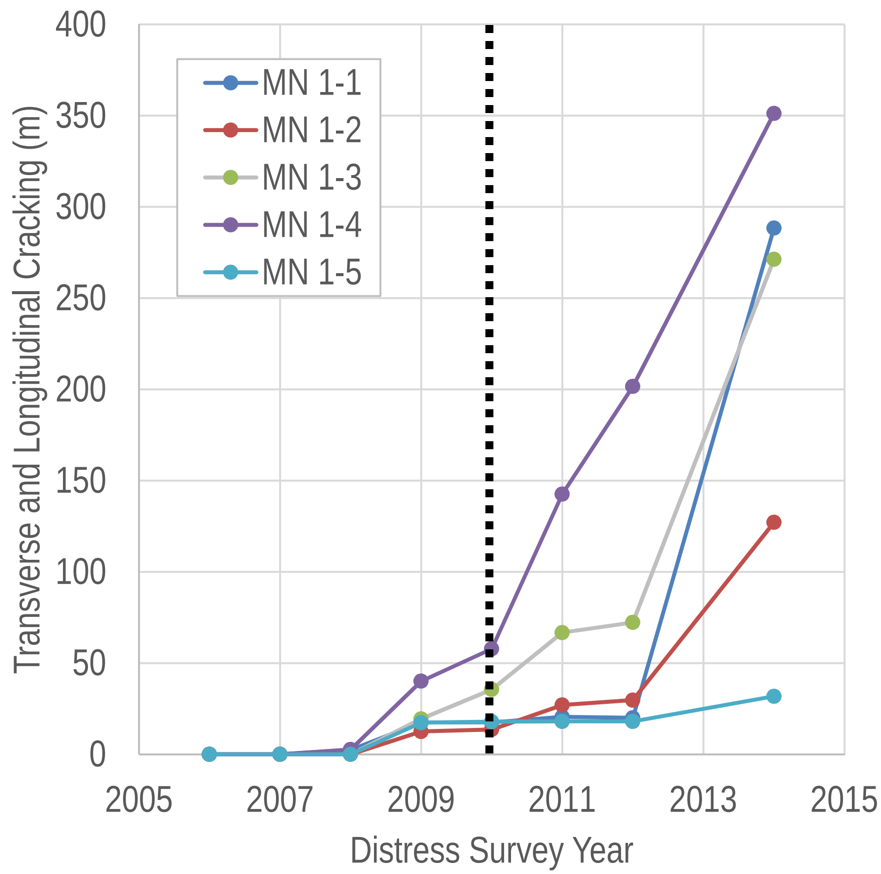
Section	Binder
MN 1-1	MIF PG 58-34 (Elvaloy modified) with 20% RAP
MN 1-2	MIF PG 58-34 (Elvaloy modified) without RAP
MN 1-3	PG 58-28 Canadian blend
MN 1-4	PG 58-28 Arab heavy/Arab medium/Kirkuk blend
MN 1-5	PG 58-28 Venezuelan blend



Lab to Field Correlation

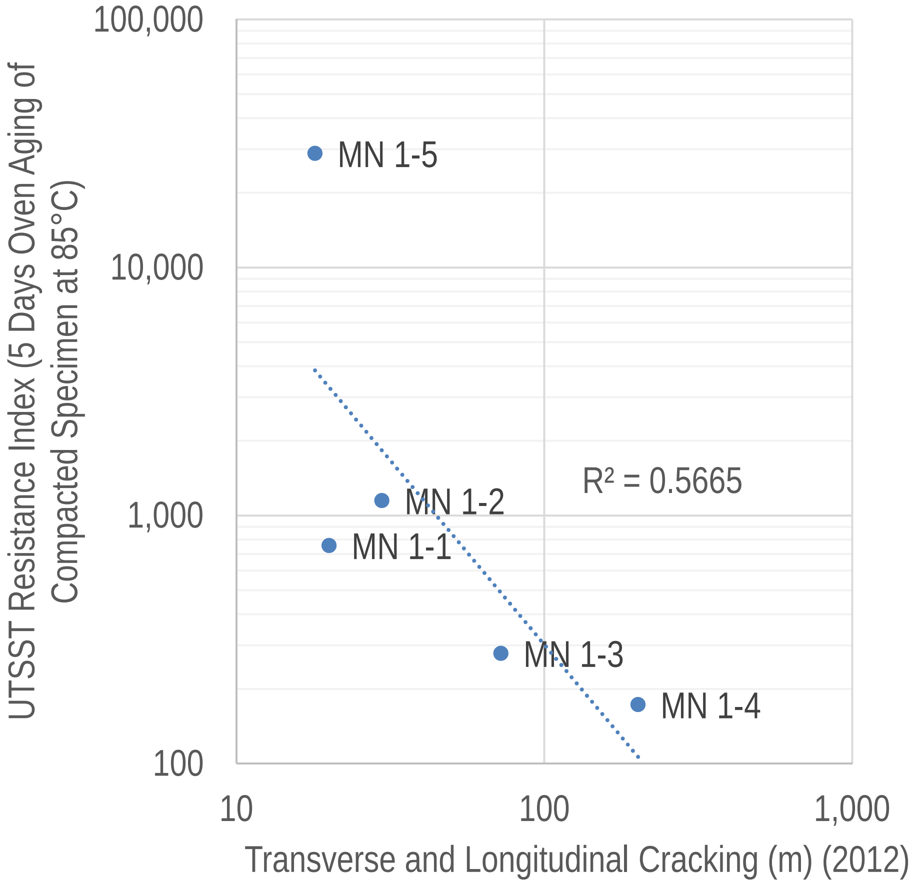
CR 112 Olmsted County, Minnesota Sections (cont'd)

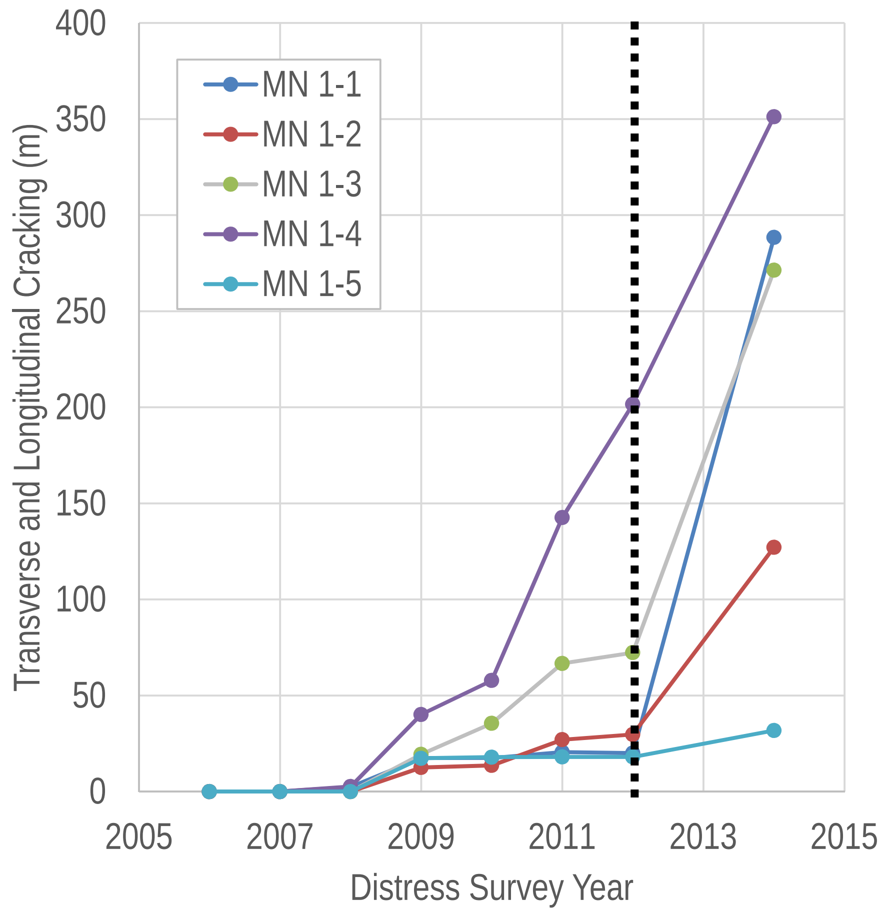




Lab to Field Correlation

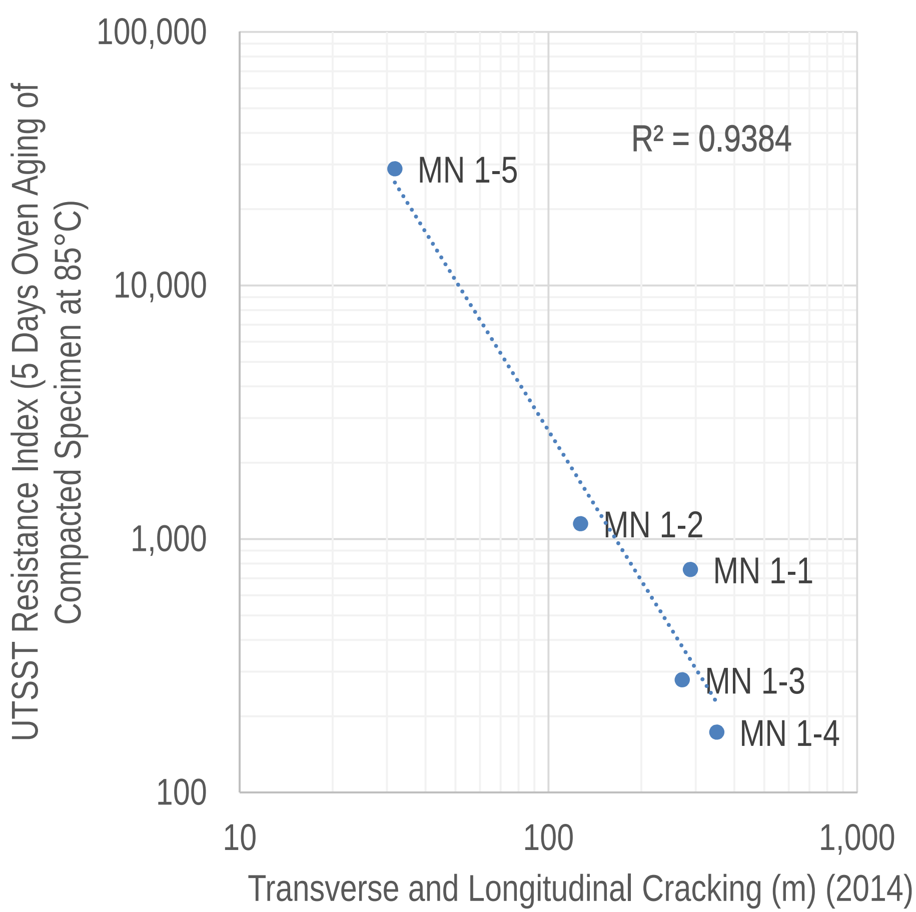
CR 112 Olmsted County, Minnesota Sections (cont'd)

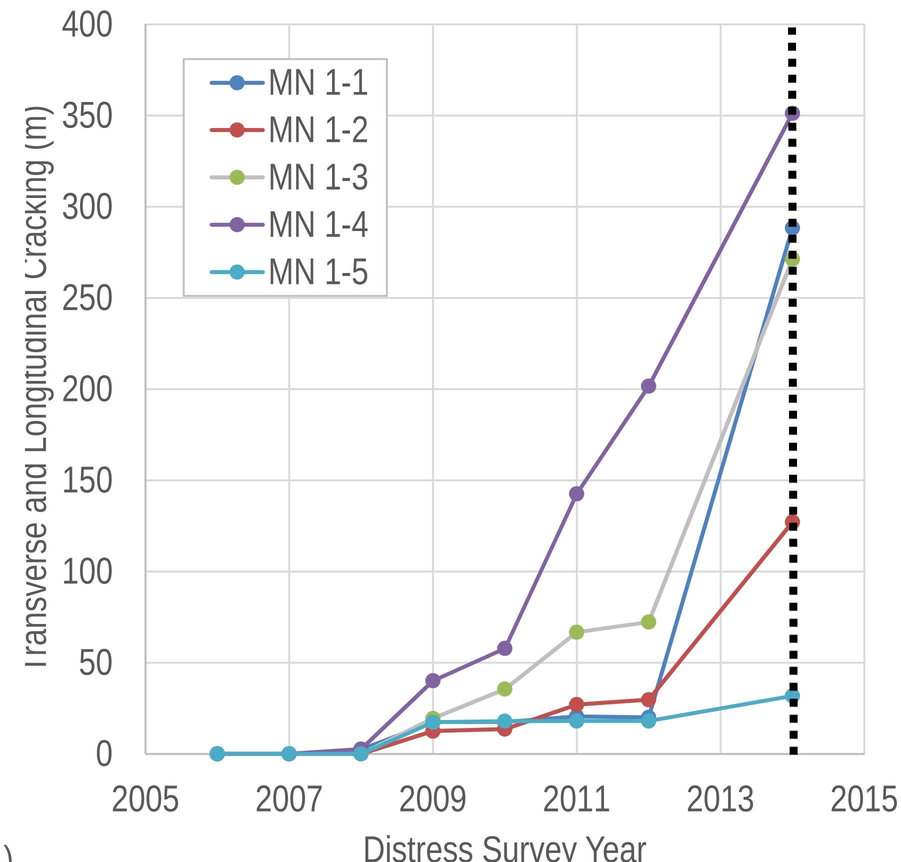




Lab to Field Correlation

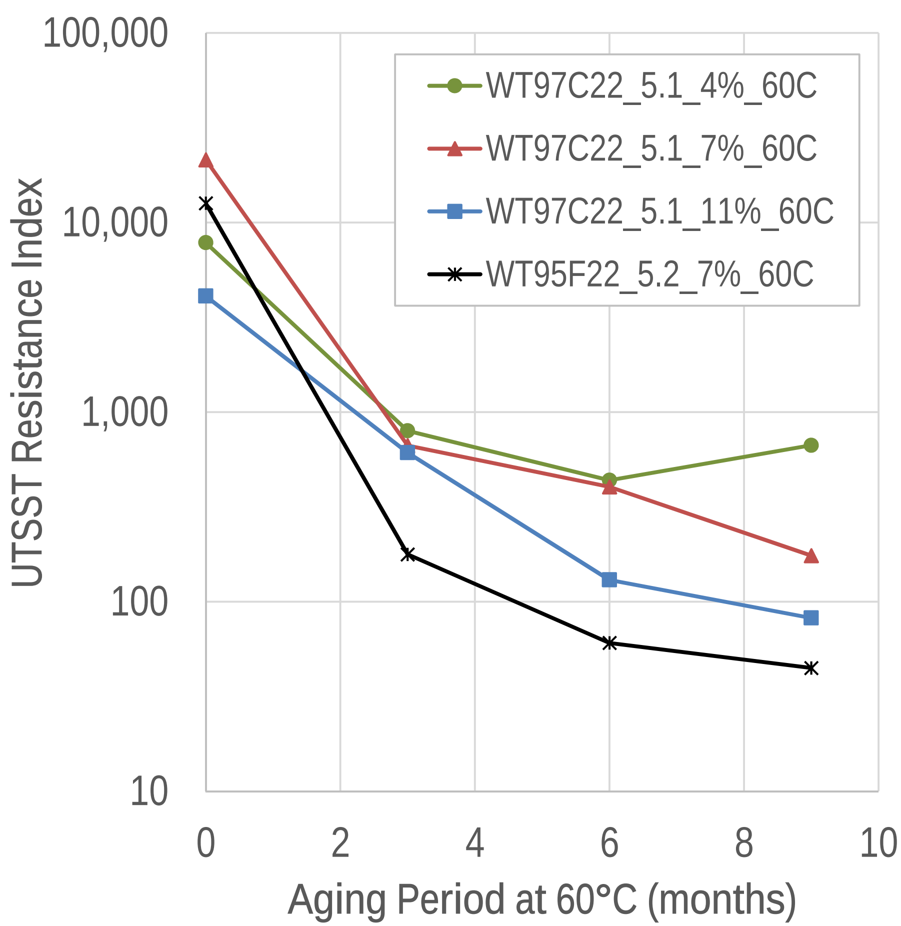
CR 112 Olmsted County, Minnesota Sections (cont'd)

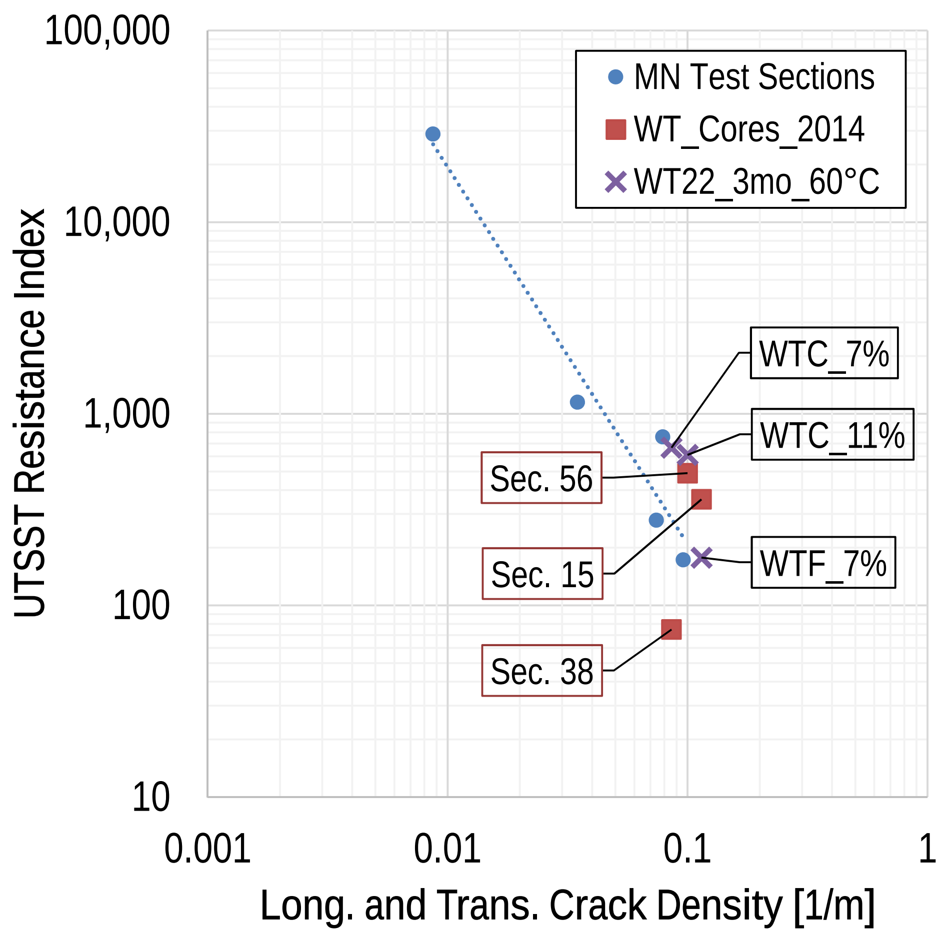




Lab to Field Correlation

CR 112 and WesTrack





Summary and Conclusions
Uniaxial Thermal Stress and Strain Test

- Test specimens obtained from SGC specimens or field cores.
  - Orientation of specimens is preserved by subjecting tensile stresses perpendicular to compaction direction.
- Allow for the determination of:
  - CTC, fracture strength/temperature, Crack initiation stress, UTSST Resistance Index, or other thermo-viscoelastic properties.
- Direct tension test under thermal loading.
  - Full characterization of asphalt mixtures as a function of temperature (various thermal transition zones).
  - Cooling rate can be selected to simulate field conditions.

Thank You!