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Low Temperature Pooled Fund Study Phase II

Task 2 - *Physical Hardening of Binders and Mixtures*

Task 3 - *Development of the Single-Edge Notched Beam (SENB) Test*

Task 5 - *Modeling Asphalt Mixtures Contraction-Expansion*

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Objectives Task 2

1. Develop method to simplify measurements of physical hardening
2. Model to adjust **Stiffness and m-value** based on climatic condition
3. Collect physical hardening for variety of asphalt binders
4. Use T_g to quantify effect of isothermal storage on dimensional stability of asphalt mixtures
5. Effect of PPA, WMA additives, and Polymers on physical hardening

Physical hardening (aging)- *Not a new topic*

- It is caused by **time dependent isothermal changes in specific volume**.
- It is similar to reducing temperature.
  - Effect completely removed when material is heated to room temperatures.
- Physical hardening for polymers can be explained by free volume theory in Glass Transition region (Struik (1978) and Ferry (1980))

Physical Hardening Model For Asphalt Binders (1) and (2)

- Mechanism of gradual particle rearrangement toward lower free volume, resulting in gradual increase in stiffness, can be described as a **“creep”** behavior.

Temp dependant “stress” term

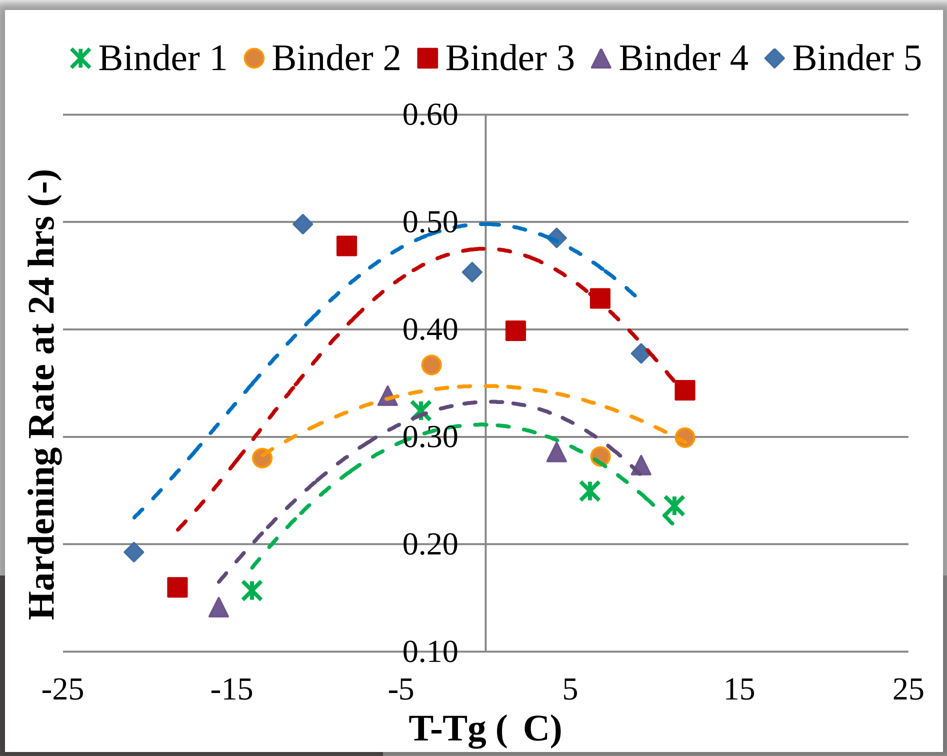
Kelvin-Voigt Model Structure

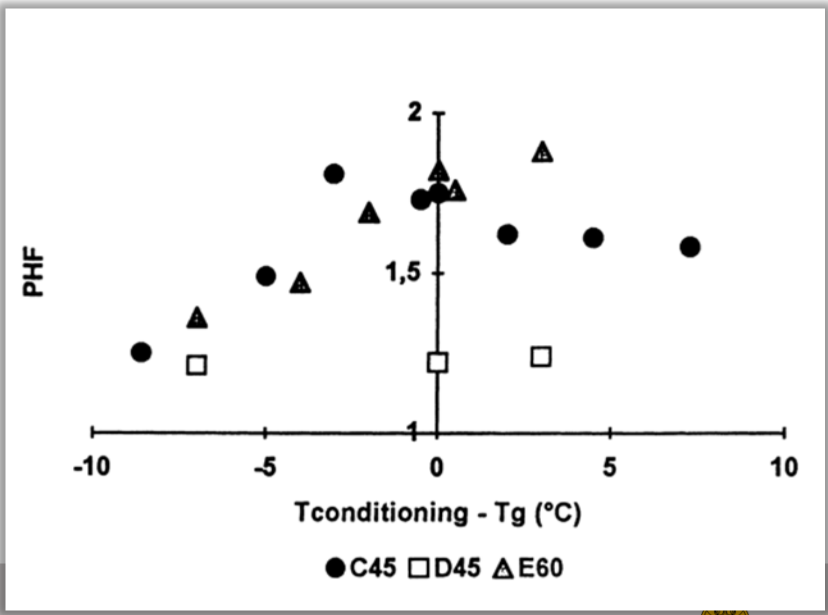
$$\epsilon_{PH} = \frac{e^{\frac{-9(T-T_0)^2}{(2x)^2}}}{G}\left(1 - e^{-t_c \frac{G}{\eta}}\right) \propto \frac{\Delta V}{V_0} \propto \frac{\Delta S}{S_0}$$

- In which:
  - ϵ_{PH} is isothermal contraction
  - $\Delta S/S_0$ is the hardening rate
  - T_0 is the peak temperature for hardening rate, assumed to be the T_g (C)
  - T is the conditioning temperature (C)
  - t_c is the conditioning time (hrs)
  - $2x$ is the length of the temperature range of the glass transition region (C)
  - G and η are model constants, derived by fitting the model

Physical Hardening and Temperature

- Physical hardening for 40 binders investigated:
  - Physical hardening was small at T >> Tg
  - Physical hardening peaked at T ≈ Tg
  - In half of binders, physical hardening was less at Tc < Tg





(Planche et al., 1998)

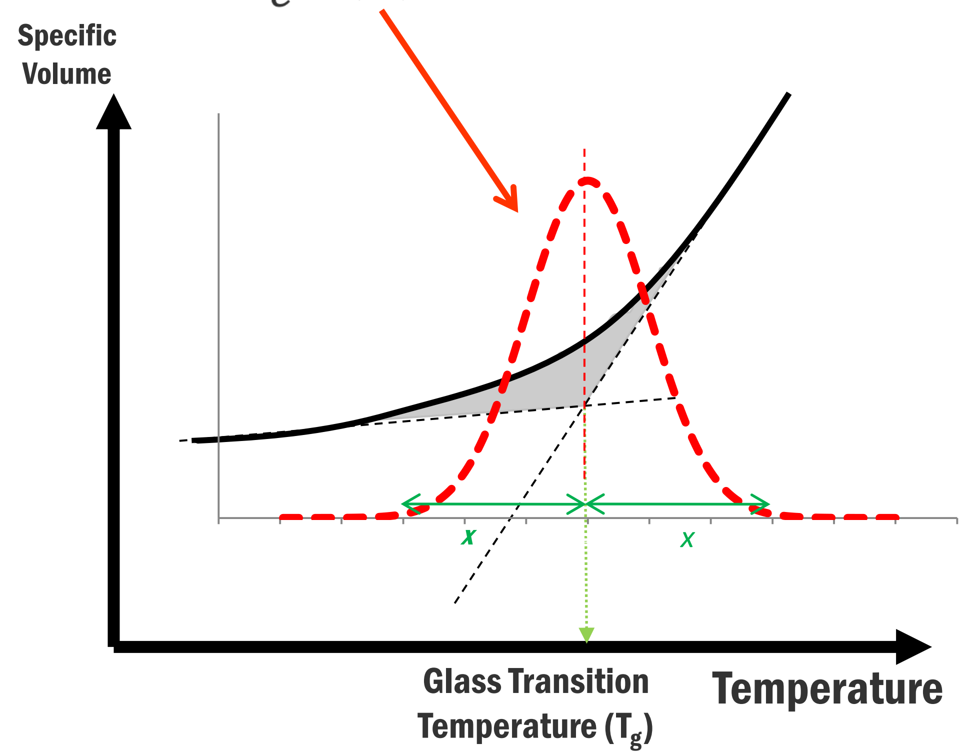
Physical Hardening Model (1) and (2)

- Physical hardening is limited to glass **transition region**
- Physical hardening Rate **peaks at T_g**

(Hardening rate= ΔS/S0)

Temp dependant "stress" term

$$e^{\frac{-a(T-T_0)^2}{(2x)^2}}$$



Obtaining parameters of physical hardening model (2)

First approach:

1. Run BBR test for sample at 3 conditioning times (i.e. 1, 3, and 6 hrs, or longer!)
2. Use Glass Transition temperature (T_g) and length of T_g region from binder T_g test.
   - *The longer the test duration, higher the accuracy*

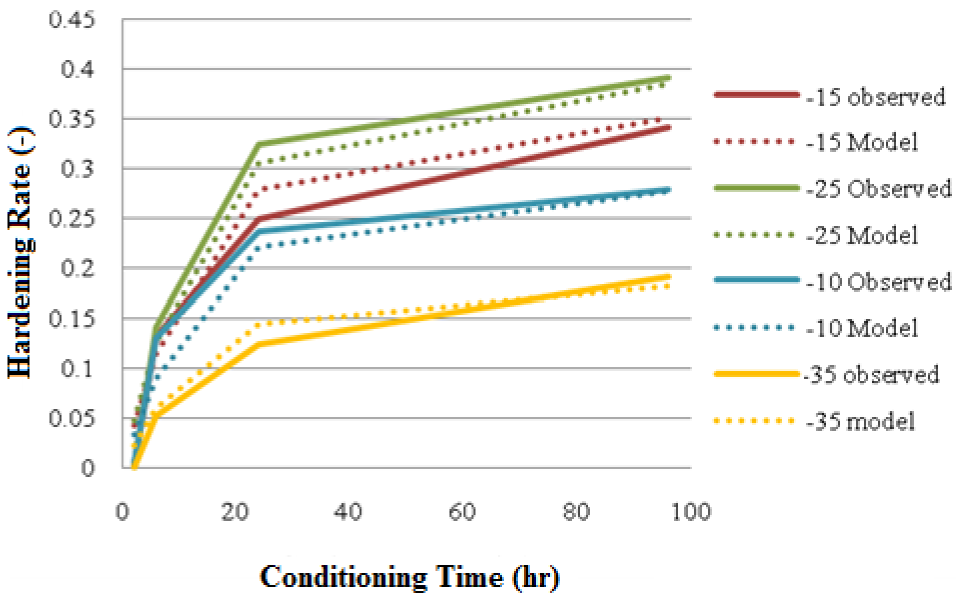
Obtaining parameters of physical hardening model (2)

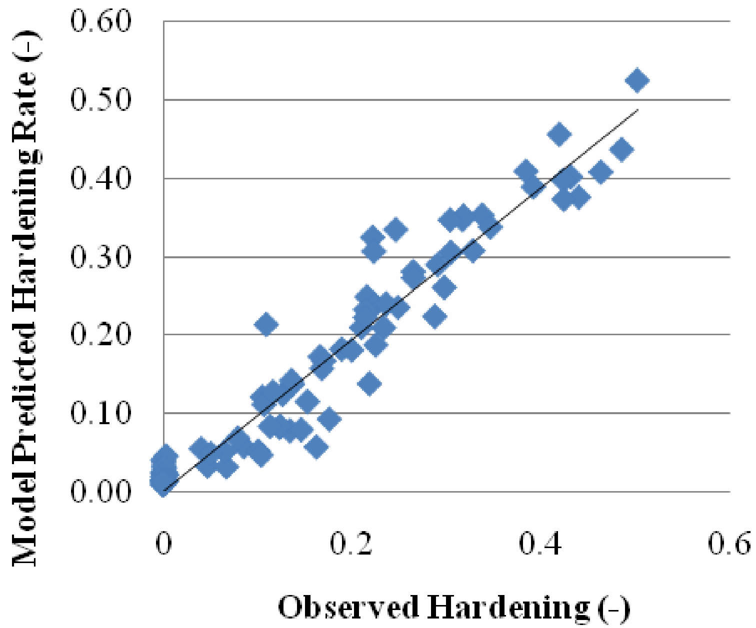
Second approach:

1. Run BBR test at 1 hr conditioning time at 3 temperatures, as in performance grading
2. Calculate power law slope, B.
3. Use B along with T_g and length of T_g region from glass transition test to predict model parameters G and η

- ***G** and **η** are <u>unique for every binder</u>, thus constant at all conditioning times and temperatures*
- ***Tg** may be indirectly <u>estimated from BBR</u> conditioning tests at 3 temperatures*

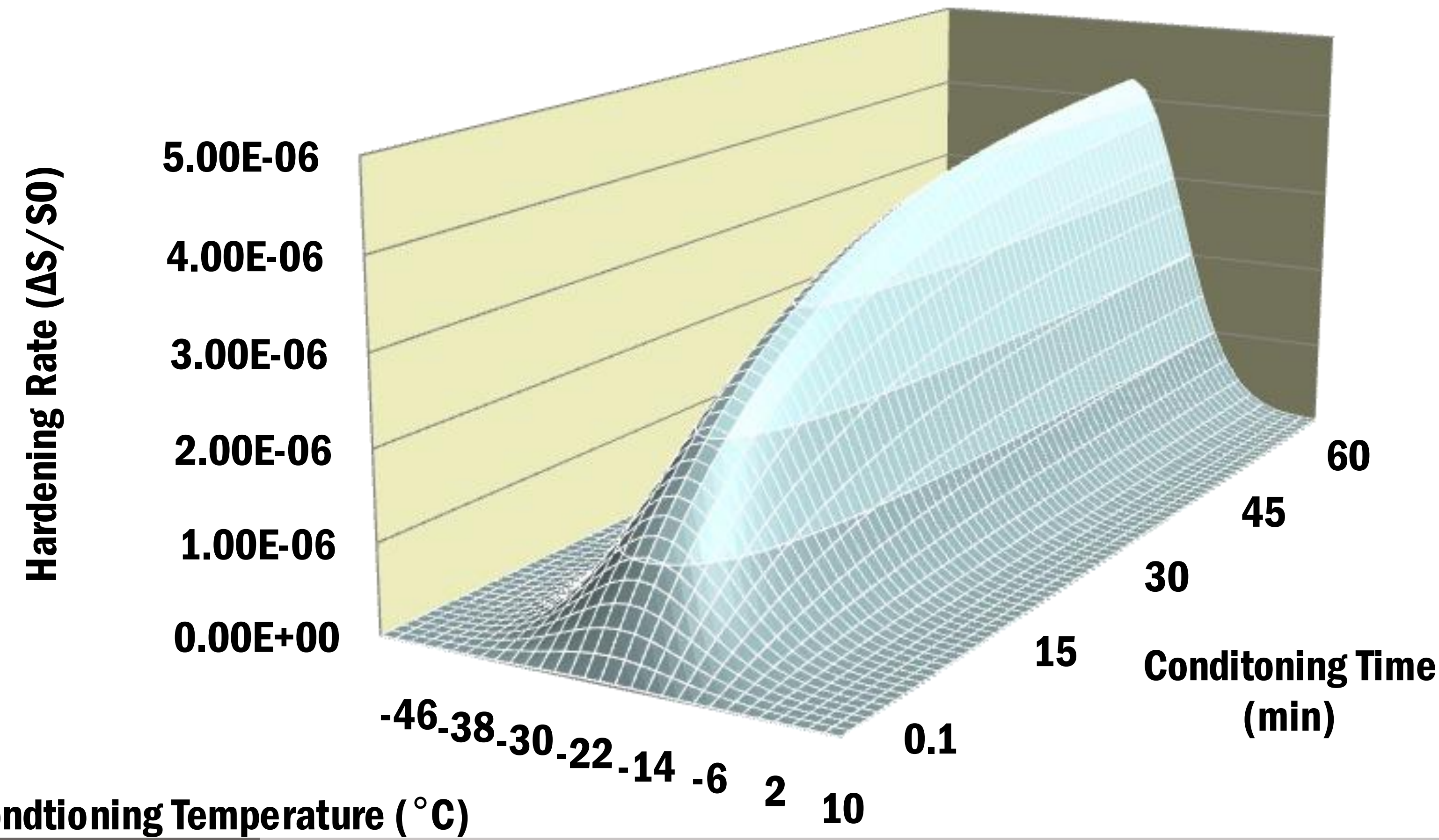
Goodness of Fit of PH model for Binders (1) (2), and (3)





Comparison of model with experimental data. (Hardening rate= $\Delta S/S_0$)

3D Representation of Model



- T_g=-20 C

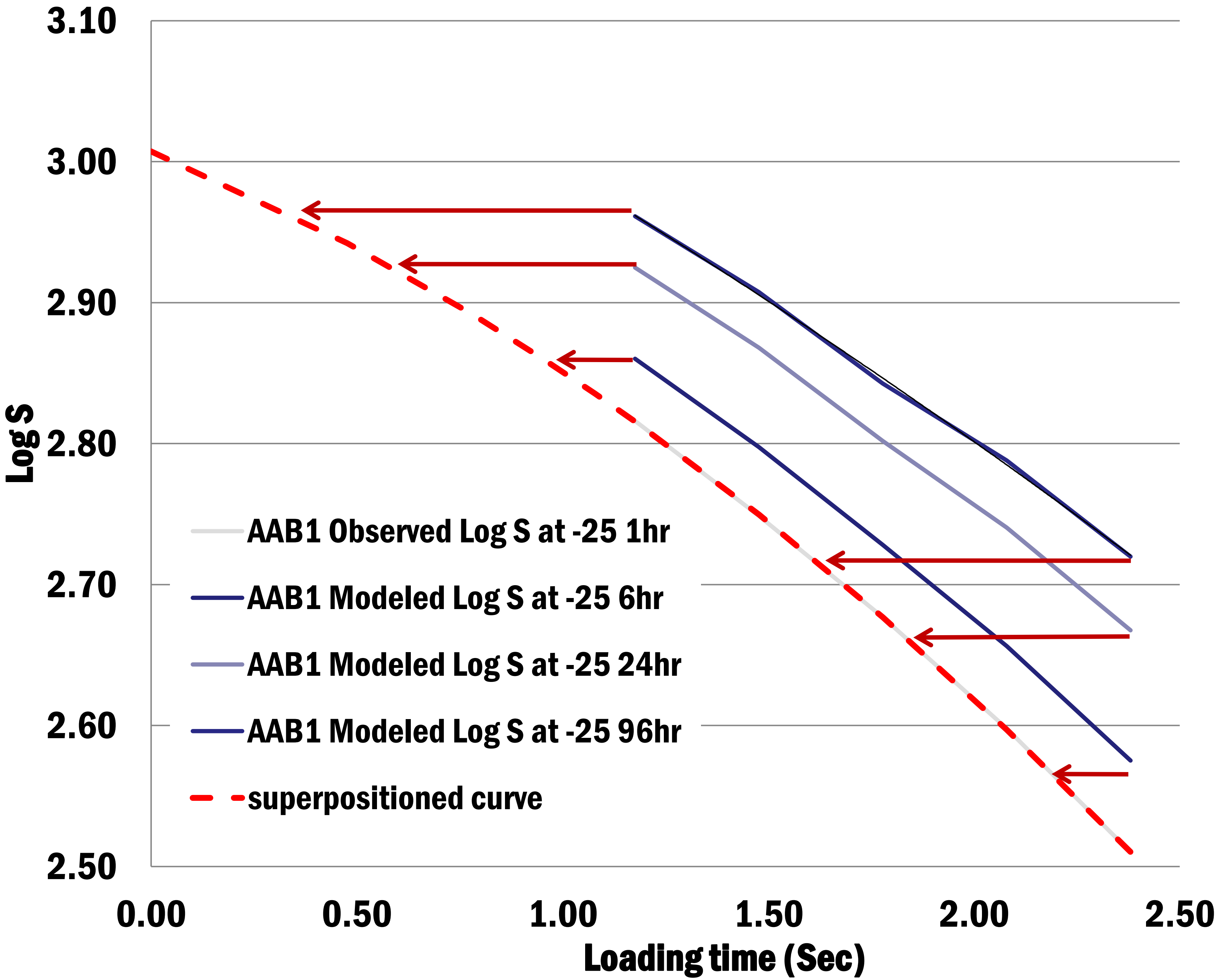
m-value calculation from model

- It has been shown that time-temperature superposition holds for hardening (Bahia and Anderson, 1993)

- The $m(x)_{t_c=Y}$ is the m-value after x seconds of loading time after Y hr of isothermal conditioning

- According to time-temp super position:

$$m(60)_{t_c=Y} = m(x)_{t_c=1}$$



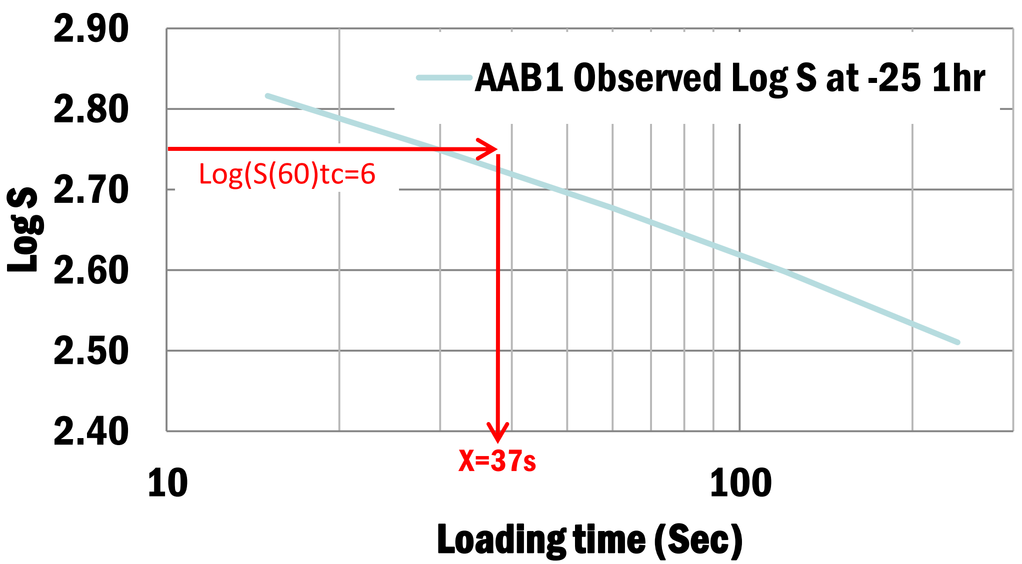
3.10
3.00
2.90
2.80
2.70
2.60
2.50
Log S
0.00
0.50
1.00
1.50
2.00
2.50
Loading time (Sec)
AAB1 Observed Log S at -25 1hr
AAB1 Modeled Log S at -25 6hr
AAB1 Modeled Log S at -25 24hr
AAB1 Modeled Log S at -25 96hr
superpositioned curve

m-value calculation from model

- Use physical hardening model to predict S(60) at different conditioning times: $S(60)_{t_c=Y}$
- Find equal $S(x) = S(60)_{t_c=Y}$, on Log(S)-log(t) at tc=1 hr curve.
  - Find m-value for time x, and use:

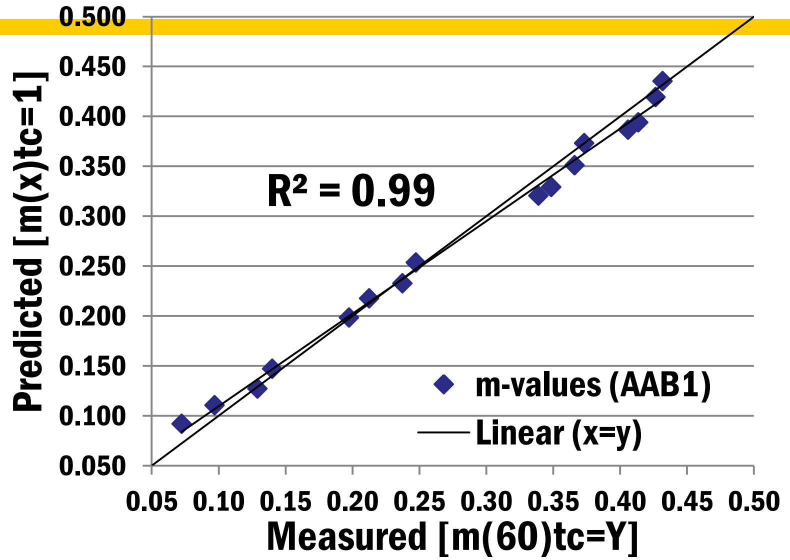
$$m(60)_{t_c=Y} = m(x)_{t_c=1}$$

$$m(60)_{t_c=6} = m(37)_{t_c=1}$$



m-value calculation from model

Temp	tc=Y (hr)	log S(60)tc=Y	Log S(x)tc=1	x (sec)	log x	m(x)tc=1	m(60)tc=Y
-10	96 hr	1.92	1.92	25	1.40	**0.406**	0.387
	24 hr	1.88	1.88	32	1.50	**0.414**	0.394
	6 hr	1.81	1.81	46	1.67	**0.427**	0.419
-15	96 hr	2.25	2.25	24	1.38	**0.339**	0.320
	24 hr	2.21	2.21	31	1.49	**0.349**	0.329
	6 hr	2.14	2.14	50	1.70	**0.366**	0.351
-25	96 hr	2.84	2.84	11	1.04	**0.198**	0.198
	24 hr	2.80	2.80	17	1.24	**0.213**	0.218
	6 hr	2.73	2.73	37	1.57	**0.238**	0.233
-35	96 hr	3.15	3.15	3	0.45	**0.072**	0.092
	24 hr	3.11	3.11	8	0.89	**0.097**	0.111
	6 hr	3.05	3.05	29	1.46	**0.129**	0.127



- **Very good agreement between prediction and measured m-value**
  - **Model prediction hold for time temperature superposition**
  - **Model can be used to predict both m and S changes**

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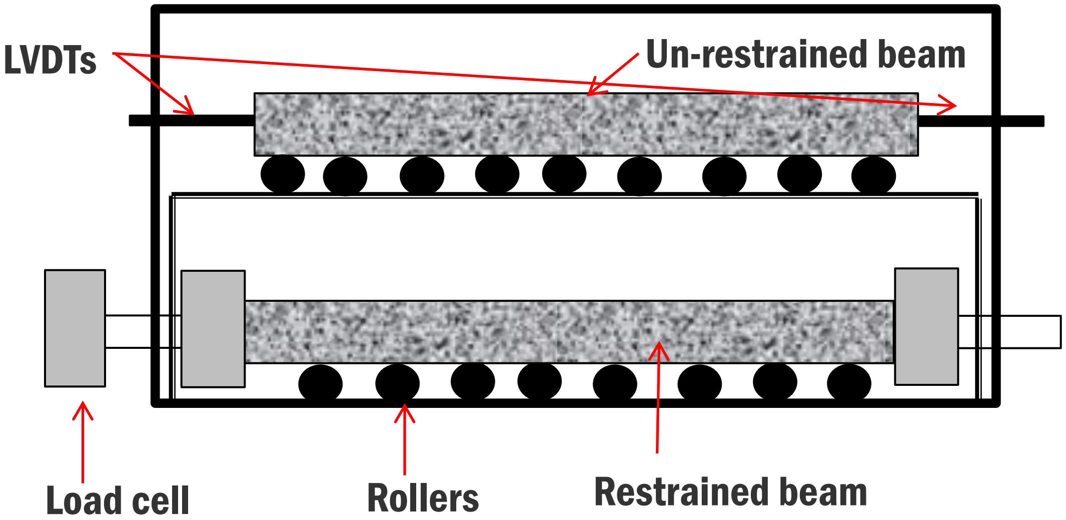
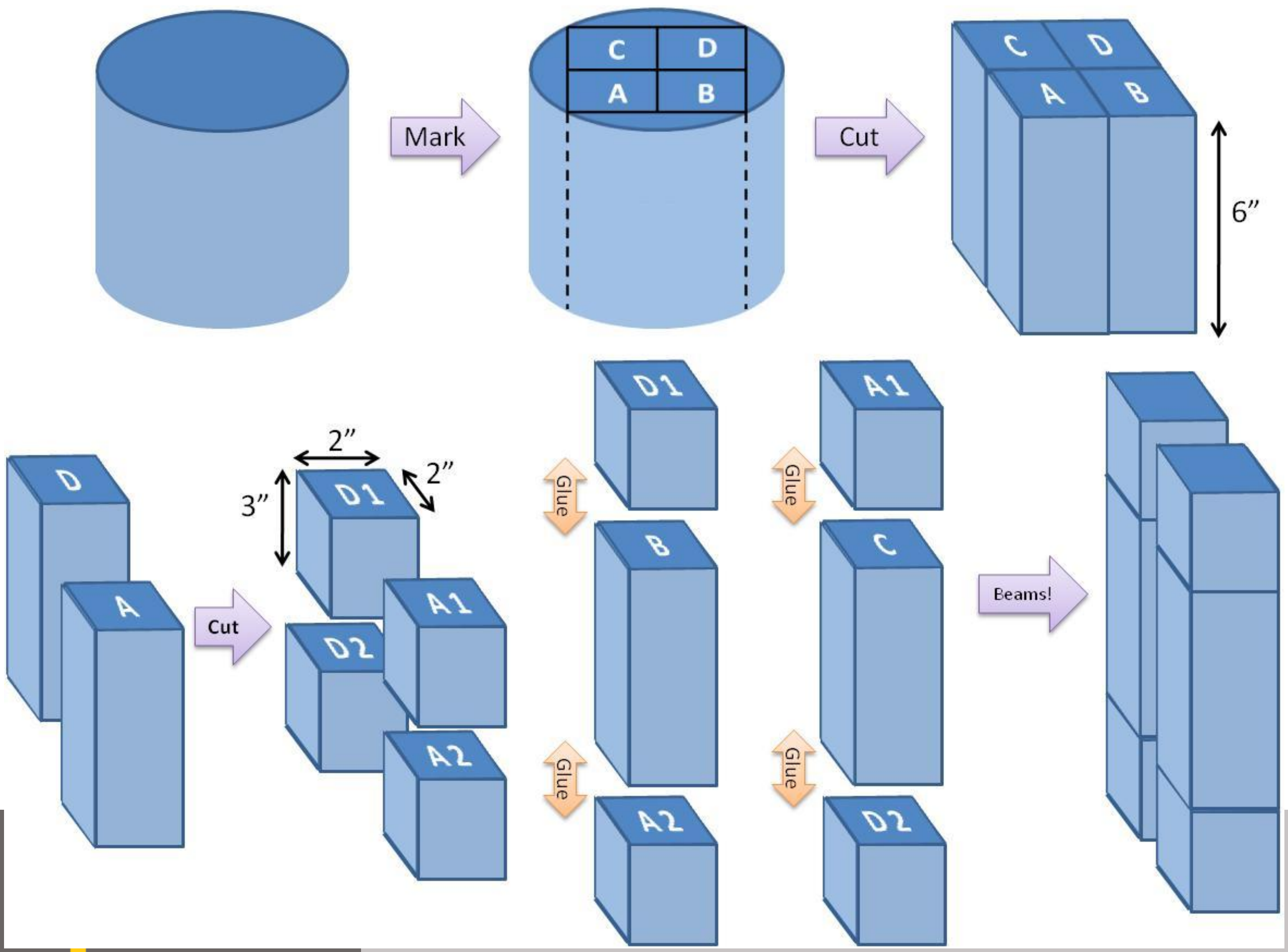
ATCA: Asphalt Thermal Cracking Analyzer



ATCA System: Sample preparation

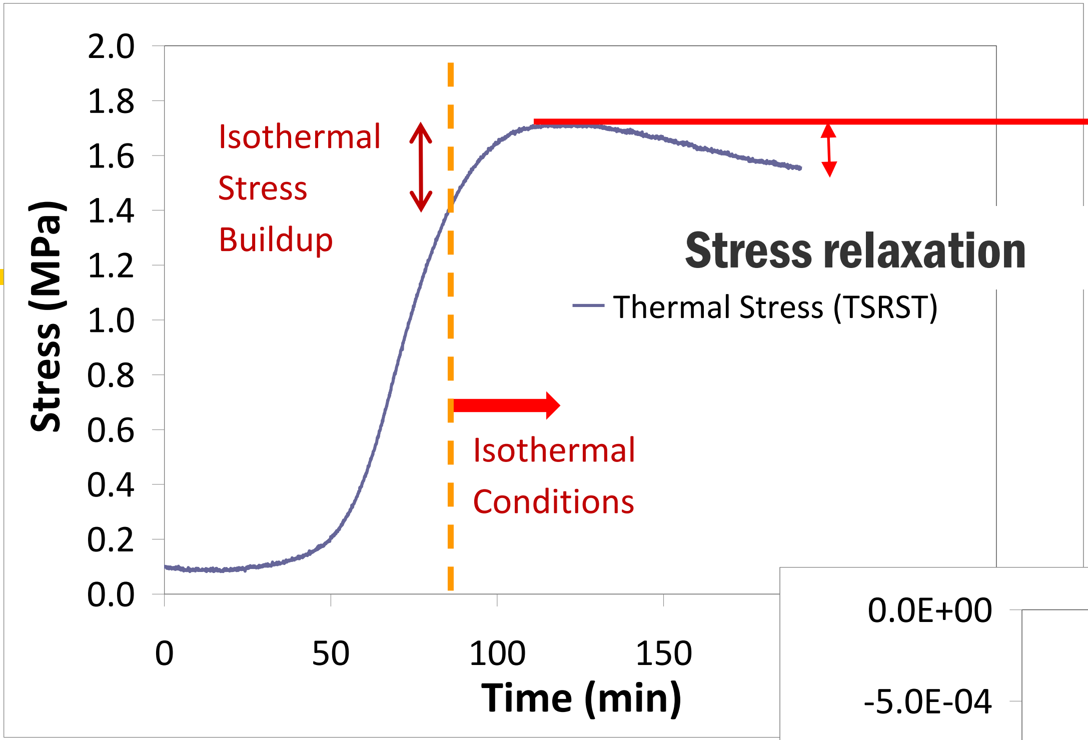


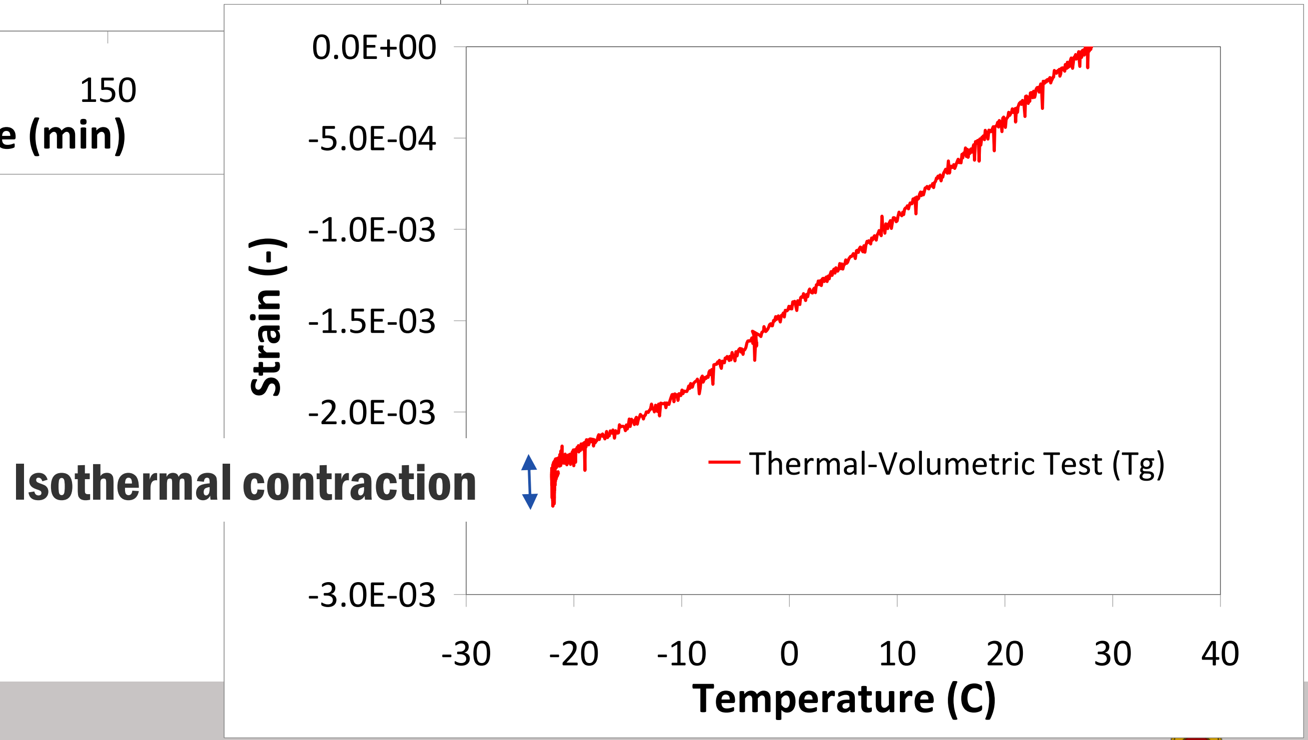
ATCA=>Quantify effect of isothermal storage on dimensional stability of asphalt mixtures (4)

The ATCA can simultaneously test two asphalt mixture beams under following conditions:

- unrestrained specimen from which change in length with temperature is measured
- restrained specimen to measure thermal stress buildup.
- Both specimens produced from same sample and both exposed to same thermal history

Isothermal testing of asphalt mixtures (4)





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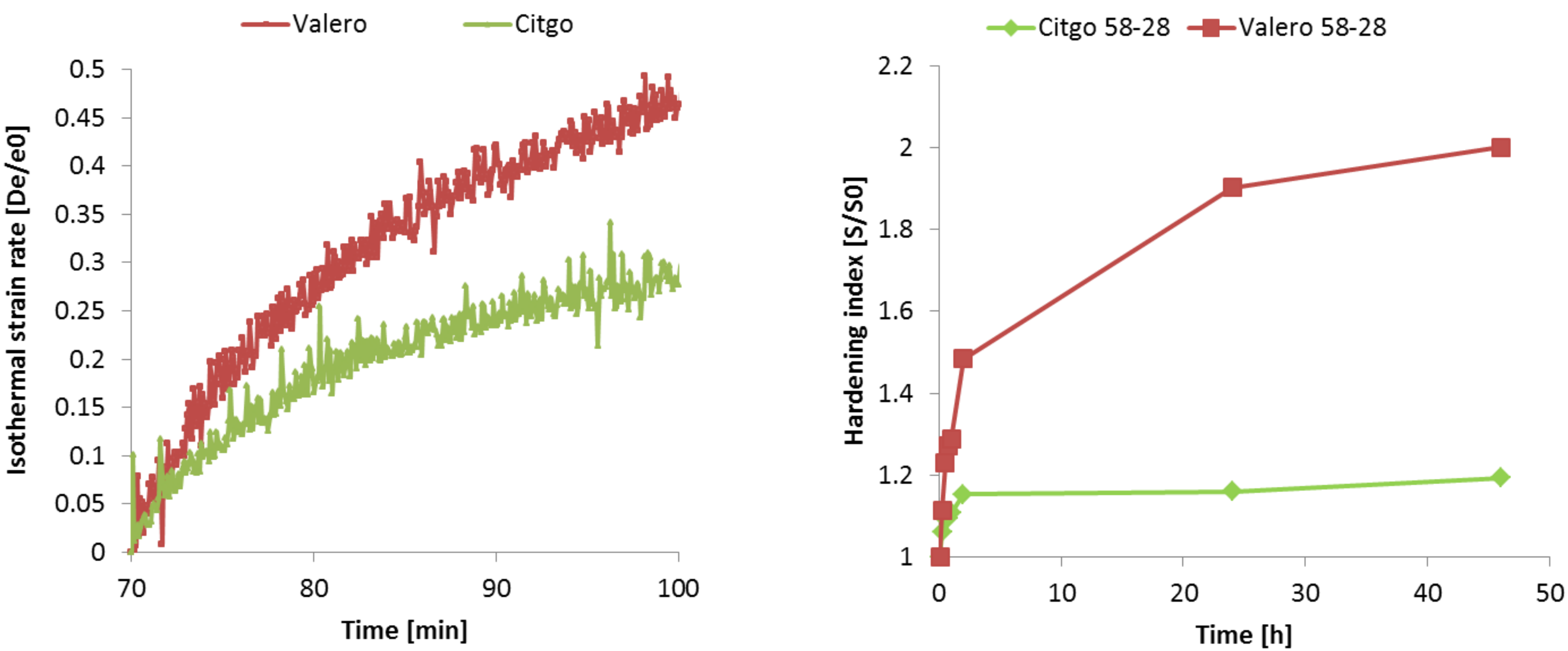
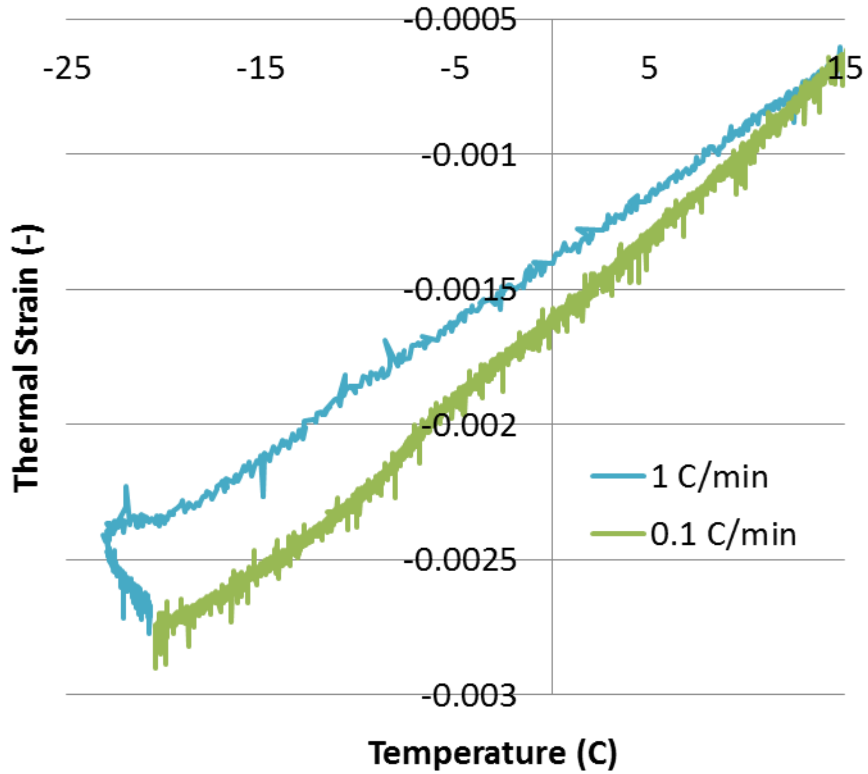
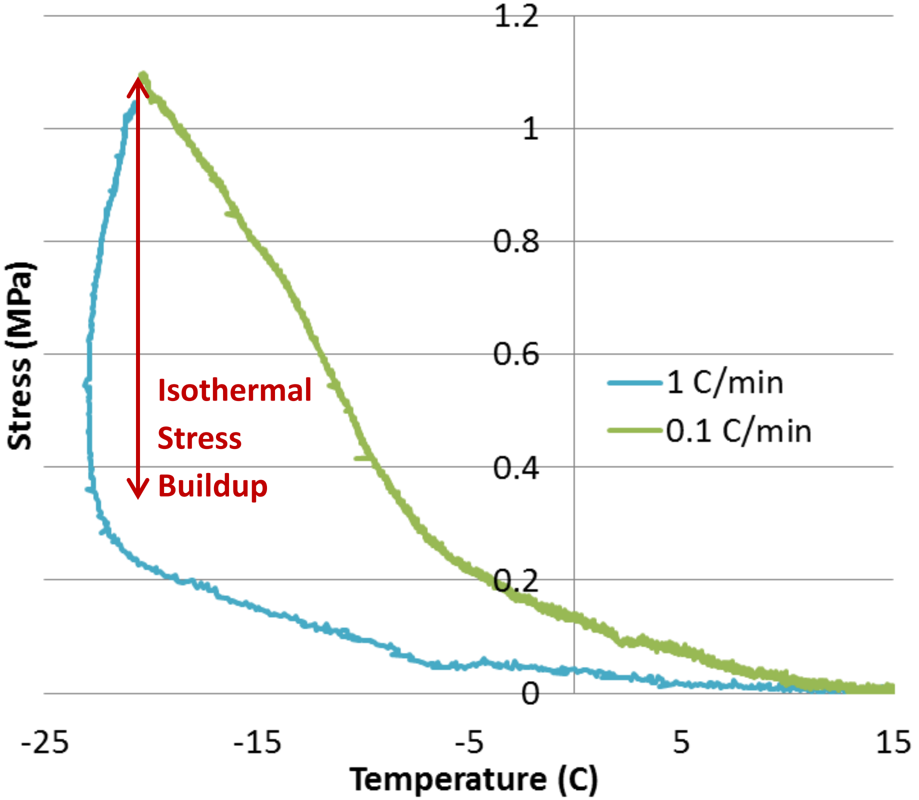
Isothermal Conditioning (ATCA and BBR) (4)



- BBR binder tests show different amount of hardening for the two types of binders at same PG.
- ATCA mixtures reflect the same hardening trend as the binders

Effect of Cooling Rate



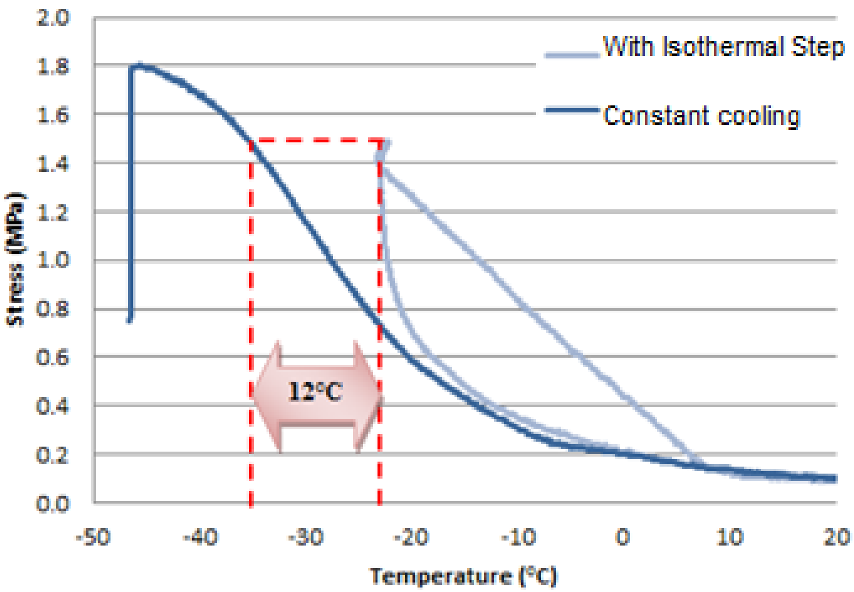


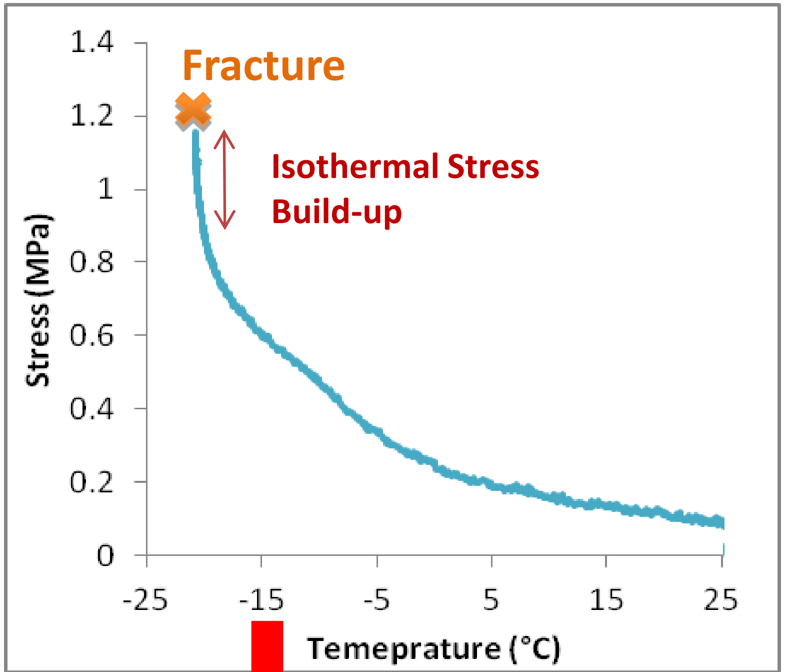
- **Delayed strain during fast cooling takes place isothermally**
- **If enough isothermal time is given, mixes reach same stress level**

Importance of Physical Hardening

1. Strain at low temperatures is function of temperature and ***conditioning time***!
2. Thermal stress at any cooling rate cannot be calculated without including time dependent strain
3. Time dependent strain = Physical Aging

Importance of Physical Hardening





MN County Road 112-CITGO restrained beam fracture under isothermal conditions

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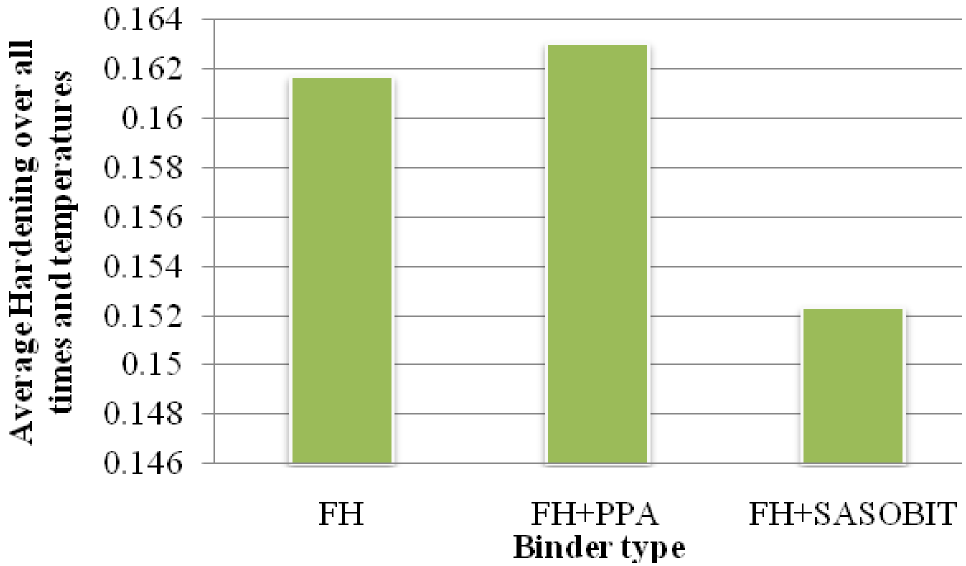
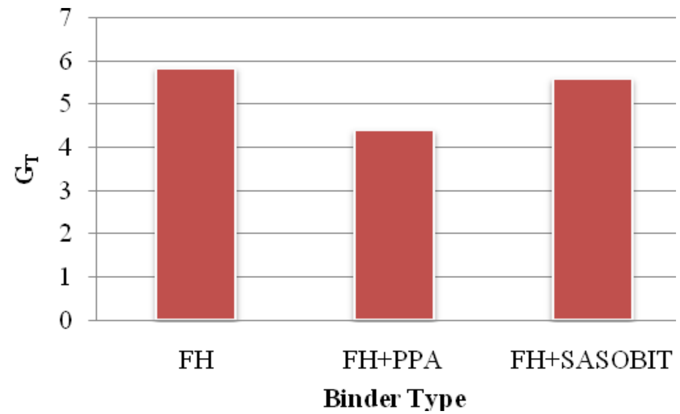
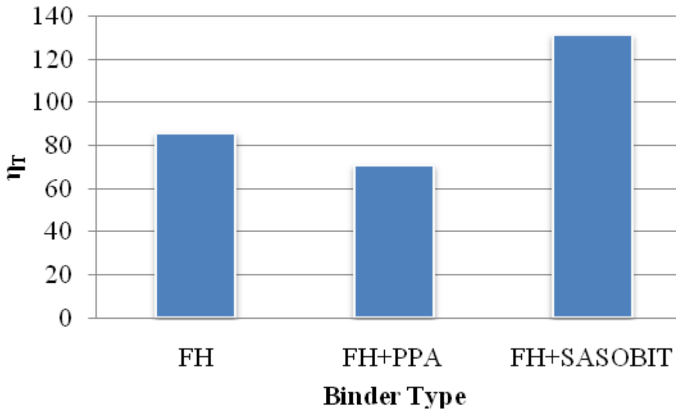
Physical Hardening of WMA and PPA (5)







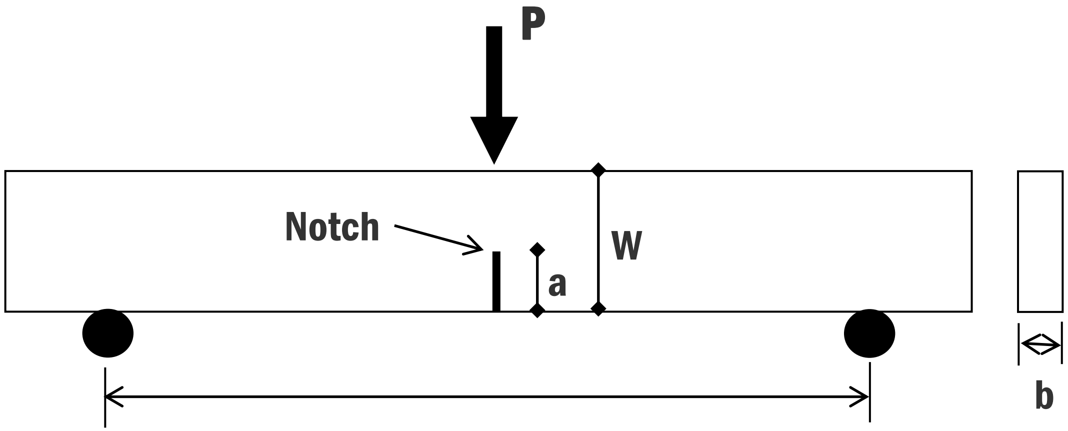
- WMA decreased and PPA increased <u>total amount of hardening</u>.
- WMA increased and PPA decreased <u>rate of hardening.</u>

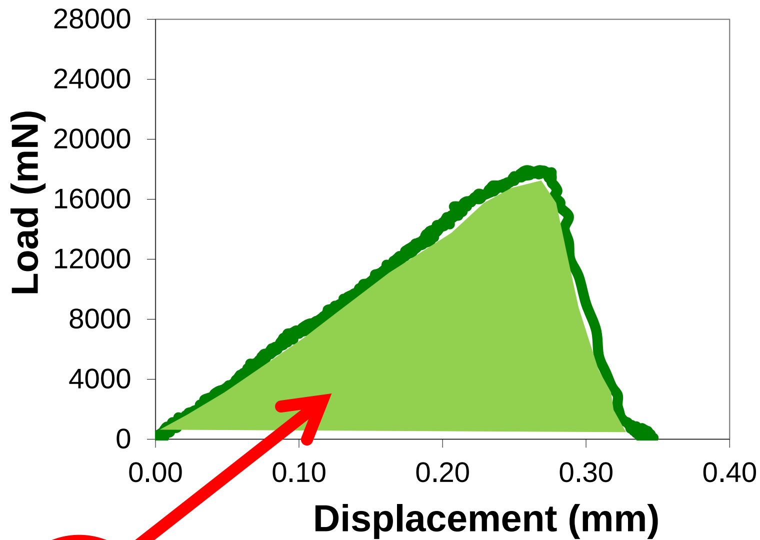
Conclusions Task 2

- Physical hardening in asphalt binders results in significant changes in their creep response at temperatures below or near glass transition
- Physical hardening can be represented with "creep" model with parameters obtained from BBR and/or Tg tests
- Thermal stress calculations are not accurate without accounting for Glass Transition and time-dependant strain (isothermal contraction)
- Effect of isothermal contraction becomes very important when using lab tests at faster cooling rates to predict field conditions

Task 3: Development of Single-Edge Notched Beam (SENB)

Follows ASTM E399 and assumes Linear Elastic Fracture Mechanics (LEFM) conditions are true





$$K_I = \frac{P \cdot S}{BW^{\frac{3}{2}}} f\left(\frac{a}{W}\right)$$

Fracture Toughness

$$G_f = \frac{W_f}{A_{lig}}$$

Fracture Energy

$$W_f = \int P du$$

Work

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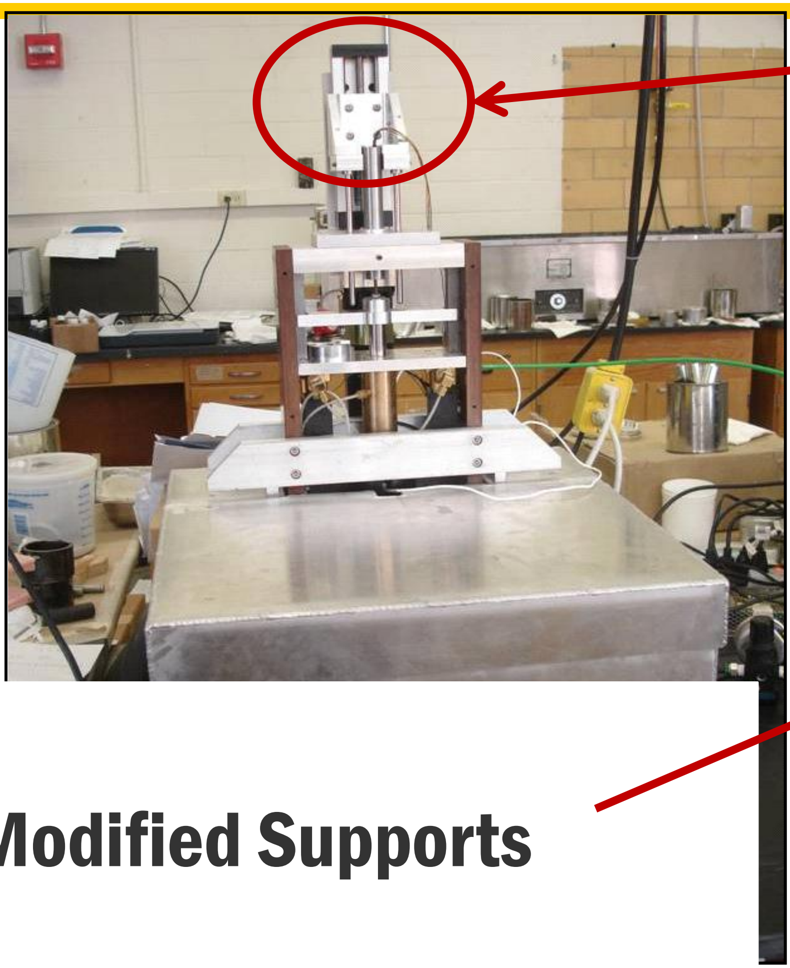
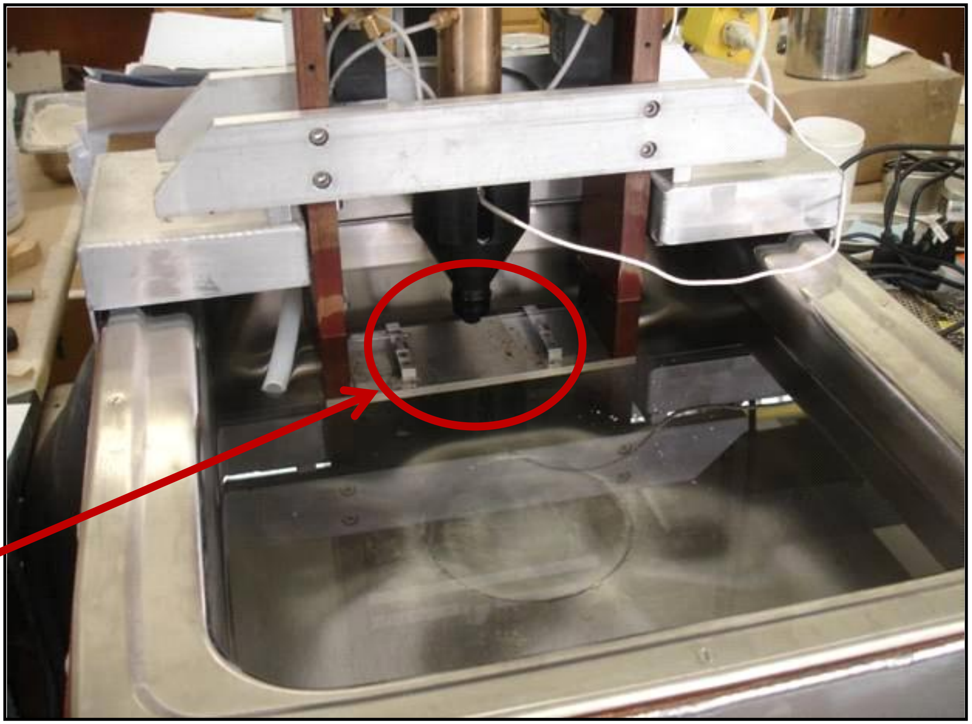
BBR-SENB system at UW-Madison

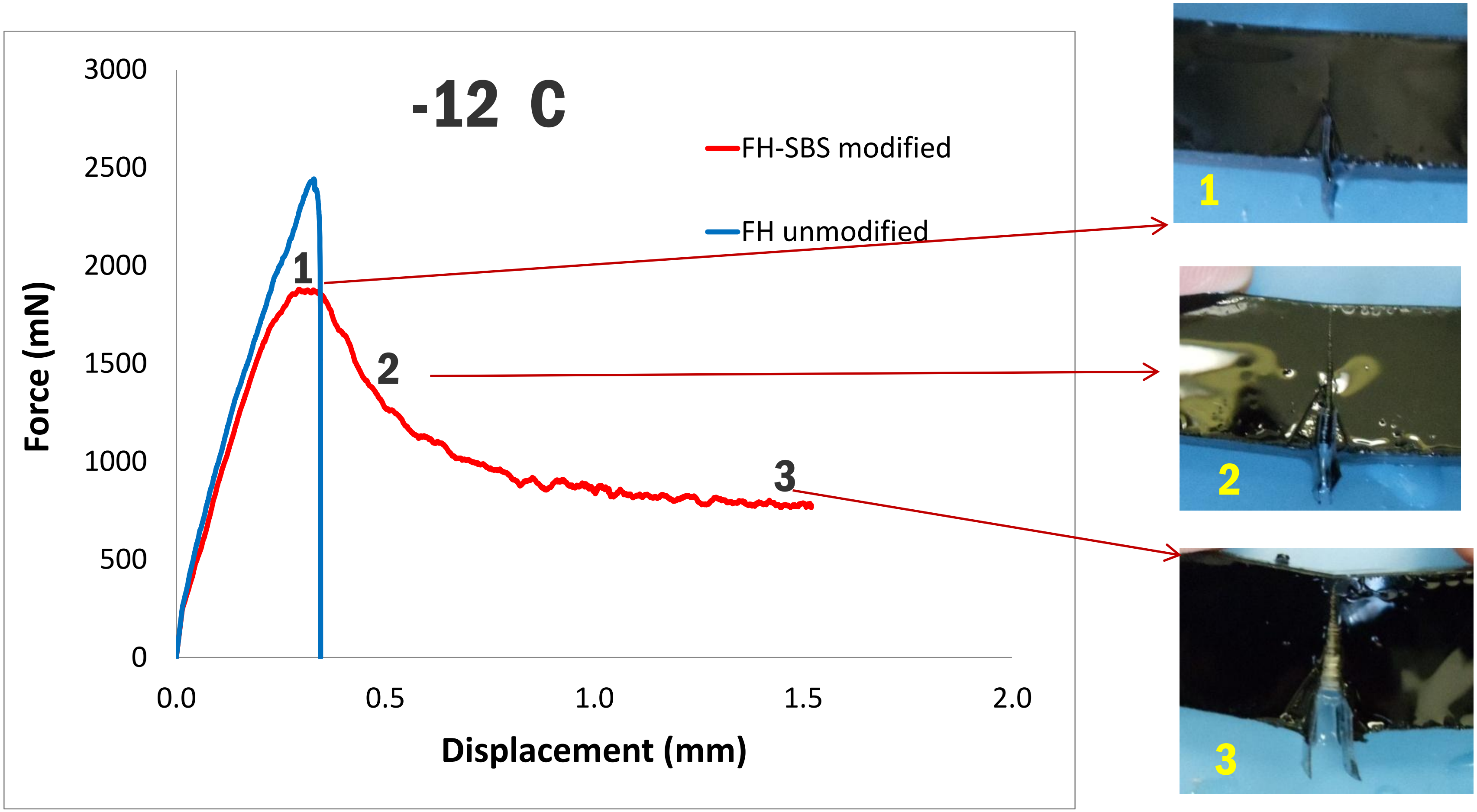


BBR+ Constant rate motor

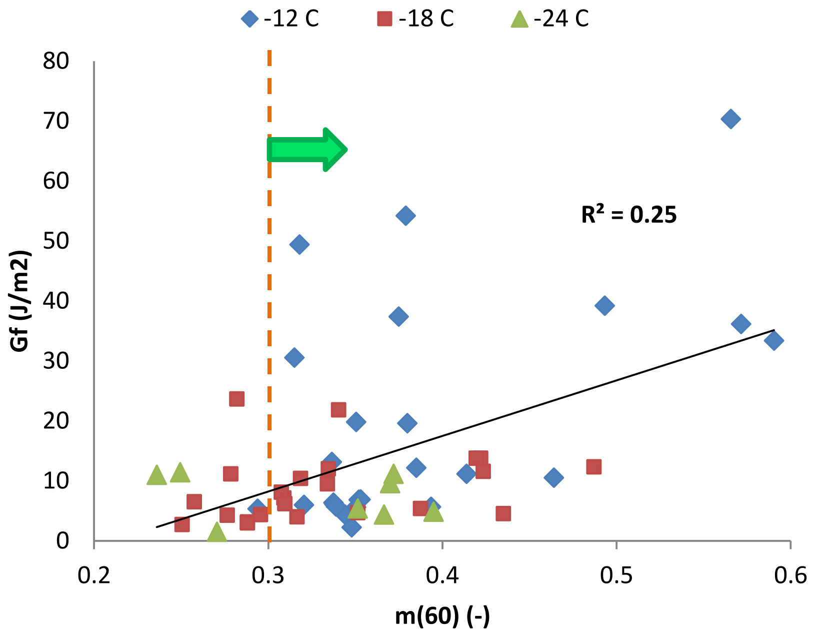


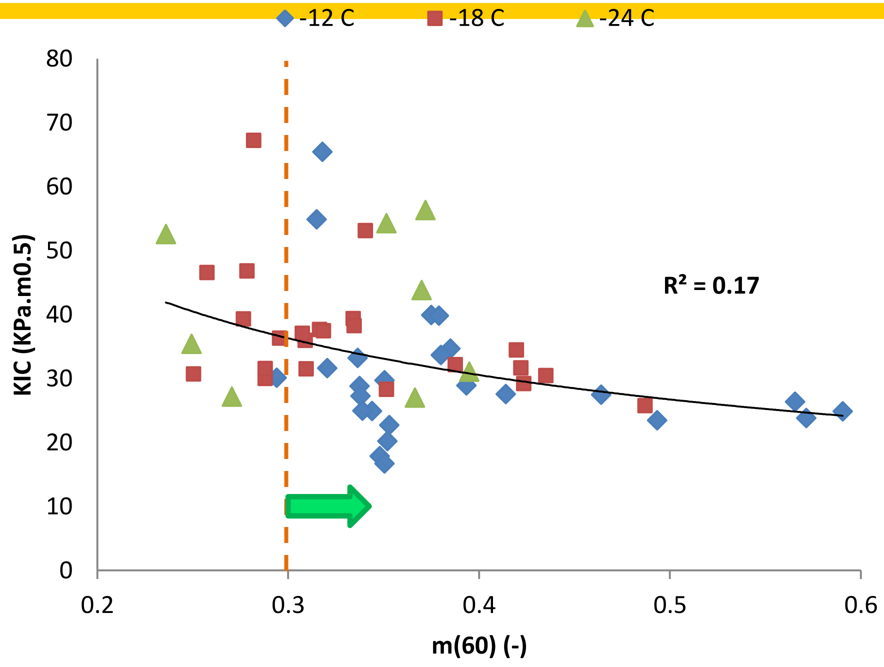
Modified Supports

BBR-SENB: Effect of Modification



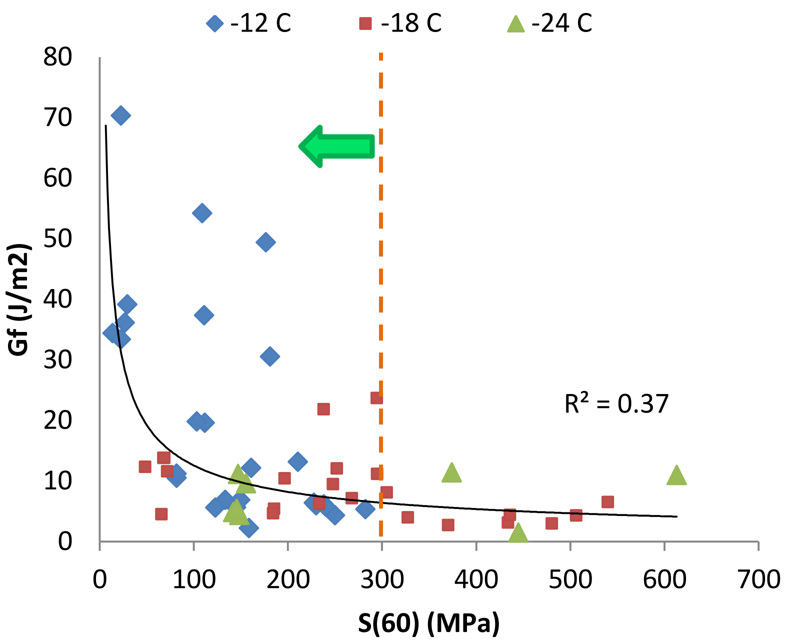
SENB vs. BBR

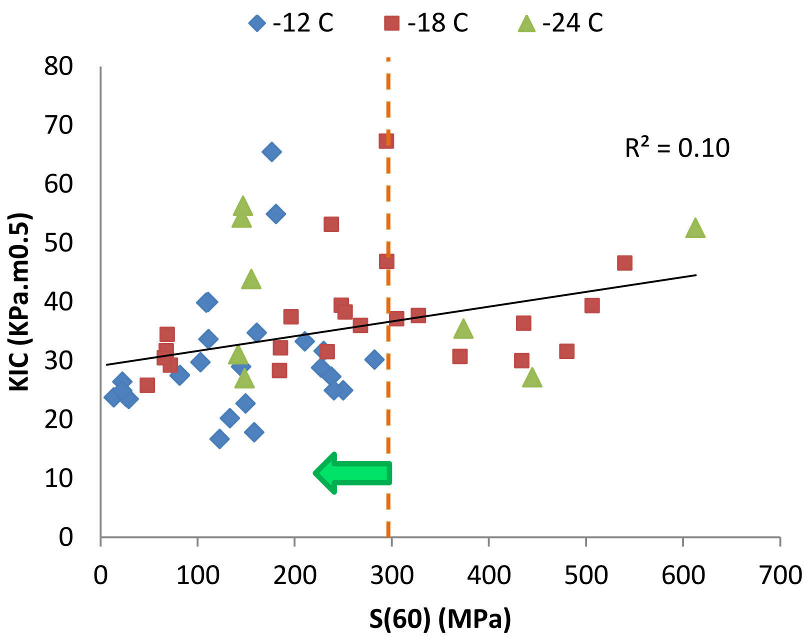




- <u>BBR m-value</u> and <u>creep stiffness</u> have very **poor correlation** with the SENB parameters.
- BBR criteria <u>fails to account for</u> many binders with **low fracture energy**.

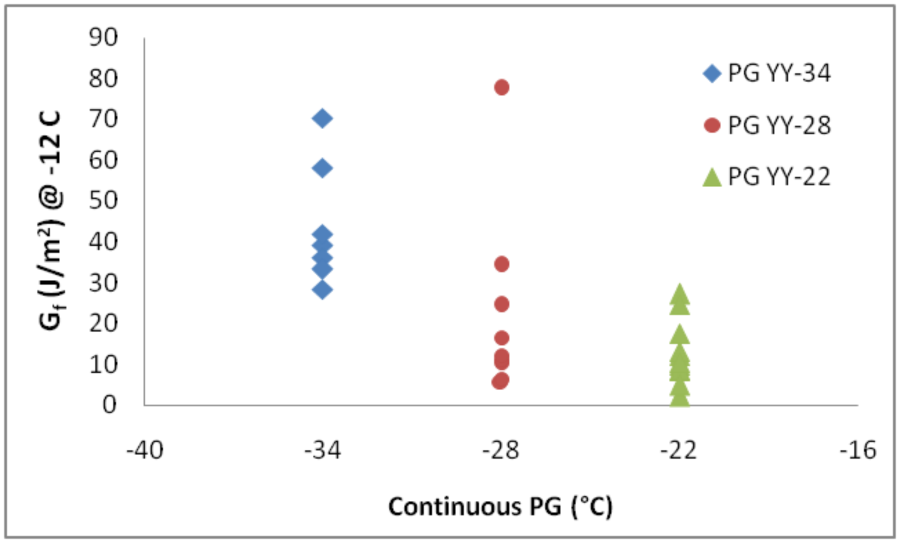
SENB vs. BBR



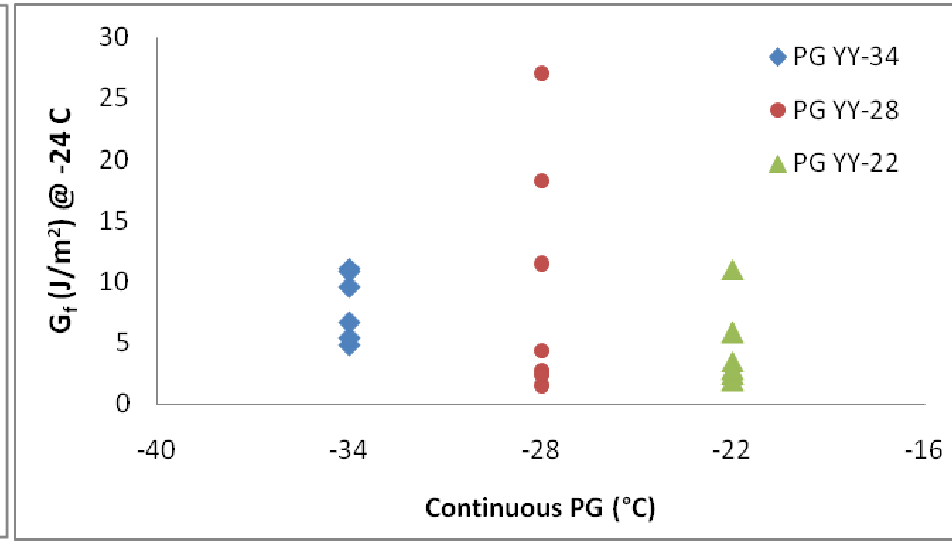


SENB fracture energy (G_f) clearly discriminates between binders with similar stiffness and m-value.

SENB Gf as Performance Indicator



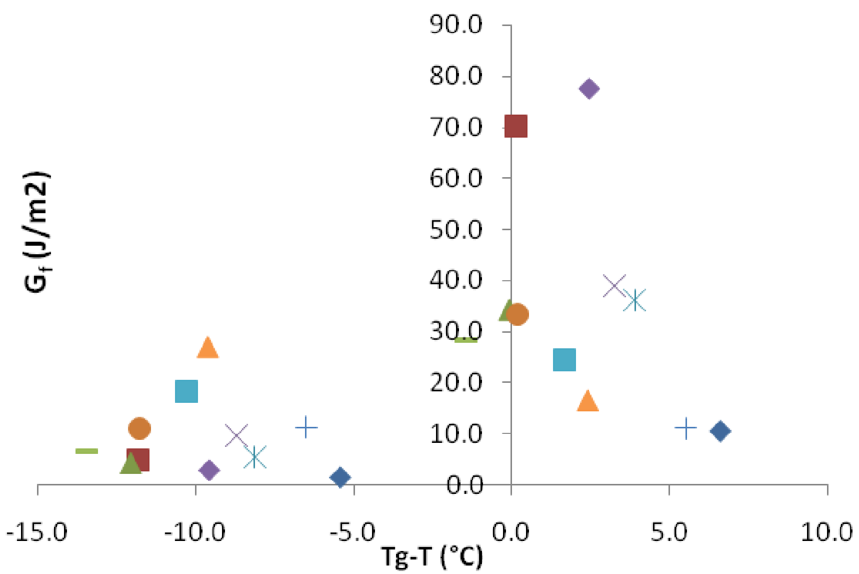
(a)

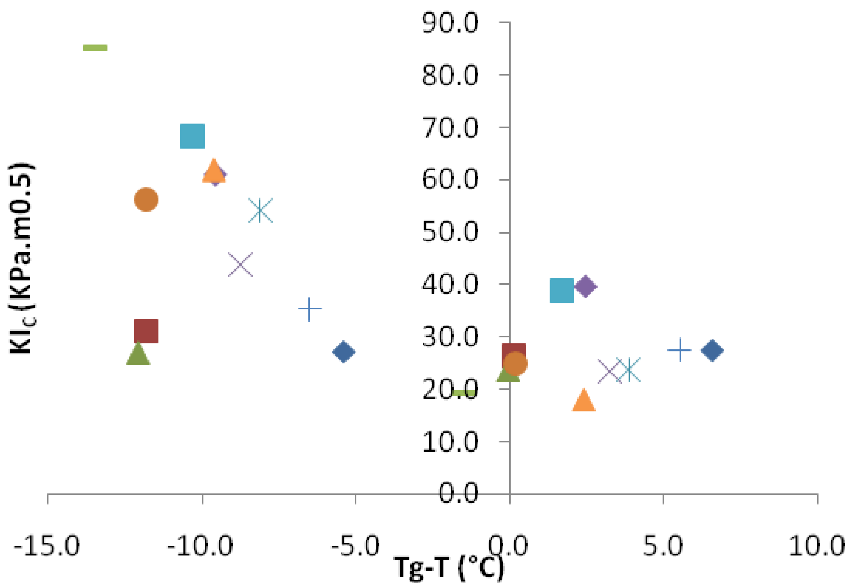


(b)

- **Difference in performance as measured by SENB G_f for binders of the same PG, tested at (a) -12 C, and (b) -24 C.**

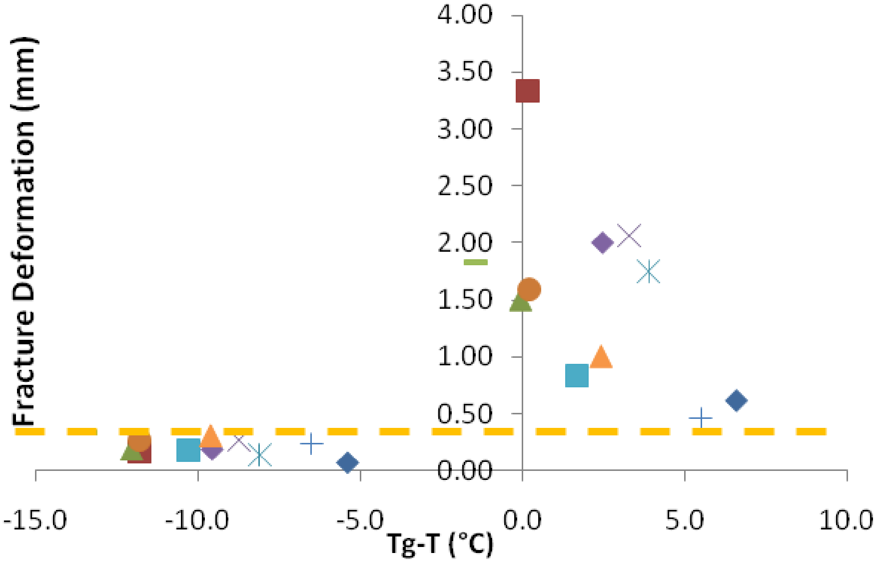
Brittle-Ductile Transition

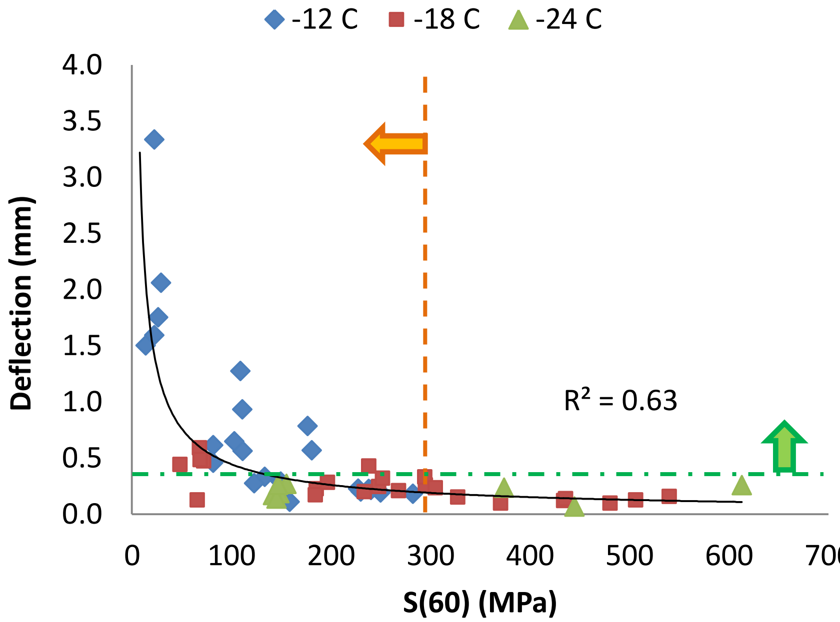




- **KIC** <u>does not show</u> a clear trend <u>above and below TG</u>.
- **Gf** <u>decreases</u> at temps below TG.

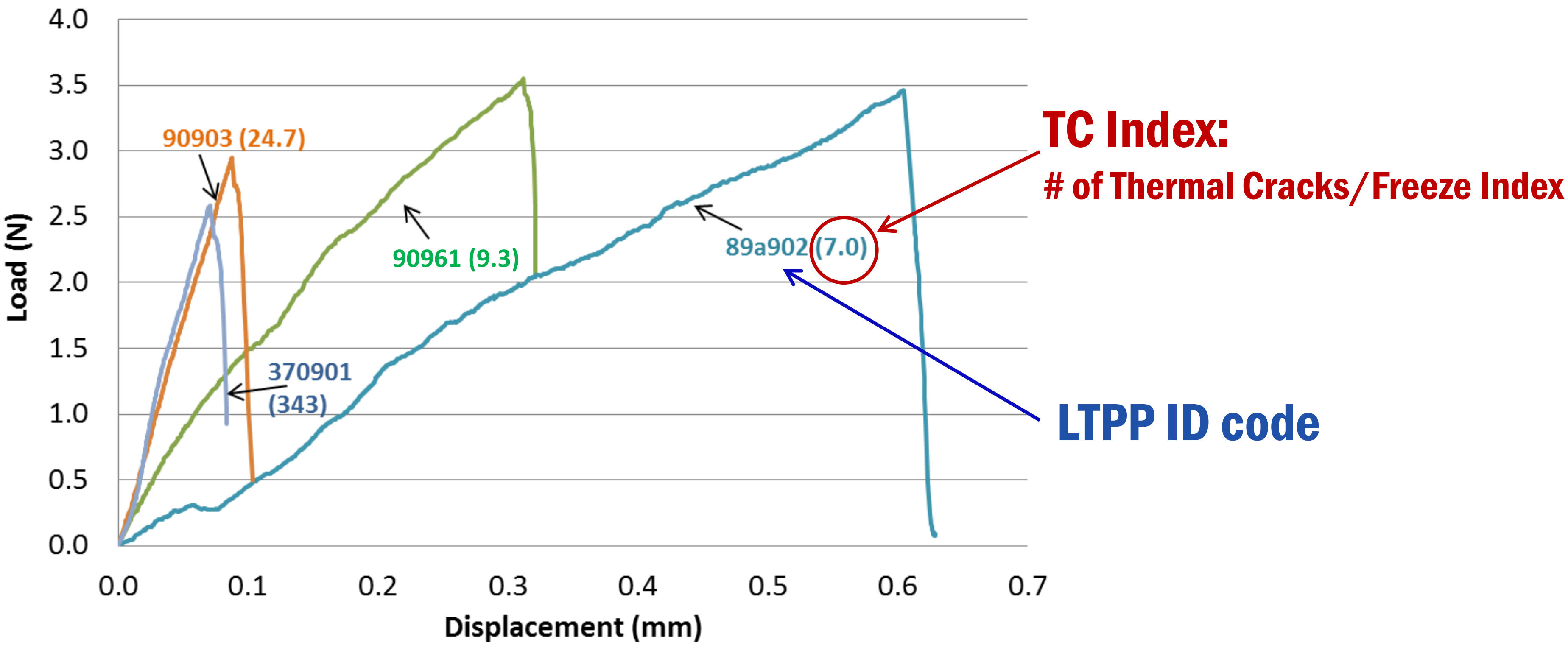
Brittle-Ductile Transition





- **Fracture deflection** **clearly shows** **brittle-ductile transition**
- **Fracture deflection of** **0.35 mm** **seems to be** **threshold value**.

SENB vs LTPP Data



- Lower TC index shows better low temp performance
- Binders with lower TC Index have higher Gf and failure deflection

Conclusions – Task 3

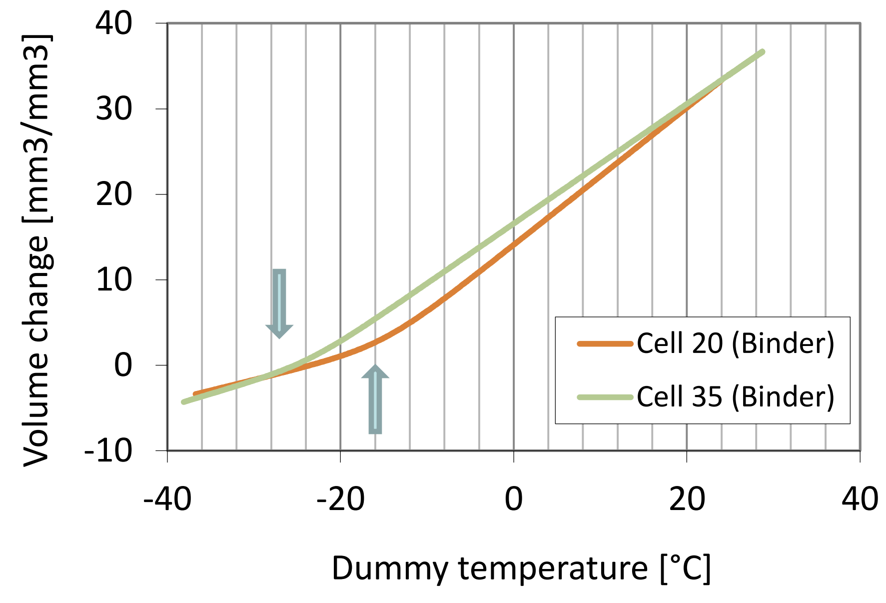
- SENB experimental results showed that deformation at maximum load and fracture energy (G_f) are good indicators of low temperature performance of asphalt binders in mixtures and pavements
- Validation efforts using LTPP materials indicate potential of using SENB measurements to accurately estimate role of binders in field thermal cracking performance
- BBR-SENB results show that binders of same low PG can have significantly different fracture energy (Gf) measured at grade temperature

Objectives Task 5

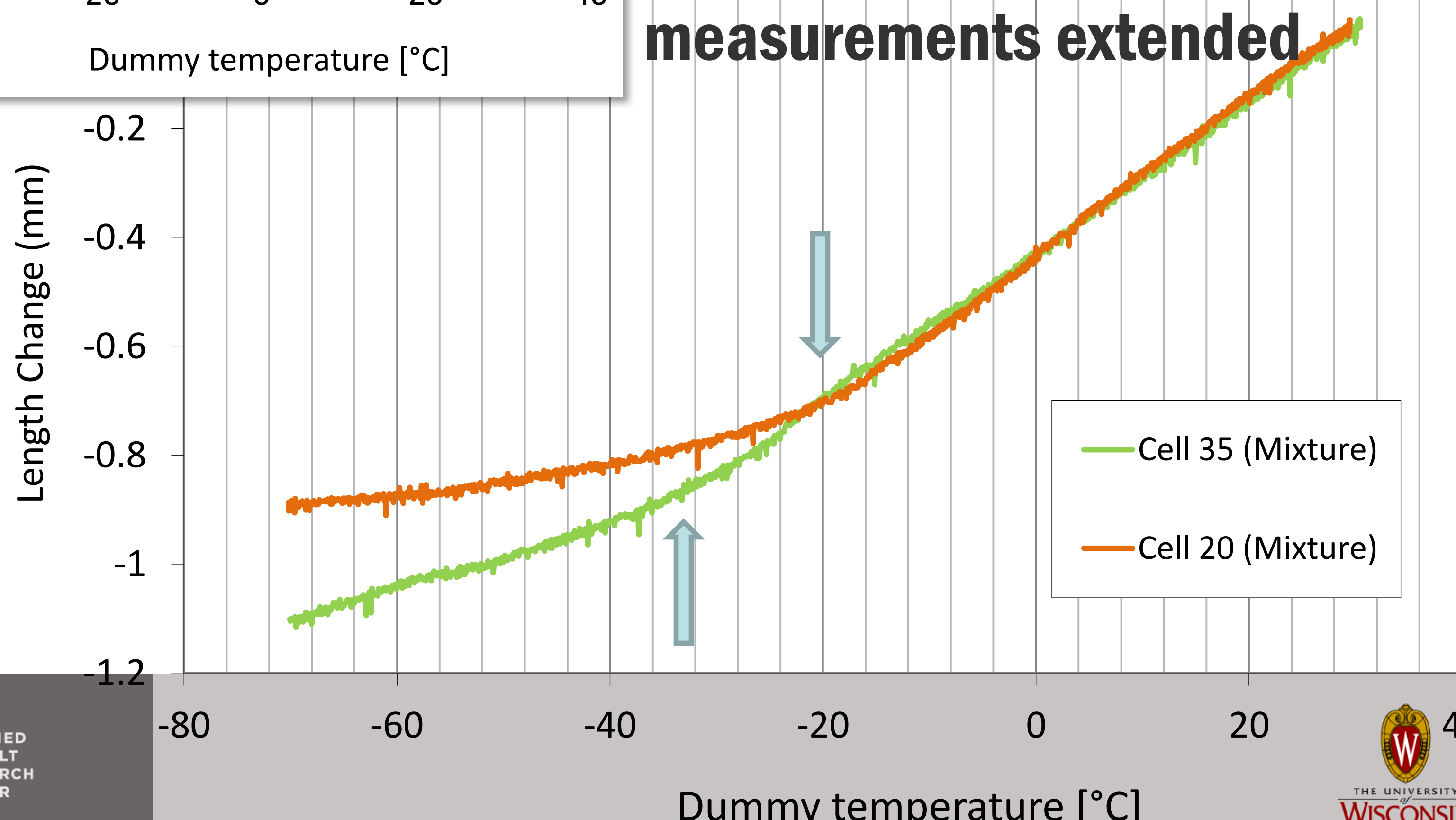
1. Expand database of thermo-volumetric properties of asphalt binders and mixtures
2. Develop micromechanics-numerical model to estimate glass transition and coefficient of thermal expansion of mixtures from properties of binder and aggregate
3. Conduct thermal cracking sensitivity to determine which of glass transition parameters are statistically important

Mixture and Binder T_G measurements (1)

$$\nu = c_v + \alpha_g(T - T_g) + R(\alpha_l - \alpha_g)\ln\{1 + \exp[(T - T_g)/R]\}$$



Database of thermo-volumetric measurements extended



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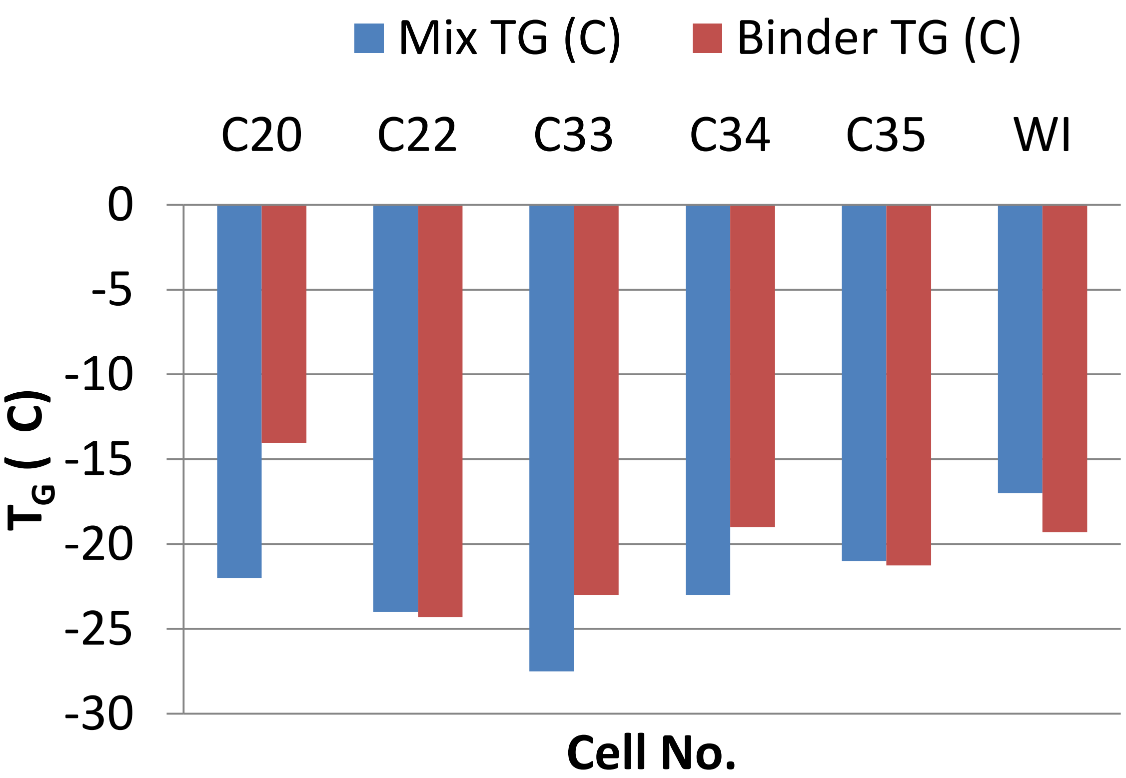
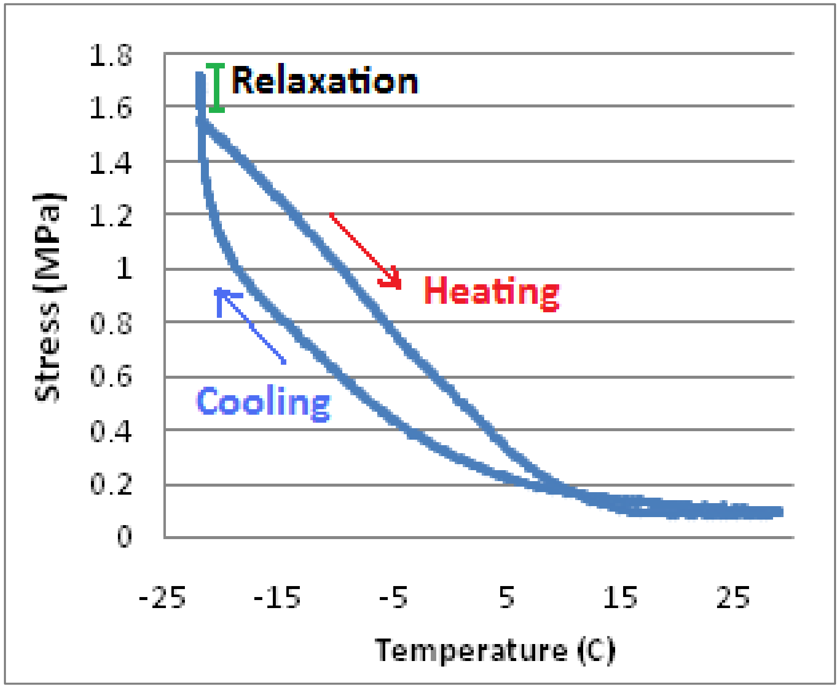
T_g of Asphalt Binders and Mixtures (1)

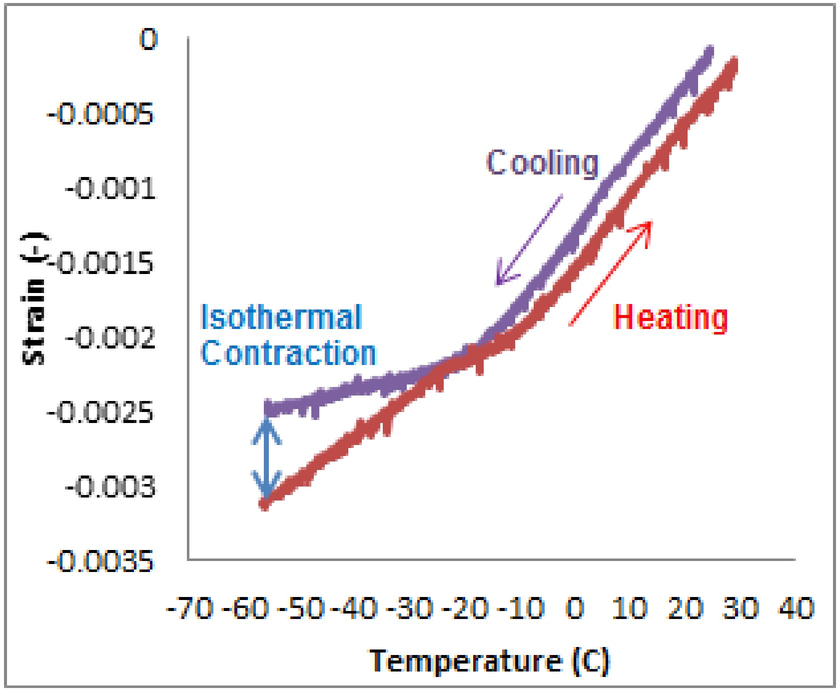


- Mix T_g range: -17 to -27 C
- Binder T_g range: -14 to -25 C
- Mix volumetrics not constant between cells

Asphalt Mixture During Thermal Cycle (1)

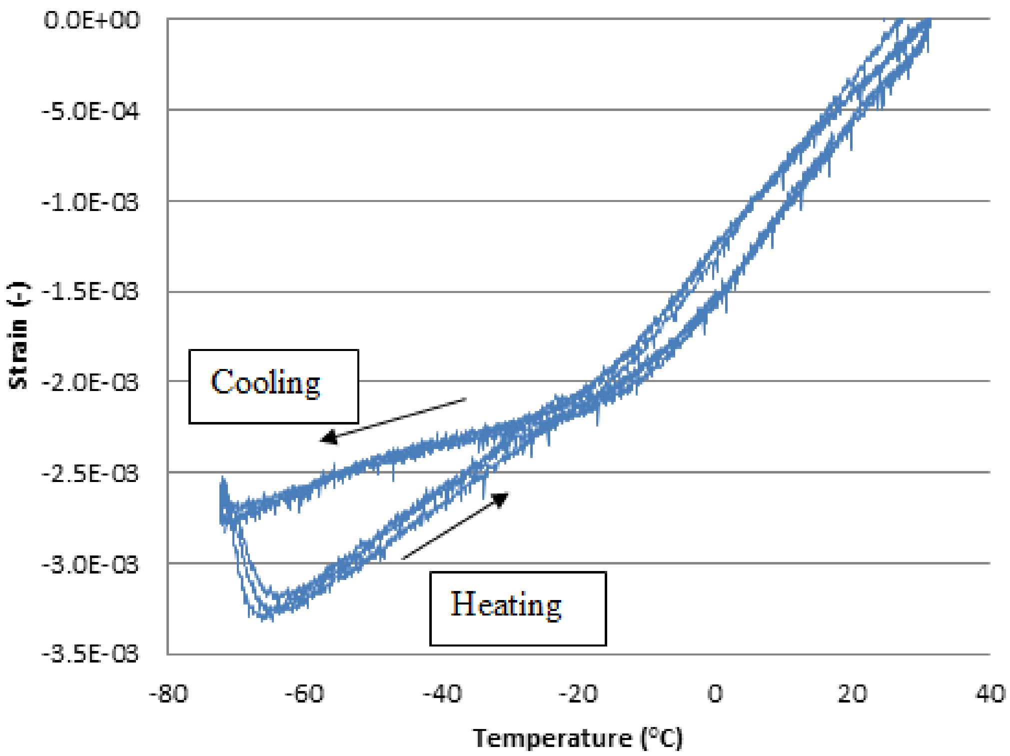


Stress



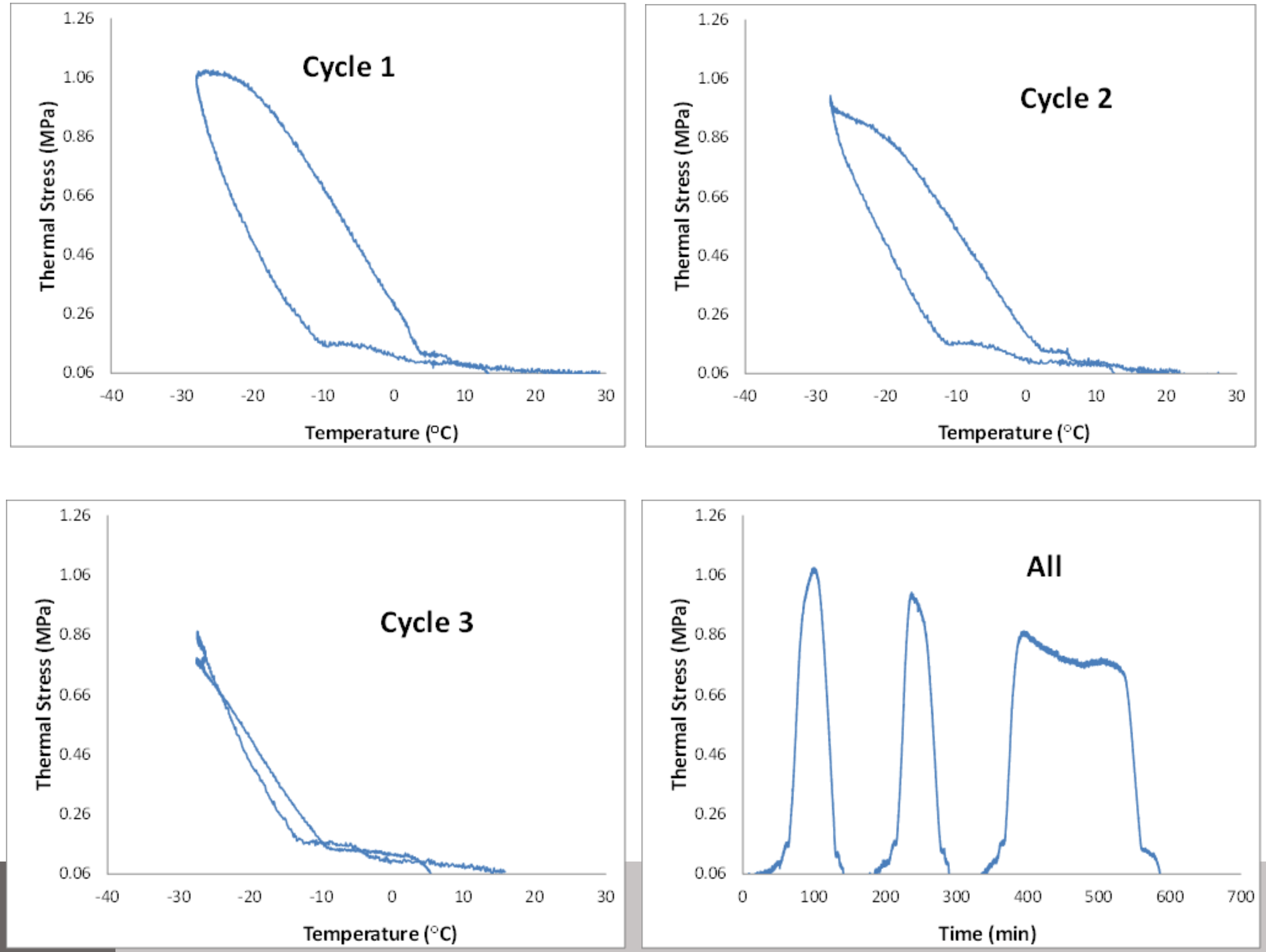
Strain

Asphalt Mixture During Thermal Cycle (1)



Thermal strain in asphalt mixture beam (WI) in 3 consecutive cycles

Stress curves under thermal cycling and isothermal conditioning for MnROAD Cell 33



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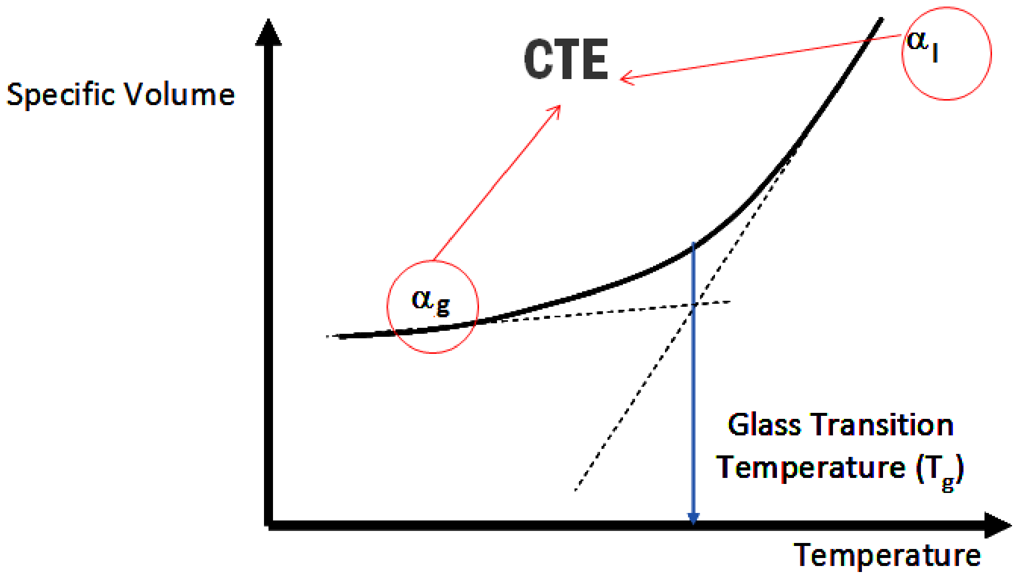
Micromechanical Modeling of Glass Transition in Asphalt Mixtures (2)

Glass transition (Tg) is a critical factor influencing low temperature performance of asphalt mixtures



How glass transition (T_g, α_l, α_g) of asphalt mastic is changed by addition of aggregate particles?

Motivation for development of micromechanical model for prediction of CTEs (2)

- Existing models for thermal cracking predictions over-simplify thermo-volumetric properties of AC

Currently in MEPDG →

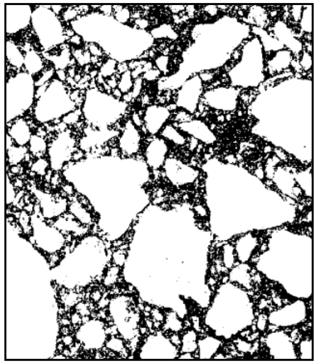
$$L_{MIX} = \frac{VMA \cdot \alpha_{binder} + V_{AGG} \cdot \alpha_{AGG}}{3V_{TOTAL}}$$

- Glass transition and coefficient of thermal expansion/contraction of mixtures above and below T_g needed for accurate prediction of thermal stresses

Internal Structure of AC: Digital Image Analysis

Scanned images of AC are converted to black and white (BW) images

BW images are matrixes of 0 (mastic) and 1 0 (aggregate)



iPas => Matlab based program to calculate aggregate proximity index (API), aggregate orientation, “contact” length, API in branches, # of branches

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iPas Image Processing & Analysis System

Developed in collaboration with Prof. Kutay from MSU

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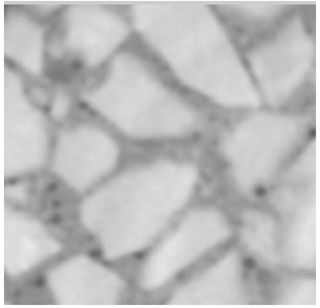
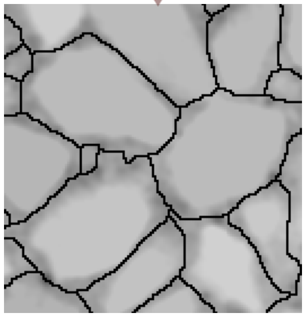
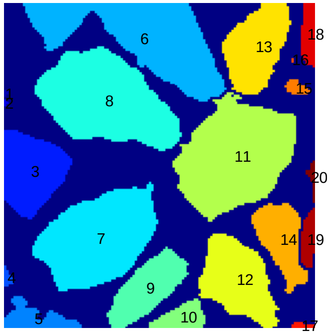
iPas- Three Steps Process

(1) Image **acquisition**

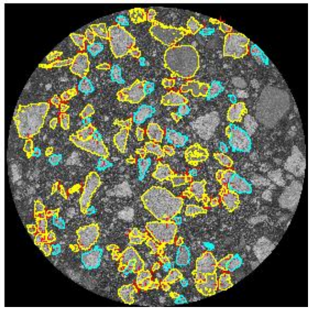
(2) Image **processing**



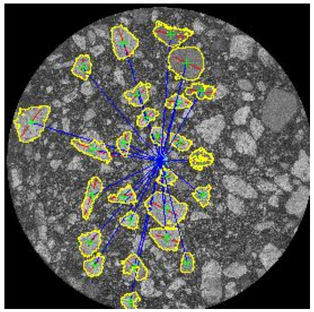




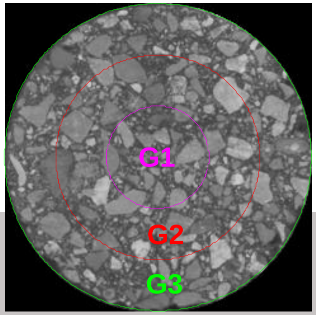
(3) Image **analysis**



Aggregate Proximity Index

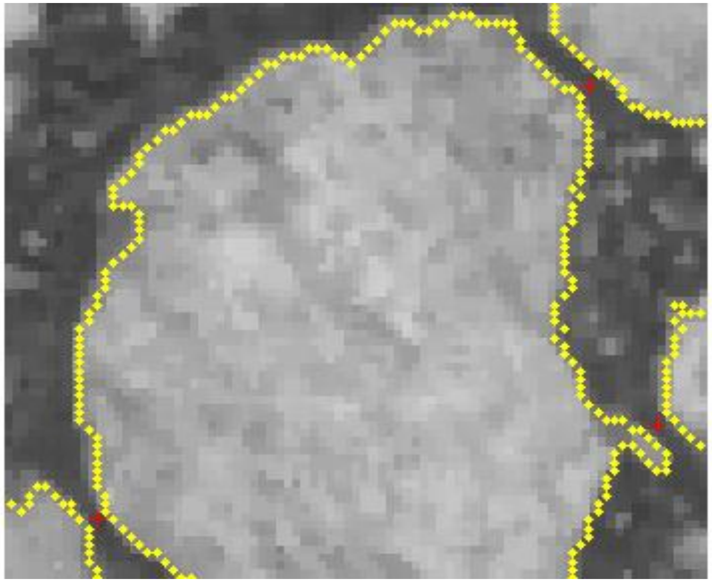


Orientation



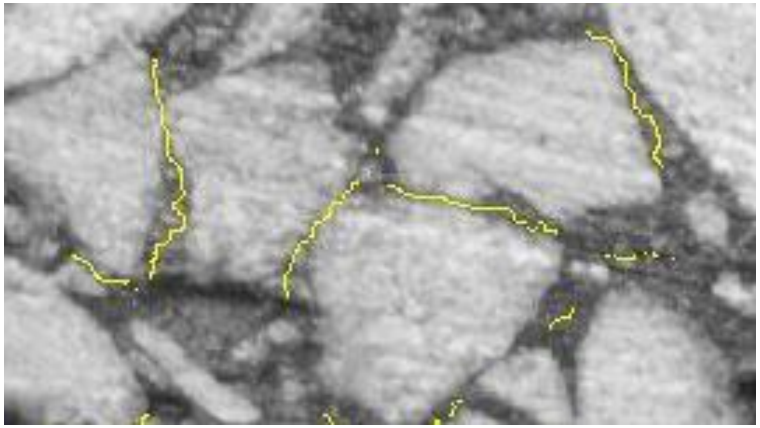
Segregation

Aggregate Proximity Index (API)=> "contact points"

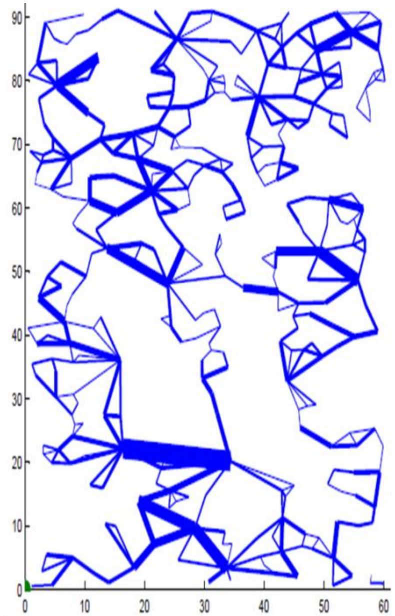


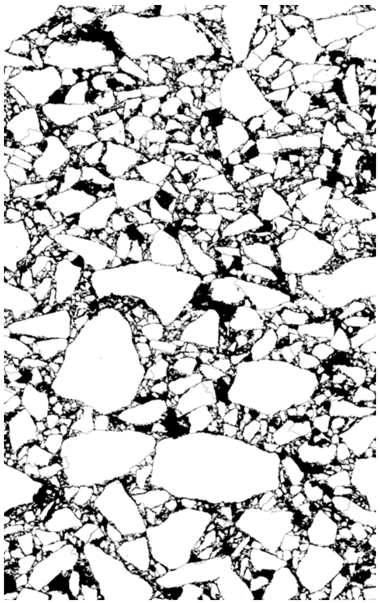
Minimum aggregate size & surface distance threshold needs to be defined for Aggregate Proximity Index (API) estimation

Other internal structural parameters

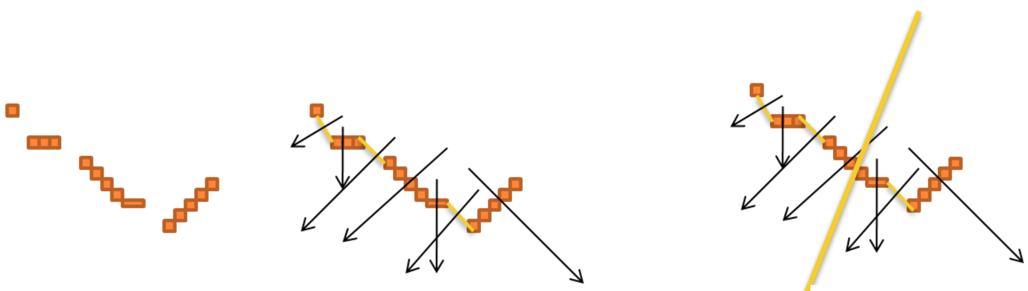


"Contact" Length





Aggregate Branches-Connectivity

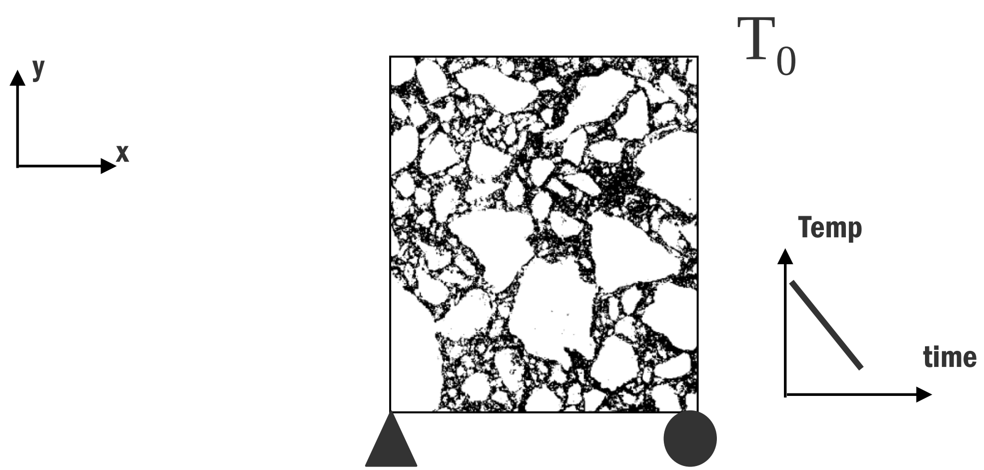


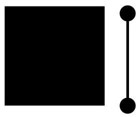
Pixels in contact line Orientation for pixel pairs

Contact Orientation

Finite Element Model (2)

- AC considered as two-phase material: aggregate and mastic => binder + aggregates smaller than 1.13 mm)
- 4-node bilinear plane stress quadrilateral and reduced integration element (CPS4R)
- Pixels in binary image mapped into CPS4R elements in model

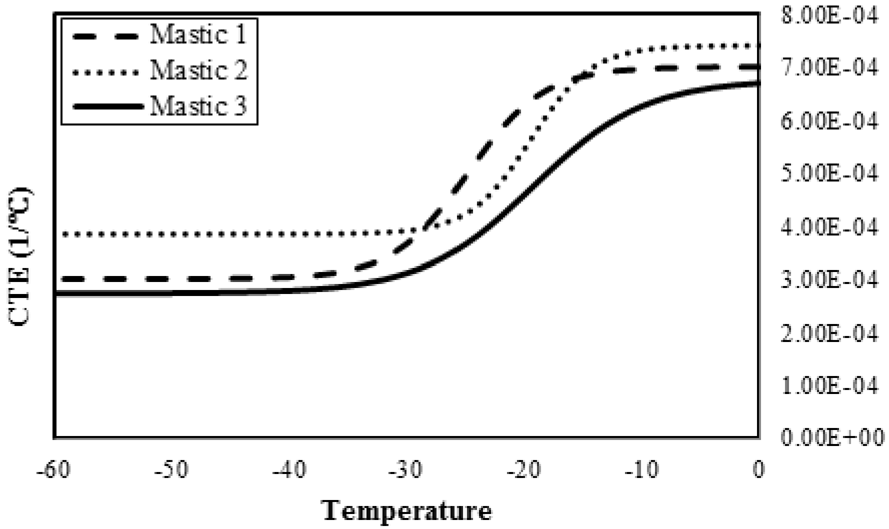


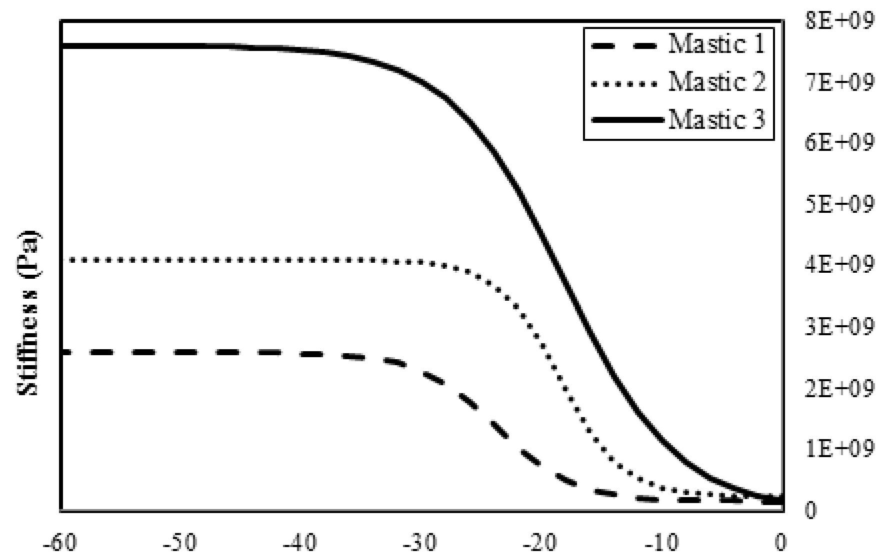


Aggregate	
Elastic Modulus	2.00E+11
Thermal Coefficient Expansion (α)	8.50E-06

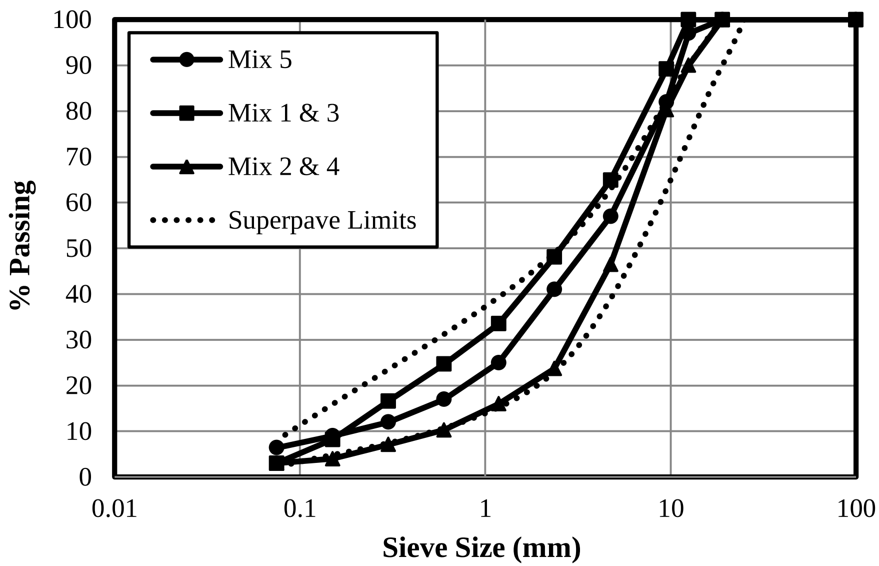
Mastic	
Elastic Modulus	2.00E+08
αl	7.00E-05
αg	3.00E-05

Finite Element Model Input (2)

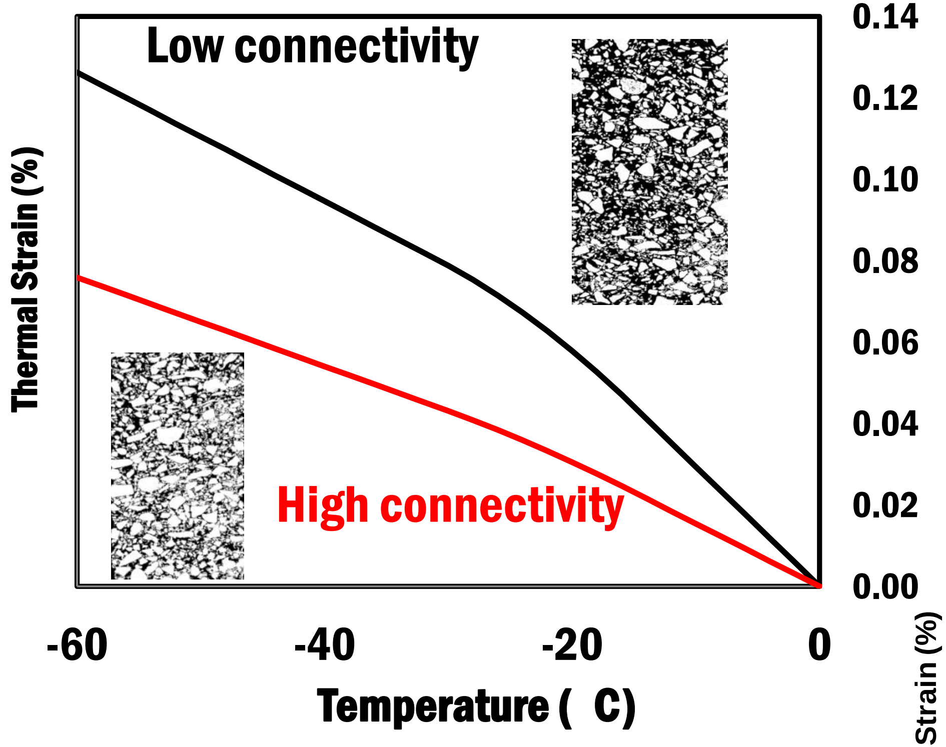




Mixes with different gradations

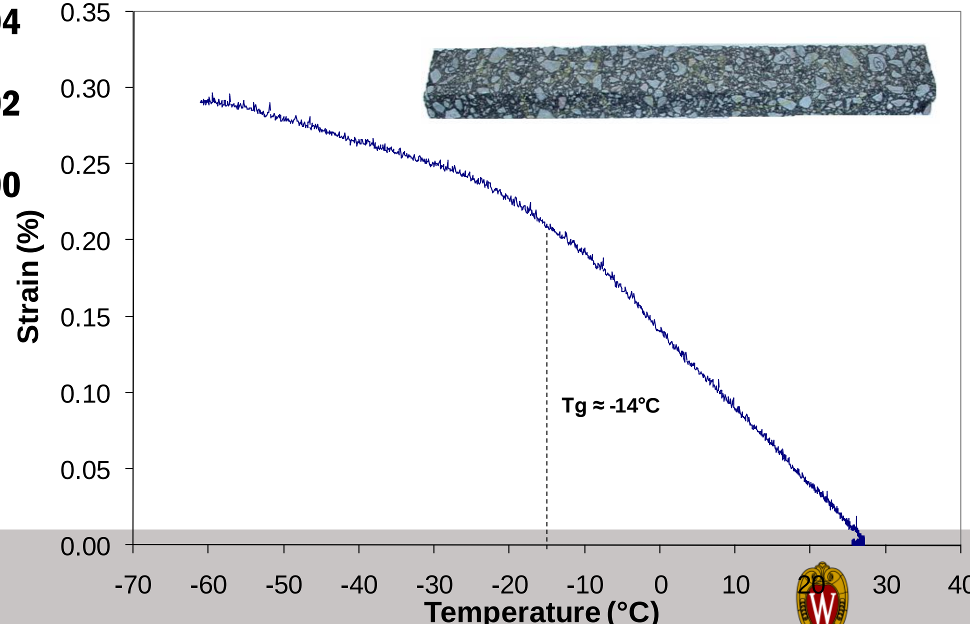


Thermo-Volumetric Response of AC

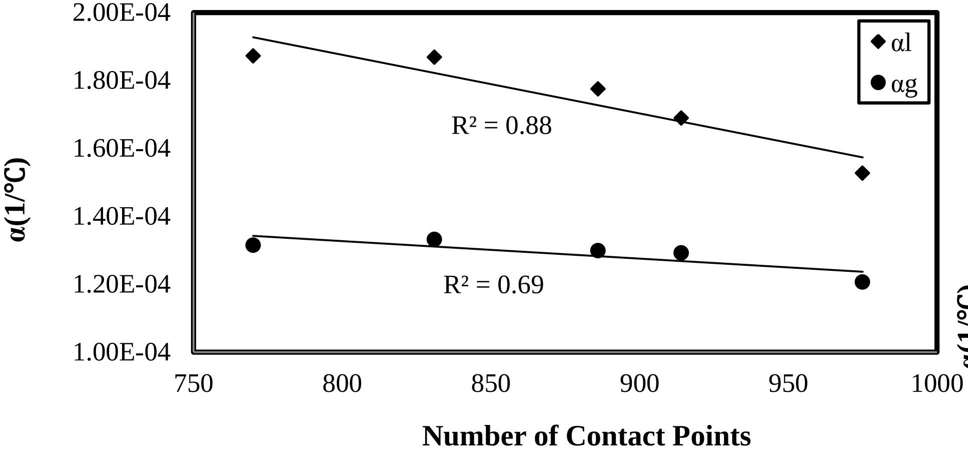


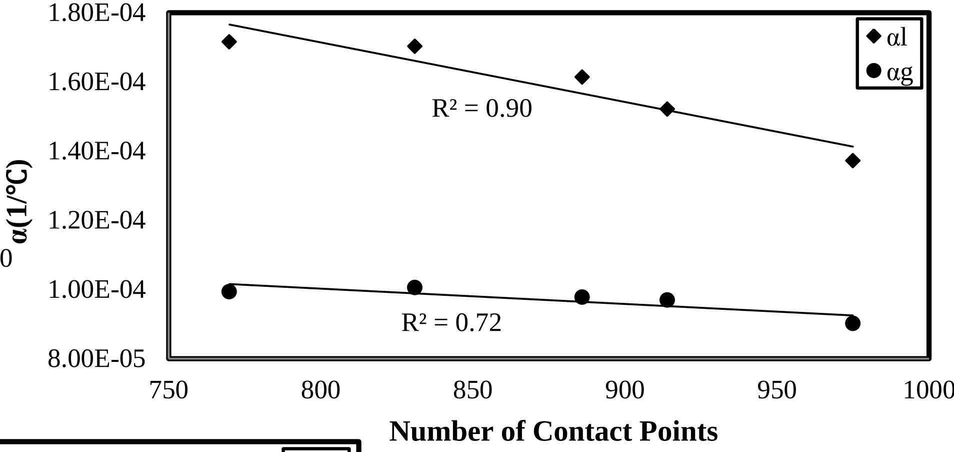
FE simulation

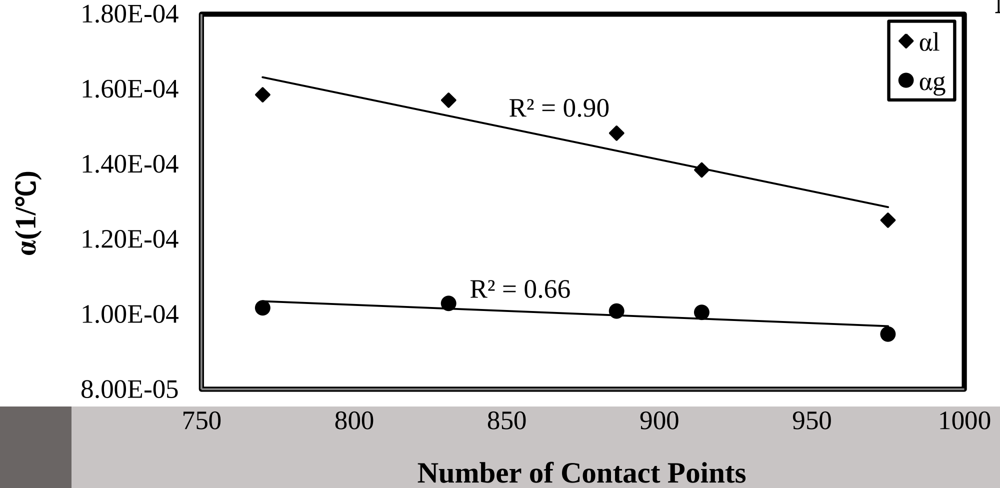
Typical measured



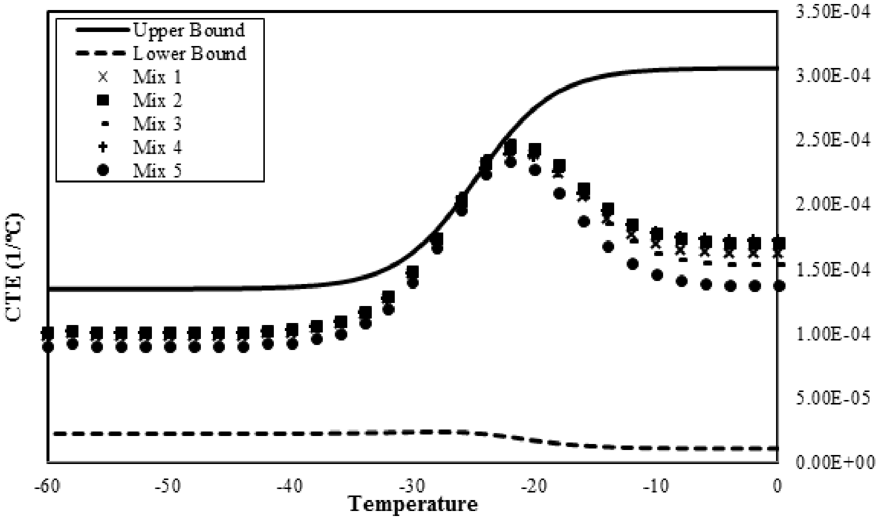
CTE vs Number of “Contact Points”

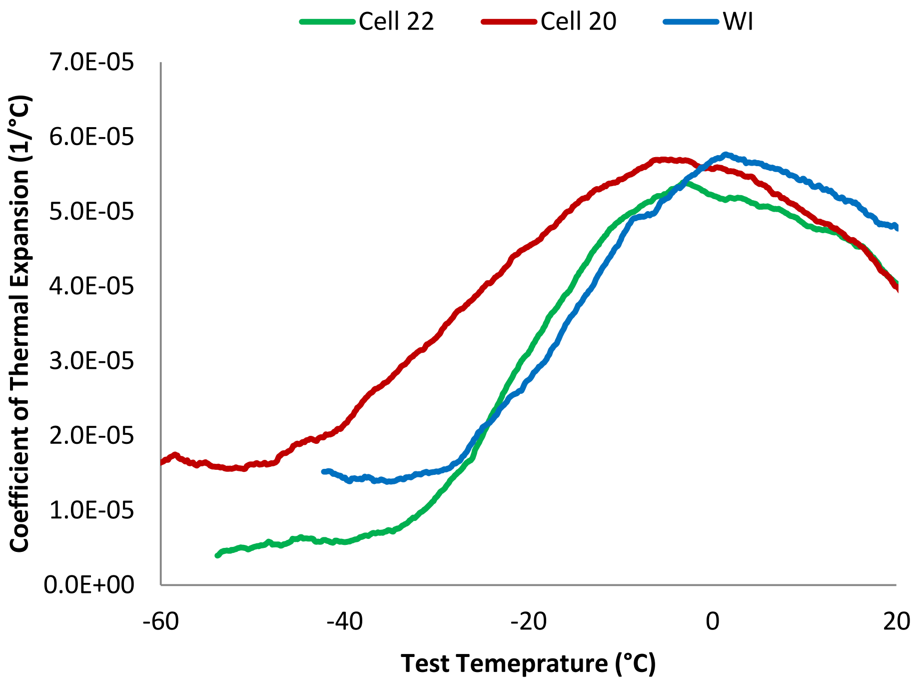






Typical results of simulations (2)





Example of ABAQUS simulation

Example of Experimental Results

Proposed Semi-empirical Micromechanics Model for CTE (2)

Based on the commonly used **Hirsch model** for estimation of modulus of asphalt mixes.

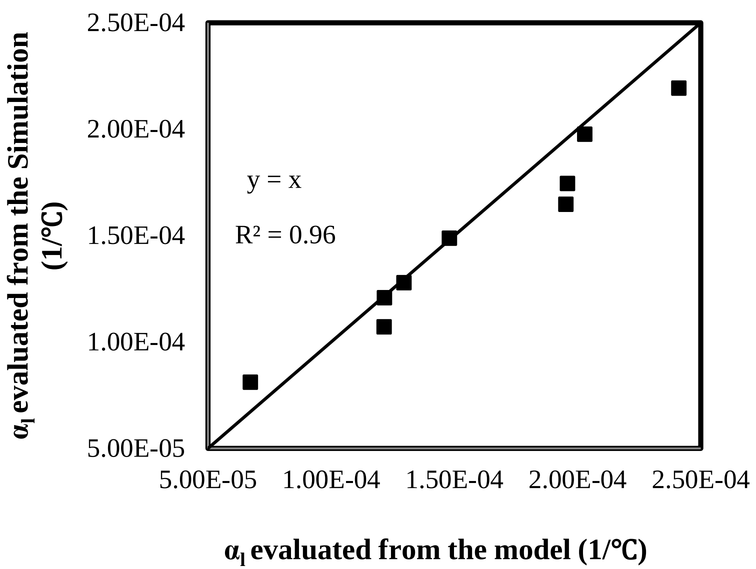
$$\alpha_{mix}^{L} = \alpha_{up}^{L} F + \alpha_{low}^{L} (1 - F)$$

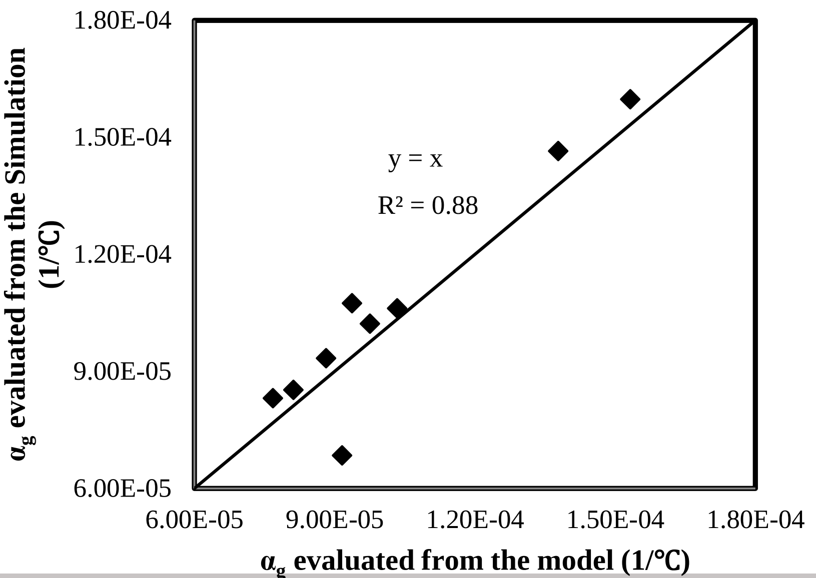
$$\alpha_{mix}^{G} = \alpha_{up}^{G} F + \alpha_{low}^{LG} (1 - F)$$

- and are arithmetic mean of CTE of mastic and aggregate
- and are harmonic mean of CTE of mastic and aggregate, which is a function of stiffness ratio ($E_{mastic}/E_{aggregate}$)
- *F* is an empirical function of mastic stiffness and aggregate contact points (internal structure)

Validation of model for CTE (2)

To validate model=> 9 different mixtures which have different aggregate structures and mastic properties have been used



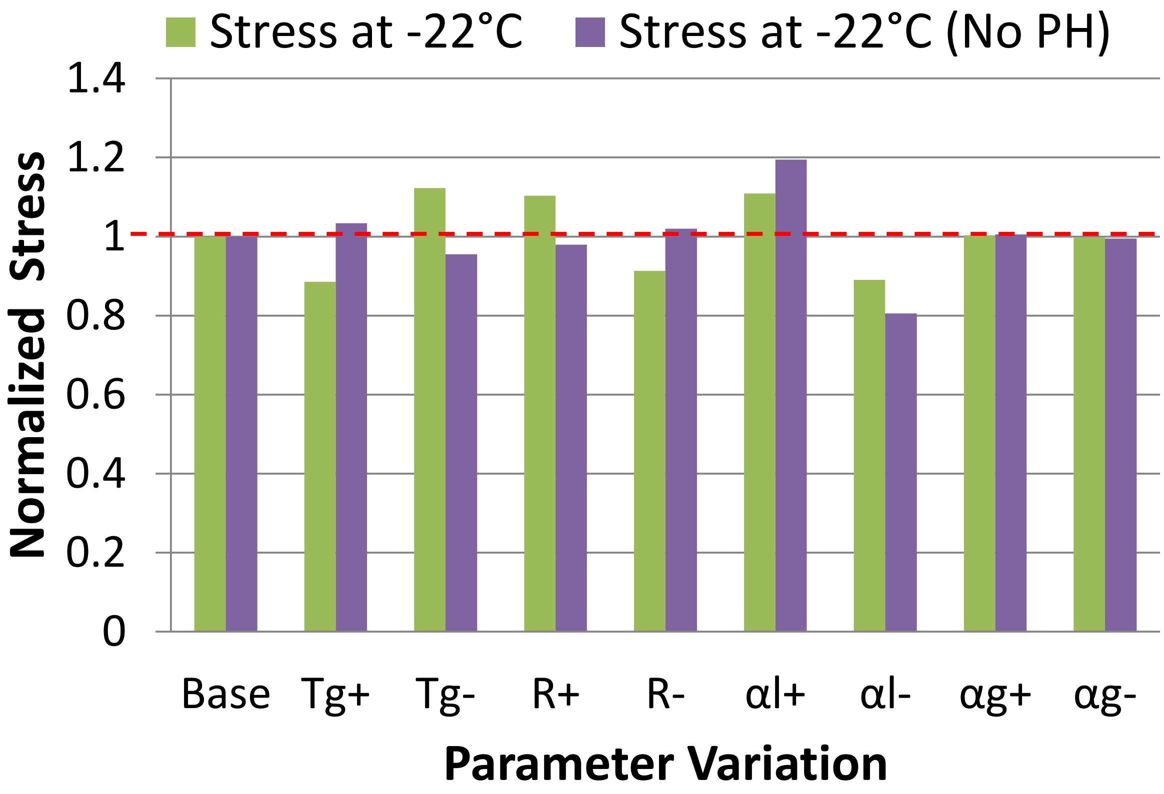


Thermal Cracking Sensitivity to Thermo-volumetric parameters (3)

		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16	Run 17
Cooling	T_g	-17	-20	-13	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17
	R	6	6	6	7	5	6	6	6	6	6	6	6	6	6	6	6	6
	α_l	5E-5	5E-5	5E-5	5E-5	5E-5	6E-5	4E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5
	α_g	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1.3E-5	9E-6	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5
Heating	T_g	-17	-17	-17	-17	-17	-17	-17	-17	-17	-20	-13	-17	-17	-17	-17	-17	-17
	R	6	6	6	6	6	6	6	6	6	6	6	7	5	6	6	6	6
	α_l	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5E-5	5.E-5	5.E-5	5.E-5	6E-5	4E-5	5.E-5	5.E-5
	α_g	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1E-5	1.3E-5	9E-6

- **Analysis matrix** was designed to systematically vary thermo-volumetric parameters in cooling and heating
- Thermal stress model from **Tabatabaee et al., 2012** (submitted to TRB) used.
- Model accounts for thermo-volumetric parameters in cooling and heating and **effect of physical hardening**.

Thermal Cracking Sensitivity to Thermo-volumetric parameters (3)



Thermal stress insensitivity to changes in α_g indicate that using a typical value for this parameter may be sufficient for calculations

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Not taking α_g in thermal stress calculation can lead to significant errors

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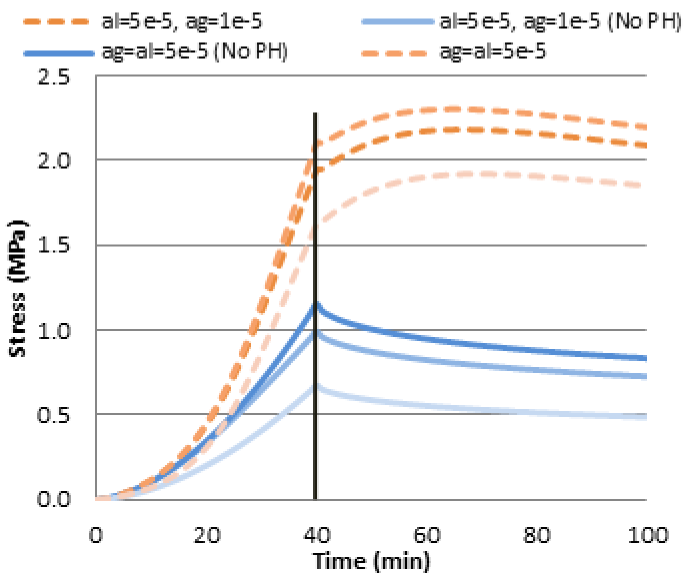
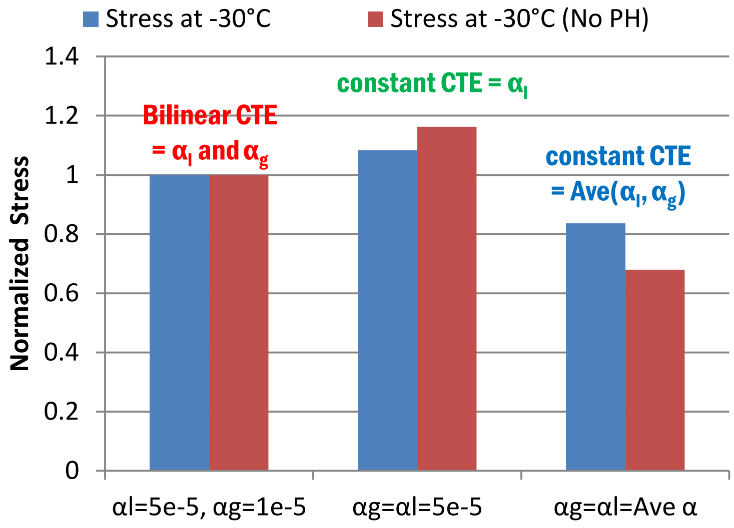
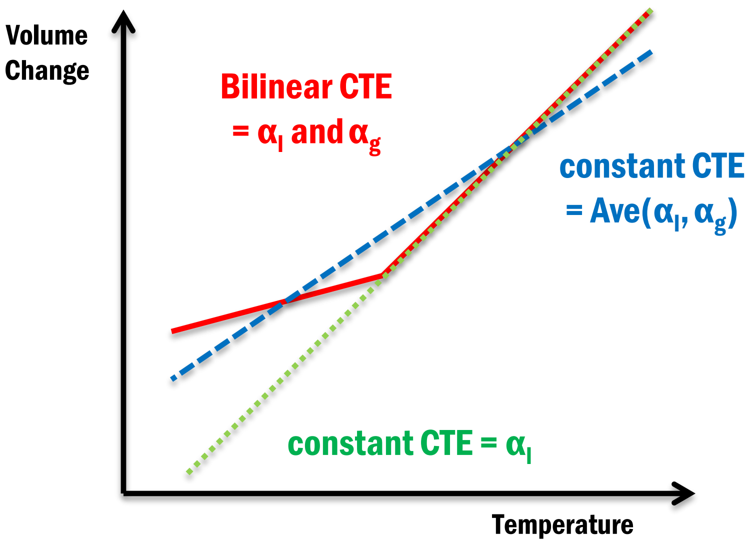
Thermal Cracking Sensitivity to Thermo-volumetric parameters (3)







Not taking α_g in thermal stress calculation can lead to significant errors

Conclusions – Task 5

- Thermo-volumetric behavior of AC can not be described only with volumetric information of constituents
- Information about internal structure of AC needs to be included in estimation of CTE
- Glass transition temperature of Binder is very similar to Mixture
- When taking into account **Physical Hardening**, thermal stress calculation is sensitive to: **α_l, T_g, width of T_g region (R)**