Phenomenological models for binder rutting and fatigue

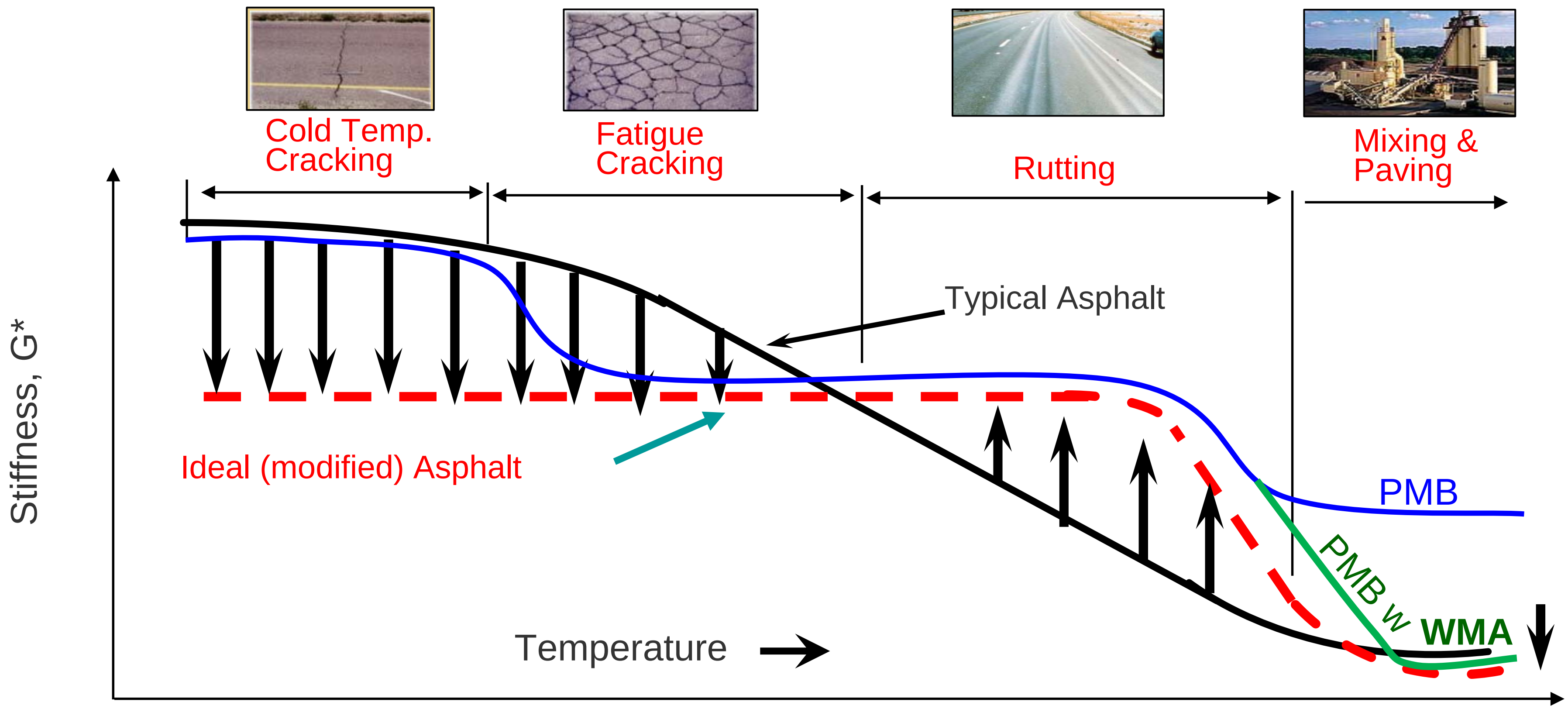
University of Wisconsin

Research Team

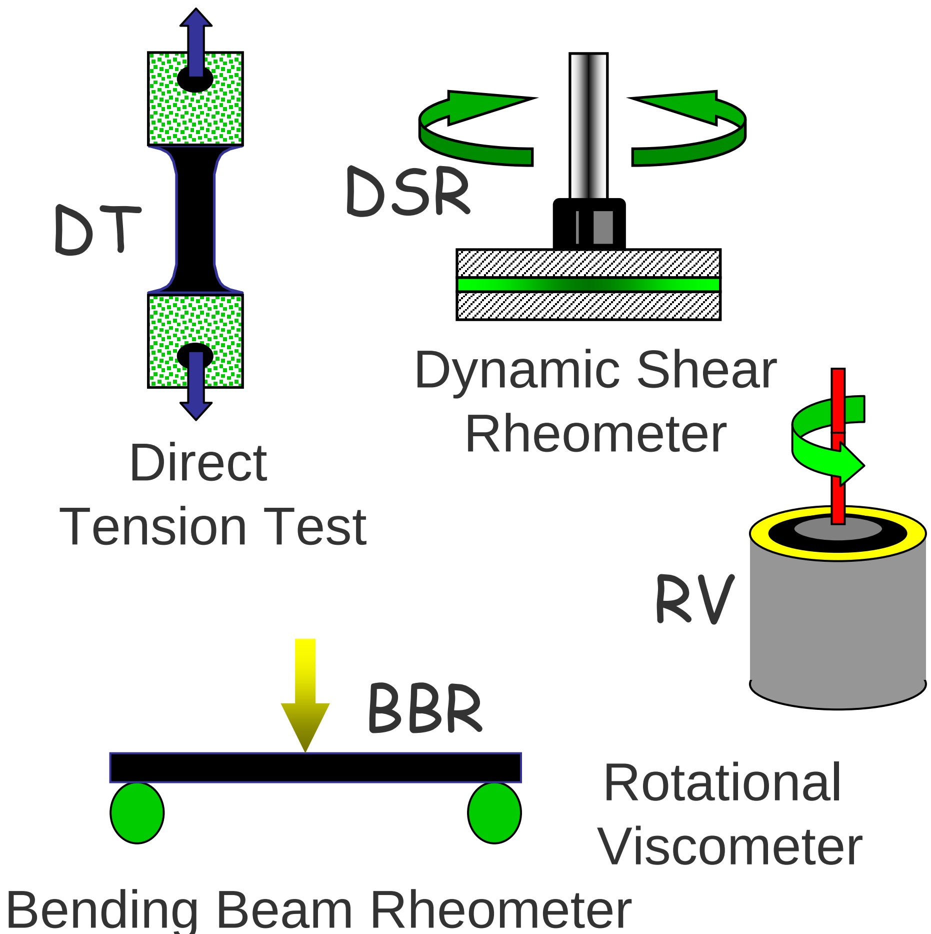
Outline of Talk

- The need for measuring damage behavior
- Current efforts , and evolution of ideas
- Gaps and what to do about them

Performance Grading and Modified (Engineered) Bitumen



Review of Superpave Binder Tests

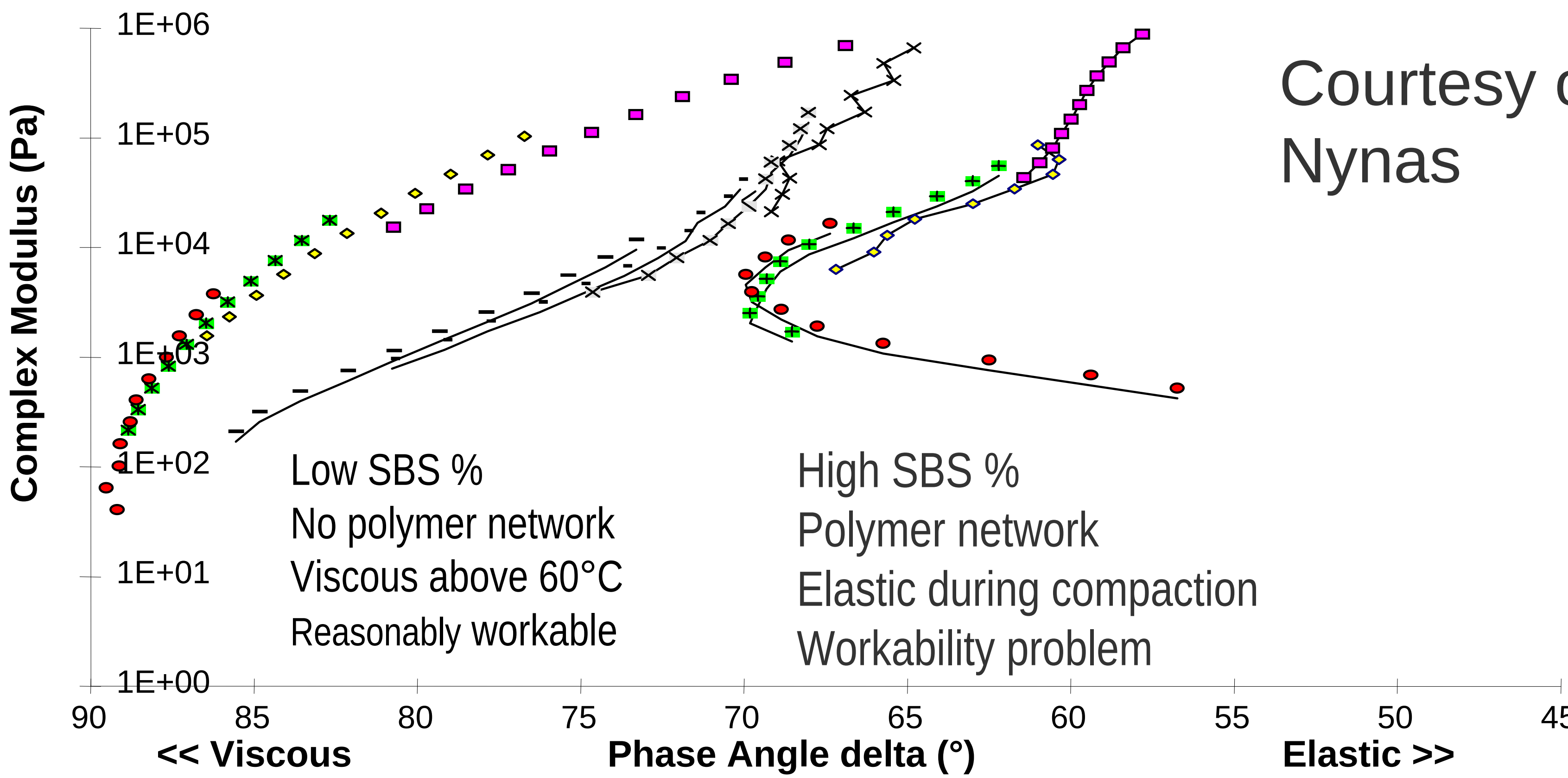


Related to Performance!

- Climate -- PG HT-LT
- Traffic Speed – DSR
- Traffic Volume – PG shift

- Traffic loading – NA
- Pavement Structure – NA
- Assumption:
  Bitumen in Linear VE range

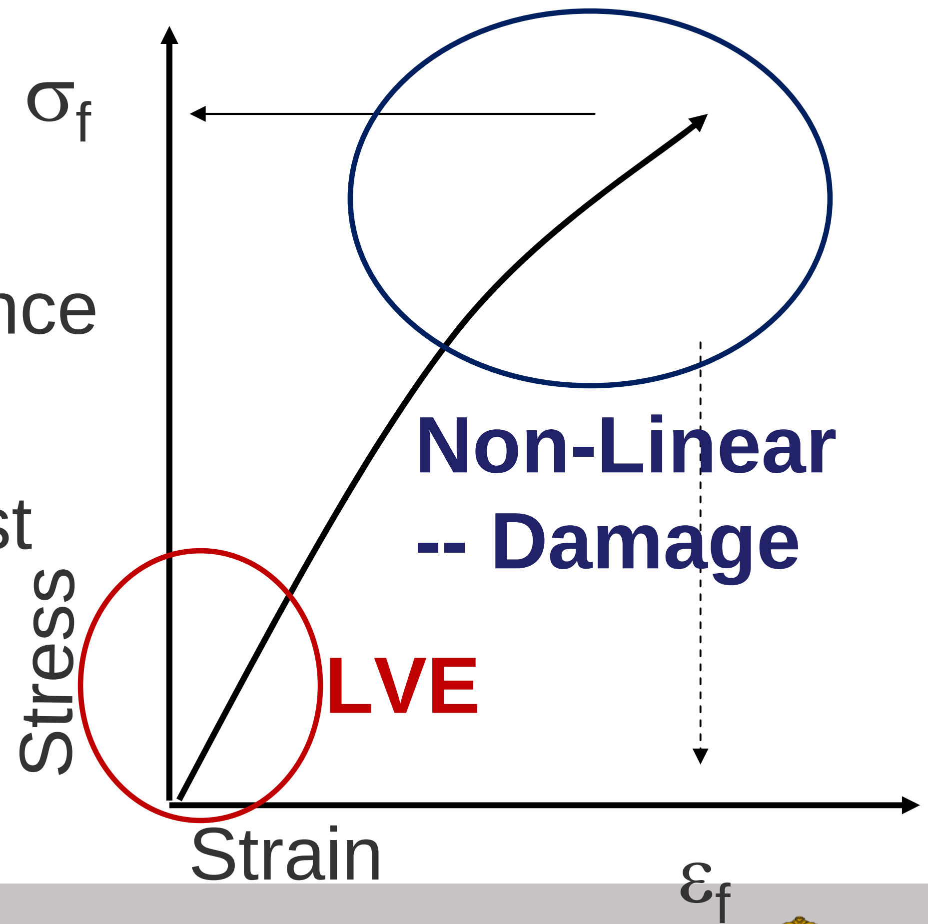
Current focus is on Linear Visco-elasticity: G*, delta



Courtesy of Nynas

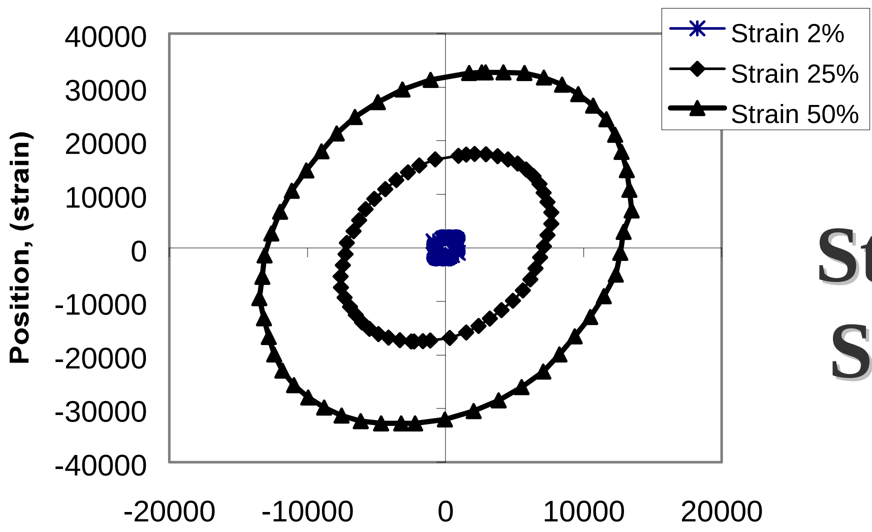
Performance Grading –Redefined (2001)

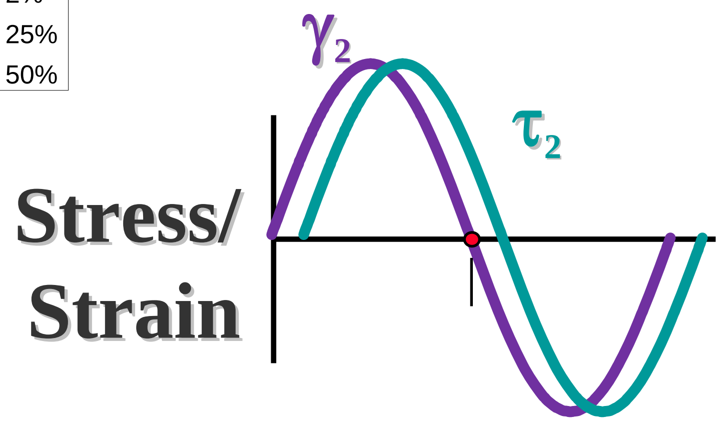
- Linear VE is not sufficient (NCHRP 9-10)
- Bitumen damage resistance is very important
- Modified bitumen are best in damage resistance



RUTTING

Current Test: Cyclic Loading



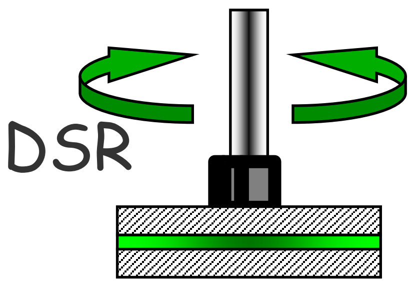


Can only give total energy:

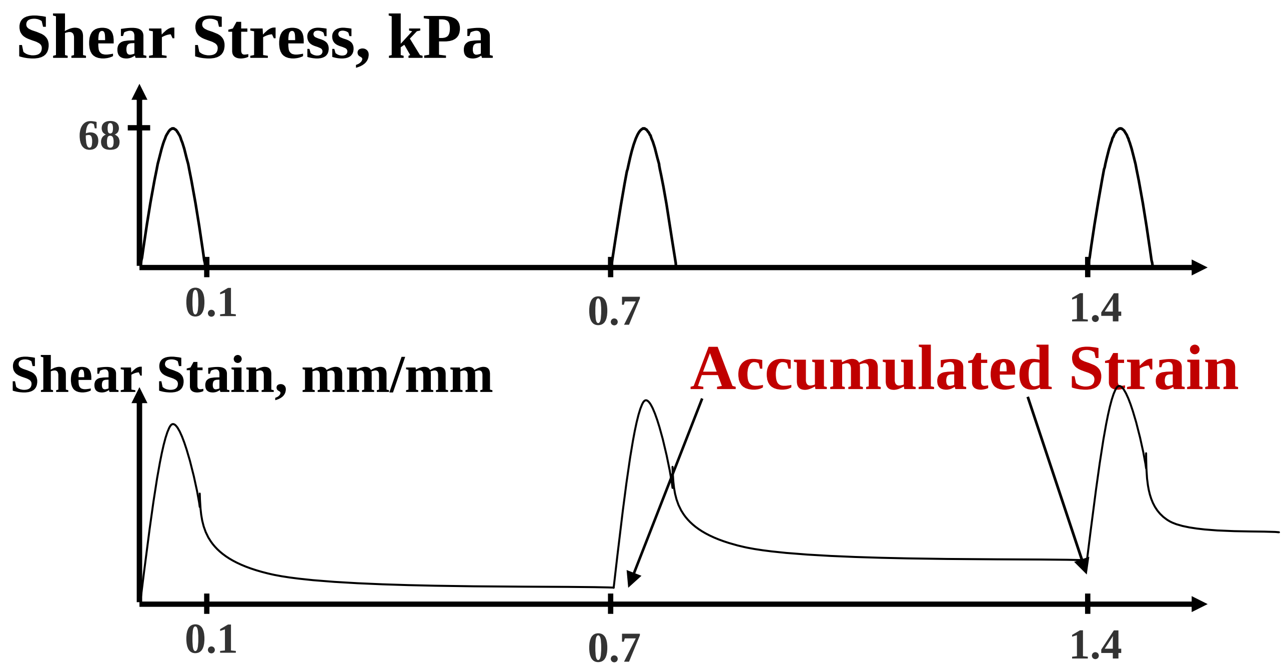
$$\text{Total } W = \pi \cdot \tau_i^2 \cdot \sin \delta / G^*$$

$$= W_{delayed\ elastic} + W_{viscous}$$

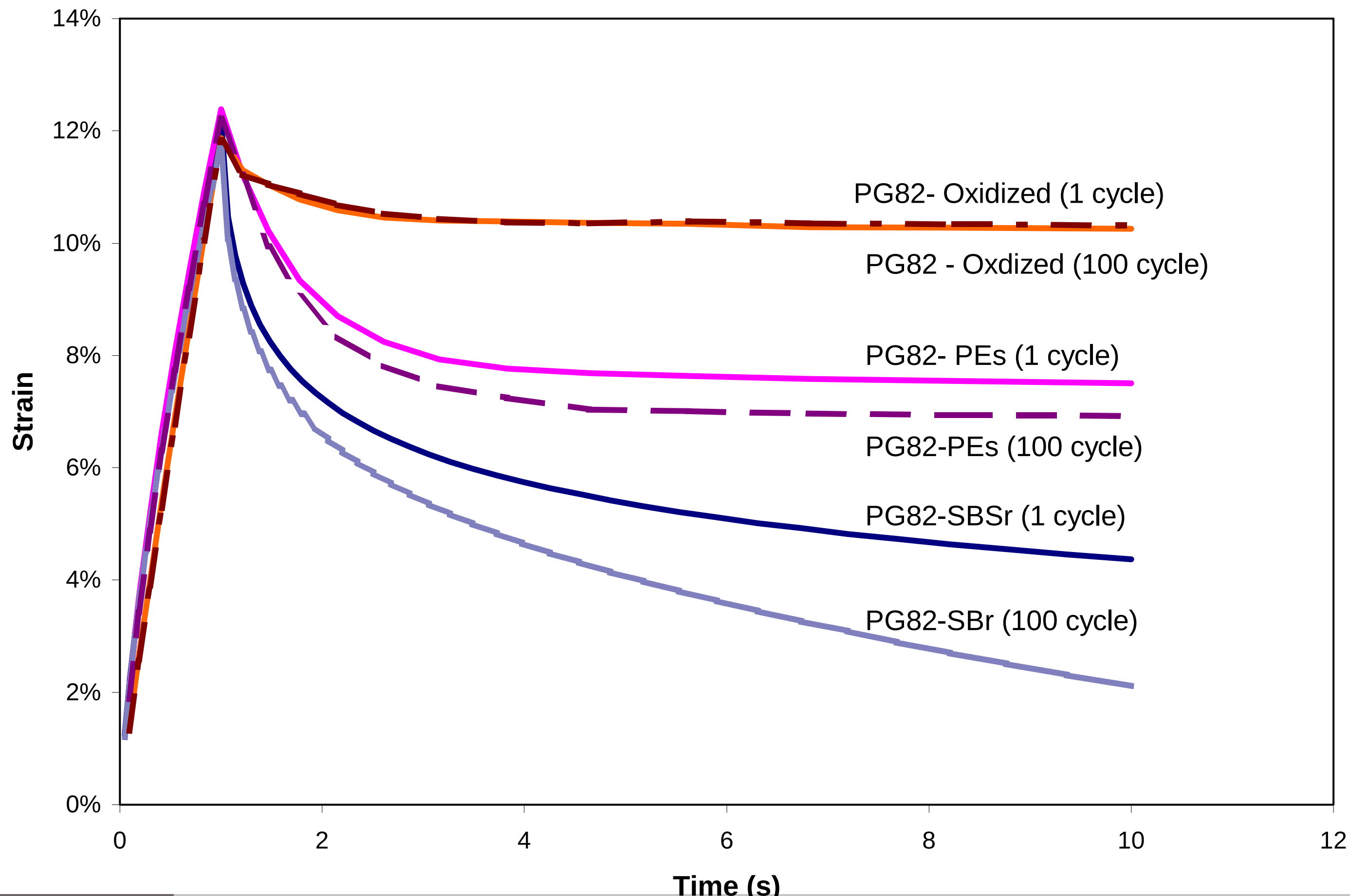
The new tests : Creep and Recovery NCHRP 9-10 >> (MSCR)



Dynamic Shear Rheometer



Binders with same G*/sinδ but different recovery >> % Recovery in MSCR



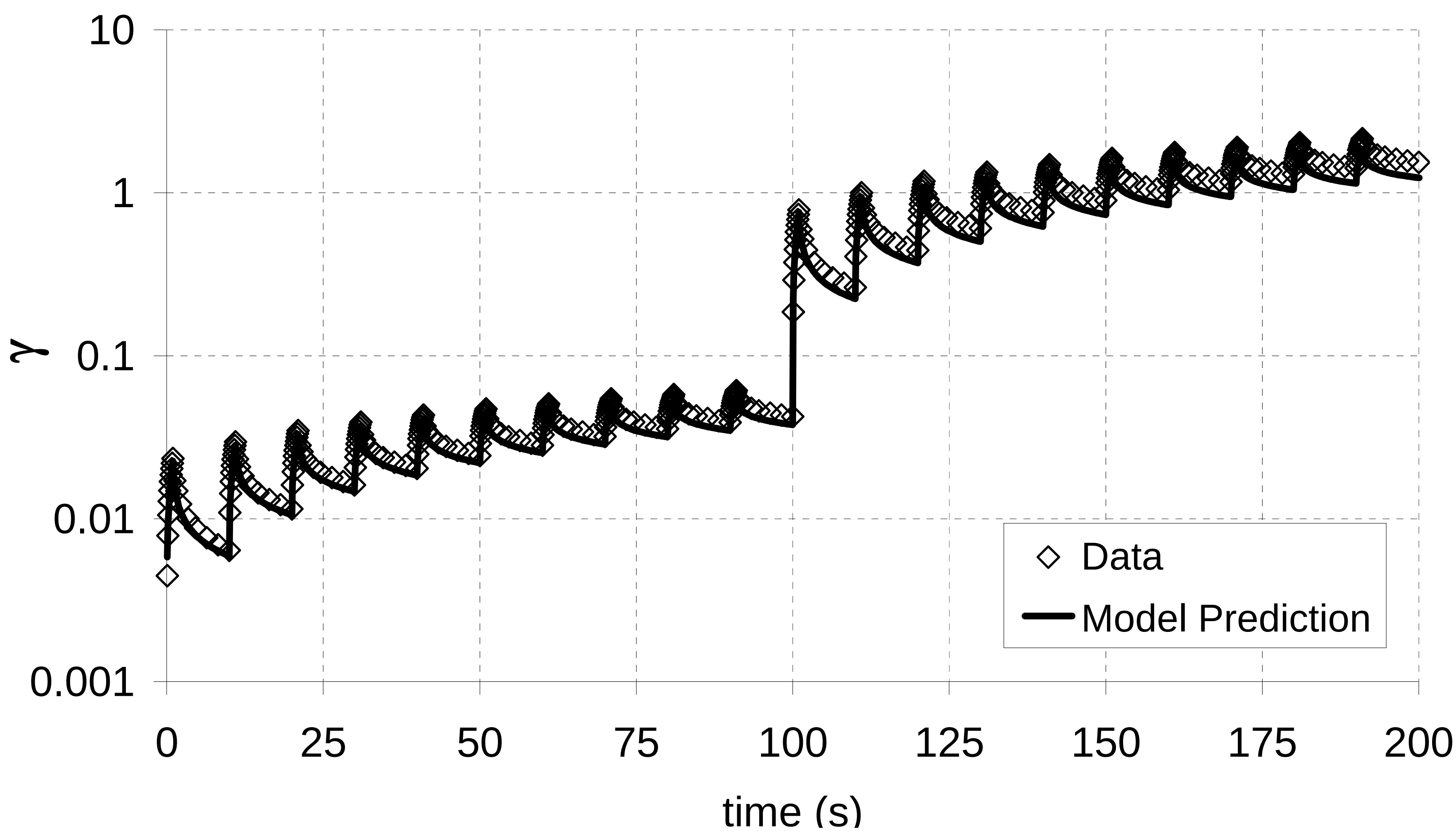
Binder Rutting Parameter

- The creep compliance, J(t), in terms of its elastic component (J_e), the delayed-elastic (J_{de}), and the viscous component (Jnr):

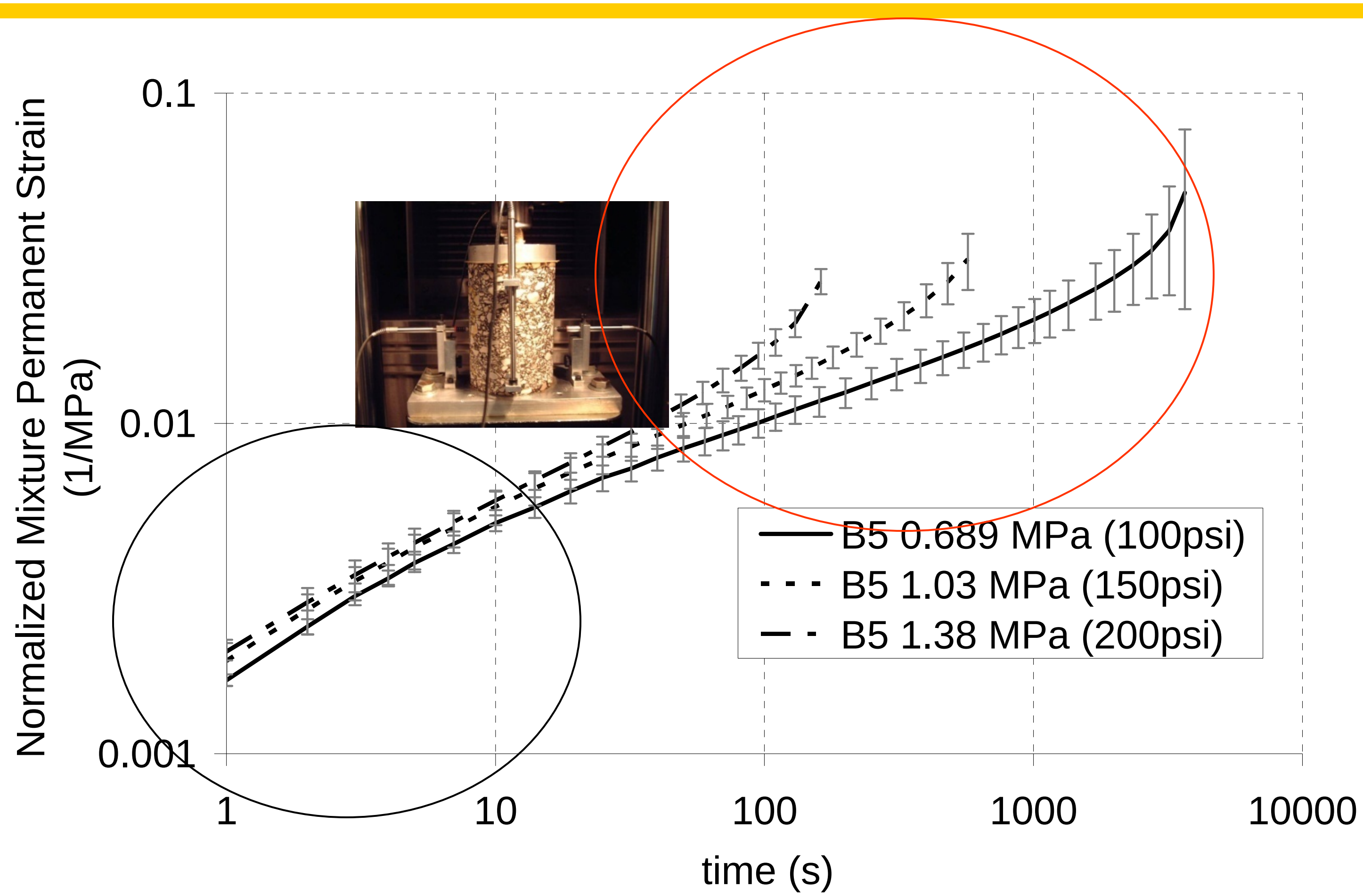
$$J(t) = J_e + J_{de} + J_{v \longrightarrow nr}$$

- Calculate the viscous, non-recoverable, compliance (Jnr).

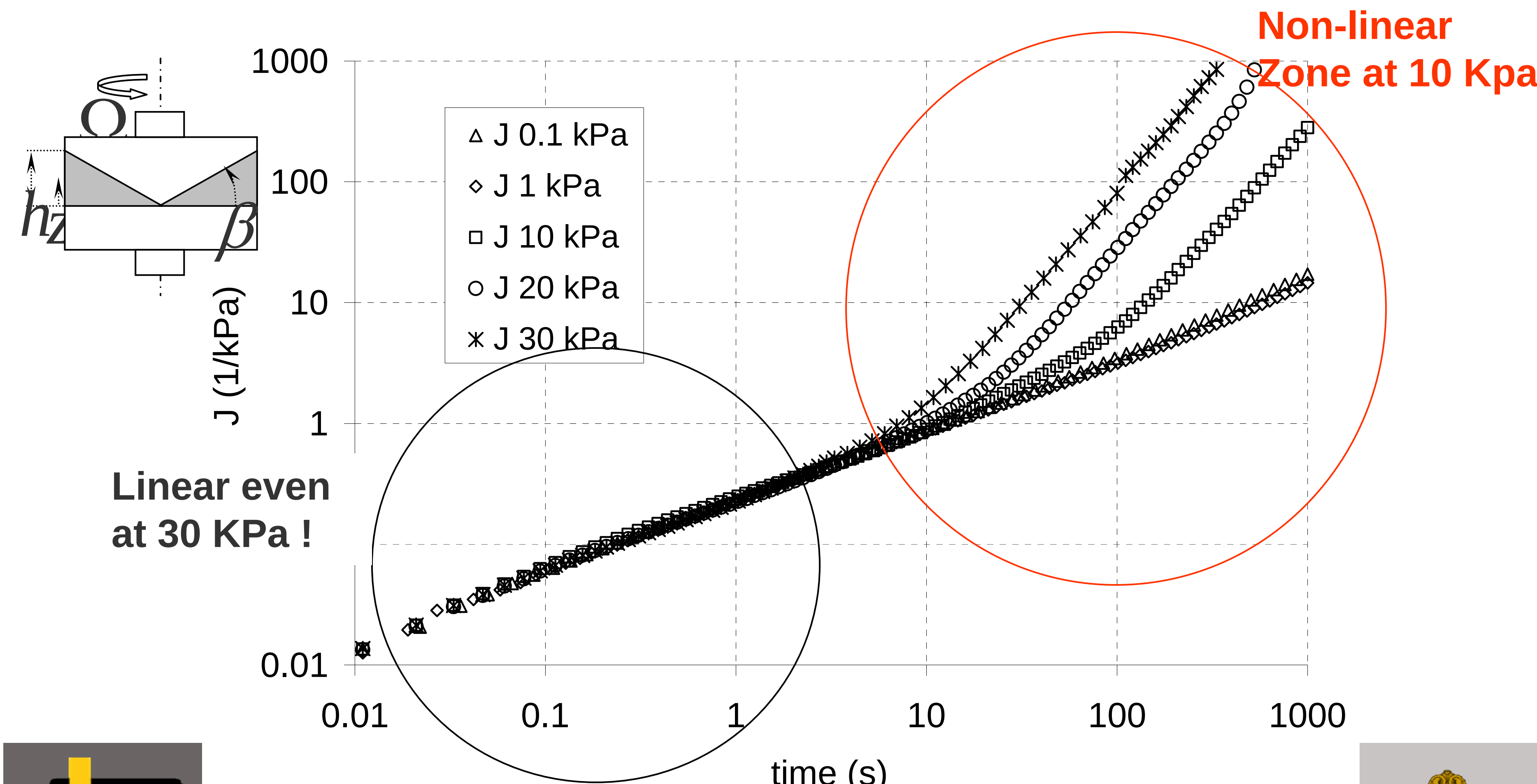
New AASHTO Standard for MSCR 100Pa , 3200 Pa



Effect of Stress and Total Strain on Mixture Rutting - R. Delgadillo, Ph.D Thesis 2008



Knowledge Gaps:
Effect of Loading Time and Stress



Current Modeling of Creep and Recovery, R. Delgadillo, 2008

- Nonlinear Power Model:

$$\gamma(t,\tau) = k_1 \cdot t^{m_1} \cdot \tau^{p_1} + k_2 \cdot t^{m_2} \cdot \tau^{p_2}$$

  - γ = shear strain (dimensionless)
  - t = time (s)
  - τ = shear stress (kPa)
  - k_i, m_i, p_i = model parameters

$$\gamma(t,\tau_0) = \tau_0 \cdot J_p(t,\tau_0) + \tau_0 \cdot J_r(t)$$

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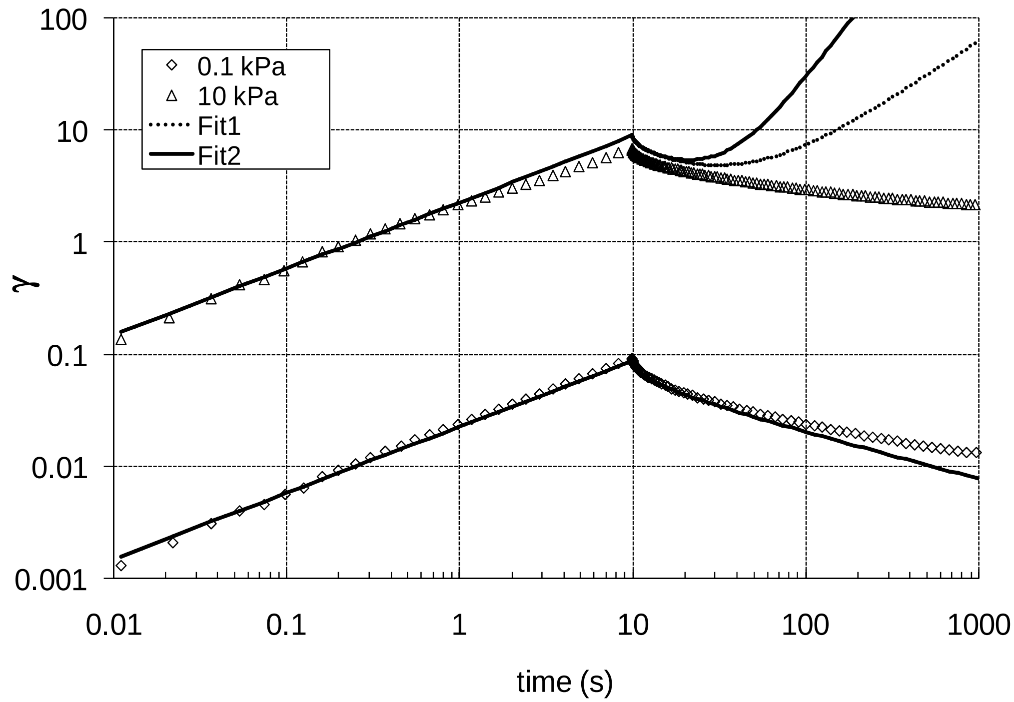
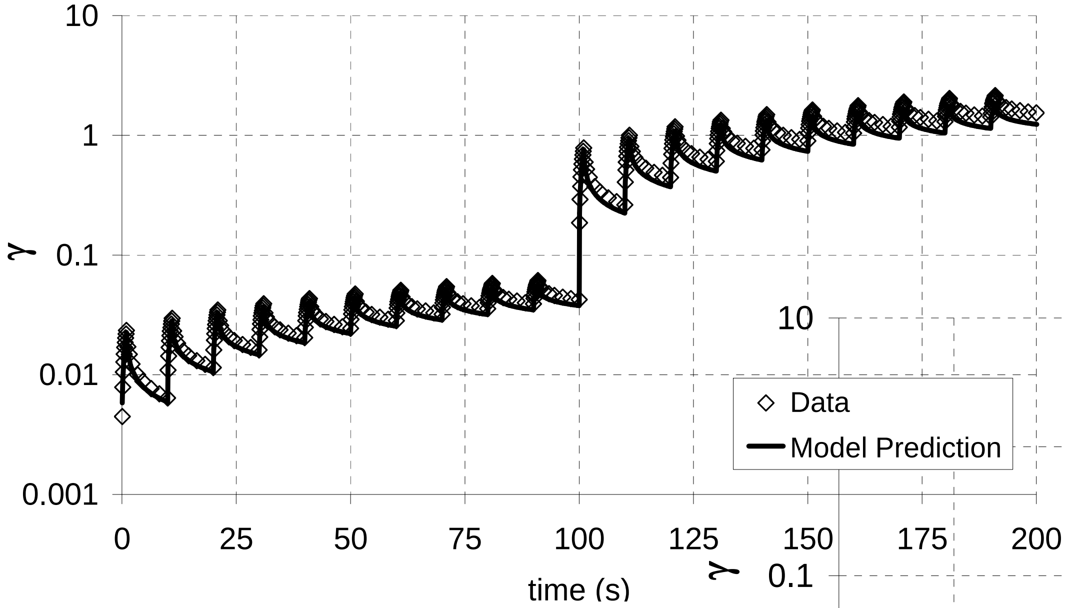
Failure of model for some binders
We have to separate recoverable from permanent

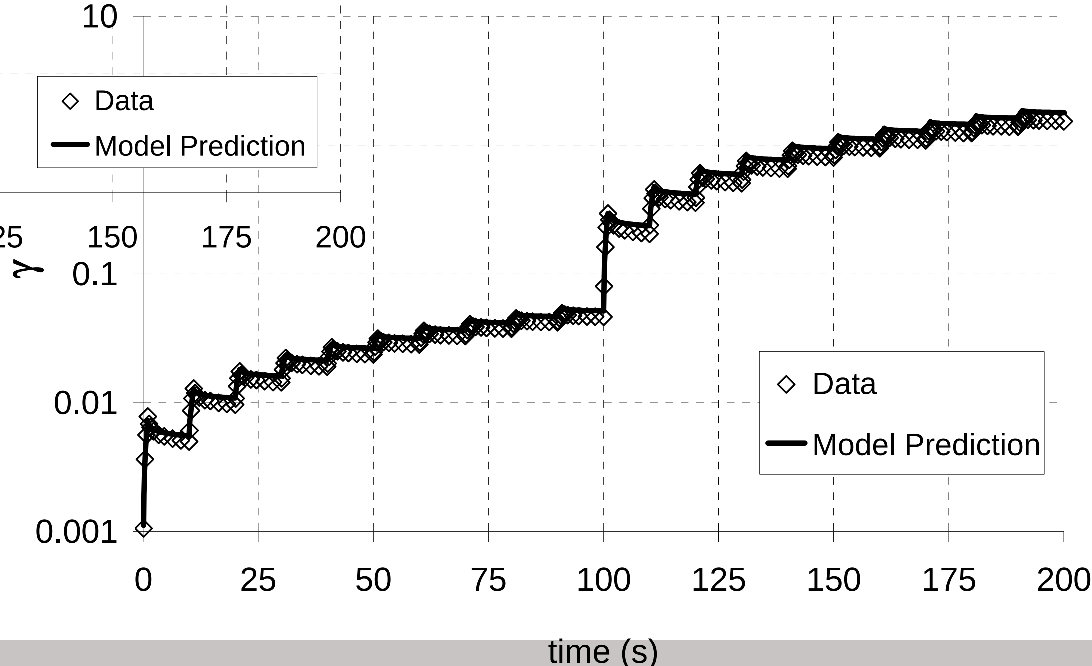


$$J_r(t) = 7.11 \cdot 10^{-2} \cdot t^{0.807} - 4.90 \cdot 10^{-2} \cdot t^{0.877}$$

$$J_p(t, \tau) = 4.90 \cdot 10^{-2} \cdot t^{0.877} + 3.37 \cdot 10^{-3} \cdot t^{1.34} \cdot \tau^{0.25}$$

Application of the models





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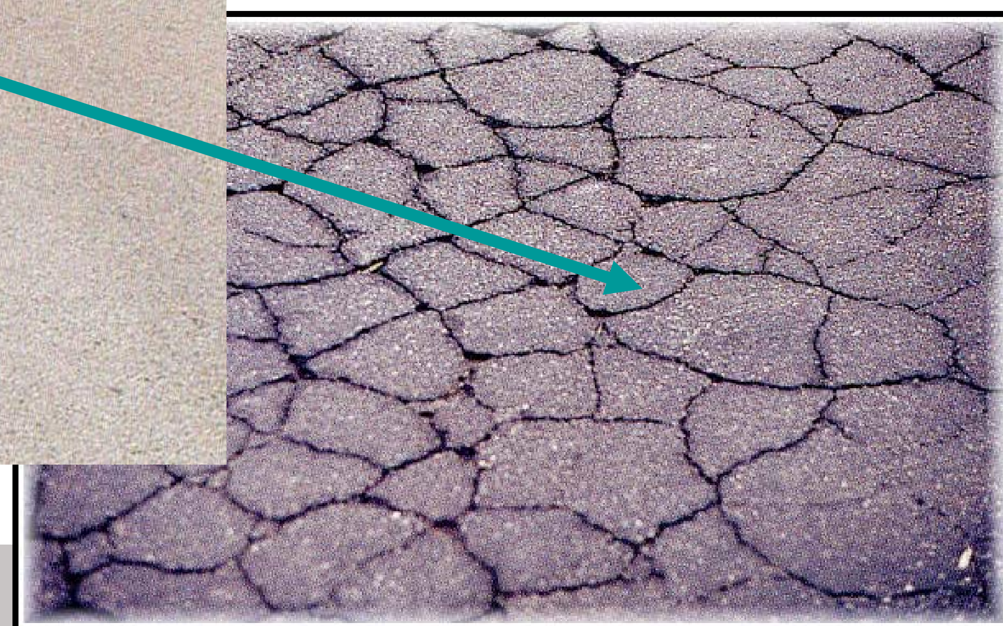
Gaps in the Knowledge

- Nonlinearity effects
  - Stress level
  - Total strain / loading time?
- Why loading behavior different than unloading behavior ? How can we model this?
- Is elastic recovery important ?
- Can binder elasticity improve resistance to rutting of mixture ?

Longitudinal Cracking In the Wheel Path – Alligator cracking

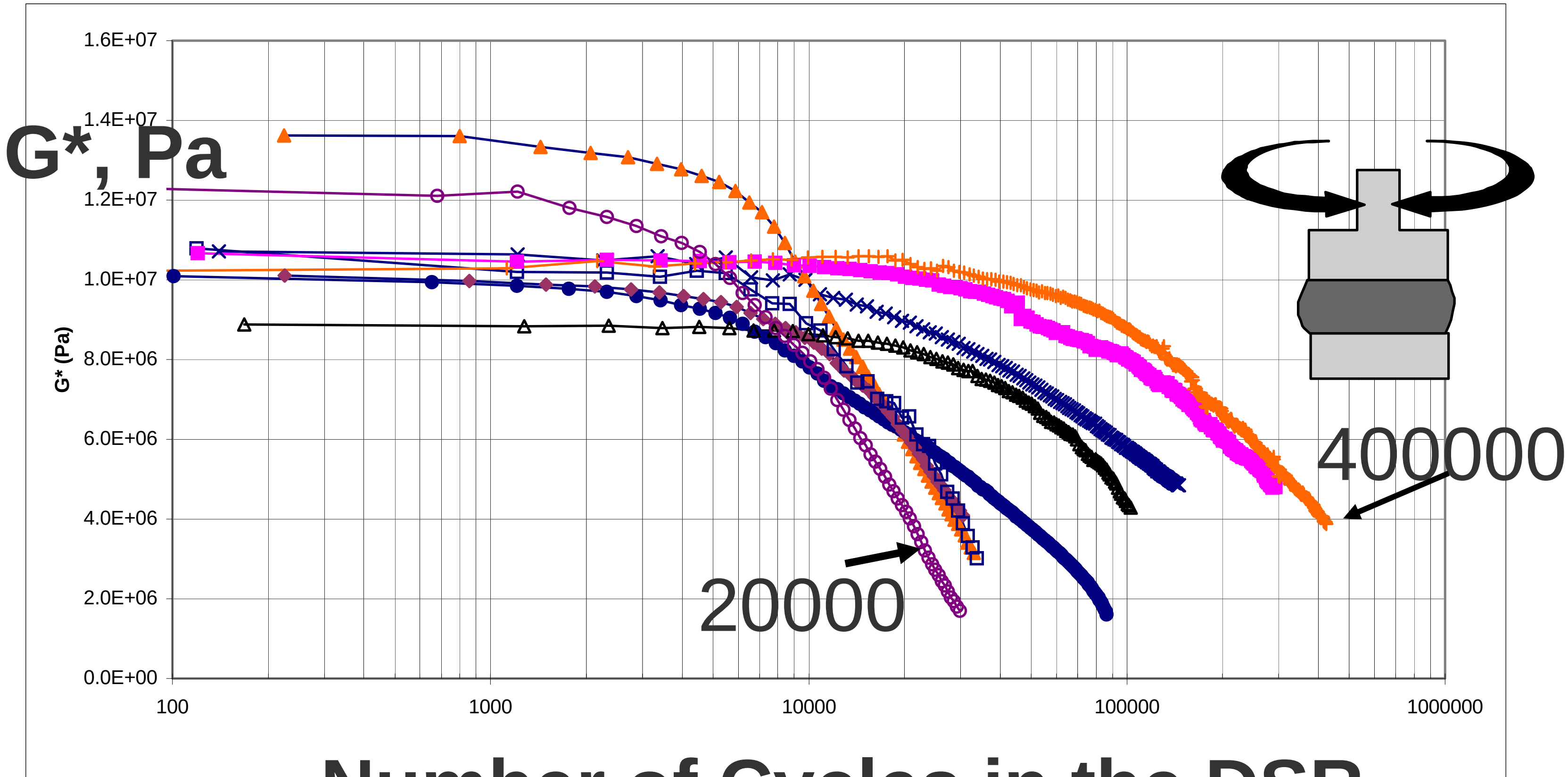
Fatigue



Evolution of binder fatigue testing

- Pre- SHRP , none --- or Penetration
- SHRP : Linear Visco-elastic
  - G* sinδ , Rheological index, m , ect….
- NCHRP 9-10
  - Binder fatigue – time sweep
- ETG – FHWA : Stress Sweep
- DENT – Canada – Ontario - FHWA
- Asphalt Research Consortium
  - Binder Yield Energy Test (BYET)
  - Linear Amplitude Sweep + VECD >>ETG >> AASHTO

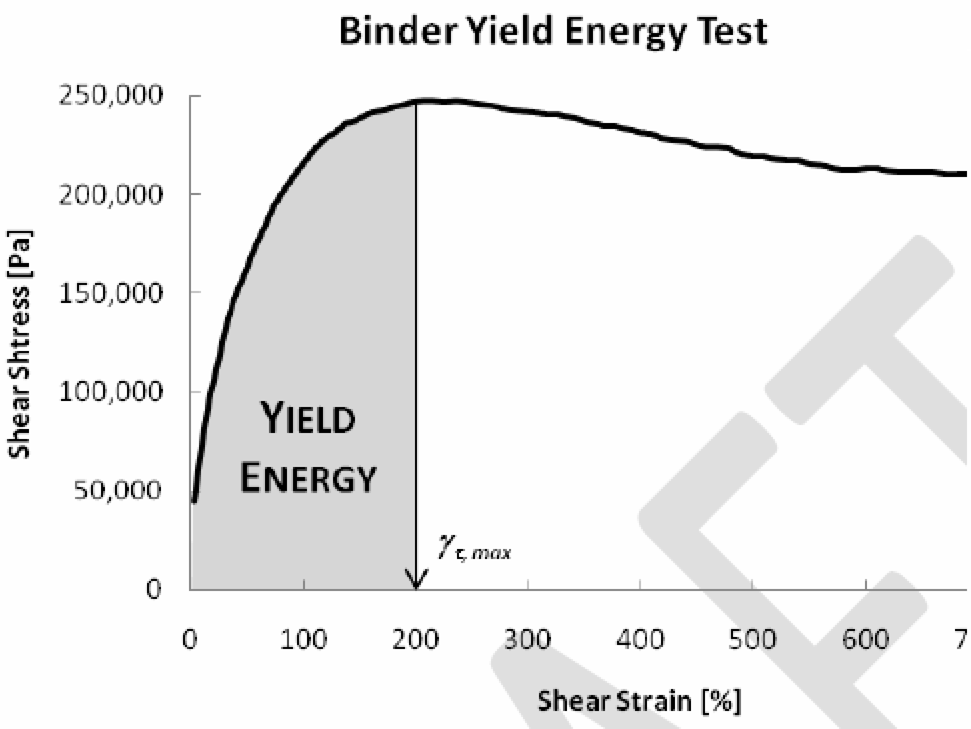
Binder only
Fatigue Test Results (DSR)

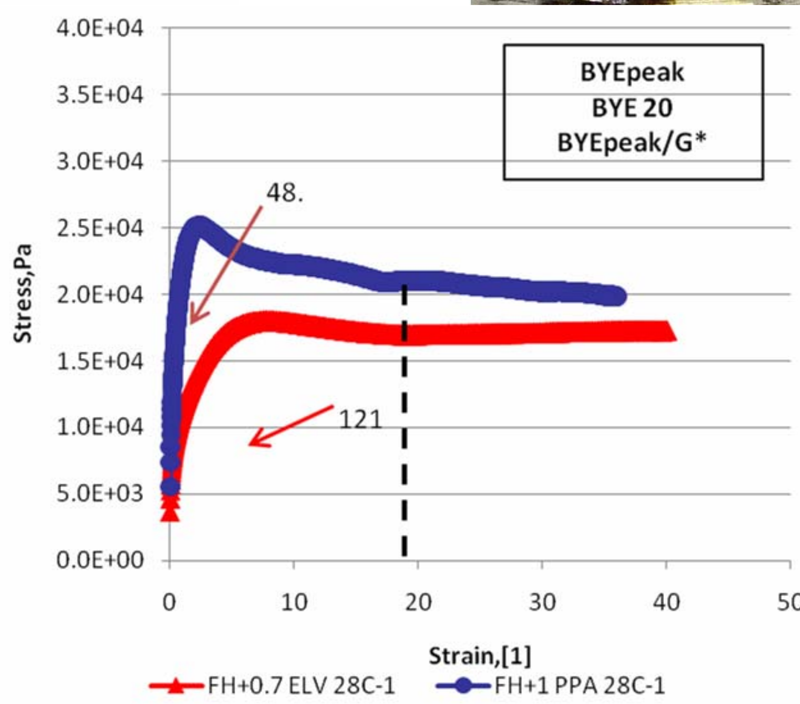


Number of Cycles in the DSR

Binder Yield Energy Test (BYET)

$$Yield\ Energy = A_{i-1} + \sum_{i=1}^{N}\left(\frac{\tau_i + \tau_{i-1}}{2}\right)(\gamma_i - \gamma_{i-1})$$





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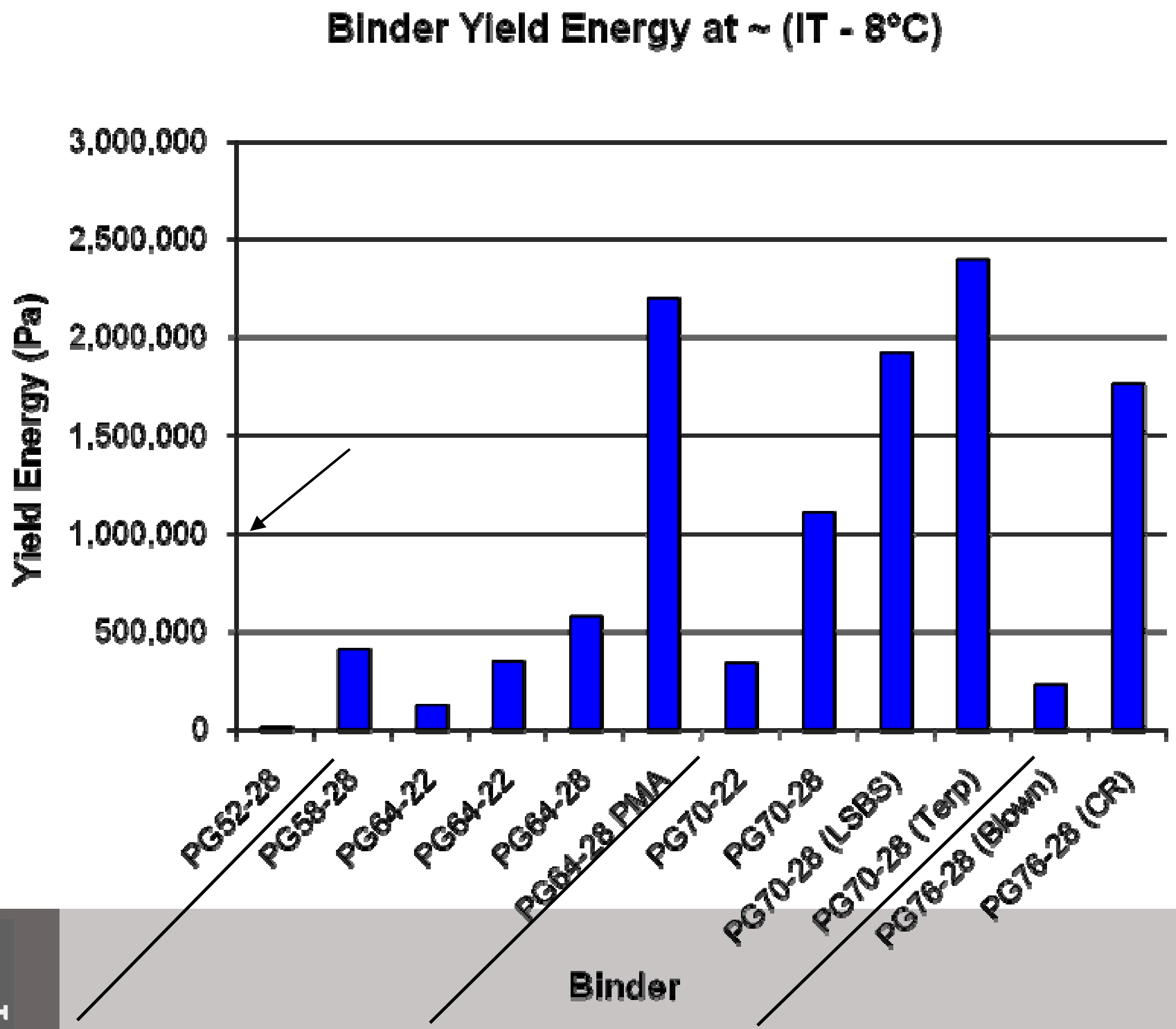
Yield Energy Evaluation of different binders



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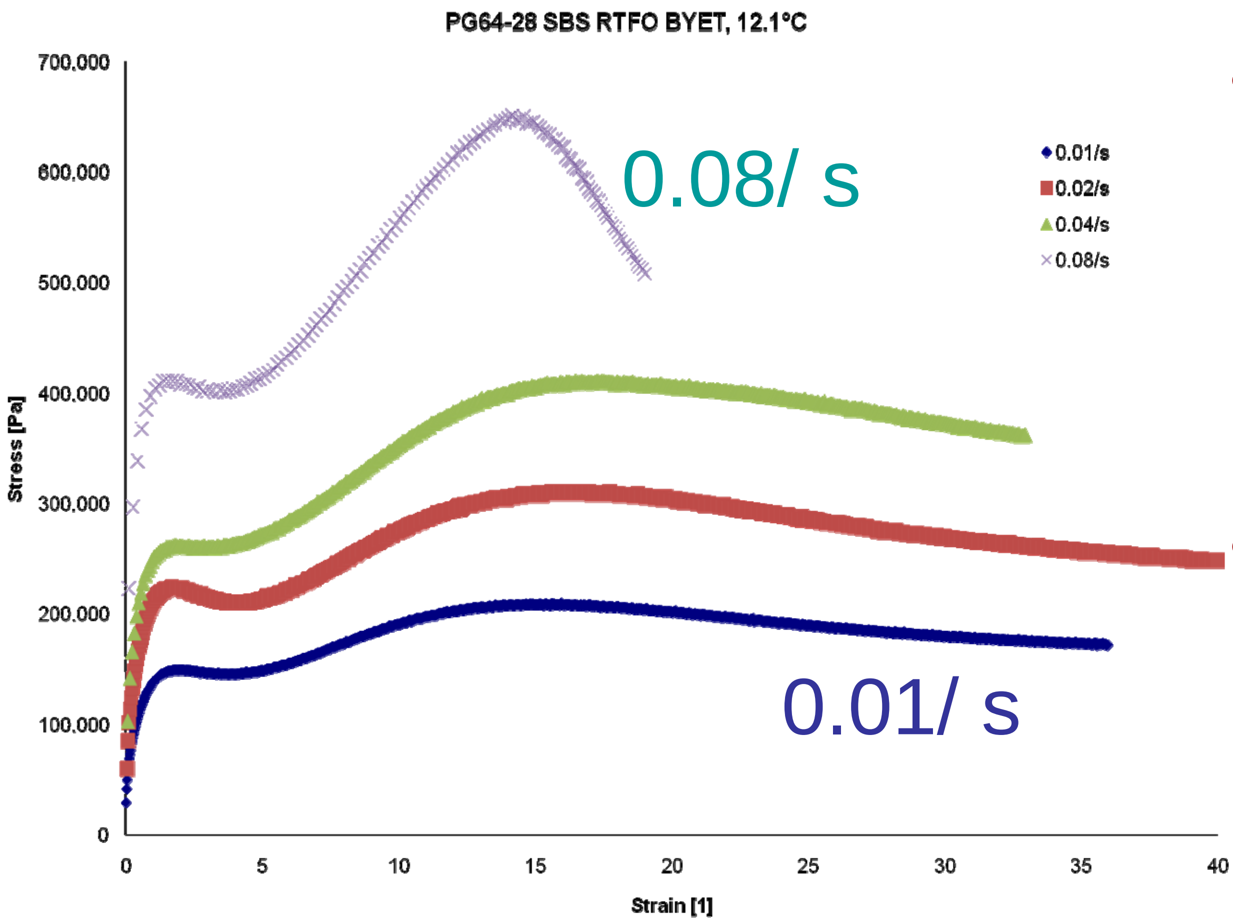
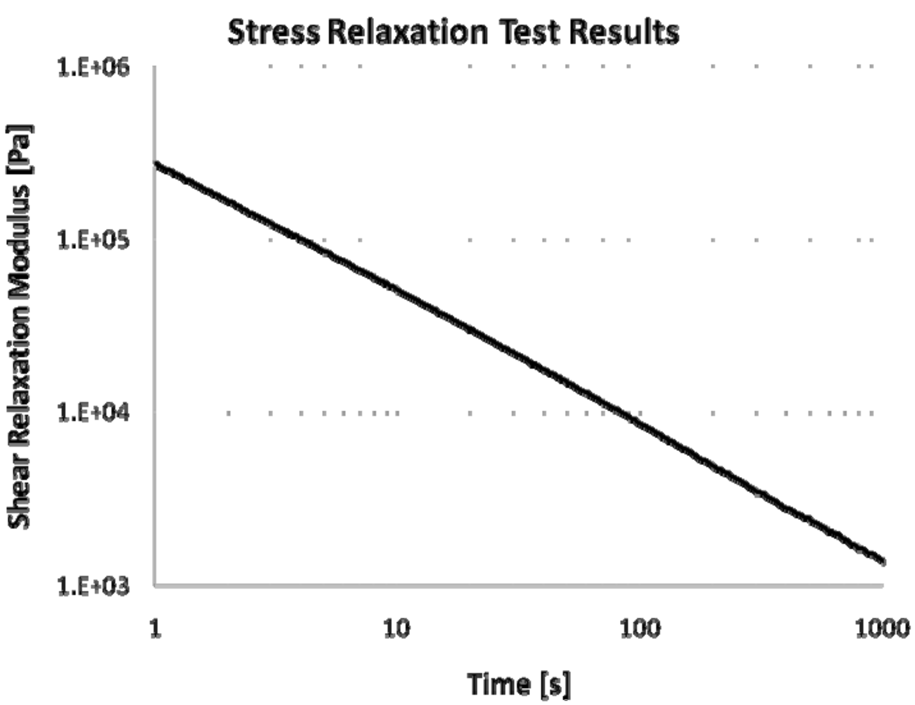
Effect of Rate on Monotonic Test- Feb-March 08

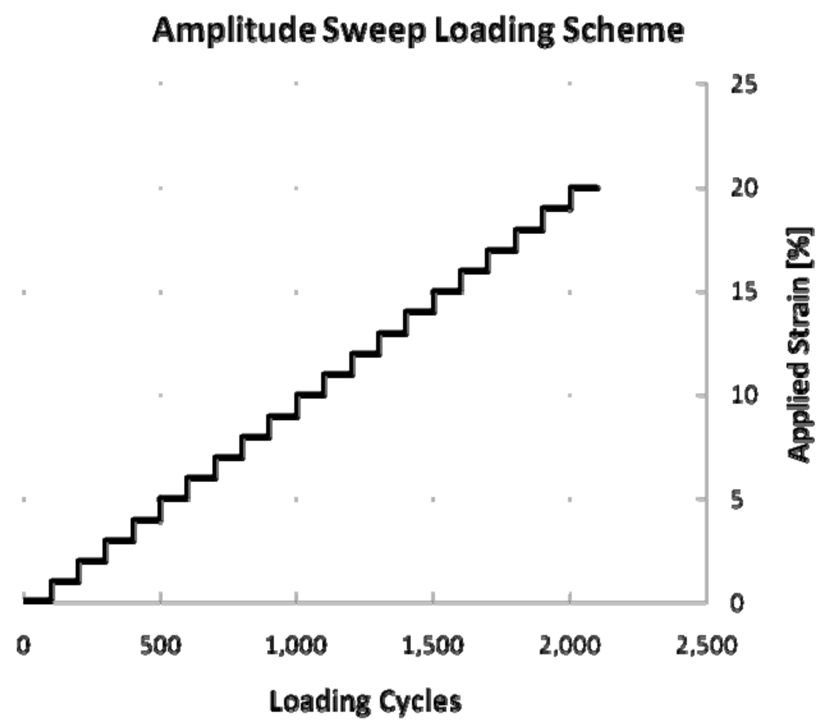


- Slippage began to occur at shear rates of 8% per second
- Limited by equipment capabilities

Linear Amplitude Sweep (LAS) Need 2 tests for VECD analysis

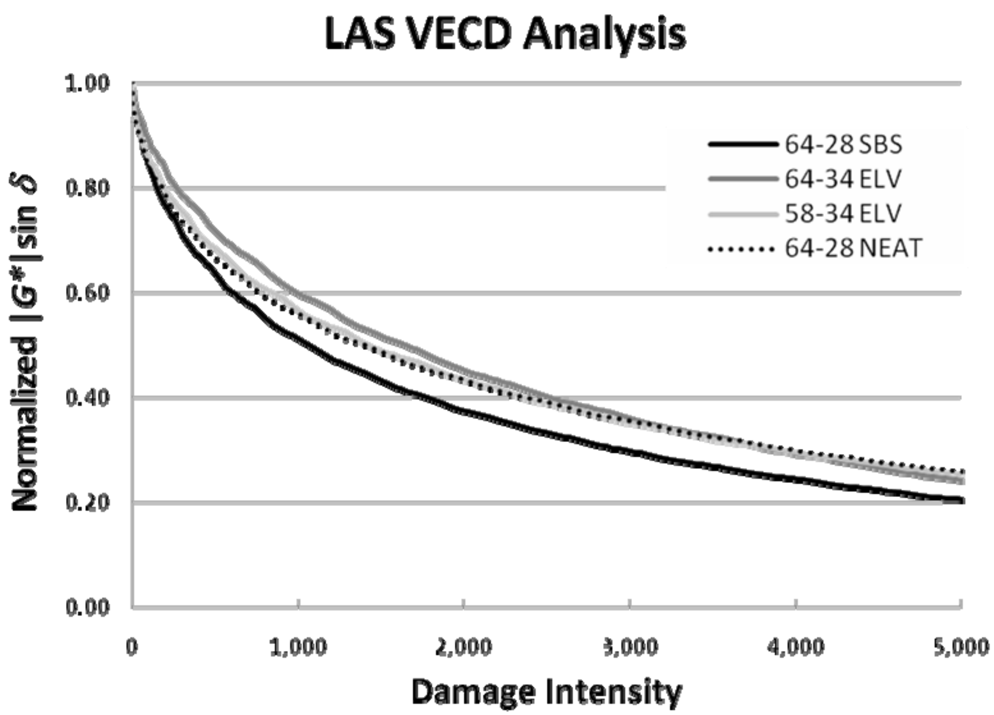


Relaxation /freq Sweep



Amplitude Sweep

VECD Analysis of LAS – Damage Curve



Damage equation following Yong-Rak Kim & D. Little work (2006)

$$D(t) \cong \sum_{i=1}^{N} \left[\pi \cdot I_D \cdot \gamma_0^2 \left(|G^*| \sin \delta_{i-1} - |G^*| \sin \delta_i \right) \right]^{\frac{\alpha}{1+\alpha}} \left(t_i - t_{i-1} \right)^{\frac{1}{1+\alpha}}$$

VECD Fatigue Prediction Model
Work with E. Kutay - 2009

- With the VECD curve fit to a simple numeric equation:

$$|G*|\sin\delta = C_0 - C_1(D)^{C_2}$$

- Fatigue life can be predicted using:

$$N_f = \frac{f(D_f)^k}{k\left(\pi \frac{I_D}{|G^*|} C_1 C_2\right)^{\alpha}} |G^*|^{-\alpha} (\gamma_{max})^{-2\alpha}$$

$$k = 1 + (1 - C_2)\alpha$$

Calculating A and B

7.4. The following parameters (A and B) for the binder fatigue performance model can now be calculated and recorded as follows:

$$A = \frac{f(D_f)^k}{k\left(\pi \frac{I_D}{|G^*|} C_1 C_2\right)^{\alpha}} |G^*|^{-\alpha}$$

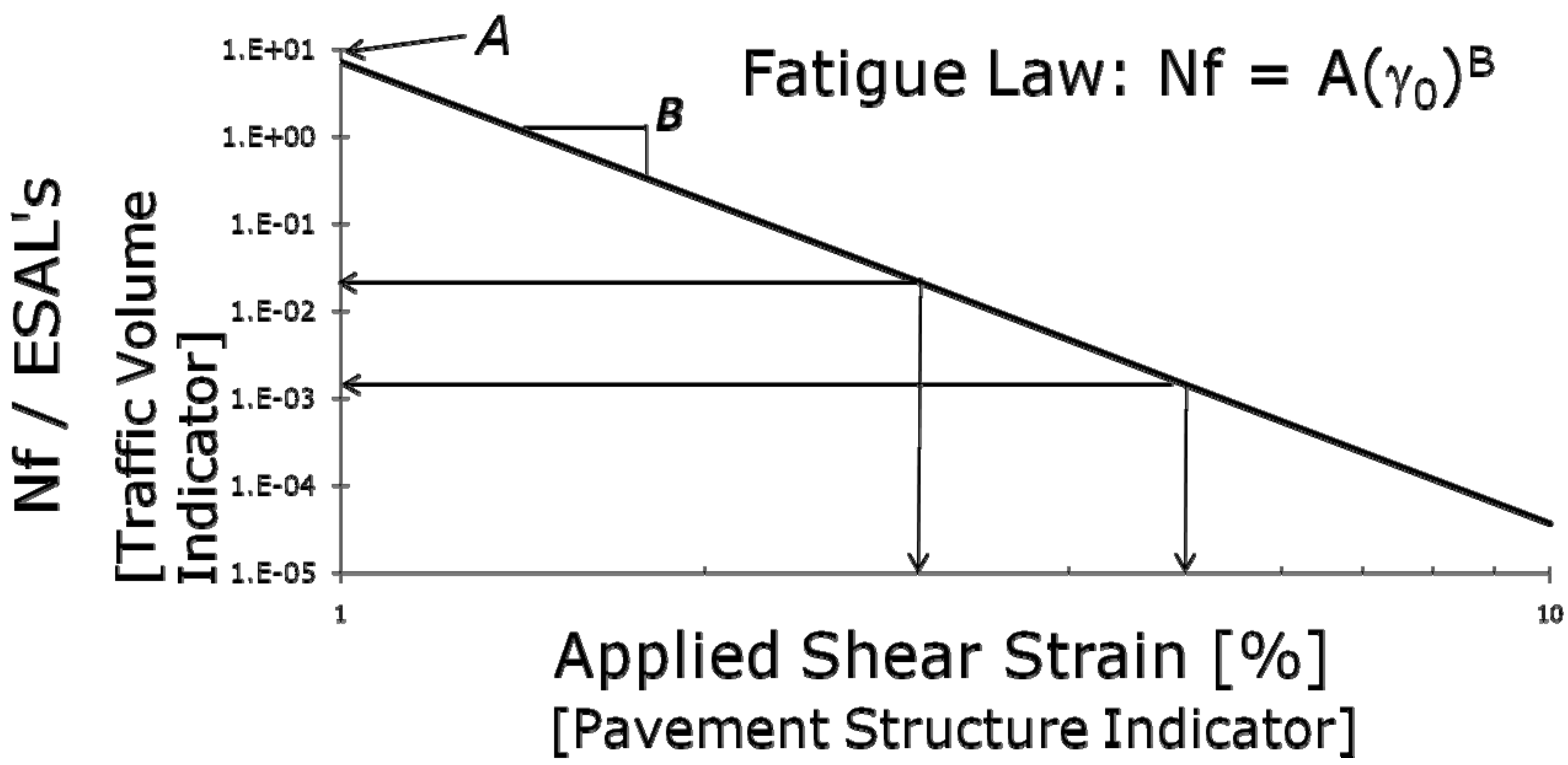
Where f = Loading frequency (10 Hz).
$k = 1 + (1 - C_2)\alpha$.
$|G^*|$ = Average value of the dynamic shear modulus from the 0.1% applied strain interval, MPa.

$B = -2\alpha$.

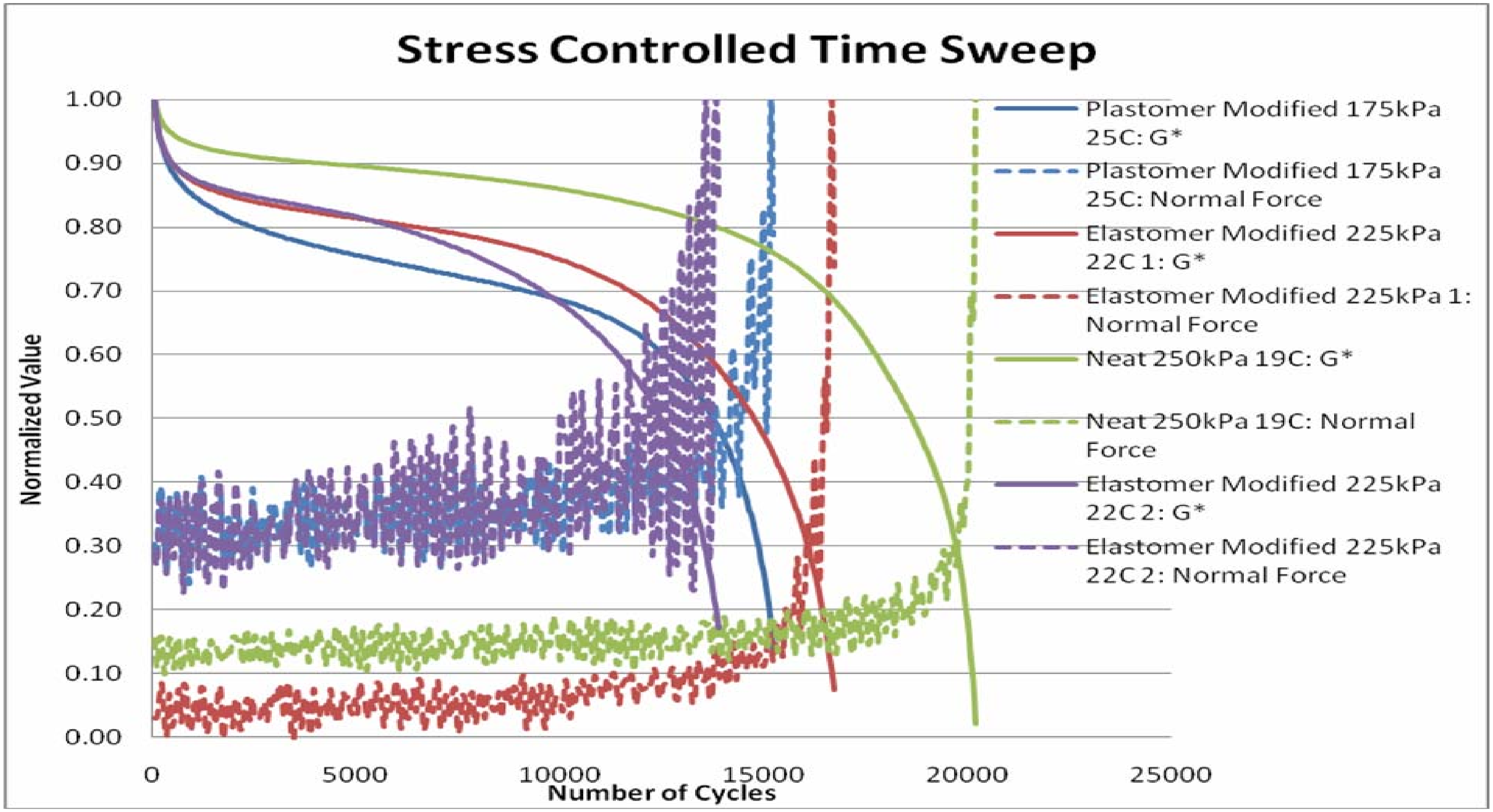
7.5. The binder fatigue performance parameter N_f can now be calculated as follows:

$$N_f = A(\gamma_{max})^B$$

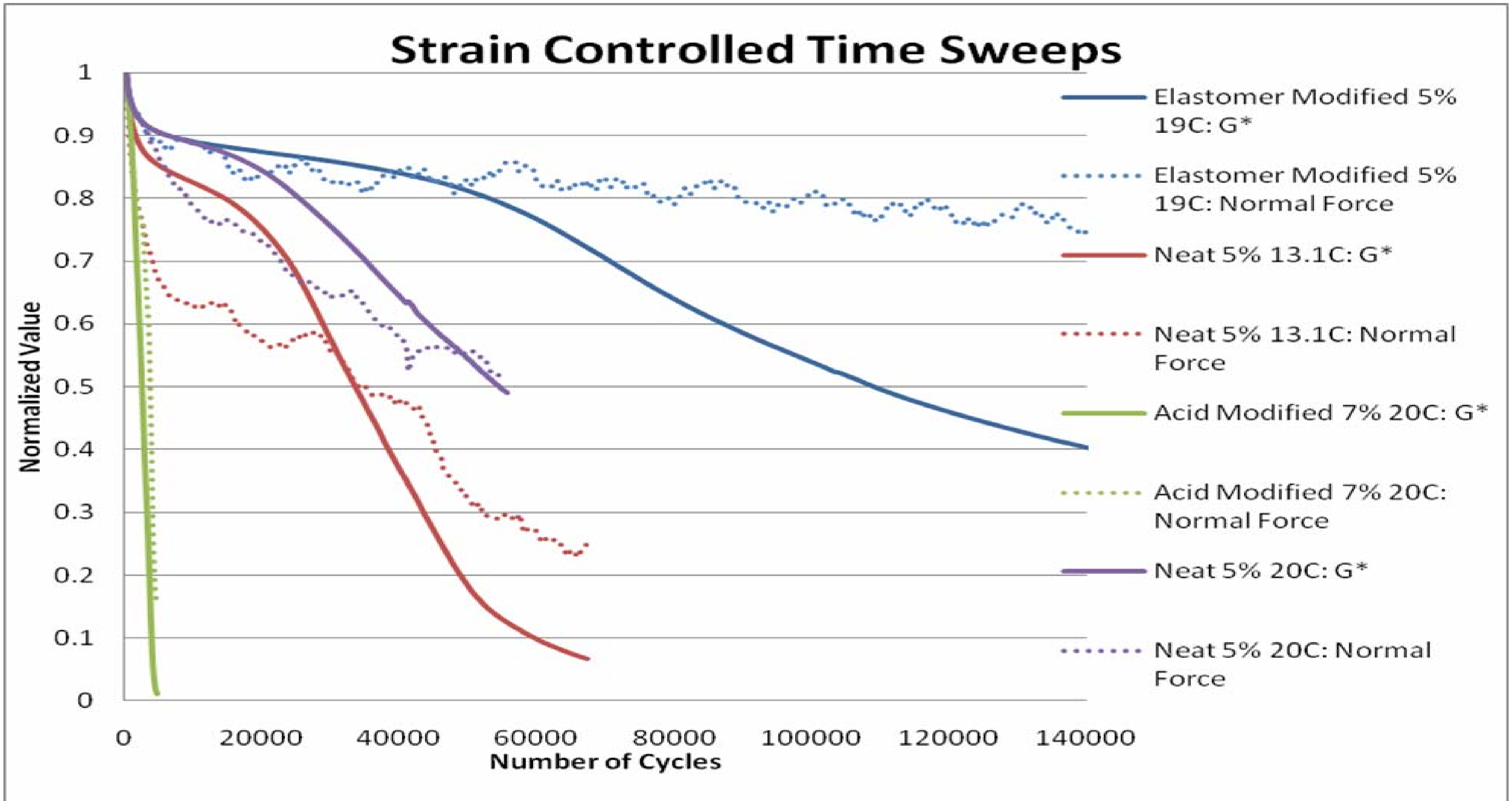
Simulated Binder Fatigue



Normal Force Issues – Stress Control

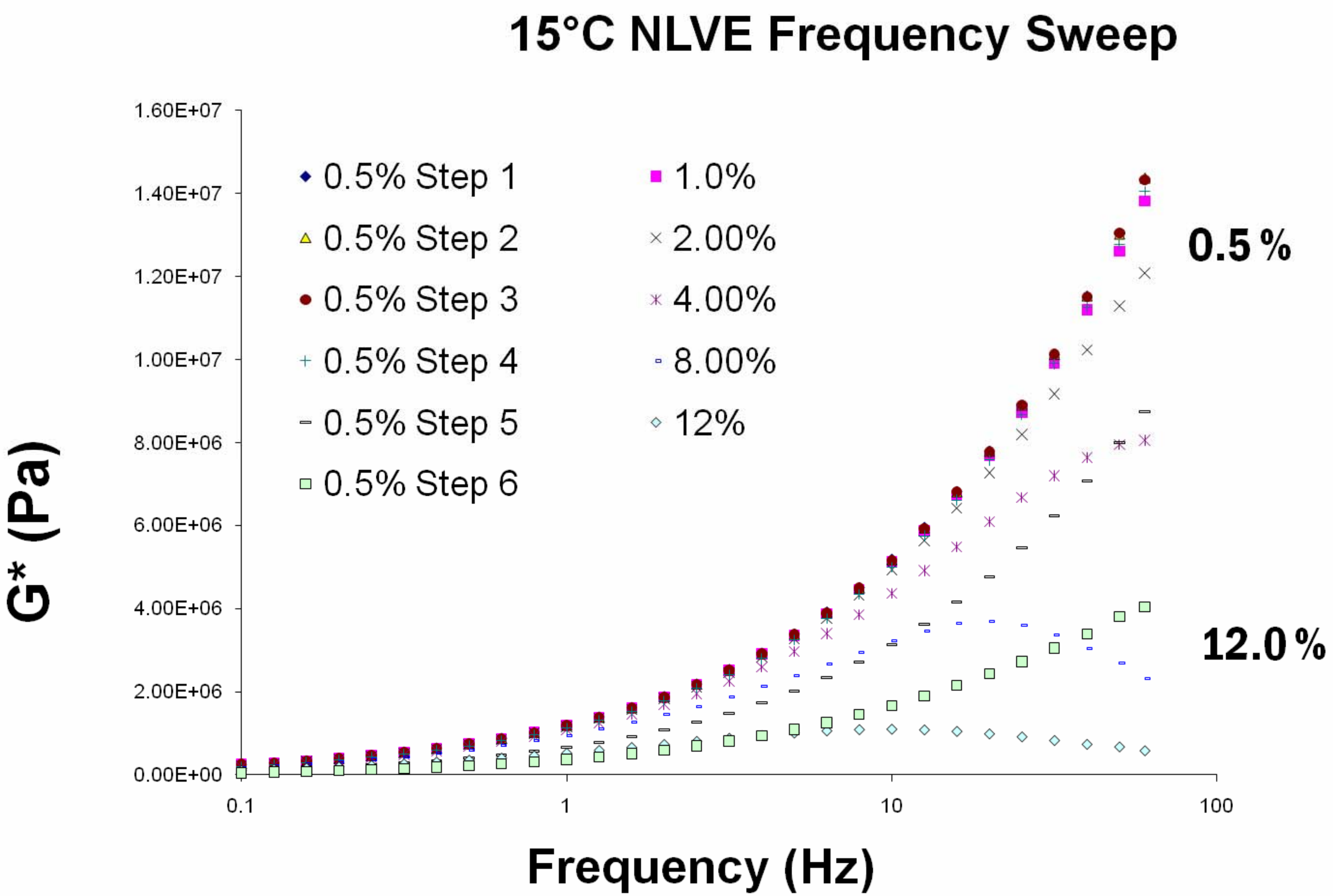


Normal Force Issues – Strain Control



Gaps in the Knowledge

- What is causing the double peak in the BYET ?
  - Is this relevant to pavement conditions ?
  - What causes this?
- VECD appears to be a good path forward, however:
  - $B = -2\alpha$! What strain/stress should we use ?
  - Do we need to separate non-linearity from damage?


15°C NLVE Frequency Sweep
G* (Pa)
Frequency (Hz)
1.60E+07
1.40E+07
1.20E+07
1.00E+07
8.00E+06
6.00E+06
4.00E+06
2.00E+06
0.00E+00
0.1
1
10
100
0.5% Step 1
0.5% Step 2
0.5% Step 3
0.5% Step 4
0.5% Step 5
0.5% Step 6
1.0%
2.00%
4.00%
8.00%
12%
0.5 %
12.0 %

AASHTO Draft Procedure

Standard Method of Test for

Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep

AASHTO Designation: T XXX-09

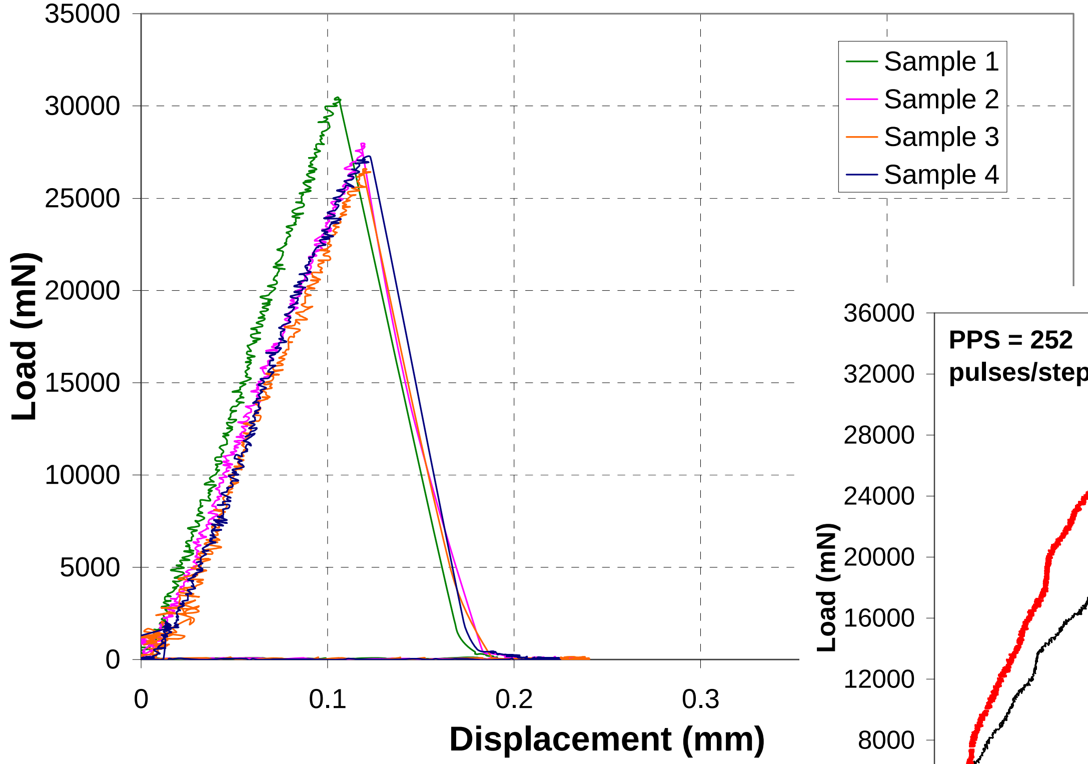
1. SCOPE

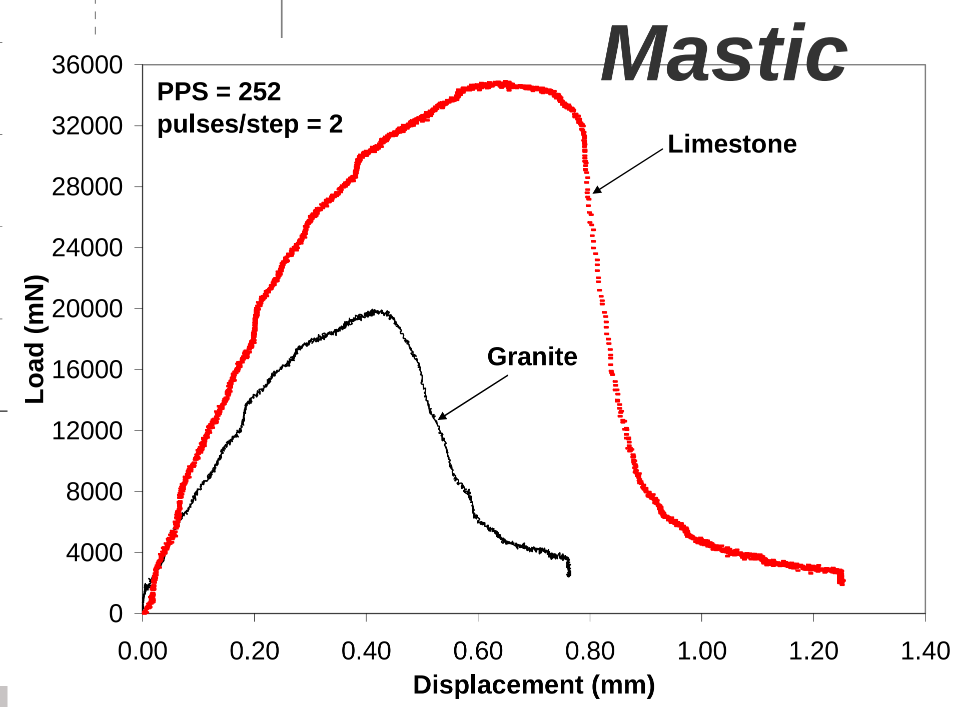
1.1. This test method covers the indication of asphalt binders' resistance to fatigue damage by means of cyclic loading employing a linearly ramping amplitude sweep test. The amplitude sweep is conducted using the Dynamic Shear Rheometer at the continuous intermediate temperature performance grade (PG Grade) of the asphalt binder. The test method can be used with material aged using AASHTO T 240 (RTFOT) and/or AASHTO R 28 (PAV) to simulate the estimated aging for in-service asphalt pavements.

Other Damage Chracterizations

- Fracture:
  - Single Edge Notch Beam (SENB)
  - What is the role of fillers ?
- Adhesion / Cohesion
  - PATTI >>>   Bitumen Bond Strength Test

SENB Example Results





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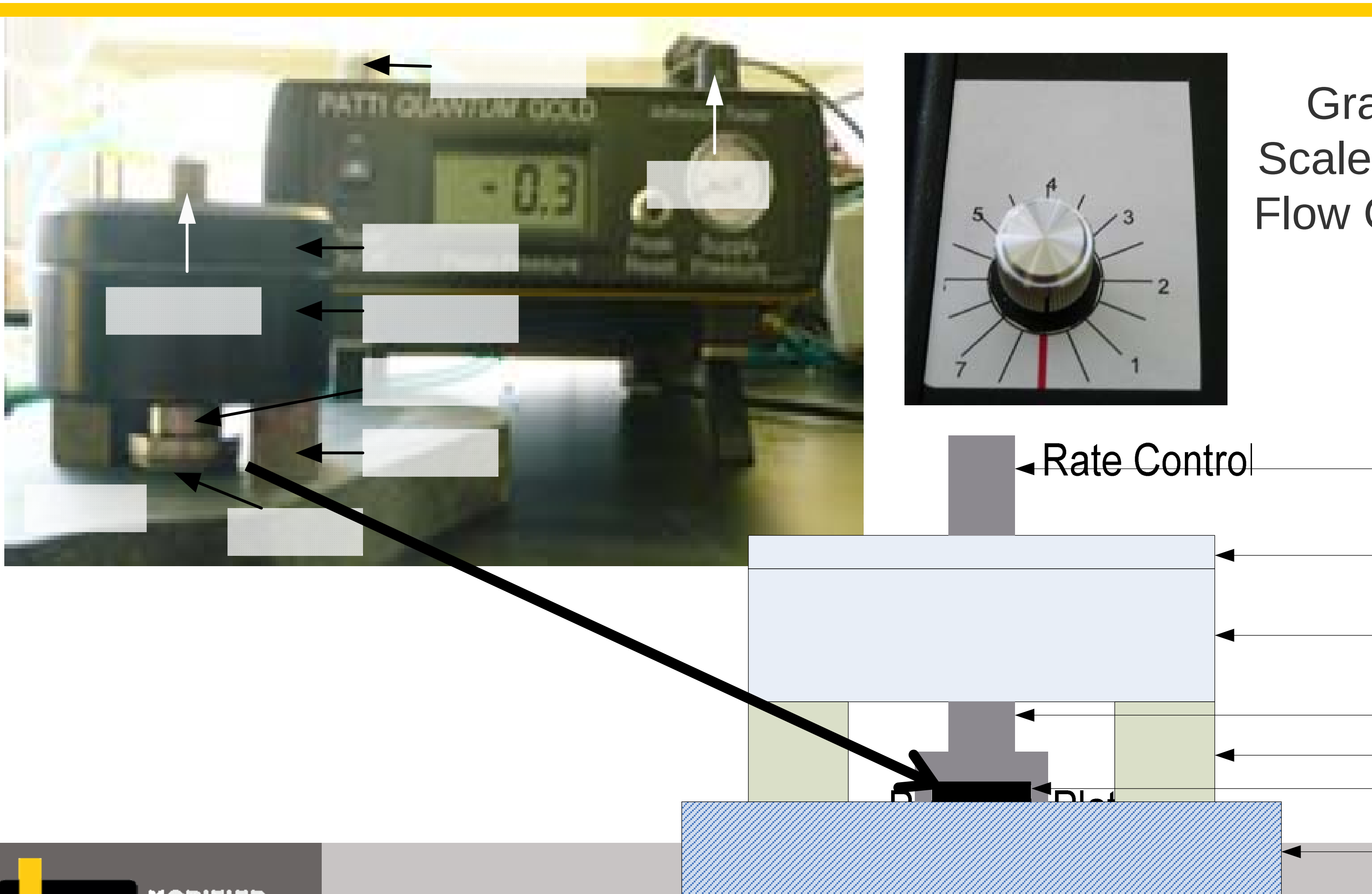
Bitumen Bond Strength Testing Apparatus



Graded Scale for Air Flow Control

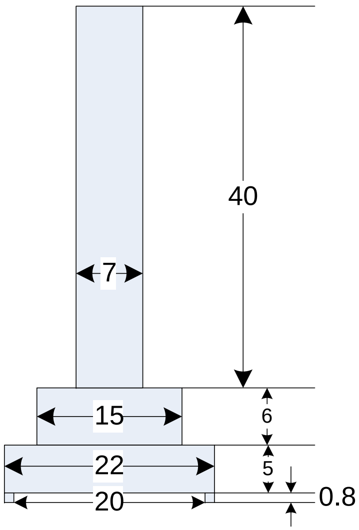
Test Button

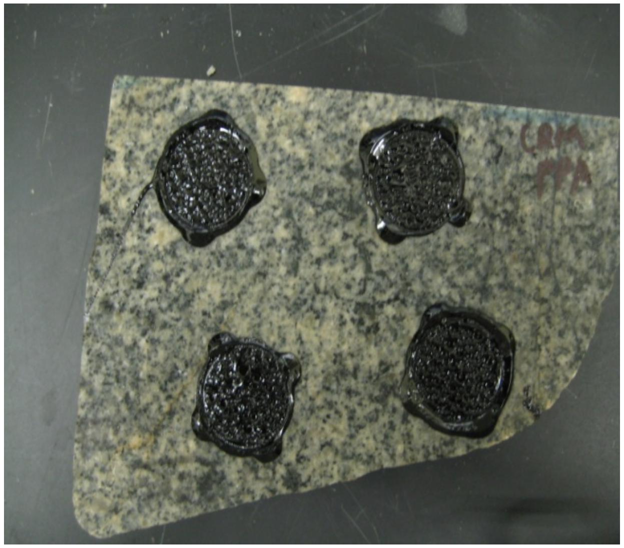
Applied Force

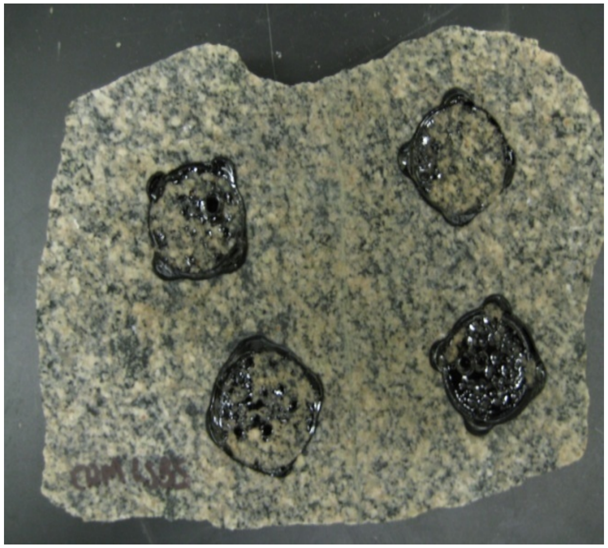
Pressure Ring

Pullout Stub

Example of Test Results





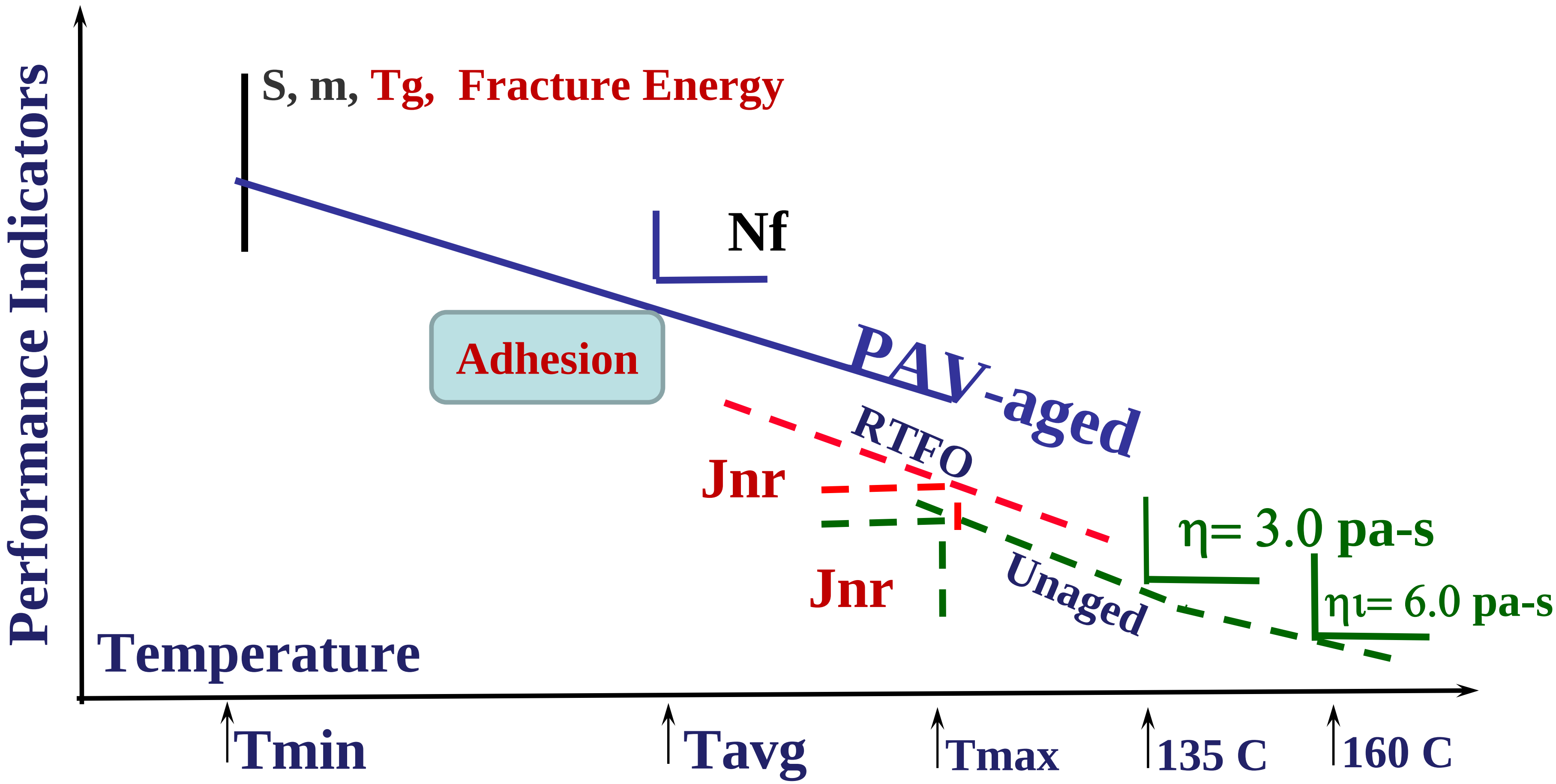


Cohesive Failure Adhesive Failure

Bitumen Adhesion

Source: Gerrie Van Zyl – RSA

Evolution of PG Bitumen Specification



Thank You!

Acknowledgments

- ARC- WRI- FHWA

- Carl Johnson – Northwest Asphalt
- Haifang Wen – Washington State Univ.
- Cassie Hintz
- Cristian Clotopel
- Raul Velasquez
- Aaron Coenen