Thermal Cracking of Asphalt binders and Mastics – Causes and Possible Mitigations

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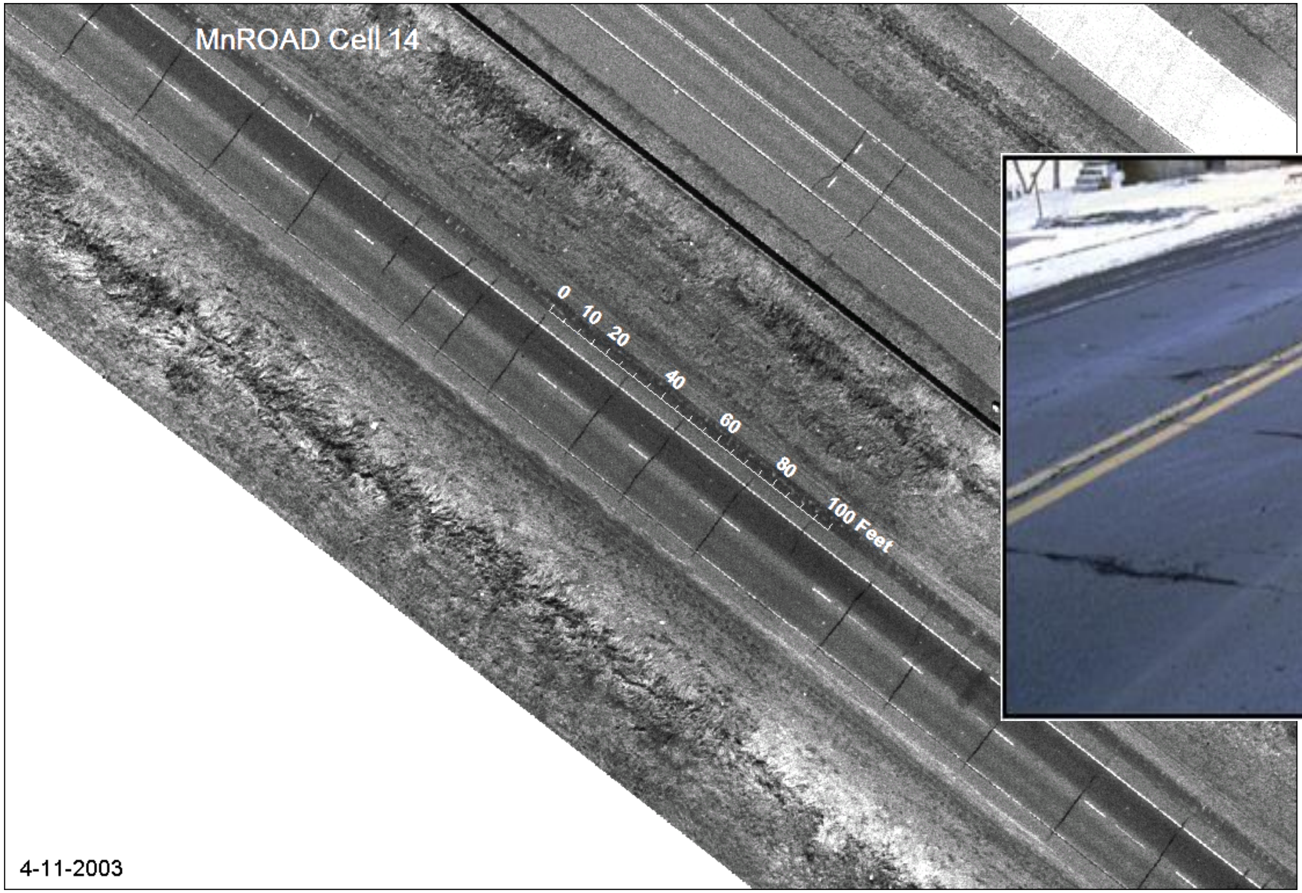
GAF Seminar
8:15 to 9:30 am
June 25, 2015 — Wayne, NJ, USA

Outline

- In the last 10-15 years many advances have been achieved in better understand of thermal cracking of binders, effect of fillers, and methods of estimating resistance to cracking.
- This talk will focus on
  - these advances in testing,
  - attempt to link them to roofing applications; and
  - show how new testing methods could help producers like GAF to estimate quality and reduce the risk of premature failures.

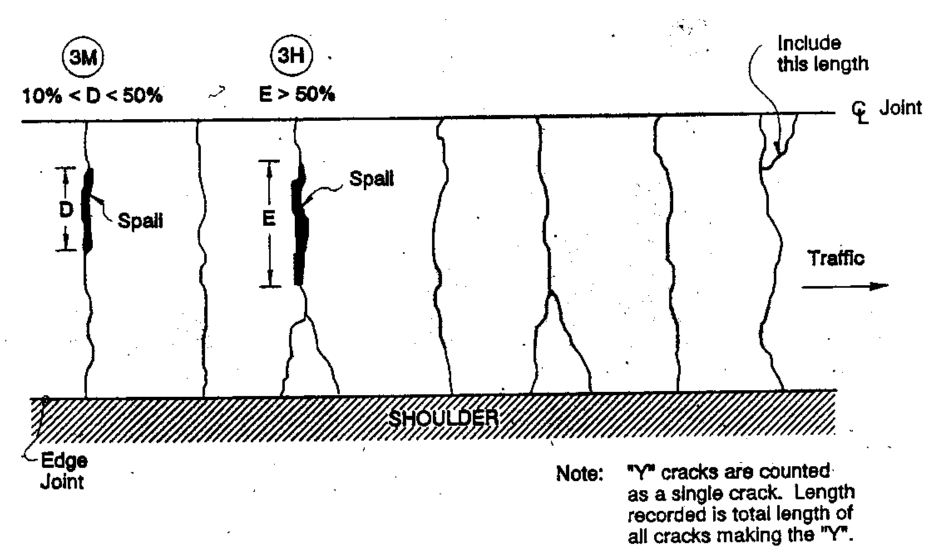
What is thermal Cracking ?



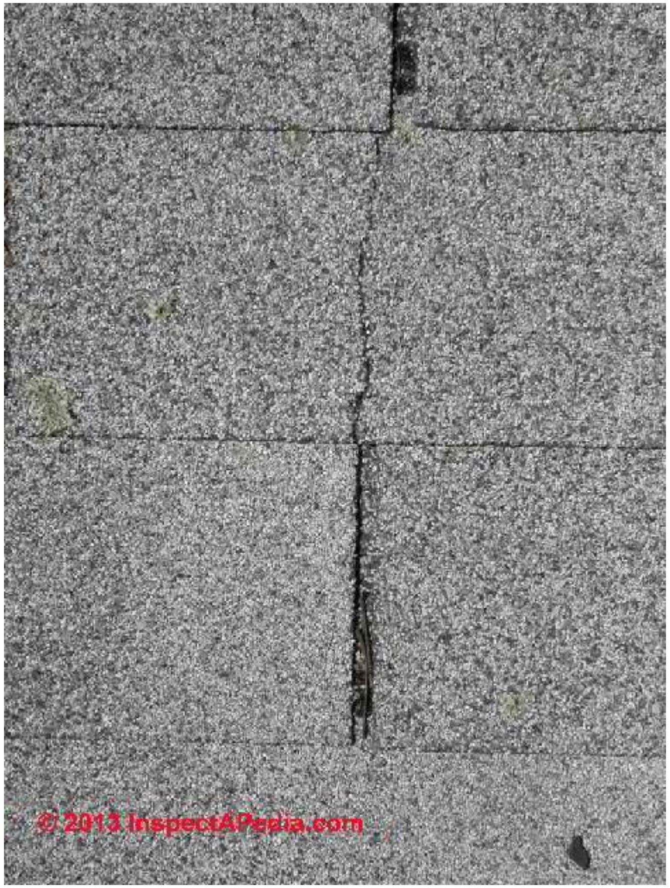
*Marasteanu (2009)

Problem Statement

- Thermal cracking of pavements **remains one of the most challenging distress** in pavements to predict, and reduce, in North America.



Asphalt Shingle Cracking



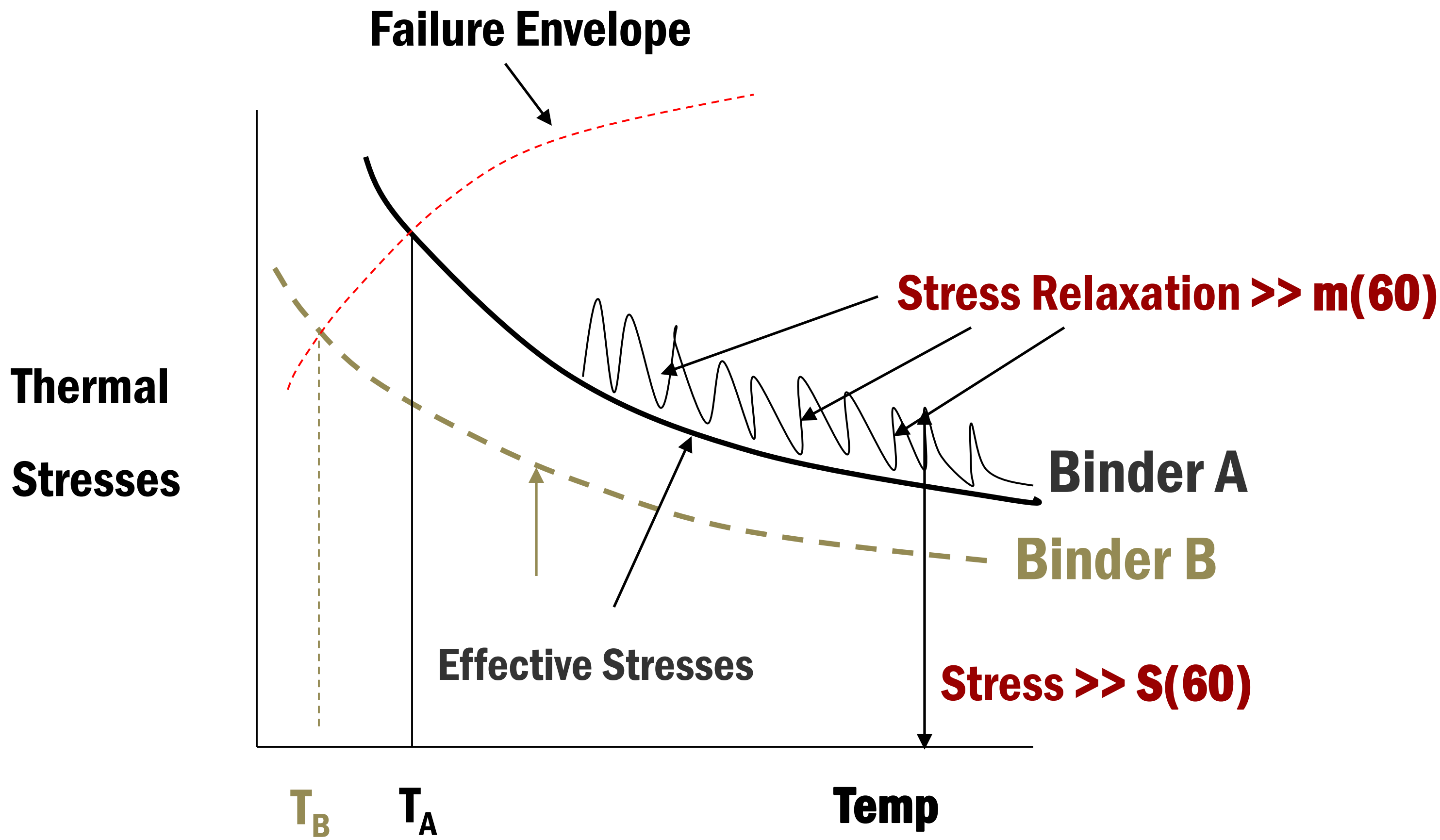
What are the main causes?

- Restraining **Thermal Shrinkage** of binder
- **High stiffness** of binder at critical temperatures
- **Low relaxation** capability of binders
- **Low strength** or strain tolerance of binder
- **Aging:**
  - Oxidative
  - UV
  - Physical

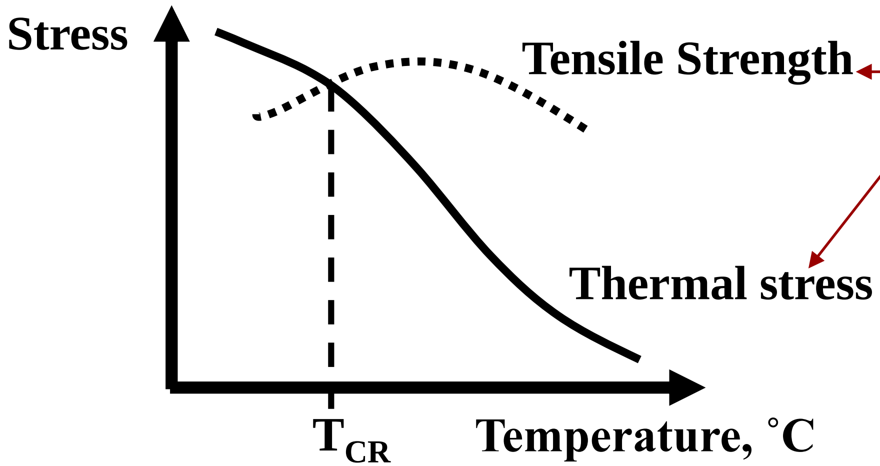
What are the solutions ?

- Binders that show less shrinkage
  - Coefficient of contraction .... (α_l , α_g)
- Softer binders/mastics
  - Stiffness/compliance and Glass transition .... (S(t), J(t), Tg)
- More relaxation:
  - Shorter relaxation time or faster creep rate .... (m(t))
- Stronger/more strain tolerant binders .... (Gf, KIC, df)
- More resistance to aging
  - Composition / morphology and filler selection

Most Recognized Mechanism



Continuum Approach



Function of

1. Composition
2. Aging

$$\sigma(t) = \int_0^t E(t-\xi)\frac{\partial \varepsilon(\xi)}{\partial \xi}\, d\xi$$

Relaxation Modulus

Coefficient of thermal contraction

$\alpha(T)$

Strains at Transient Temperature Conditions

$$\varepsilon(t) = \varepsilon^{tot}(t) + \varepsilon^{T}(t)$$

where:

$\varepsilon(t)$ = stress-associated, mechanical strain,

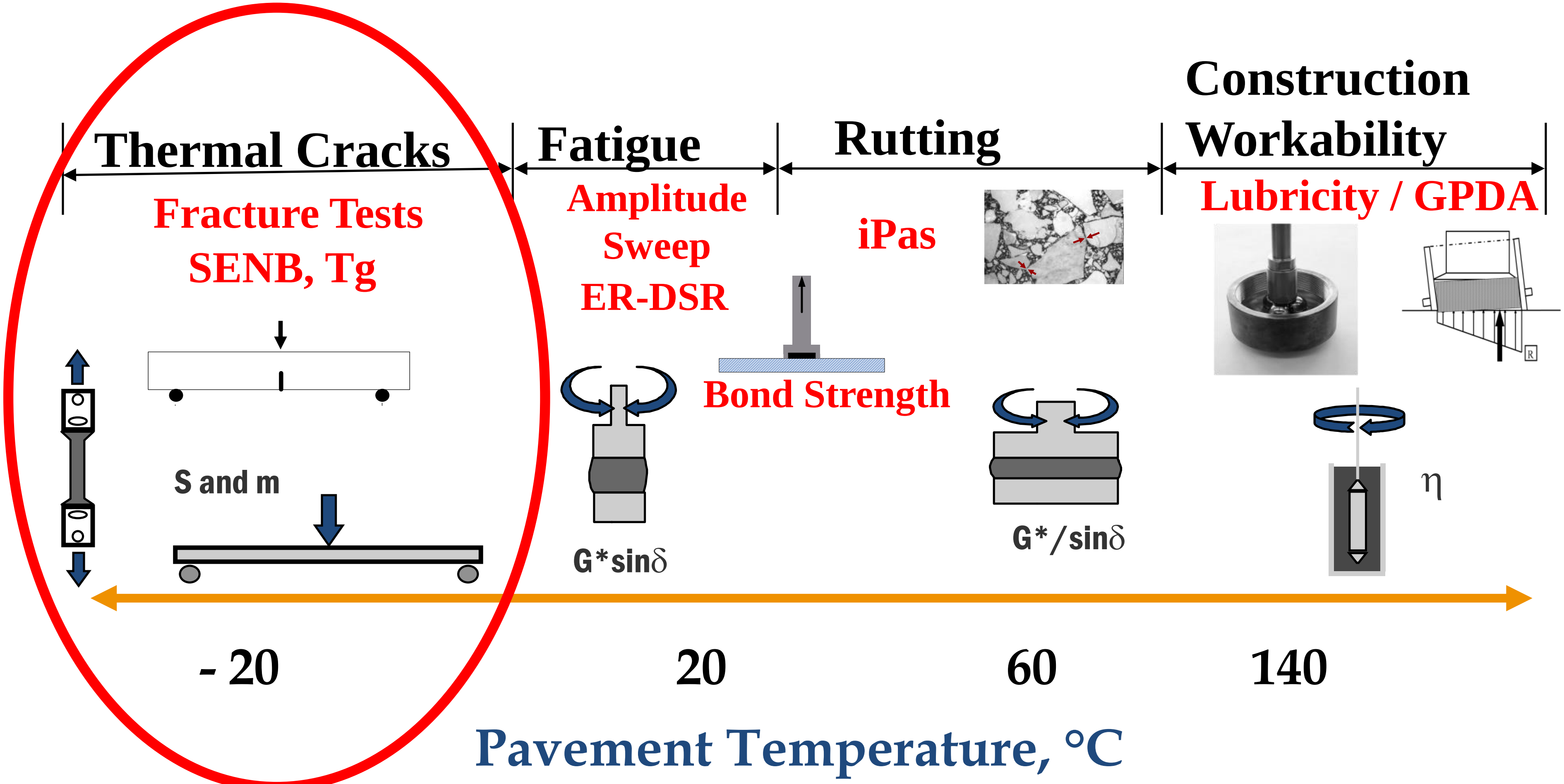
$\varepsilon^{tot}(t)$ = apparent total strain, and

$\varepsilon^{T}(t)$ = stress-free, thermal strain.

Thermal Cracking

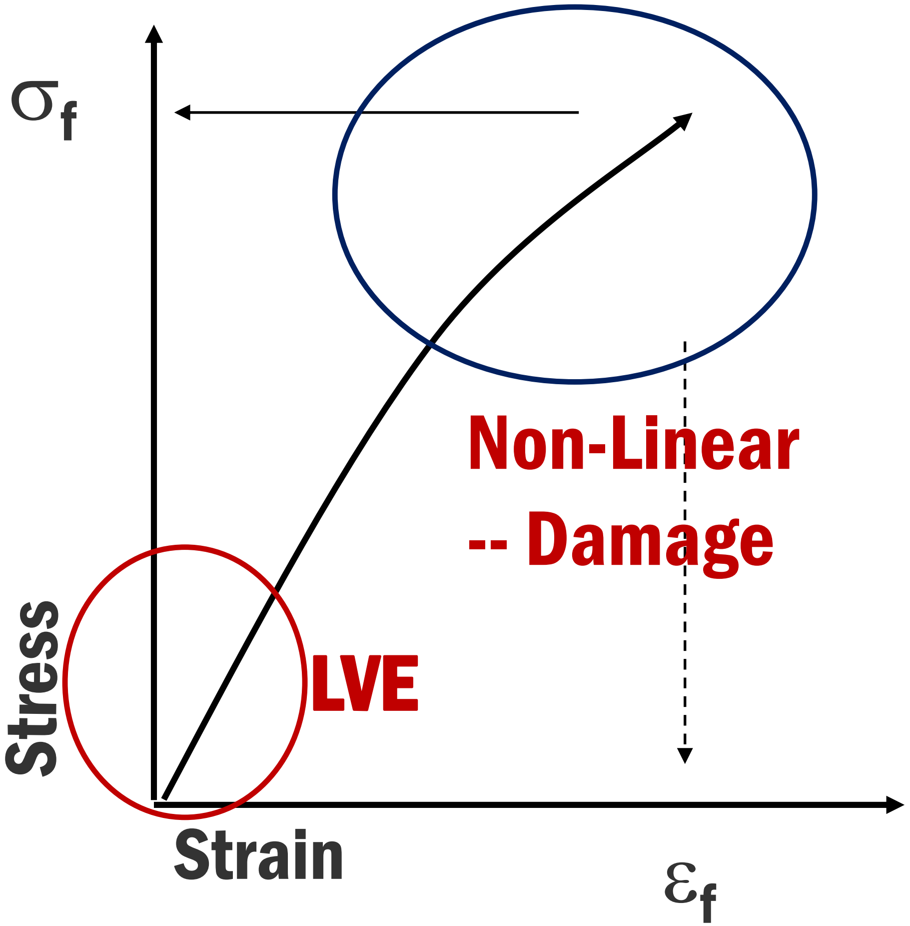
- **Thermal Cracking**
  - Caused by **combination** of cooling and bending.
  - Critical at **low temperatures** and/or **rapid cooling** rates.
    - Single Event or cyclic (thermal fatigue)
  - Late in binder life (**aged binder**)
  - Occurs because of **restraint on shrinkage** of binder layer due to adherence to underlying layer.
  - Restraint causes **stress build-up**. If stresses not **relaxed**, they exceed the strength of binder and initiate cracking.

Performance Based Characterization of Asphalt Binders and Mixtures- Superpave



Need for Damage Resistance Characterization

- Small stress/strain, Linear VE is not sufficient (NCHRP 9-10)
- Asphalt damage resistance is very important
- Modified Asphalt are best in damage resistance



SUPERPAVE BINDER LOW TEMPERATURE TESTS

BENDING BEAM RHEOMETER
DIRECT TENSION TEST

Bending Beam Rheometer (BBR)

Source: http://pavementinteractive.org

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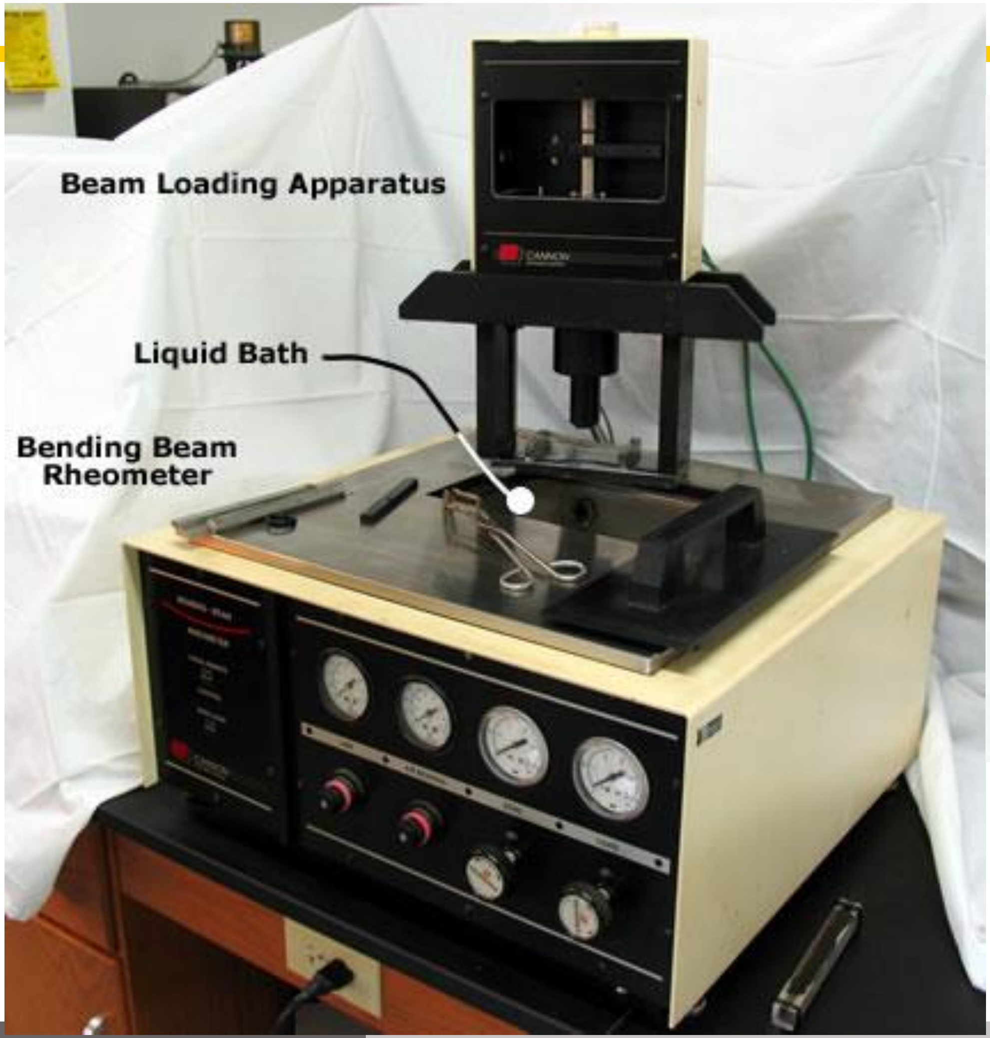
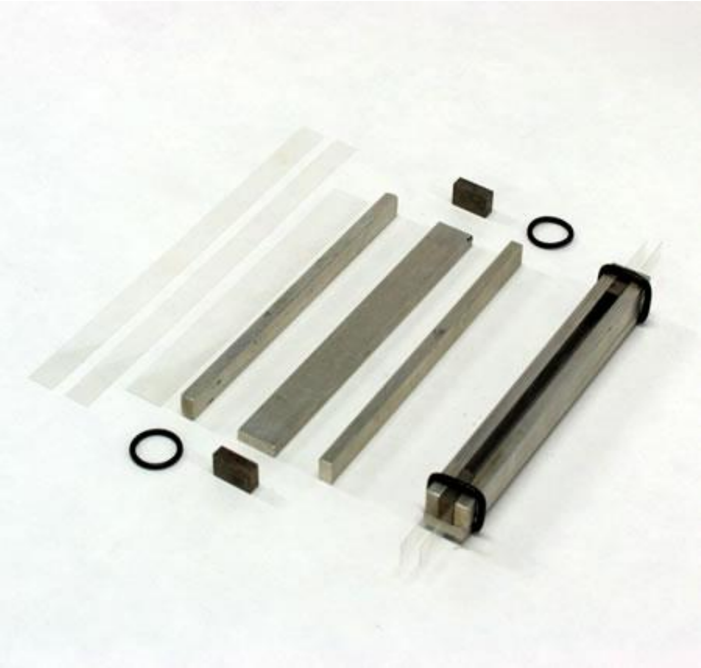
Background

- Constant load of 100g is applied to the midpoint of a simply supported beam of asphalt binder and the midpoint deflection of the beam is measured continuously for 240s
- Stiffness range: 30MP-3 GPa
- Temperature range: -40 to 25◦C, depending on the aging and the thermo history of the binder.

Equipment used

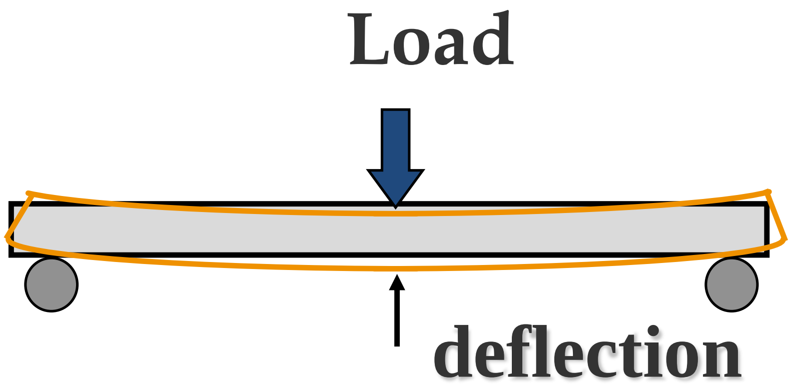


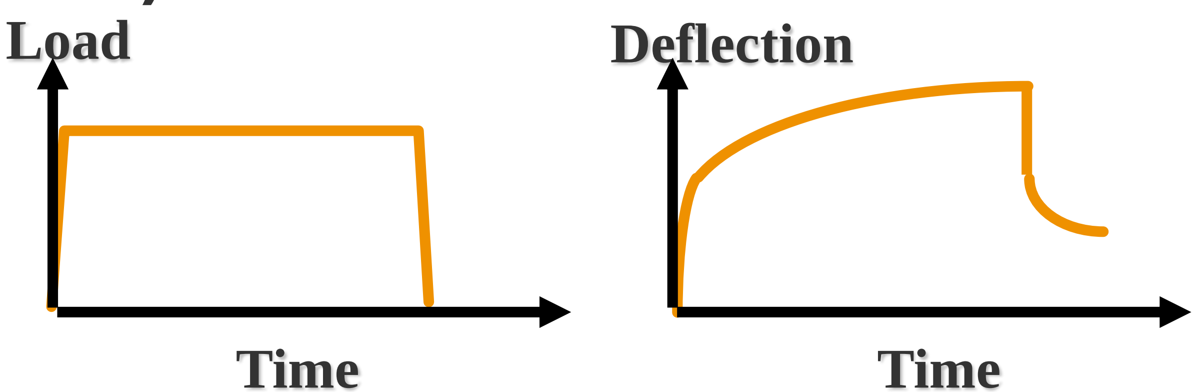


Source: http://pavementinteractive.org

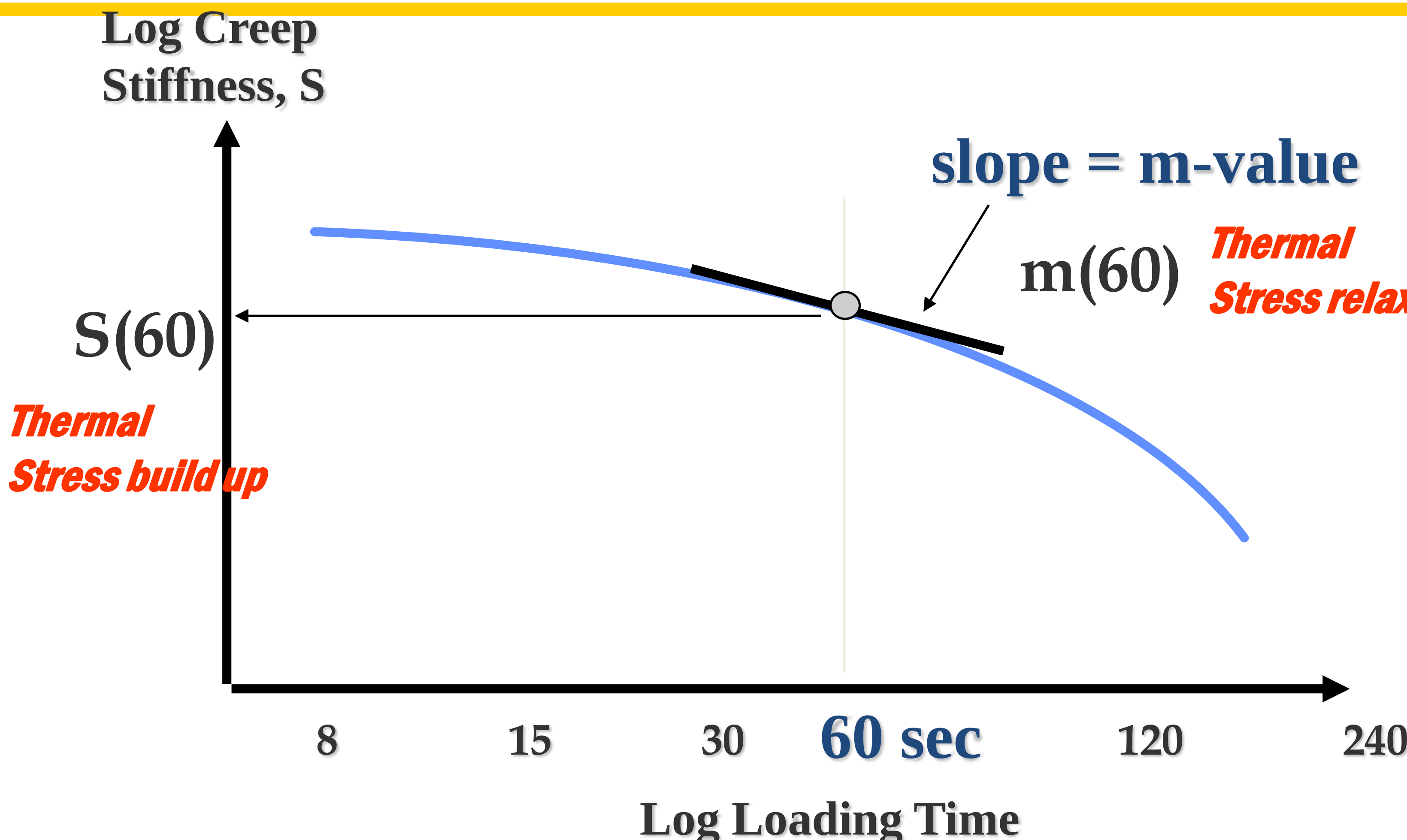
Bending Beam Rheometer (BBR)

- Evaluates
  - low temperature properties
- Output
  - creep stiffness (S)
  - m-value (relaxation)





Results of the Bending Beam Rheometer



Stiffness and m-value

- **Stiffness** is a measure of overall resistance to deformation
- **The m-value** is a measure of the relaxation rate of accumulated stresses

Higher "m" → higher **relaxation** rate

Good for performance

Why Test at Min. Pavement T+10ºC

- Criterion most widely used is S(7200 s).
- Validated in many field studies.
- Testing for 7200 s is not practical.
- Time-temperature equivalency factors for most asphalts are similar.
- Increase temperature and reduce time.

- S(7200) @ Min T ~= S(60) @ MinT+10ºC.

Direct Tension Test (DTT)

Source: http://pavementinteractive.org

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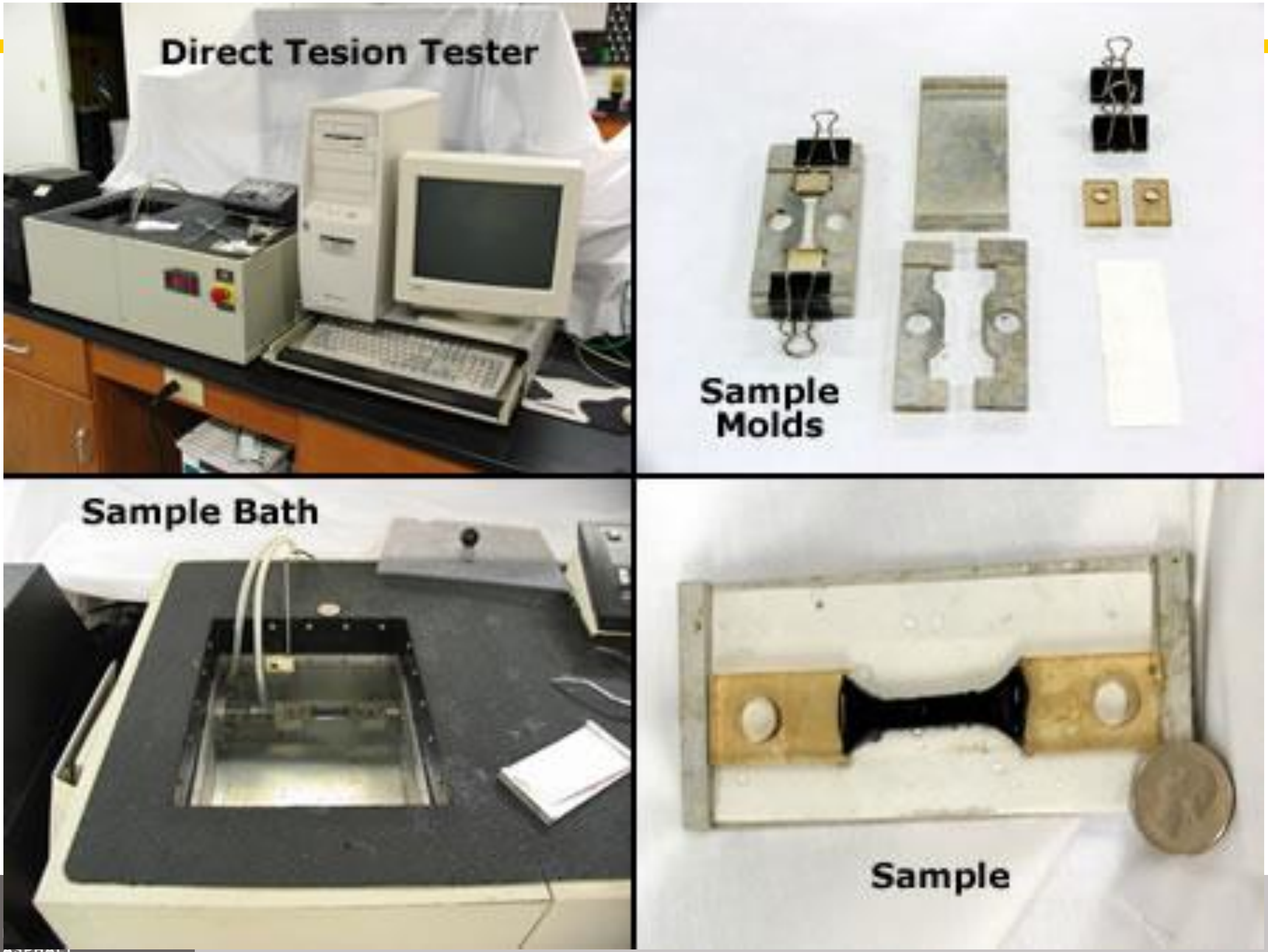
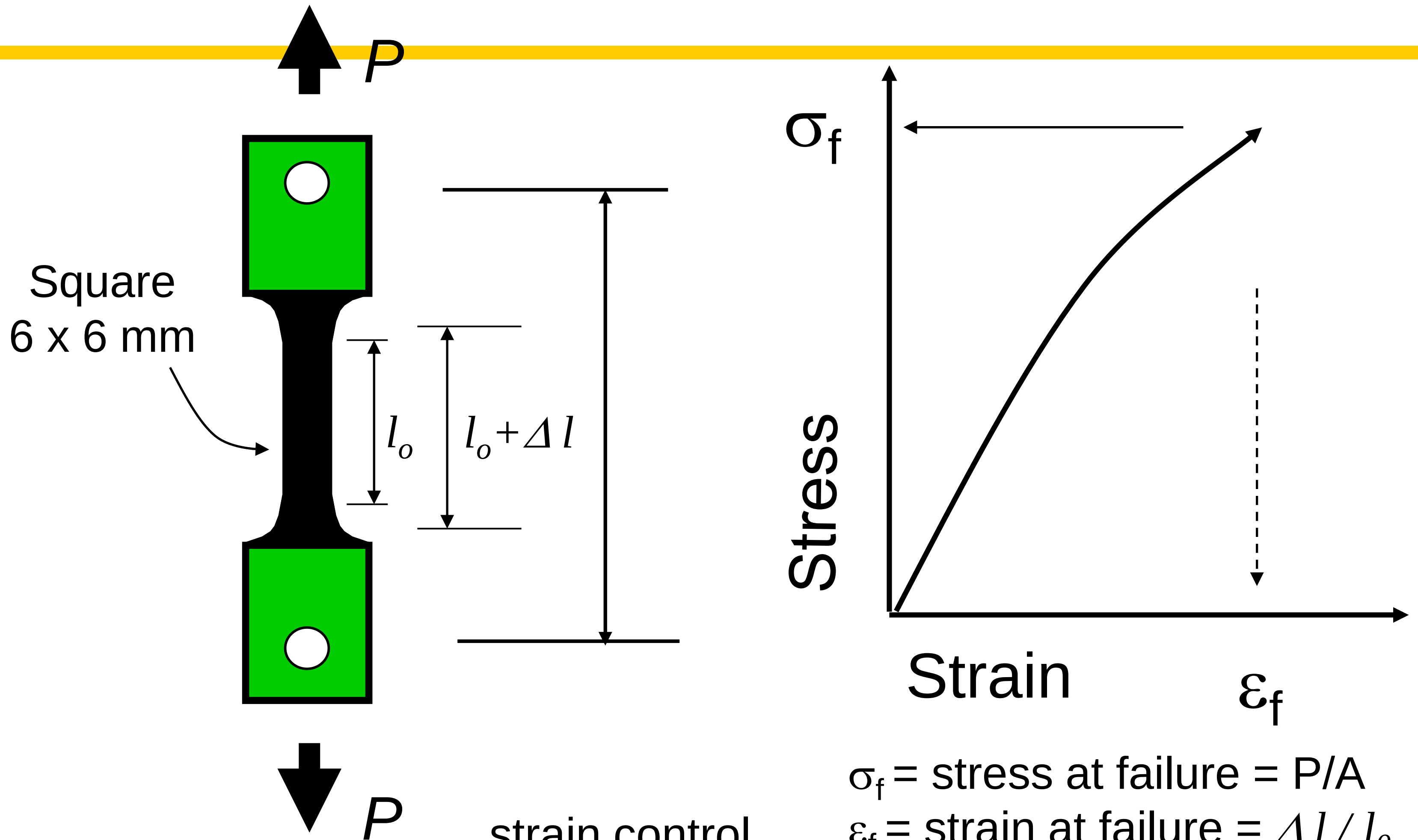
Equipment Used



Source: http://pavementinteractive.org

Result of DTT test

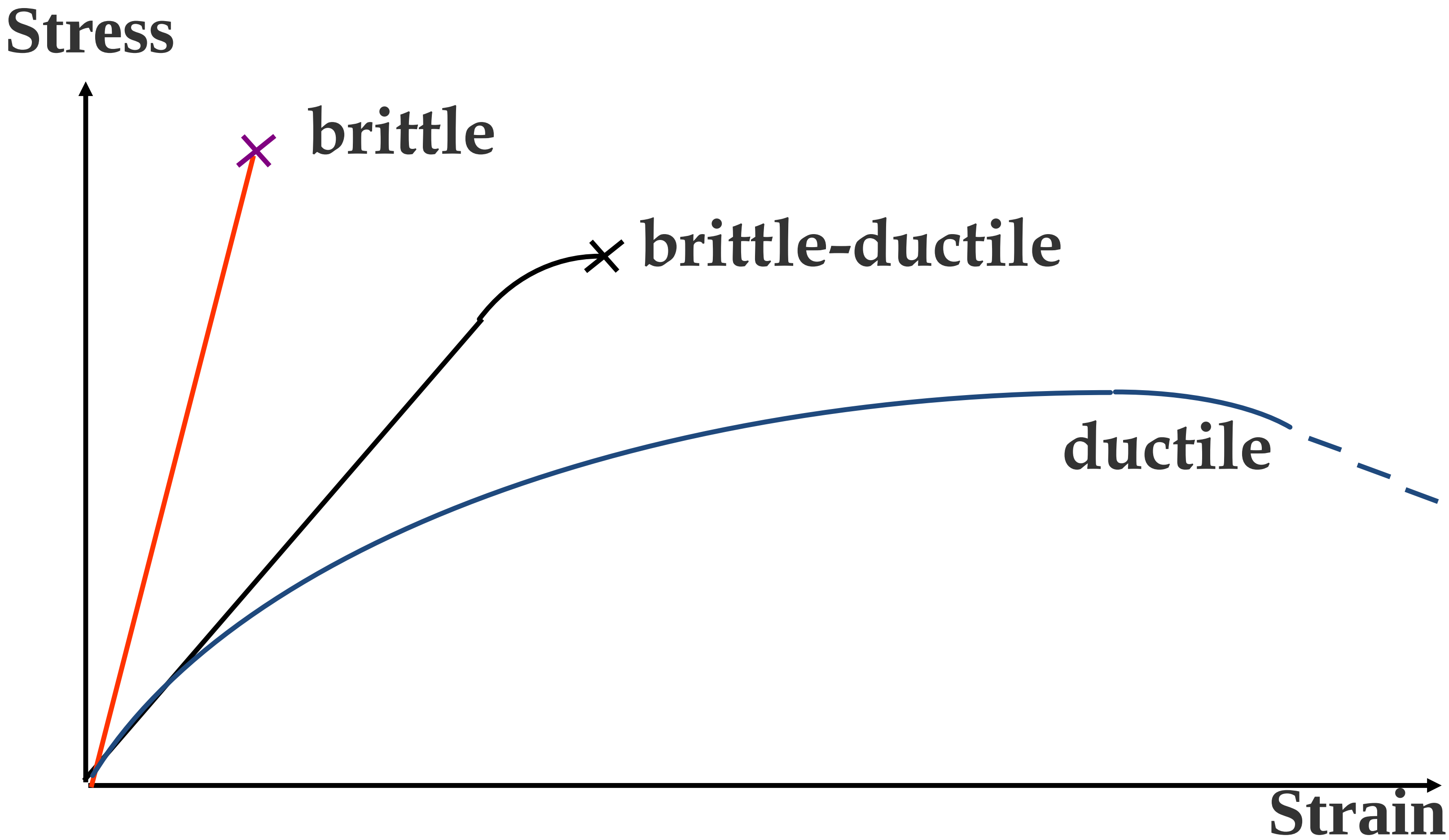


strain control

σ_f = stress at failure = P/A

ε_f = strain at failure = $\Delta l / l_0$

Failure Properties:
Strength and Strain Tolerance

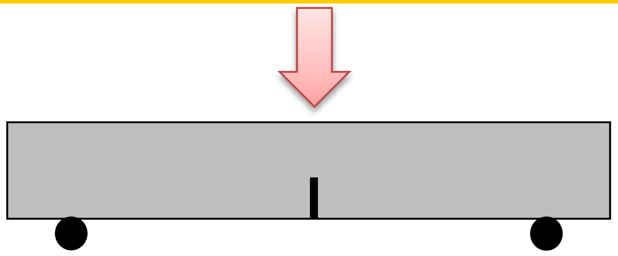


NEW BINDER FRACTURE TESTING

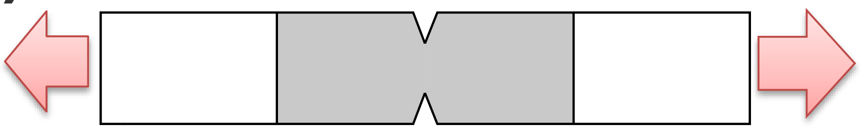
SINGLE EDGE NOTCHED BEAM (SENB) TEST

Binder Low Temperature Fracture Tests

- Single Edged Notched Beam (SENB)

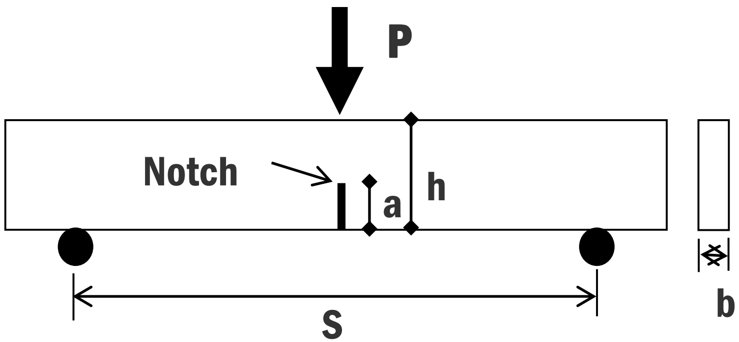


- Double Edged Notched Test (DENT)



- Asphalt Binder Cracking Device (ABCD)

Single-Edge Notched Beam (SENB)

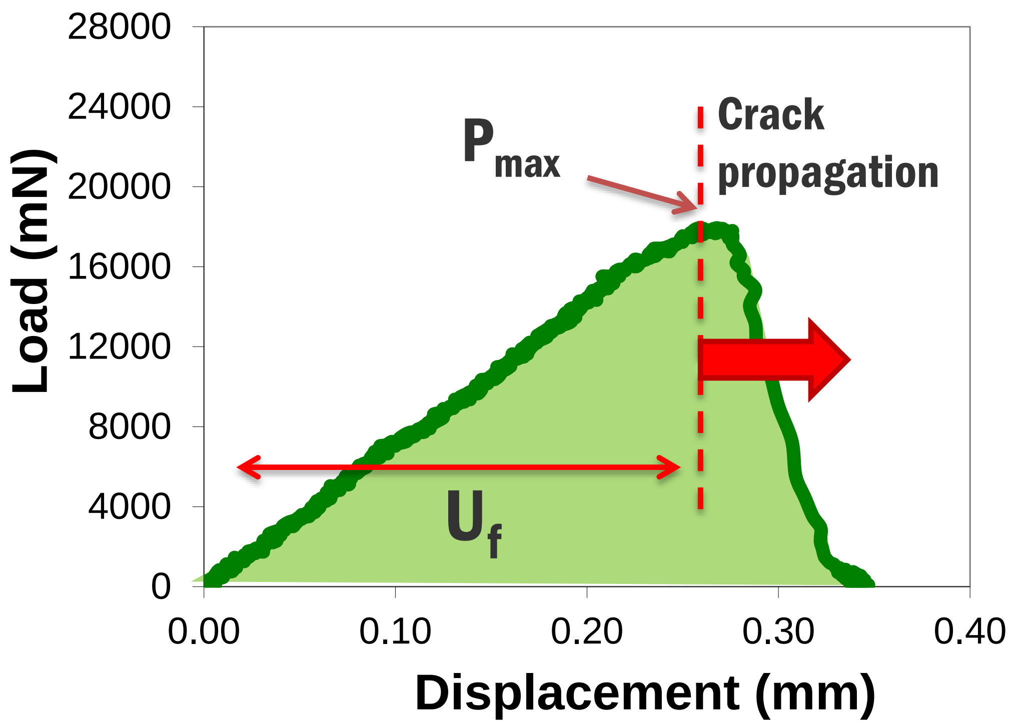


$$K_I = \frac{P_{max} \cdot S}{b \cdot h^{3/2}} f\left(\frac{a}{h}\right)$$ **Fracture Toughness**

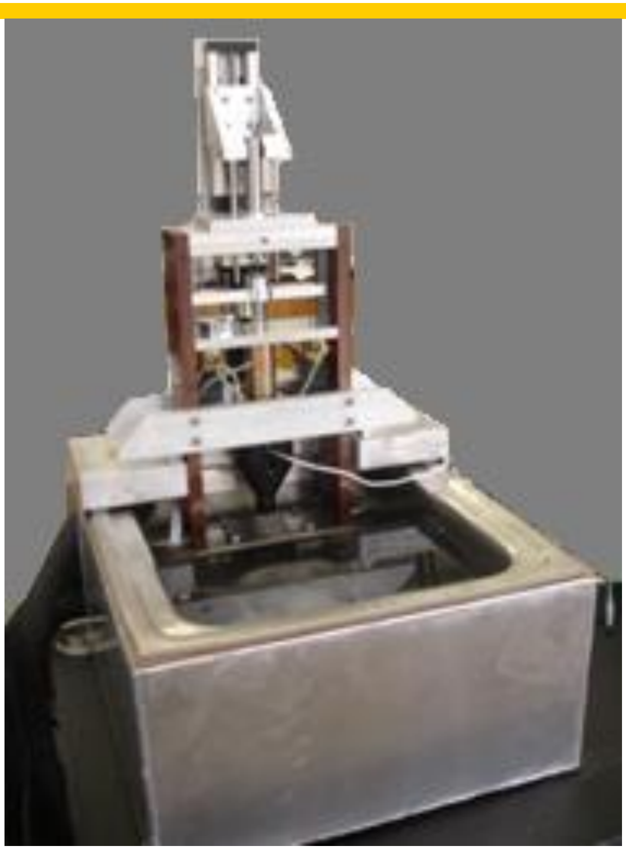
$$G_f = \frac{W_f}{A_{lig}}$$ **Fracture Energy**

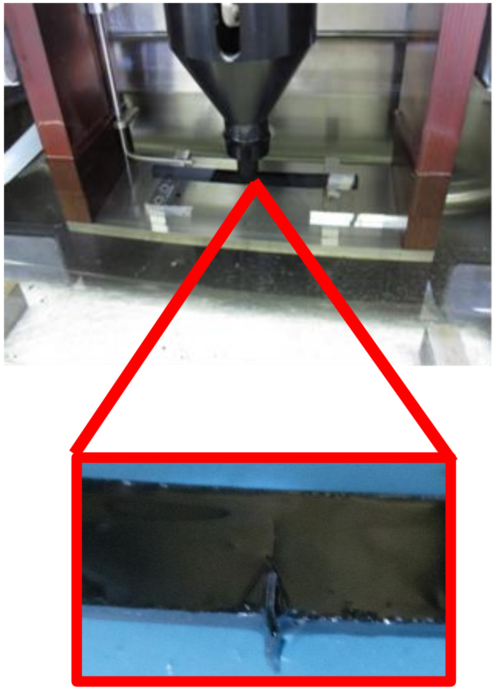
$$W_f = \int P du$$ **Work**

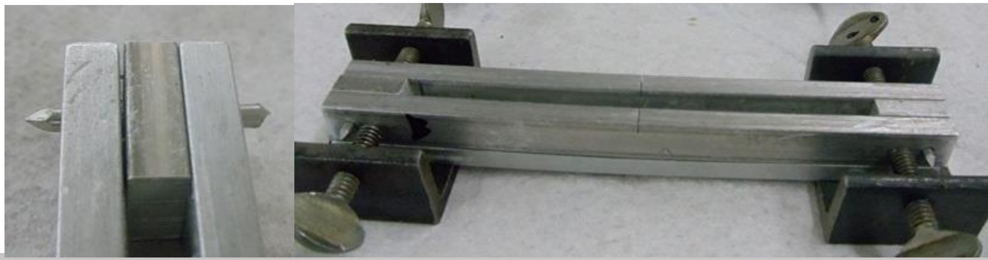
Follows ASTM E399 and assumes Linear Elastic Fracture Mechanics (LEFM) conditions are true.



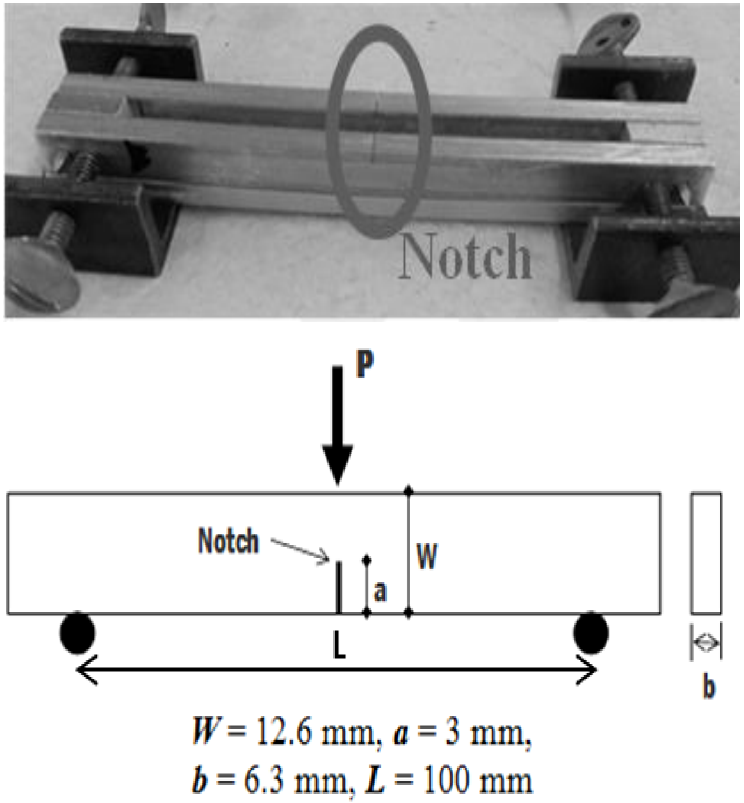
BBR-SENB System

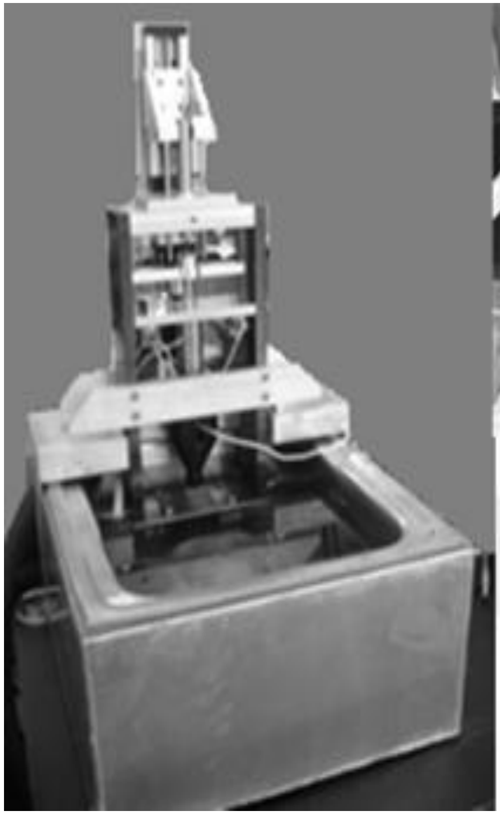




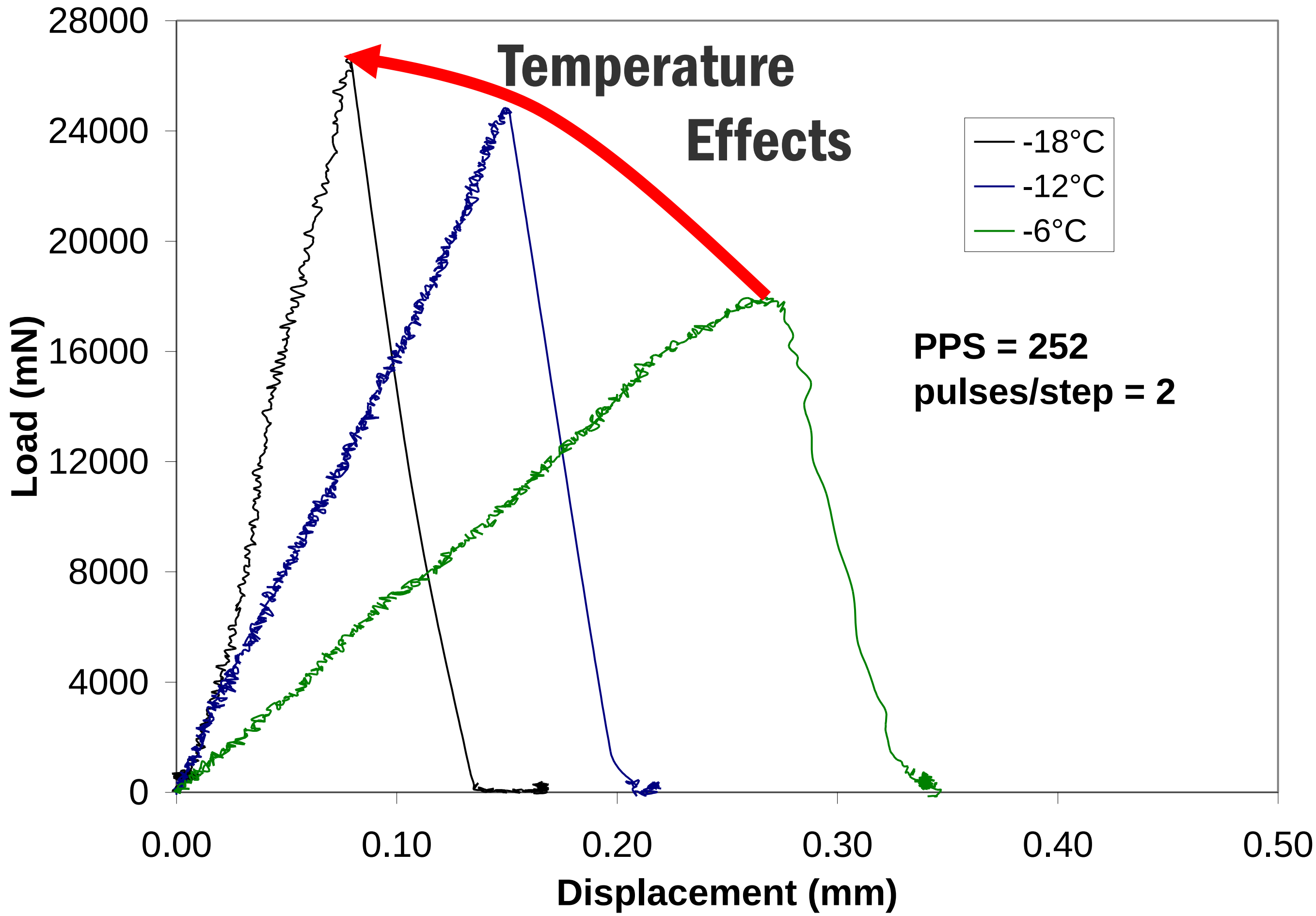


BBR-SENB System

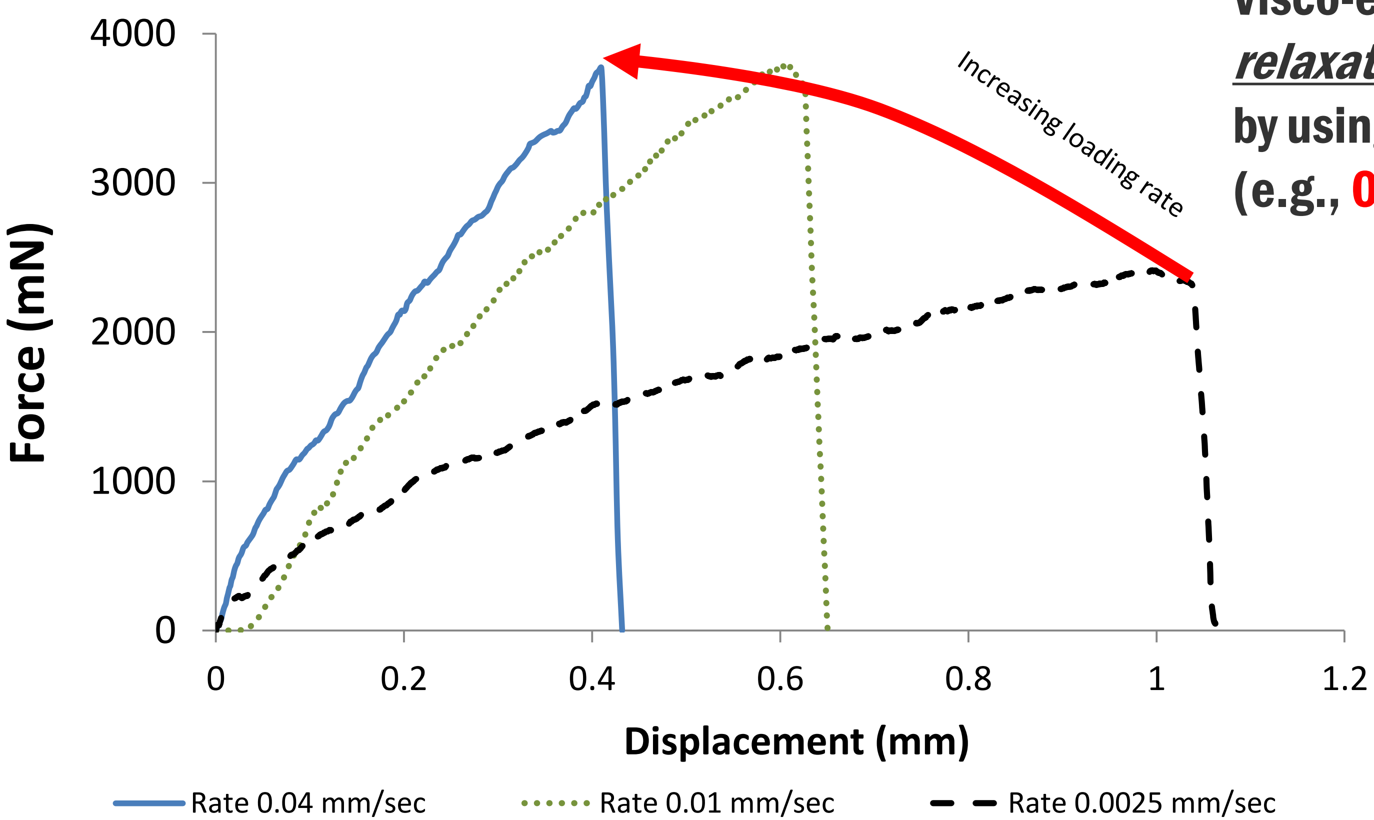




BBR-SENB: Typical Results



Effect of Loading Rate

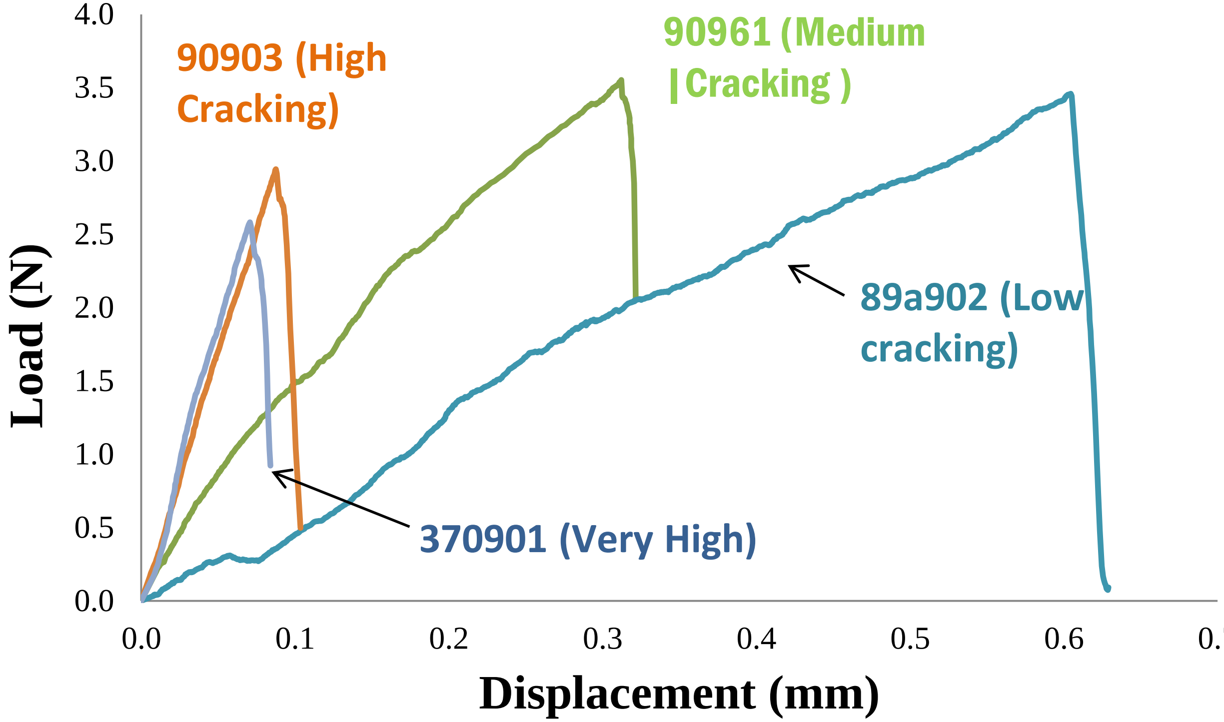


Visco-elastic effects (*Stress relaxation*) can be minimized by using proper loading rate (e.g., 0.01 mm/sec)

BBR-SENB and of actual paving binders

Section ID	No. of Cracks	Performance Grouping[1]	PG	LT PG Grouping	$G_f (J/m^2)$	u_f (mm)	Testing Temp (°C)
350902	0	1	PG 64-22	2	34	0.89	-12
350903	0	1	PG 58-22	2	**27.5**	**0.90**	-12
340901	2	1	PG 64-22	2	24.5	0.60	-18
370964	0	1	PG 76-22	2	25	0.74	-12
370963	0	1	PG 64-22	2	27	0.64	-12
340902	0	1	PG 58-28	1	17.5	0.51	-18
370962	0	1	PG 76-22	2	14.5	0.44	-12
340961	11	2	PG 78-28	1	15.5	0.58	-18
370960	15	2	PG 76-22	2	**8.5**	**0.25**	-12
370901	29	3	PG 64-22	2	9.7	0.34	-12

BBR-SENB and Field Performance (LTPP)



Higher uf and higher Gf) == Low Cracking

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SENB: Summary

- In contrast to BBR, **BBR-SENB** test can capture effects of non-linear viscoelastic and damage resistance behavior of binders at low temperatures
- Results show that fracture deformation and fracture energy are **good indicators** of low temperature performance of asphalt binders

- Potentially, it is **ideal performance characterization** test.

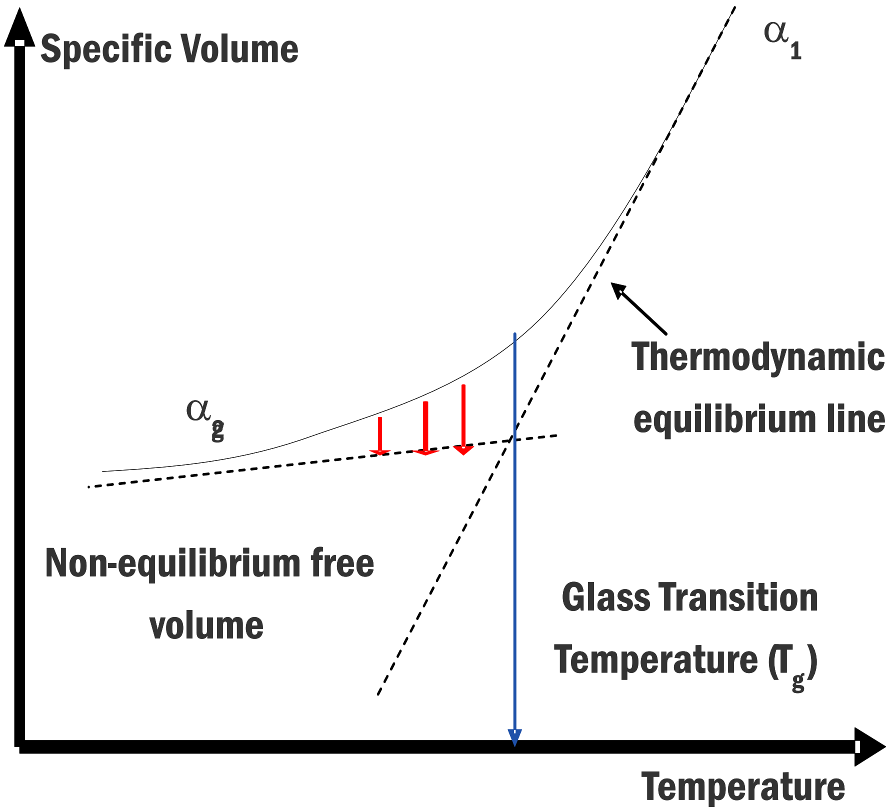
BINDER SHRINKAGE & GLASS TRANSITION TEMPERATURE

Glass transition

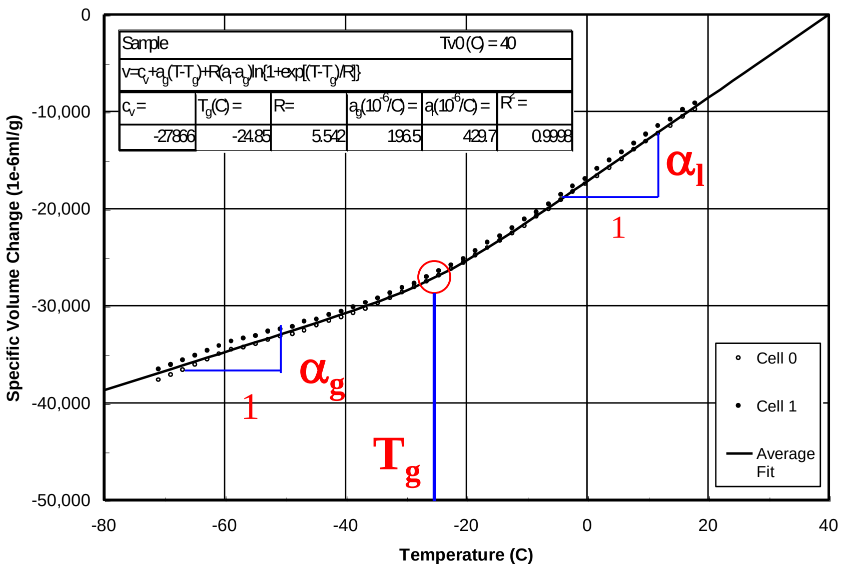
- At high and intermediate temperatures thermo-volumetric change is **linear** with a **constant rate (α_l)**.

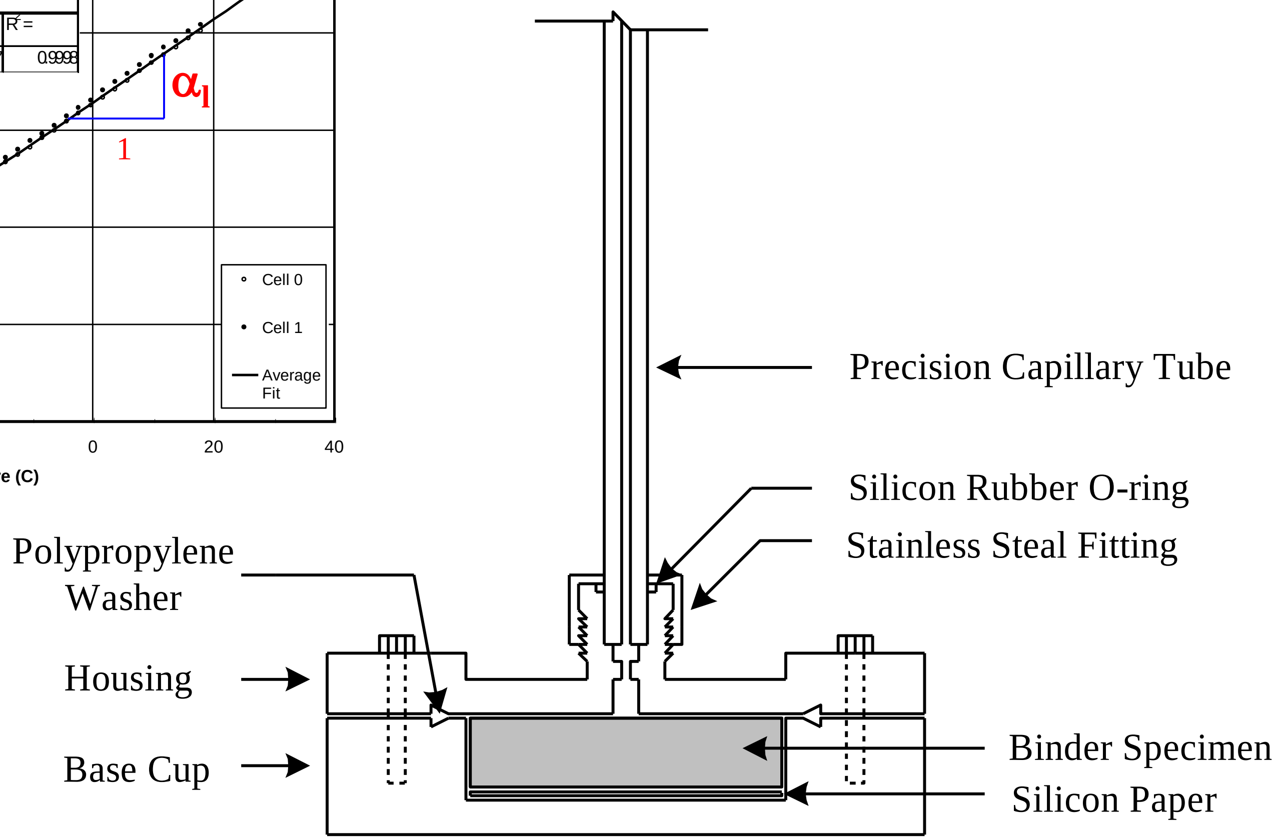
- At low temperatures rate of volumetric change **non-linearly** decreases as *molecular free volume and mobility* decreases (**Glass Transition**).

- At very low temperatures material becomes "glassy", and rate of change becomes **linear** at a lower **constant rate (α_g)**.



Glass Transition Measurements



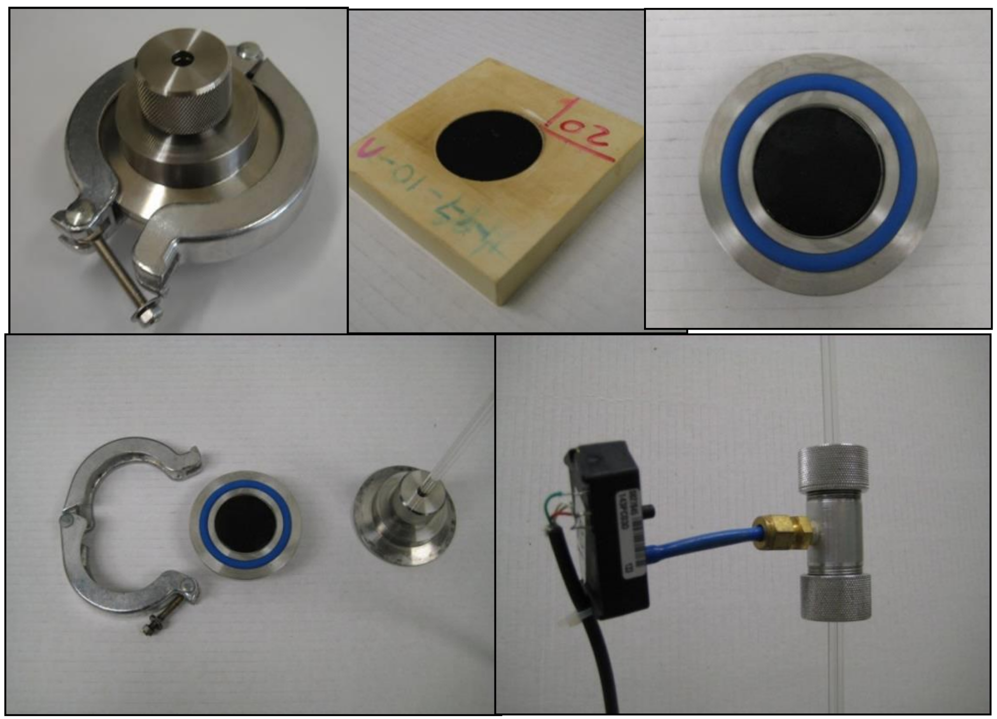


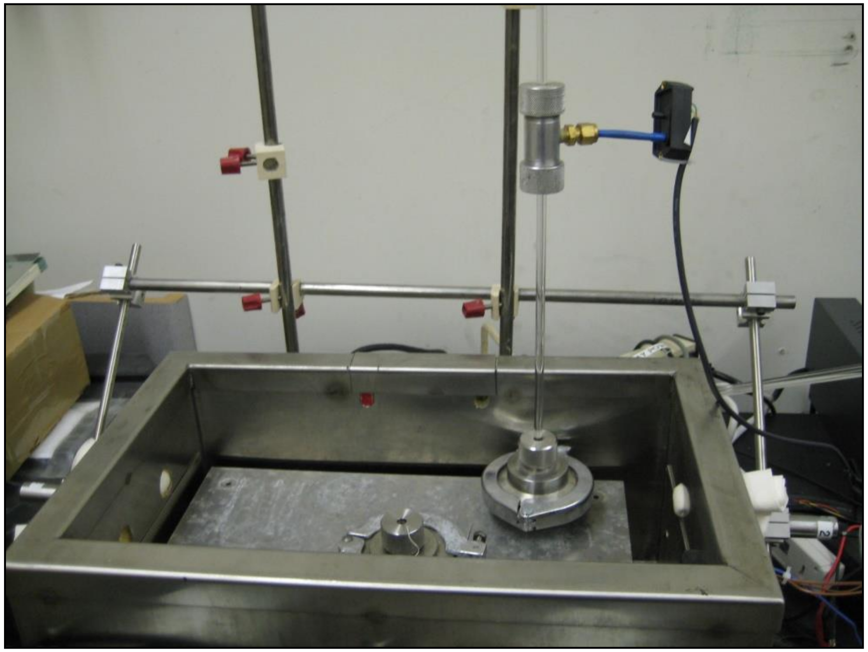
T_g Properties

- Tg is a strong function of the chemical composition of the asphalt:
  - The polar entities of asphalt
    - asphaltenes
    - polar aromatics
- Tg has been shown to be related to:
  - the peak of the loss modulus (G")
  - the molecular weight of the material
  - the asphaltenes content

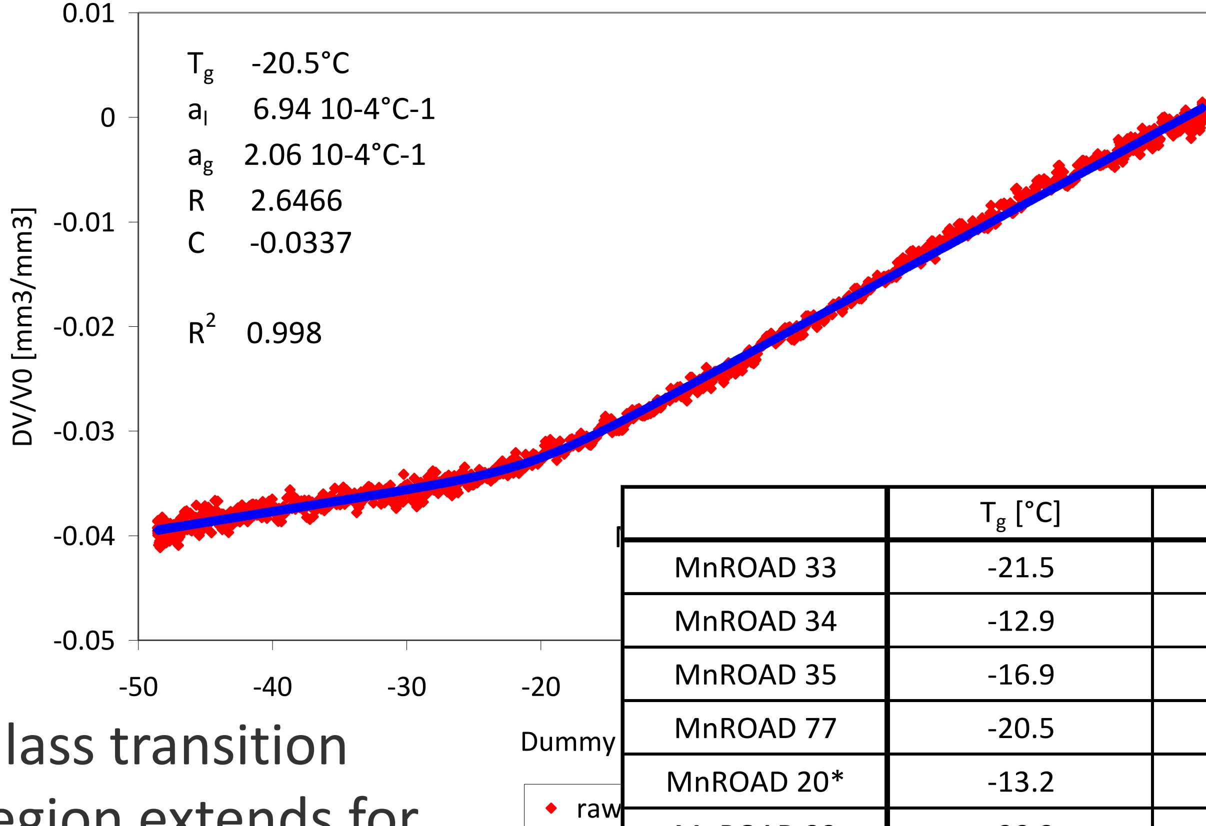
Measurement of Glass Transition Temperature

- Developed at UW-Madison
- Dilatometric system
- Based on measurement of volume change per temperature





Typical Results of Glass Transition

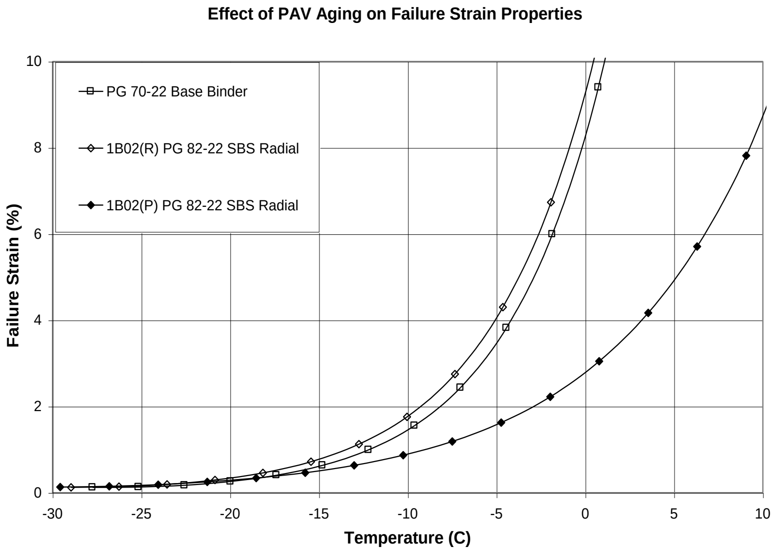


- Glass transition region extends for 10°C or more

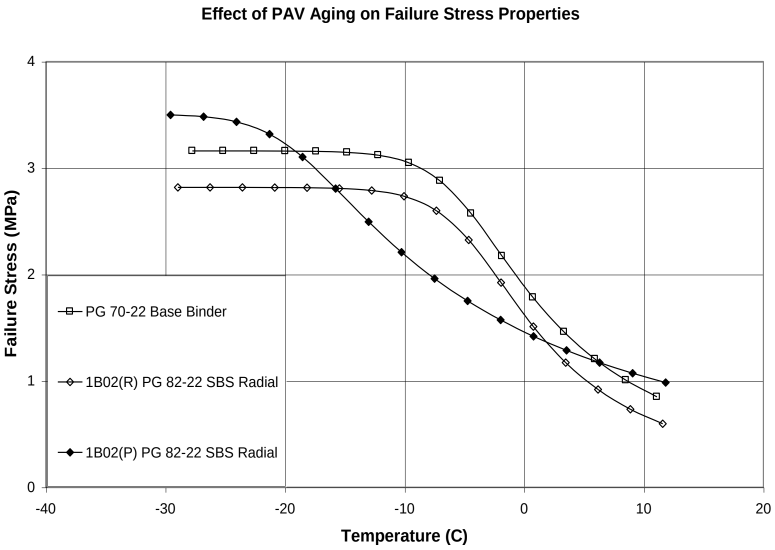
	T_g [°C]	α_l [°C^{-1}]	α_g [°C^{-1}]
MnROAD 33	-21.5	6.87E-04	3.59E-04
MnROAD 34	-12.9	7.36E-04	4.63E-04
MnROAD 35	-16.9	6.67E-04	3.13E-04
MnROAD 77	-20.5	6.94E-04	2.06E-04
MnROAD 20*	-13.2	8.66E-04	2.27E-04
MnROAD 22	-20.2	7.25E-04	4.06E-04
Wisconsin	-19.4	7.55E-04	3.47E-04

Effect of PAV Aging on Failure Properties

- Failure Strain Master Curves

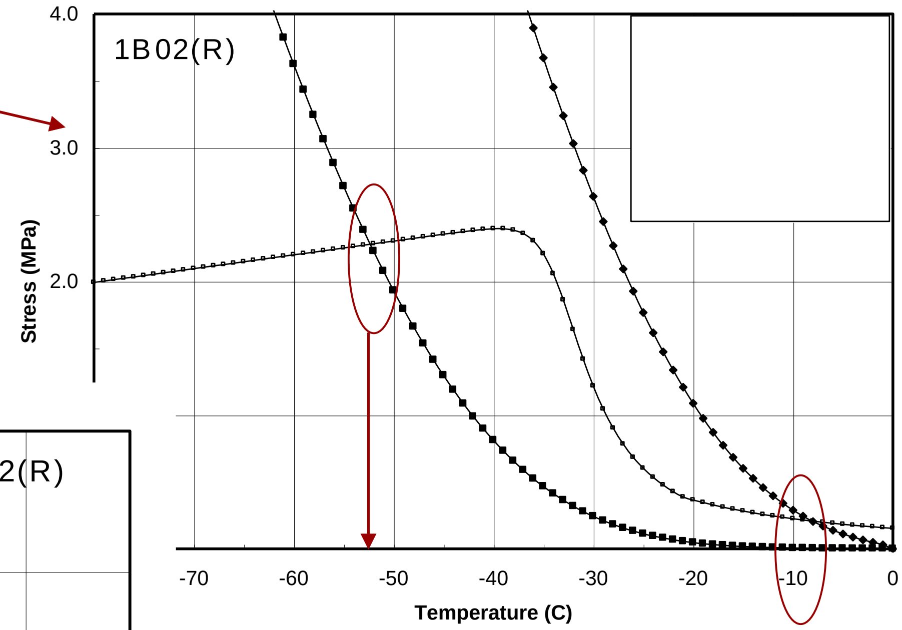


- Failure Stress Master Curves

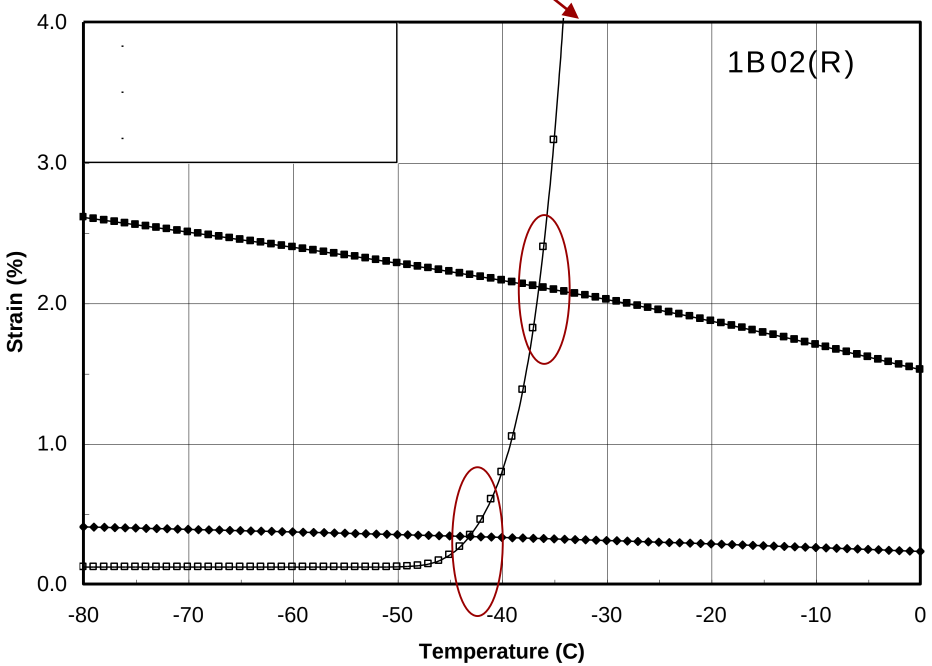


Critical Failure Temperatures Estimated From: Tg, S, m, stress and strain envelops

- **Failure Stress**



- **Failure Strain**



EFFECTS OF FILLERS

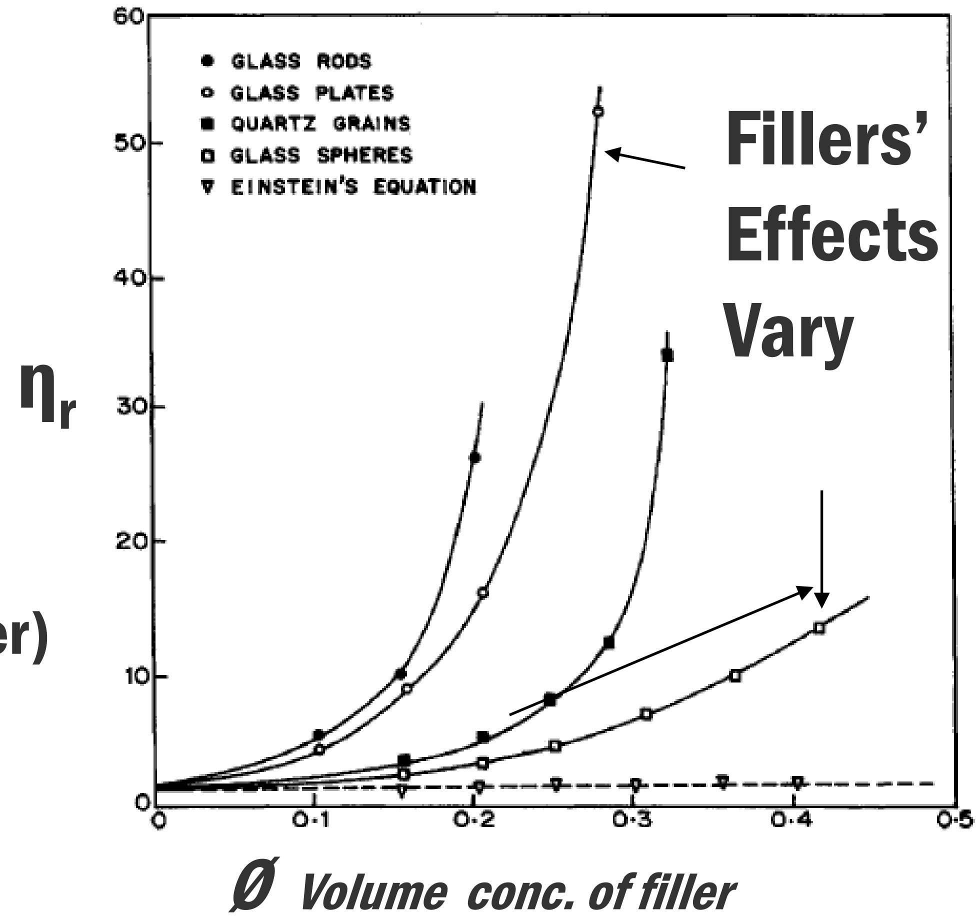
It is difficult to Predict effects of fillers

- Fillers vary in their effects on bitumen properties
- Einstein Model for Diluted Composites (1911):
  - $\eta_r = 1 + K_E ø$

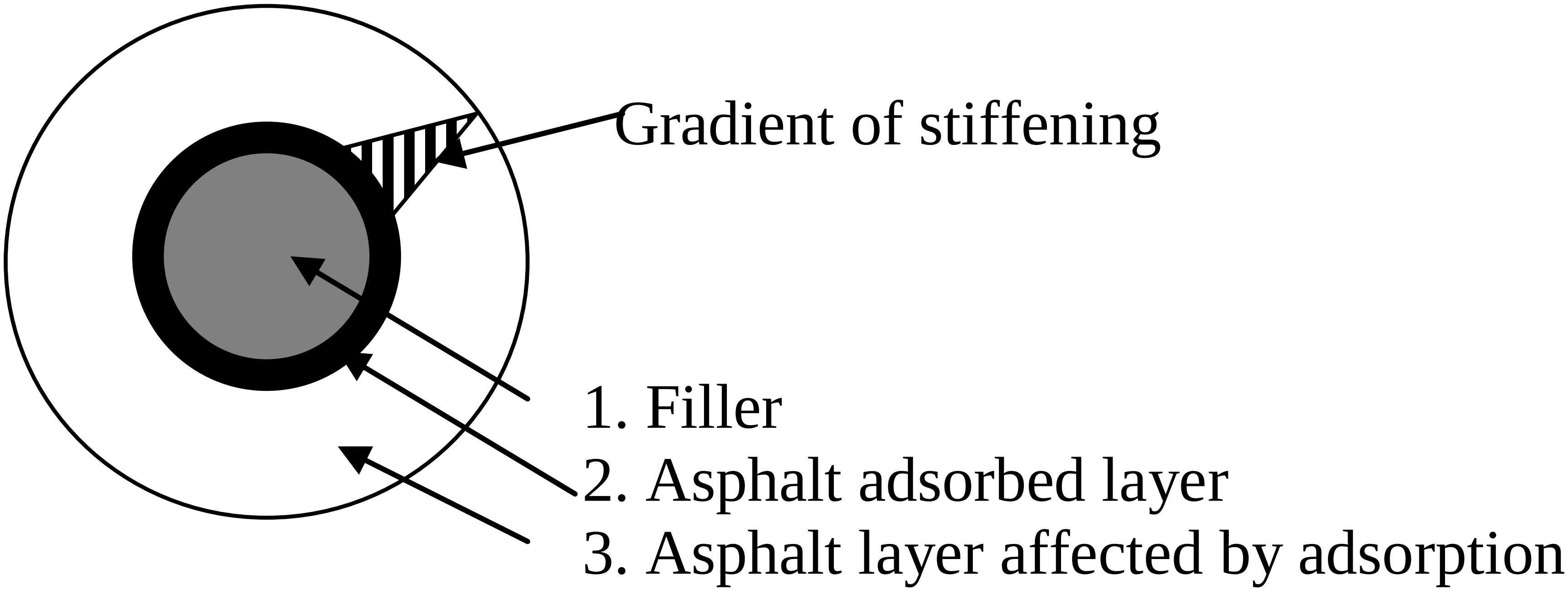
η_r= Visc. of mastic/visc. of (Binder)

K_E= Einstein Constant ~2.5

Ø: Filler volume fraction



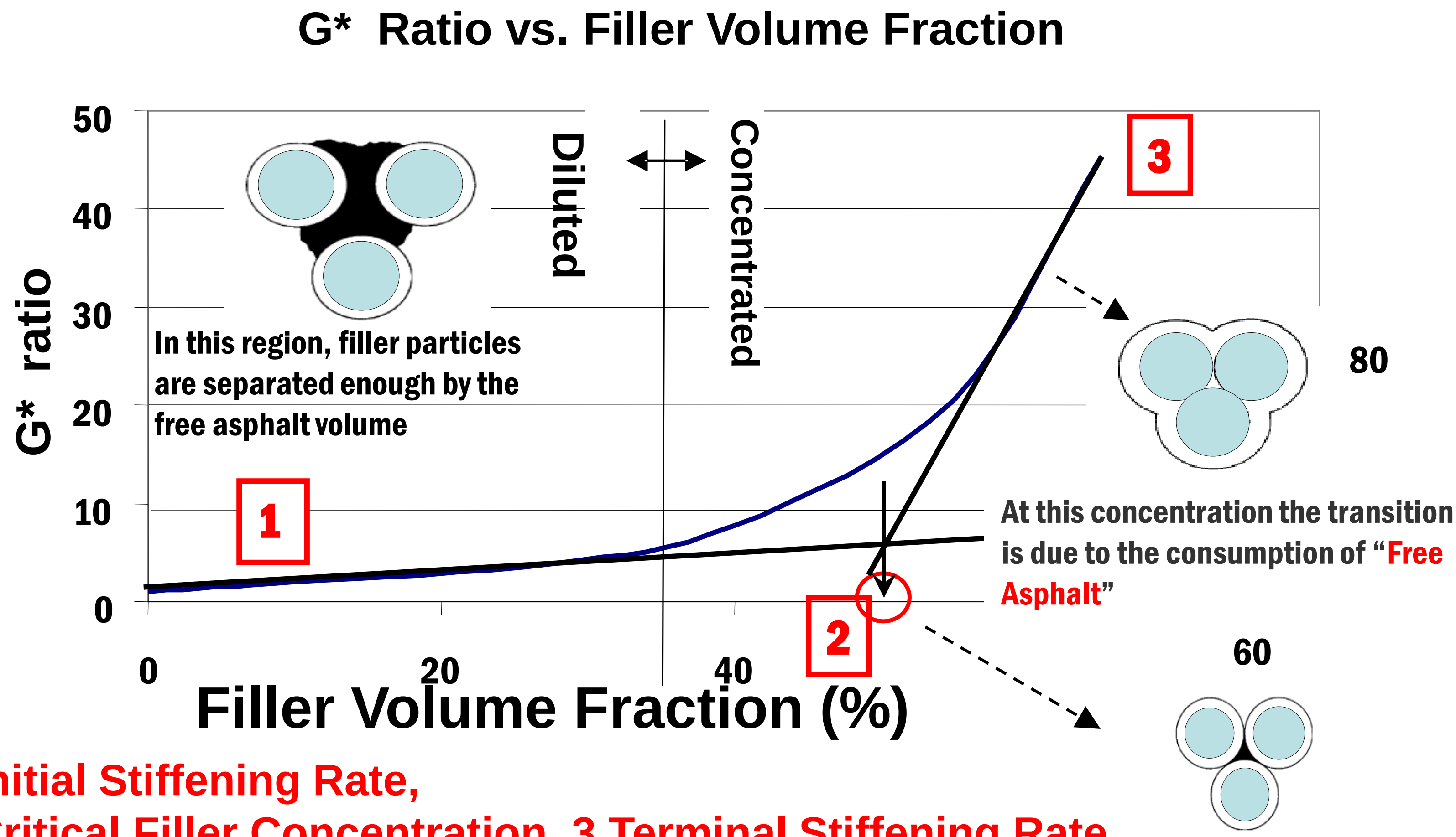
Basic concept of filler effects: Fillers' Interaction with Binders (Tunnicliff in 1960)



Important Filler Properties:

1.Geometry , and 2.Composition

Conceptual Model –
Binder& Filler Interaction (Faheem et al. 2008)

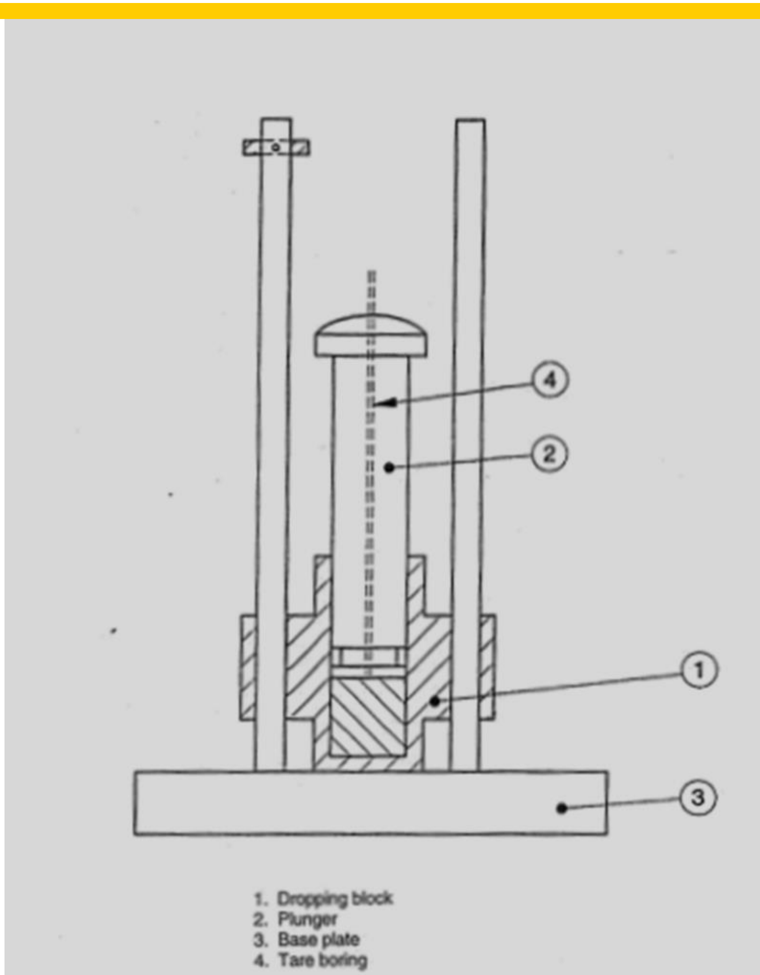


1. Initial Stiffening Rate,
2. Critical Filler Concentration, 3.Terminal Stiffening Rate

Important Filler Properties- Geometry and Size

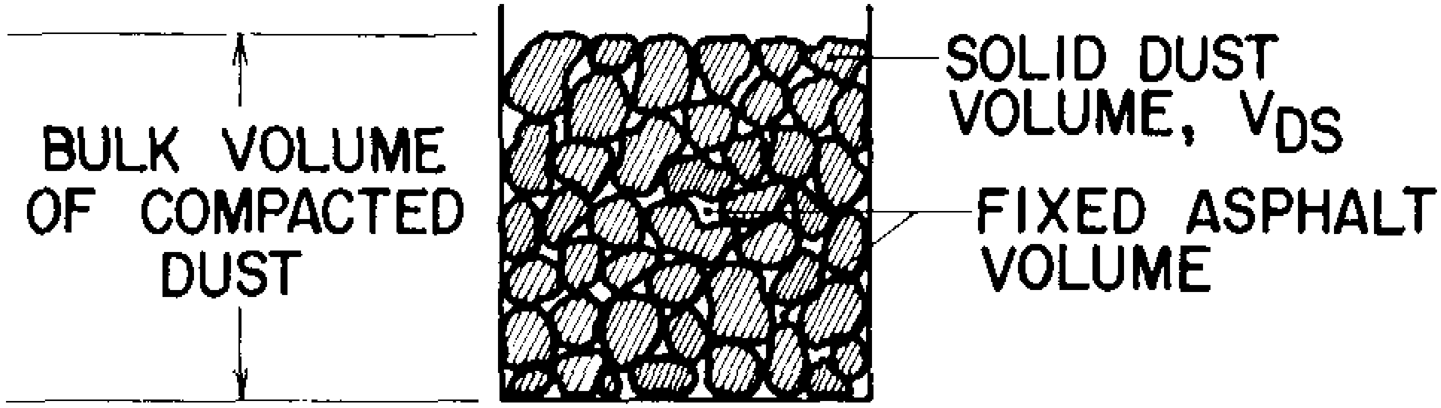
- Fillers' geometry can be defined by four measurements:
  - Size, shape, angularity, & texture.
    - Last 3 are difficult to measure individually.
  - A good indicator of all is (Packing)
  - Fractional Voids , also called Rigden Voids
- Two Secondary : Absorption & Specific Gravity

RIGDEN VOIDS (BS 812, EN 1097-4)



Rigden Voids -- Fixed & Free binder

- Fractional voids' content
  - Volume percentage of voids in a dry, compacted filler sample
- Higher Rigden voids leads to higher stiffening of binder

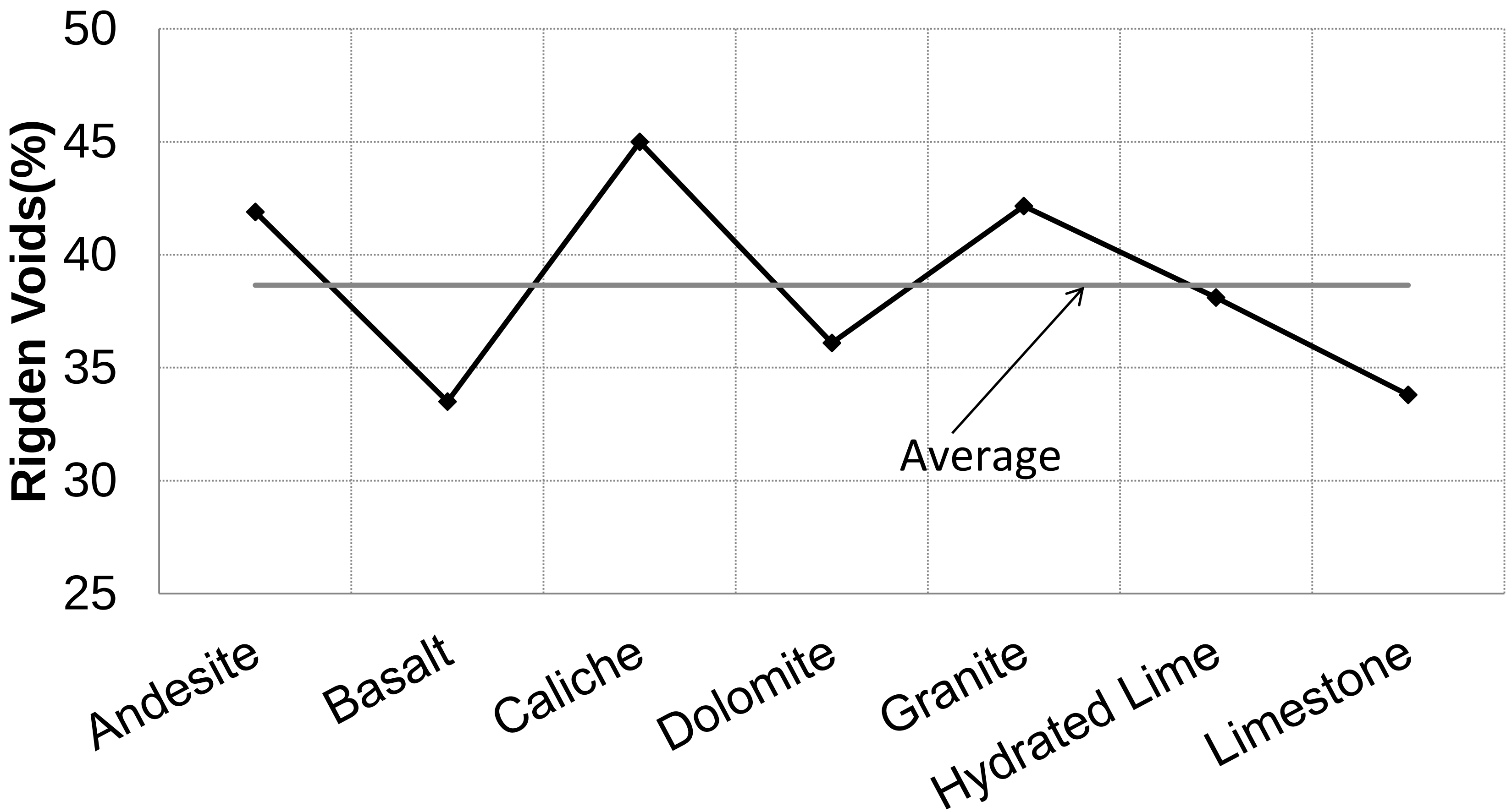


Filler Mineralogical Properties

- **Natural Fillers**
- **Imported Fillers**

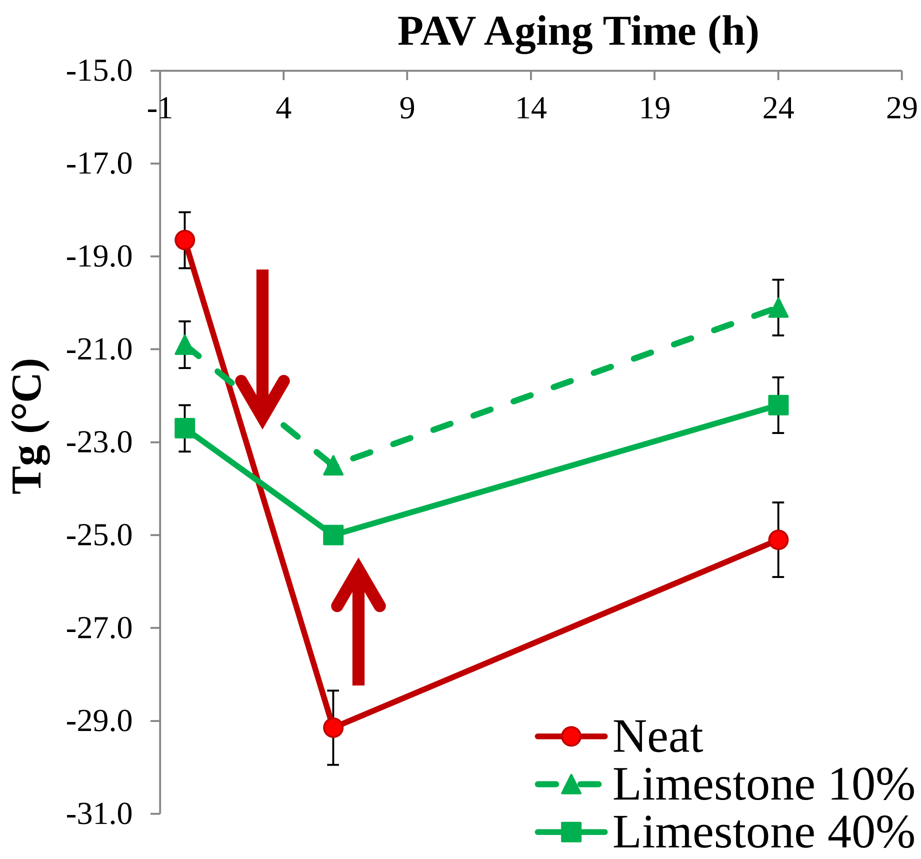
Filler Type
1.Andesite
2.Basalt
3.Caliche
4.Dolomite
5.Granite
6. Limestone
1.Hydrated Lime
2.Fly Ash
3.Slag

Distribution of Rigden Voids Can be grouped by Mineralogy



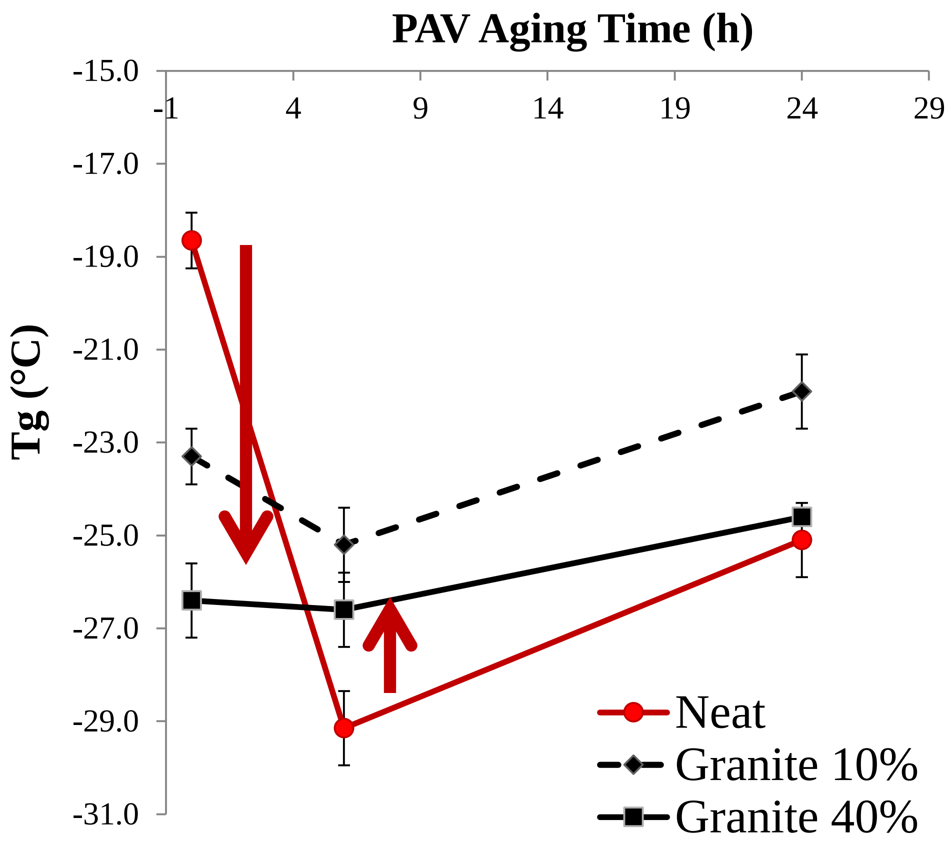
T_g Analysis of Asphalt Mastics

Limestone



Lower Surface Area

Granite

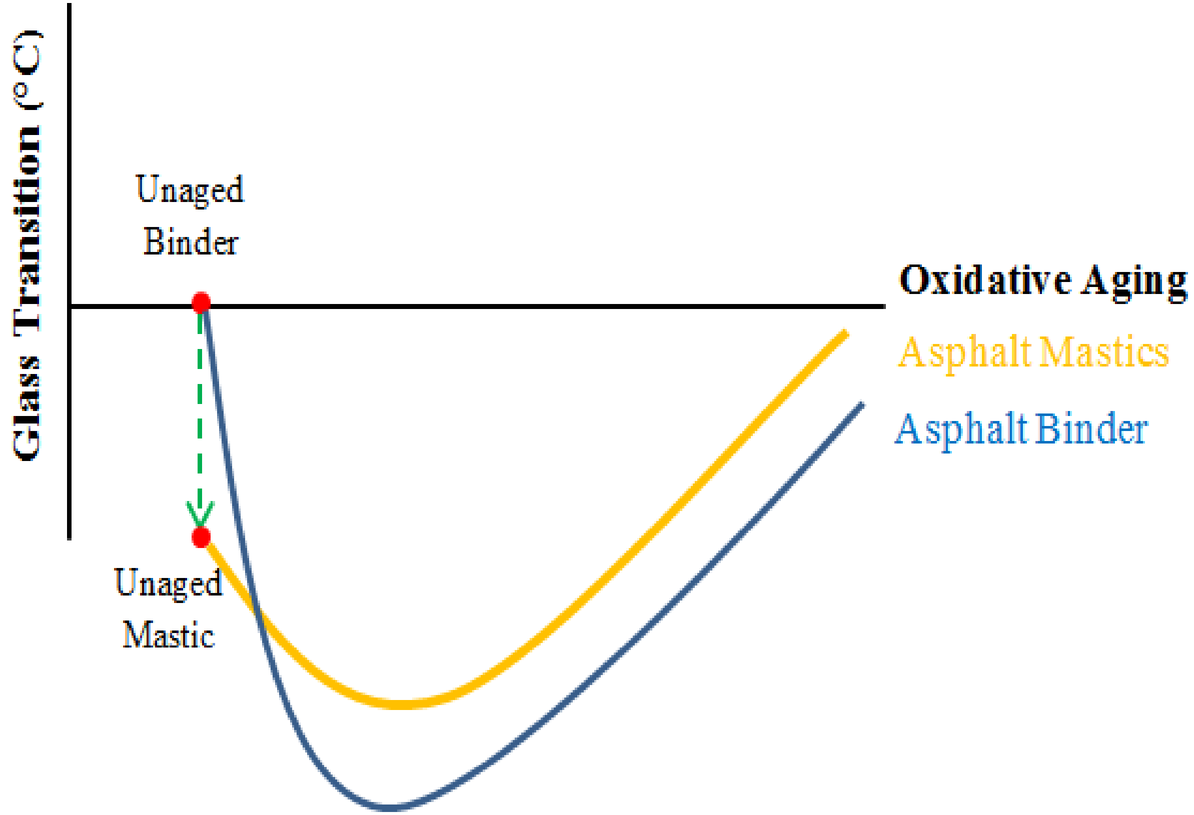


Higher Surface Area

T_g Analysis of Asphalt Mastics

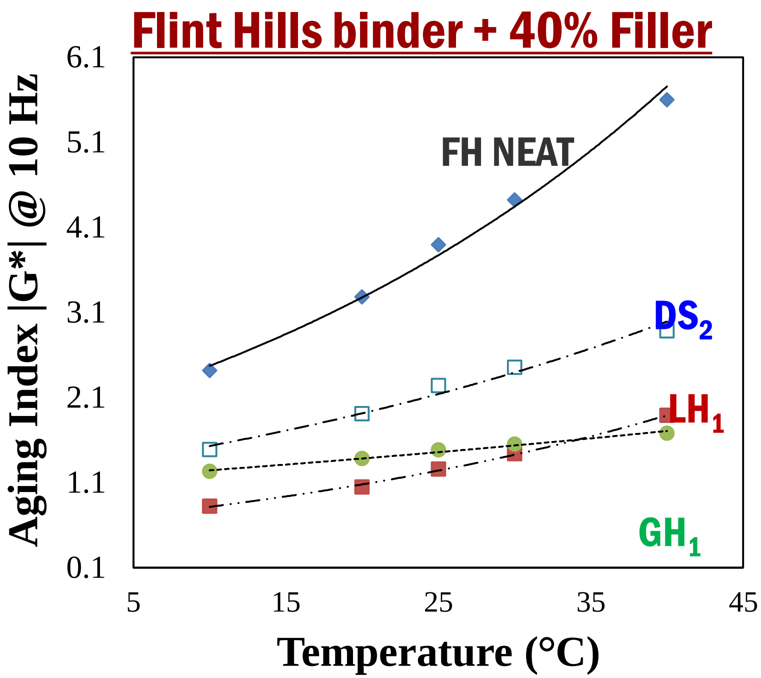
(after Moraes 2014)

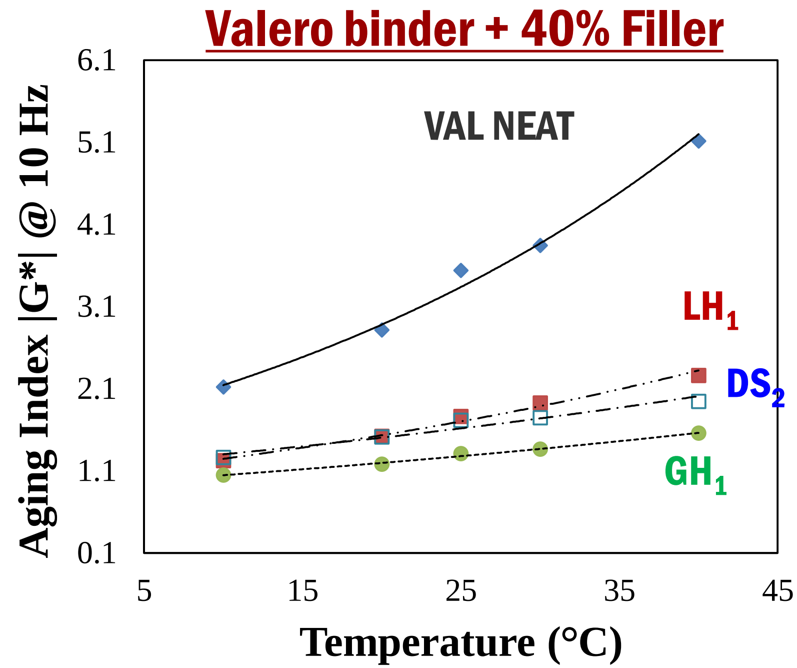
- Presence of mineral filler **shifts curve with increased aging** conditioning. Shift is influenced by mineral filler surface area and concentration



Relating |G*| Aging Index and Temperature

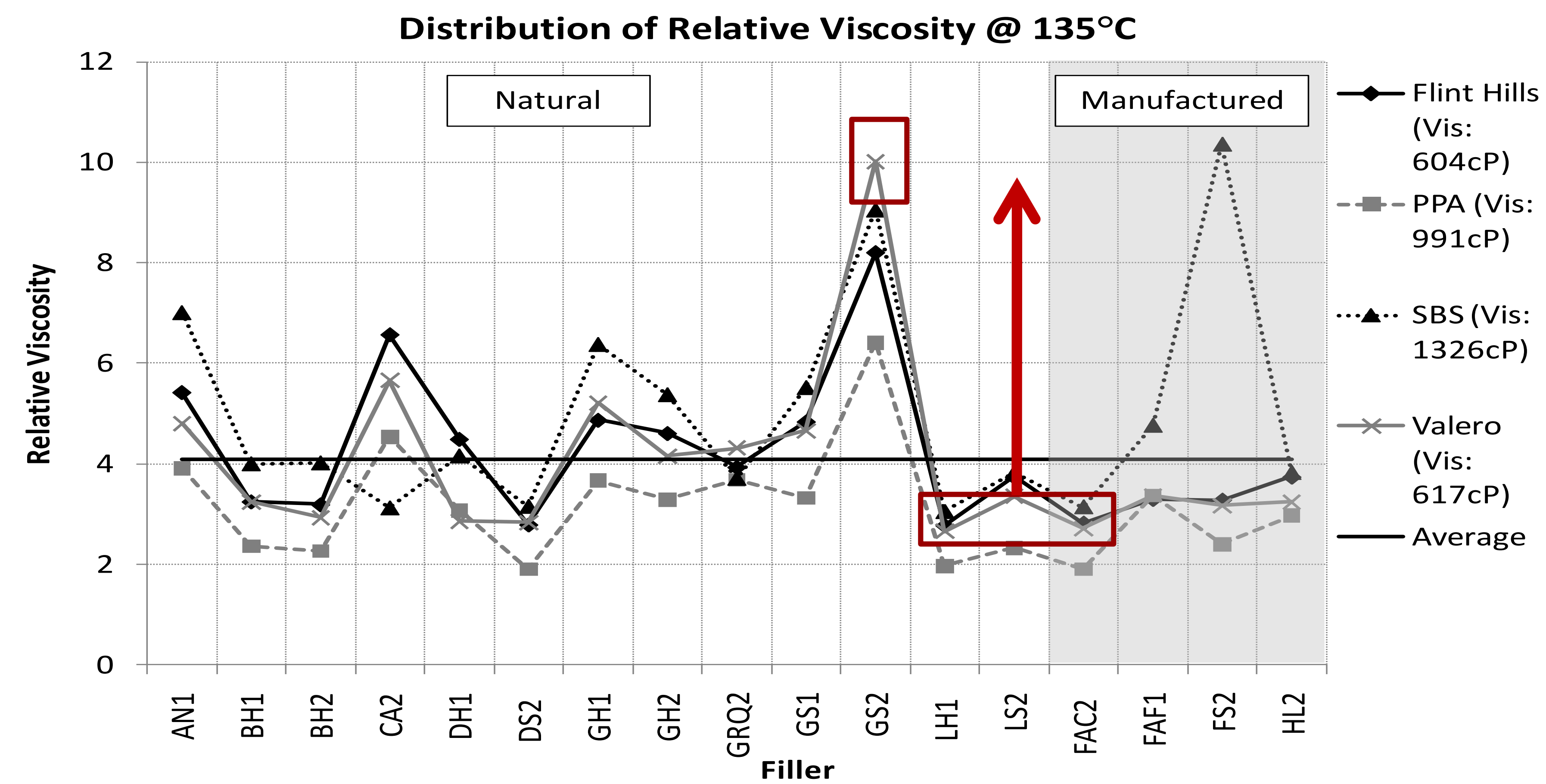
Fillers can reduce aging (Moraes 2014)





- ✓ **Presence of filler reduces the binder susceptibility to aging.**
  - ✓ **Impact of oxidative aging can be changed significantly by selection of type of filler to be included in mastics.**

NCHRP 9-45 - EFFECTS OF FILLERS ON BINDER VISCOSITY AND LOW TEMP PROPERTIES



Legend:

1st Letter: Filler

A:Andesite
B: Basalt
C: Caliches
D: Dolomite
FA: Fly Ash
FS: Furnace Slag
G: Granite
HL: Hydrated Lime

2nd / 3rd Letter:

H: Hard
S: Soft

4th/5th Letter:

1: Source 1
2: Source 2

Relative Viscosity at 135 C

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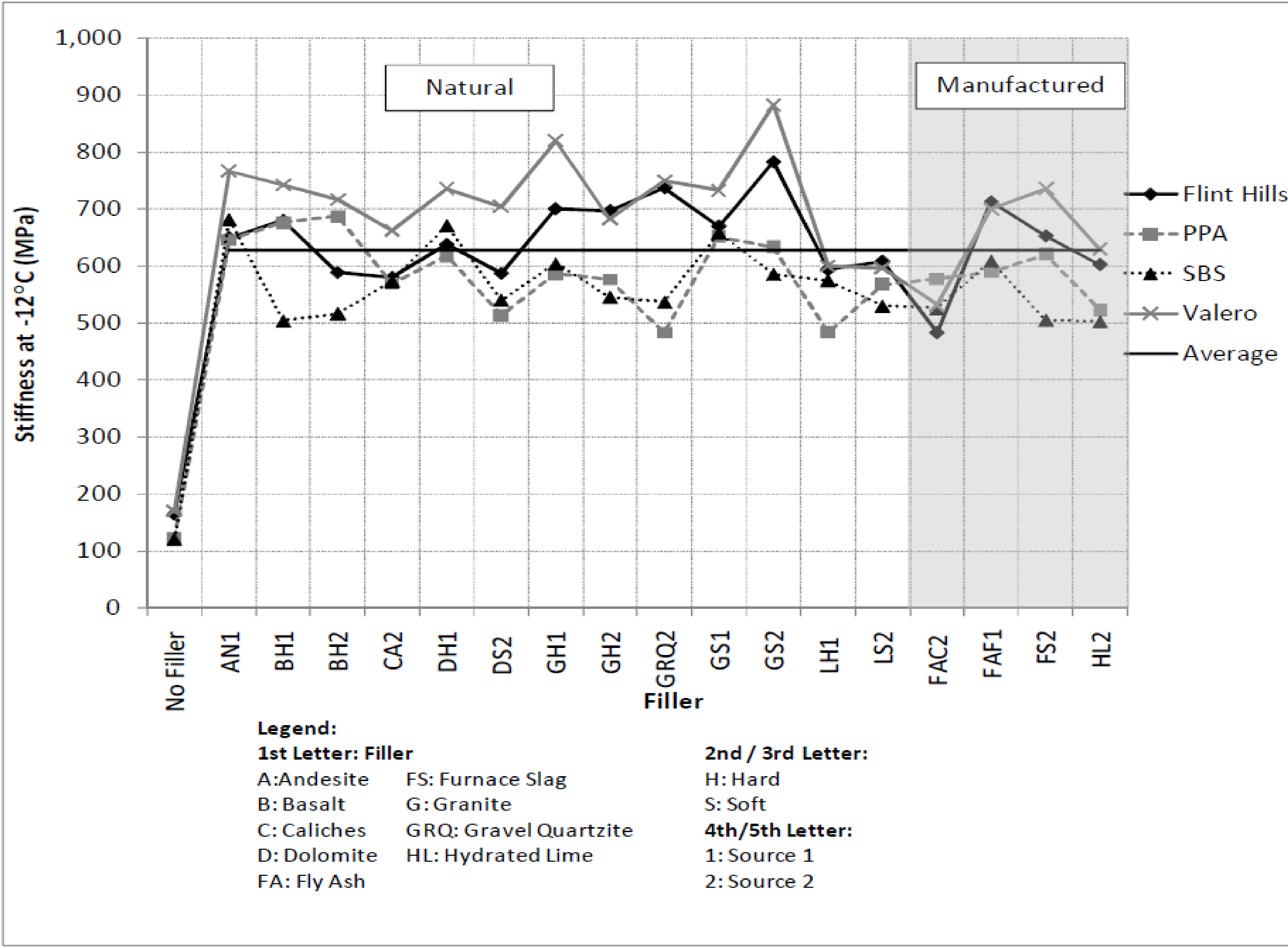


Figure 2-27. Distribution of Mastic Low Temperature Stiffness at -12°C

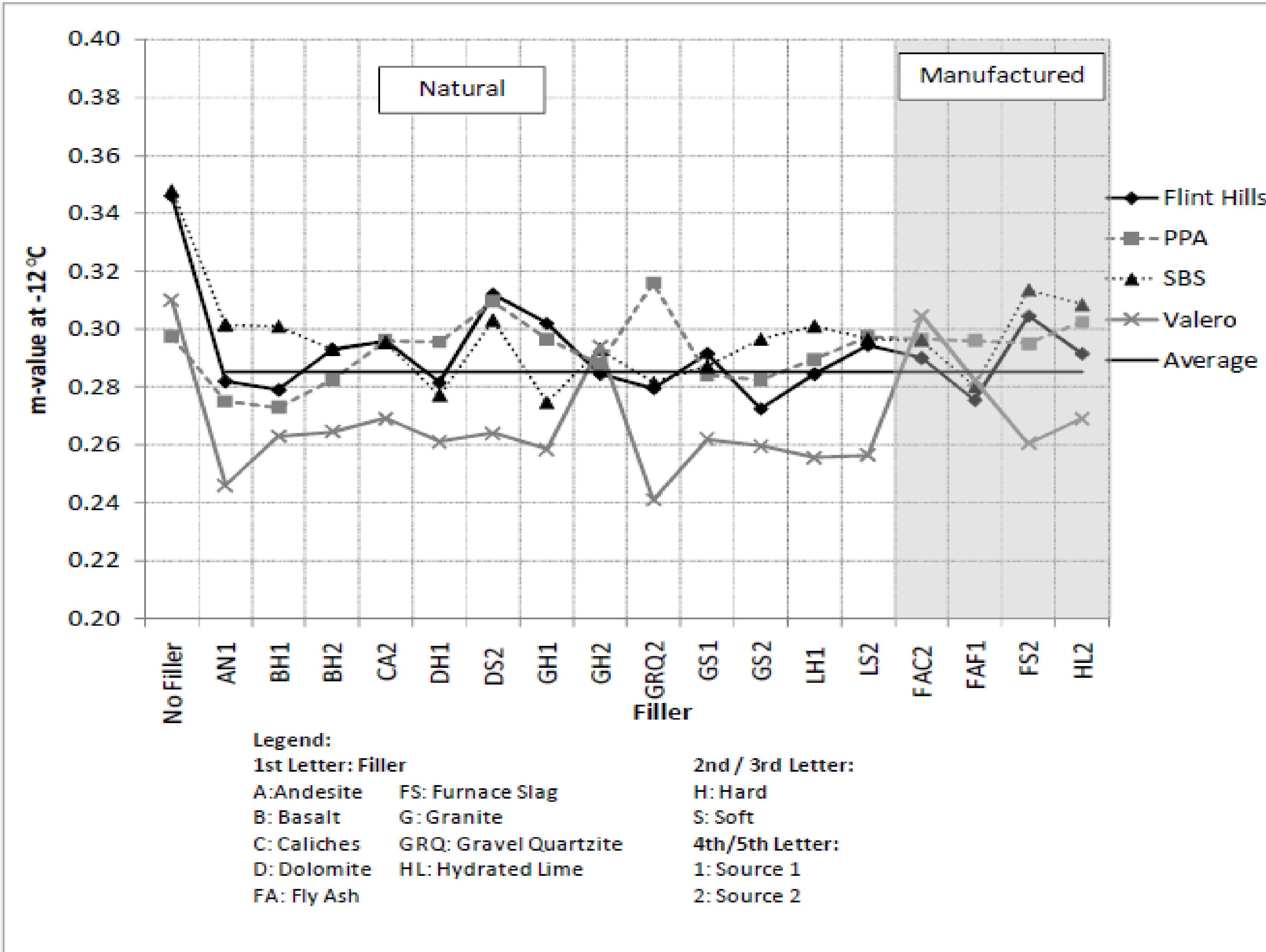
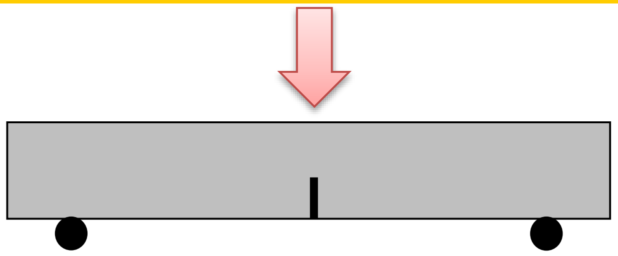


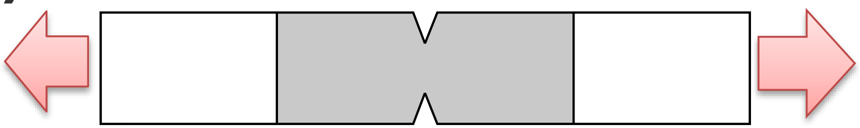
Figure 2-29. Distribution of Mastic m-value at -12°C

Binder Low Temperature Fracture Tests

- Single Edged Notched Beam (SENB)



- Double Edged Notched Test (DENT)



- Asphalt Binder Cracking Device (ABCD)

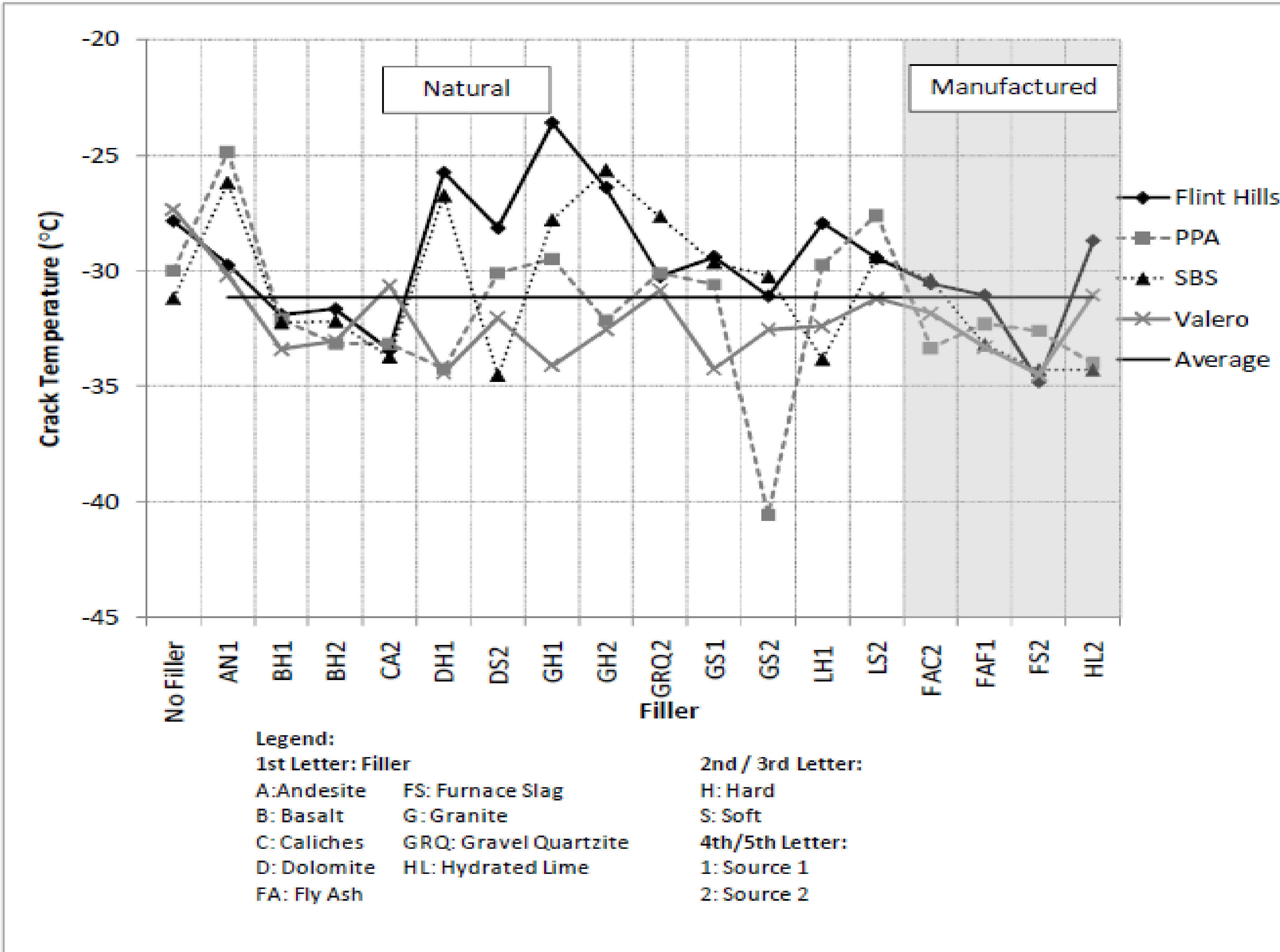


Figure 2-31. Distribution of Mastic Crack Temperature

Concluding Remarks

- Binder Rheology, Glass Transition, and fracture properties are important for prediction and controlling of cracking.
- Measurements methods are advanced enough and feasible to conduct.
- Aging and interaction with fillers can change behavior totally.
- To qualify binders, it is best to test with the filler and to make sure long term aging is simulated.

Thank you for the Opportunity

Questions & Discussion

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