Development of Failure Criterion for Linear Amplitude Sweep (LAS) Test

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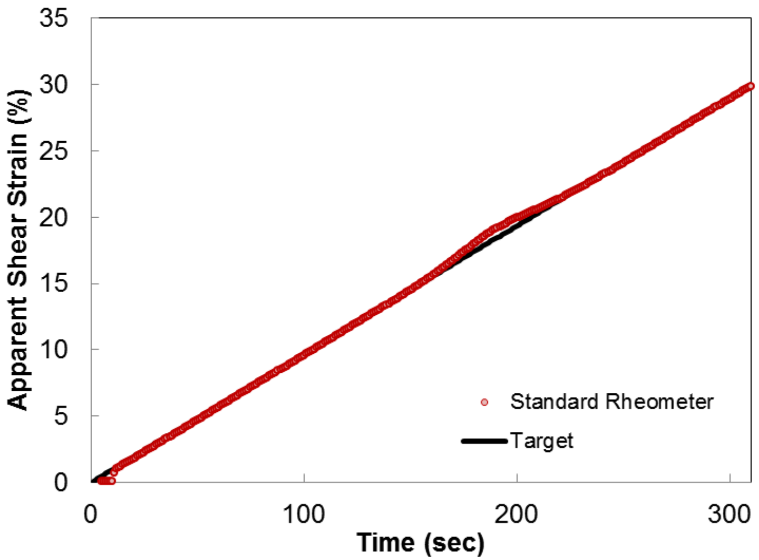
LAS Test Procedure

Frequency Sweep

+



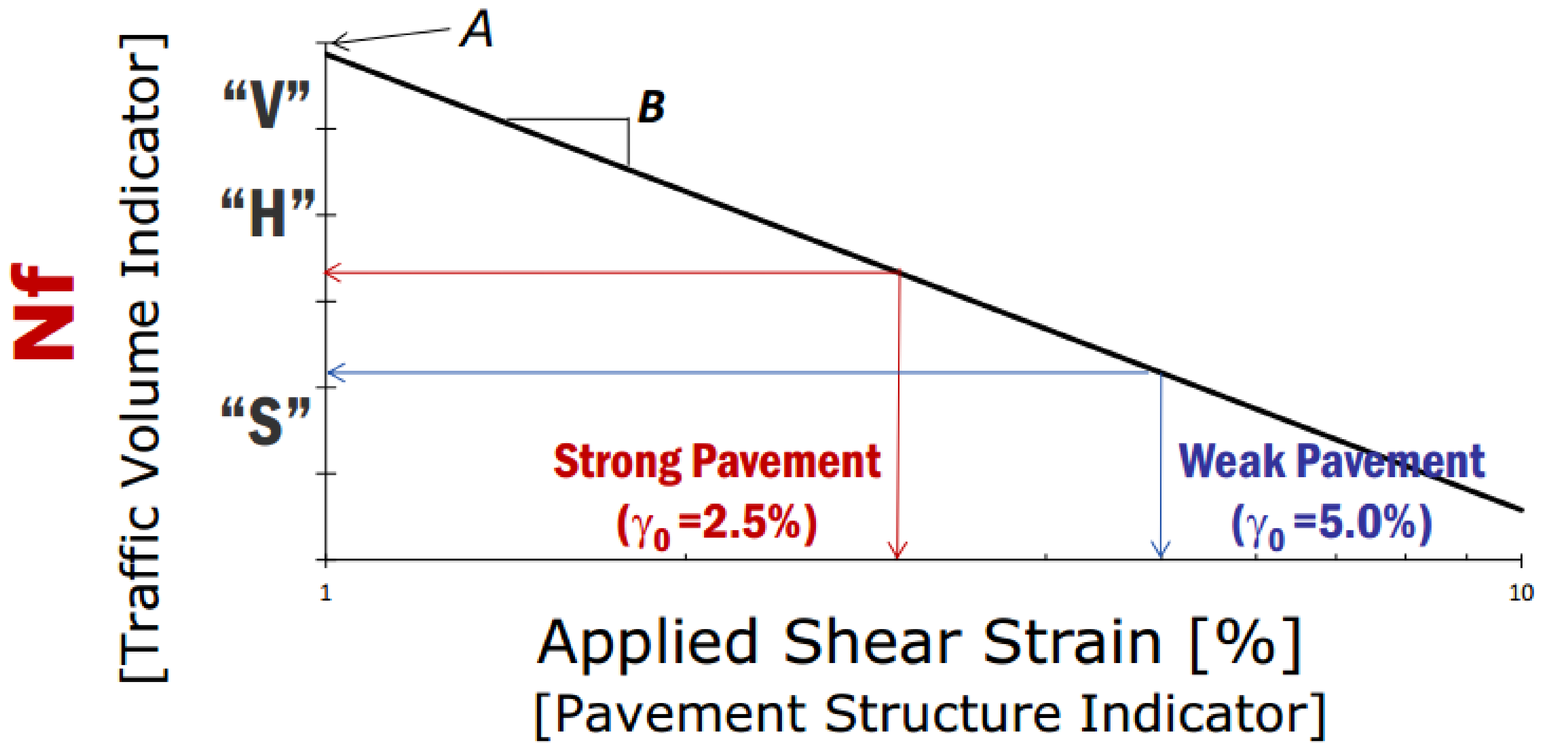
Undamaged Material Response

Damaged Material Response

Simplified Viscoelastic Continuum Damage (S-VECD) analysis used to derive relationship between fatigue life and strain amplitude

Fatigue in Pavements

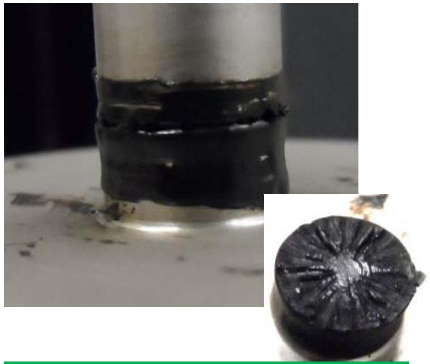
Fatigue Law: $Nf = A(\gamma_0)^B$



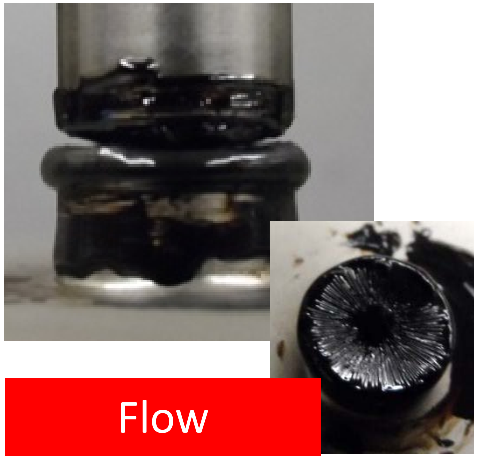
Failure Mechanism

- LAS targets characterization of cohesive cracking resistance
  - Need to avoid
    - ✓ Distortion due to flow
    - ✓ Adhesive failure
  - Select test temperature such that initial |G*| is between 10MPa and 60MPa to ensure cohesive cracking failure

Adhesive Failure



Cohesive Cracking



Flow

Increasing Temperature

S-VECD Analysis

- Relies on relationship between **material integrity** and **damage**
- Material integrity quantified using **pseudo-stiffness (C)**

$$C = \frac{\tau_{damaged}}{\gamma^R (= \tau_{undamaged})} \longrightarrow \gamma^R = |G^*|_{LVE} \cdot \gamma \longrightarrow C = \frac{|G^*|_{damaged}}{|G^*|_{LVE}}$$

Linear viscoelastic stress response

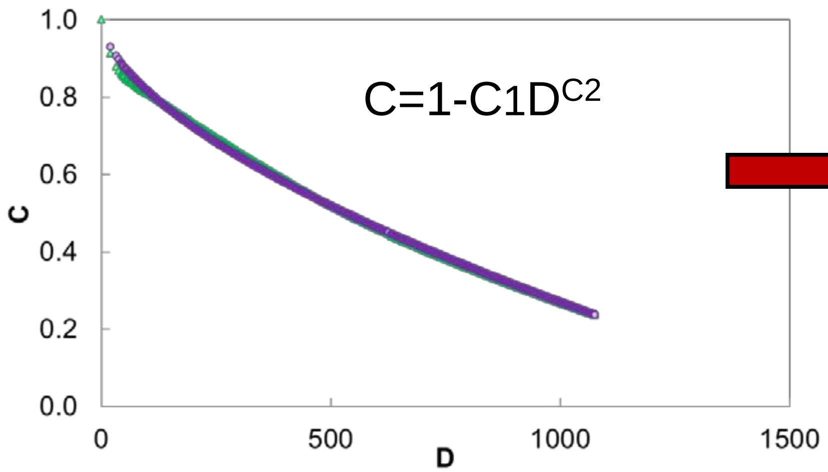
- Damage quantified using **internal state variable(D or S)** derived using Schapery's work potential theory

$$D = \sum_{i=1}^{N} \frac{1}{2}\left(\gamma^R\right)^2 (C_{i-1} - C_i)^{\frac{\alpha}{1+\alpha}} \cdot (t_i - t_{i-1})^{\frac{1}{1+\alpha}}$$

where γ^R = pseudostrain and α = material dependent constant

S-VECD Analysis

- Unique relationship between material integrity and damage allows for deriving closed form solution for fatigue law
  - Analysis can be accomplished automatically using an Excel spreadsheet



$$N_f = A\gamma^B$$

Based on LVE properties

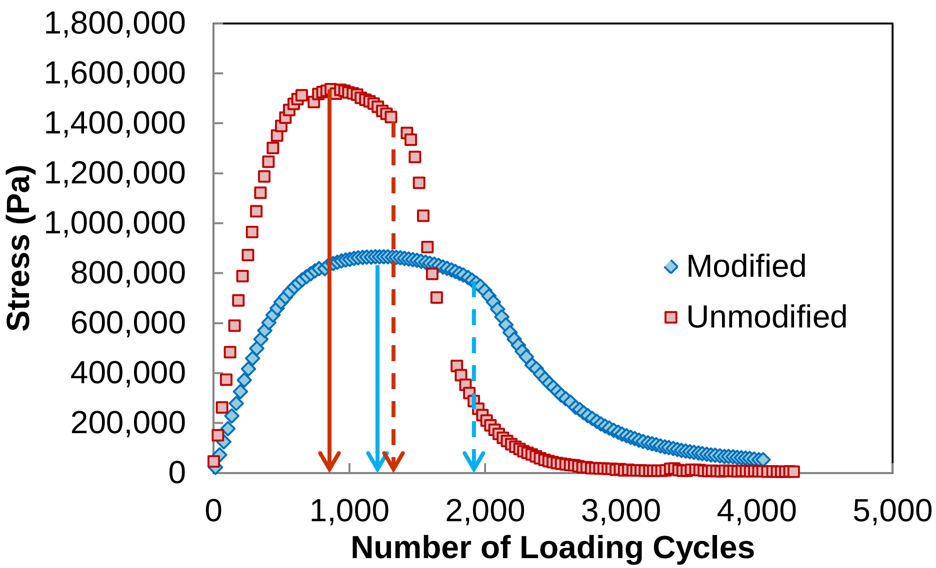
Based on damage resistance
=> Function of damage at failure

Fatigue Life Prediction

- Fatigue life prediction requires knowledge of when failure occurs
  - Initial failure definition in LAS procedure
    - ✓ Arbitrary 35% reduction in material integrity
  - Revised material-dependent failure definition
    - ✓ Peak in shear stress
  - **Improved failure definition and corresponding failure criterion**
    - ✓ Based on pseudo-strain energy analysis

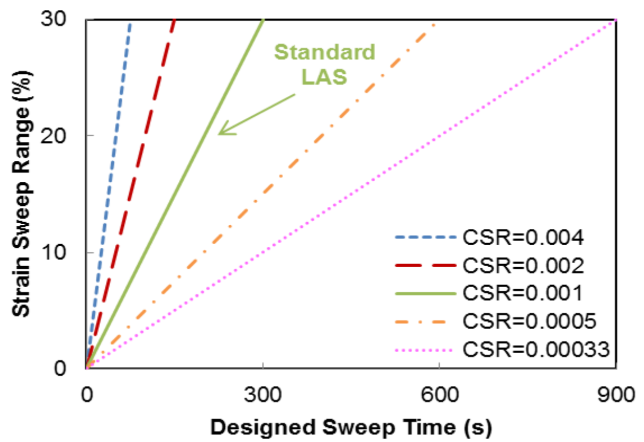
Failure Definition

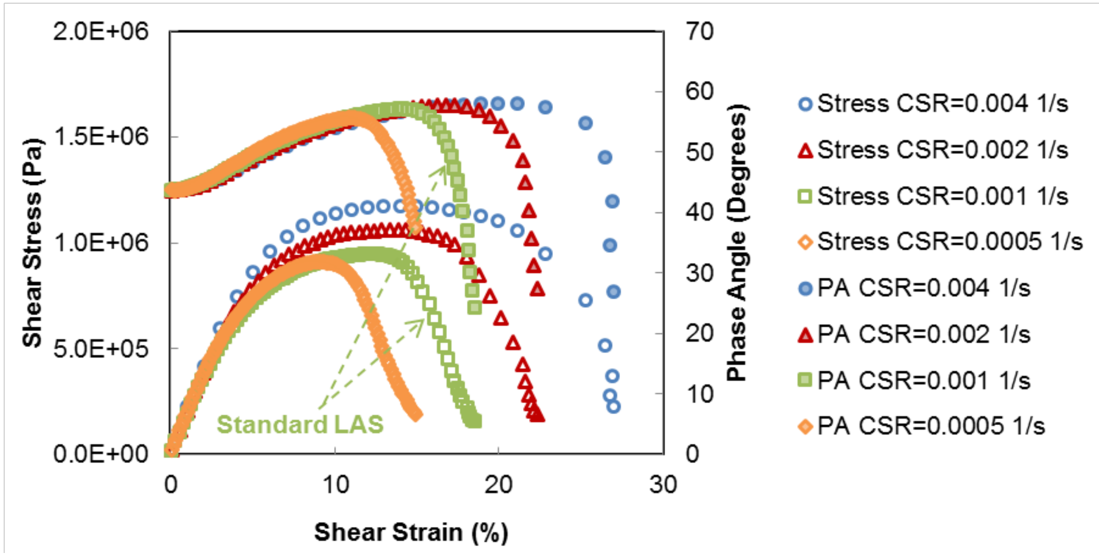
- Peak stress
  - Material dependent
- Issue
  - Ultimate failure delayed from peak stress



Failure Definition: LAS

- Investigation of alternative material dependent failure definitions
  - Peak in CxN corresponds to peak in stress
  - Peak in phase angle corresponds to ultimate failure

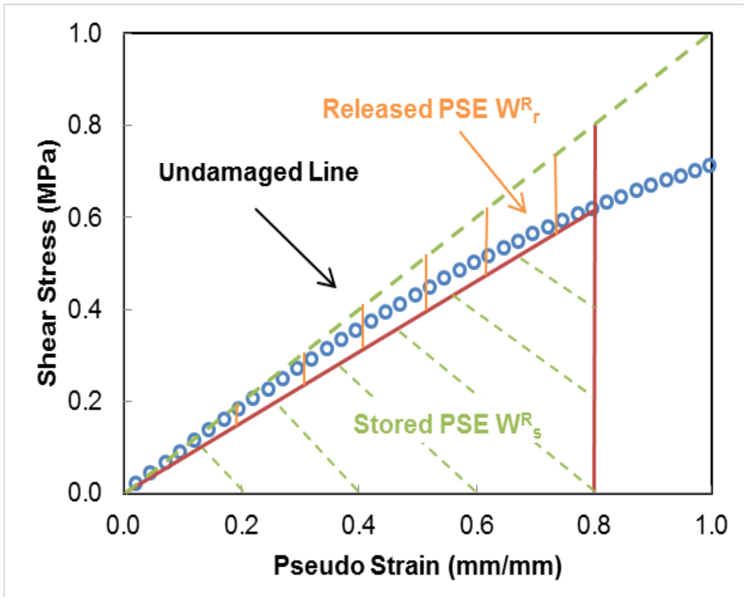




*CSR = constant strain amplitude rate

Pseudostrain Energy Analysis

- Peak in phase angle difficult to identify in some cases
- Phase angle not included in S-VECD model
  - Trends in pseudostrain energy (PSE) investigated



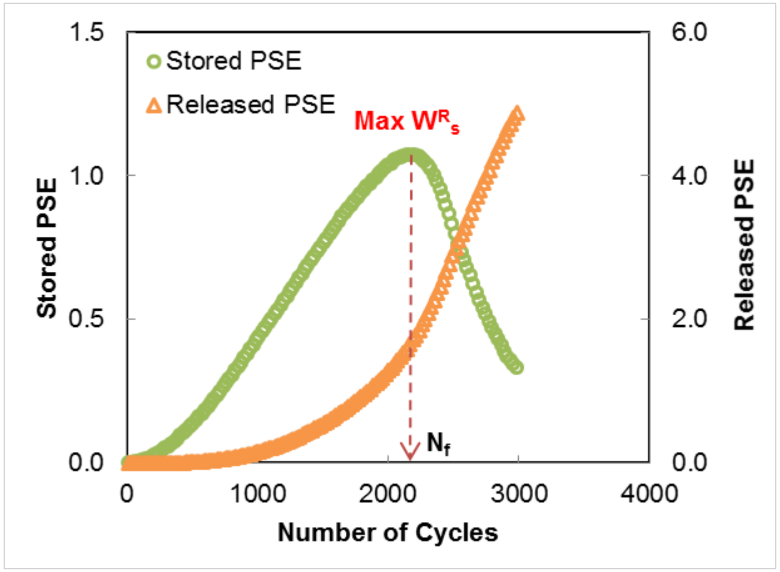
$$W_s^R = \frac{1}{2}\tau_p \cdot \gamma_p{}^R = \frac{1}{2} \cdot C \cdot \left(\gamma_p{}^R\right)^2$$

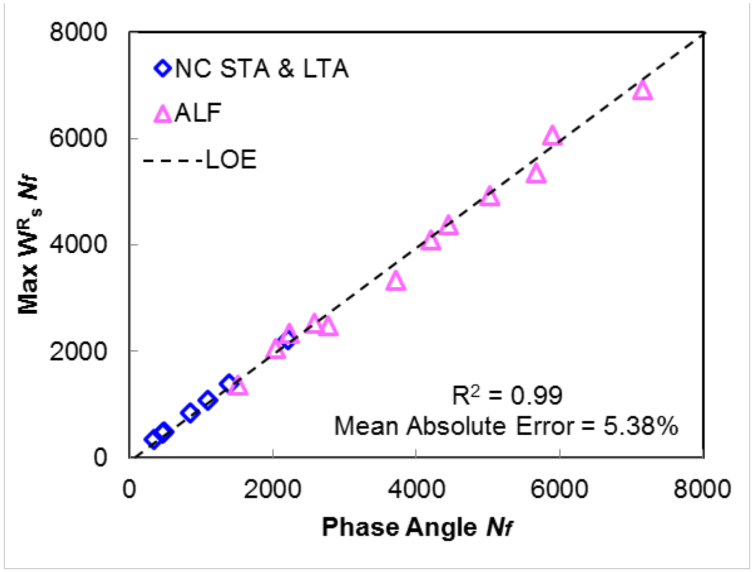
$$W^R_{total} = \frac{1}{2} \cdot \tau_{undamaged} \cdot \gamma_p^R = \frac{1}{2} \cdot (\gamma_p^R)^2$$

$$W^R_r = W^R_{total} - W^R_s = \frac{1}{2} \cdot (1 - C) \cdot (\gamma_p^R)^2$$

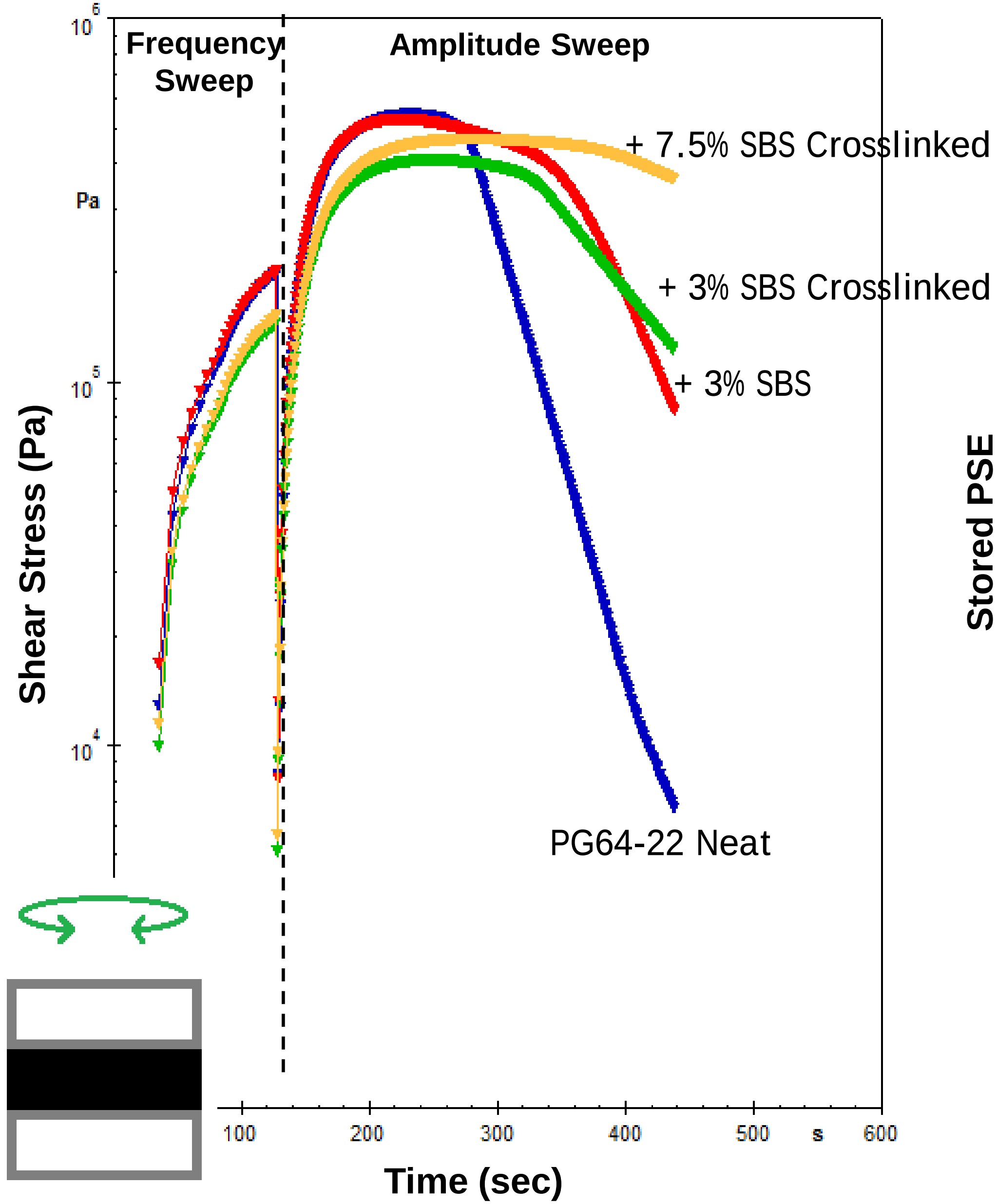
Pseudostrain Energy Analysis

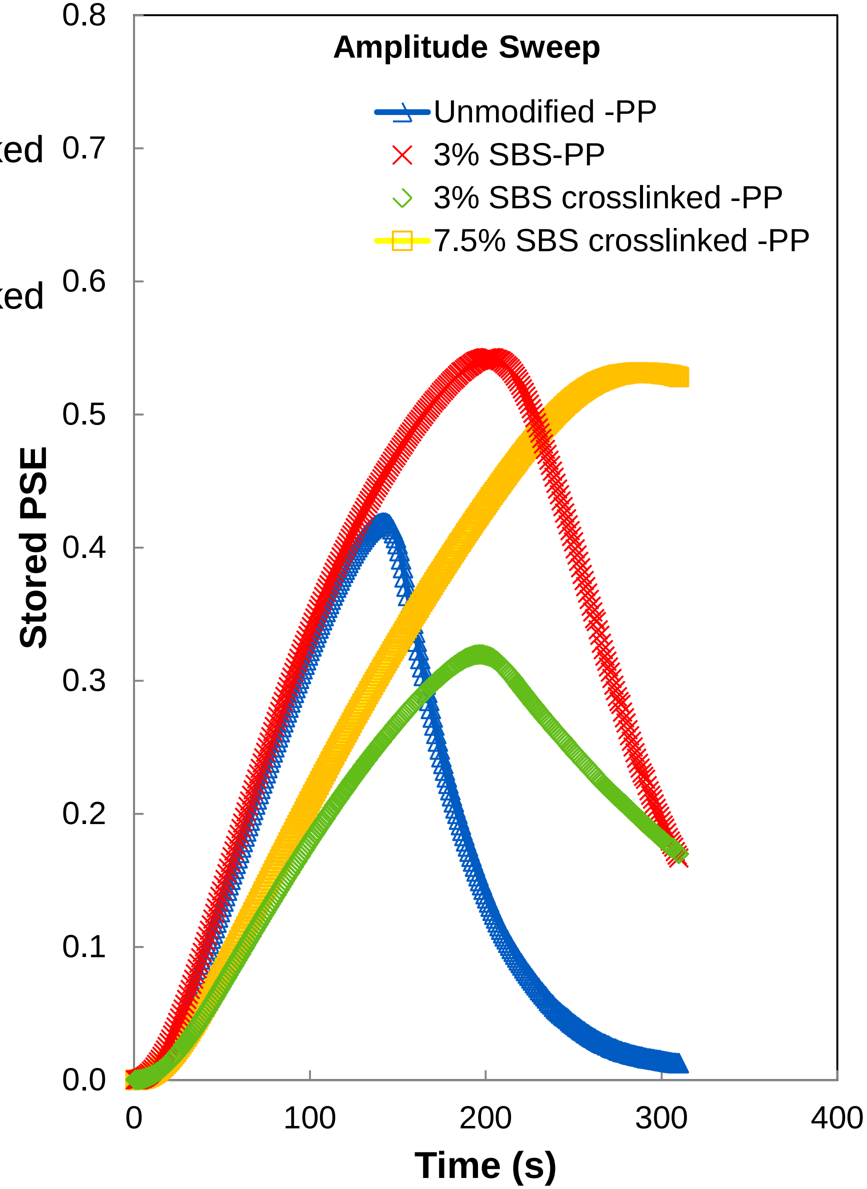
- Peak in stored PSE can be used to define failure in LAS test





Kraton Polymer Results

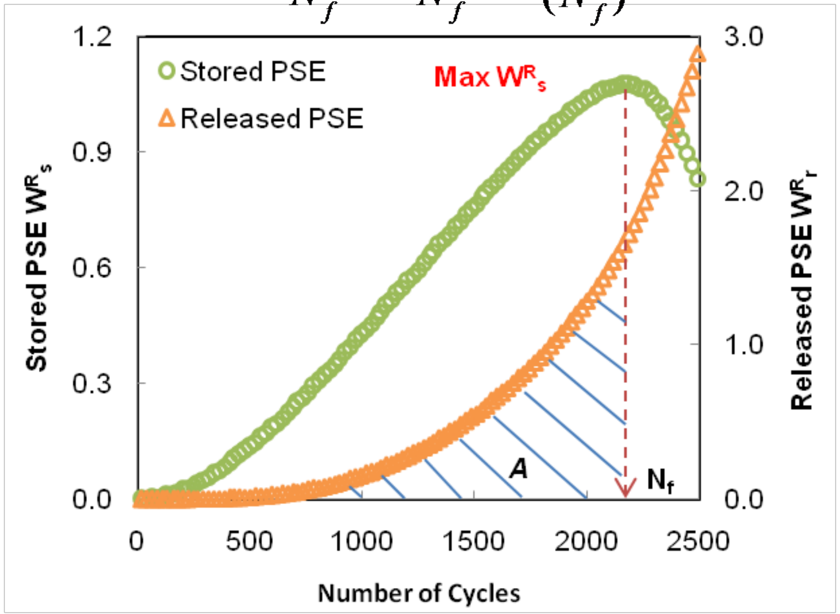


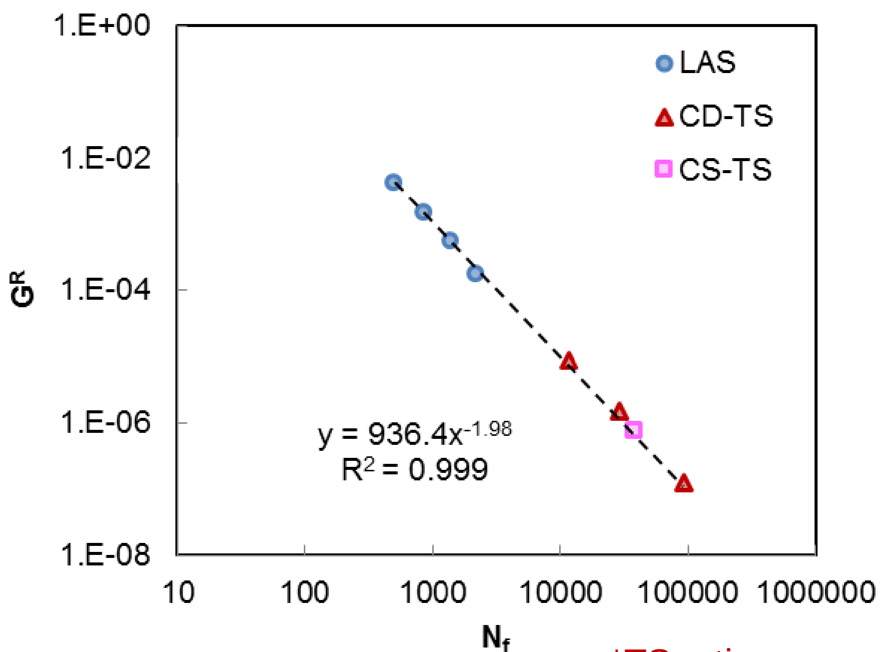


Failure Criterion

- Necessary for performance prediction
  - Material integrity at failure dependent on loading history
- G^R = averaged rate of pseudo strain energy release during the fatigue test until failure
  - Relationship between G^R and N_f independent of loading history

$$G^R = \frac{\overline{W^R_r}}{N_f} = \frac{A/N_f}{N_f} = \frac{A}{(N_f)^2}$$





*TS = time sweep

Failure Criterion

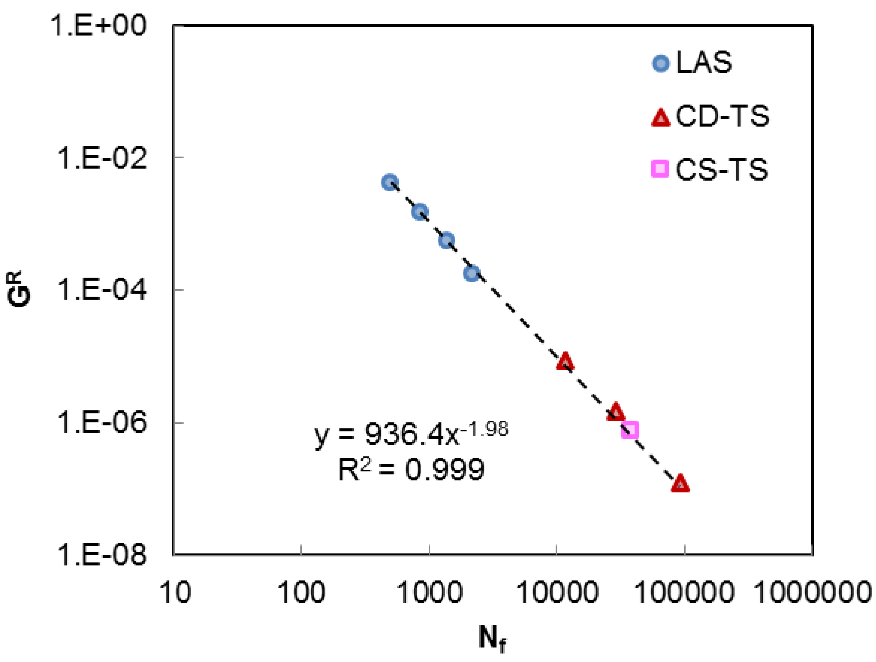
- Can be incorporated into S-VECD model for performance prediction in Excel Spreadsheet

$$G^R = a \cdot (\mathrm{N_f})^b$$

$$N_f = \left[\frac{k}{a} \cdot (\gamma)^{2+2\alpha(\frac{C_2}{p})} \right]^{\frac{1}{b+1-\frac{C_2}{p}}}$$

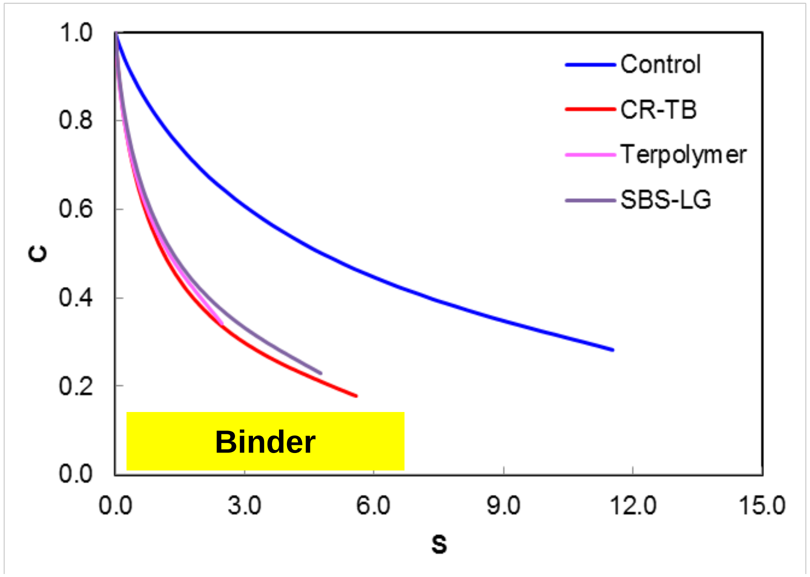
$$p = 1 - \alpha \cdot C_2 + \alpha \qquad k = \frac{1}{2} \cdot C_1 \cdot (|G^*|_{\mathrm{LVE}})^2 \cdot q^{(-\frac{C_2}{p})} \cdot \frac{1}{\frac{C_2}{p}+1}$$

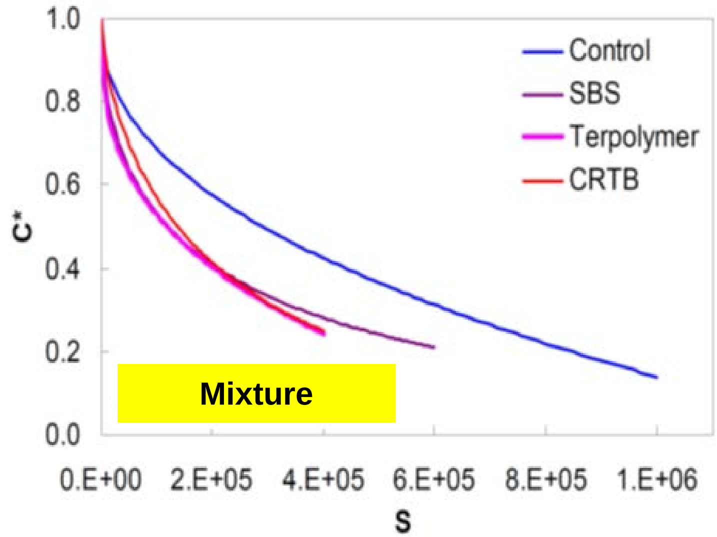
$$q = \frac{f \cdot 2^\alpha}{(1-\alpha \cdot C_2 + \alpha)(C_1 \cdot C_2)^\alpha (|G^*|_{LVE})^{2\alpha}}$$



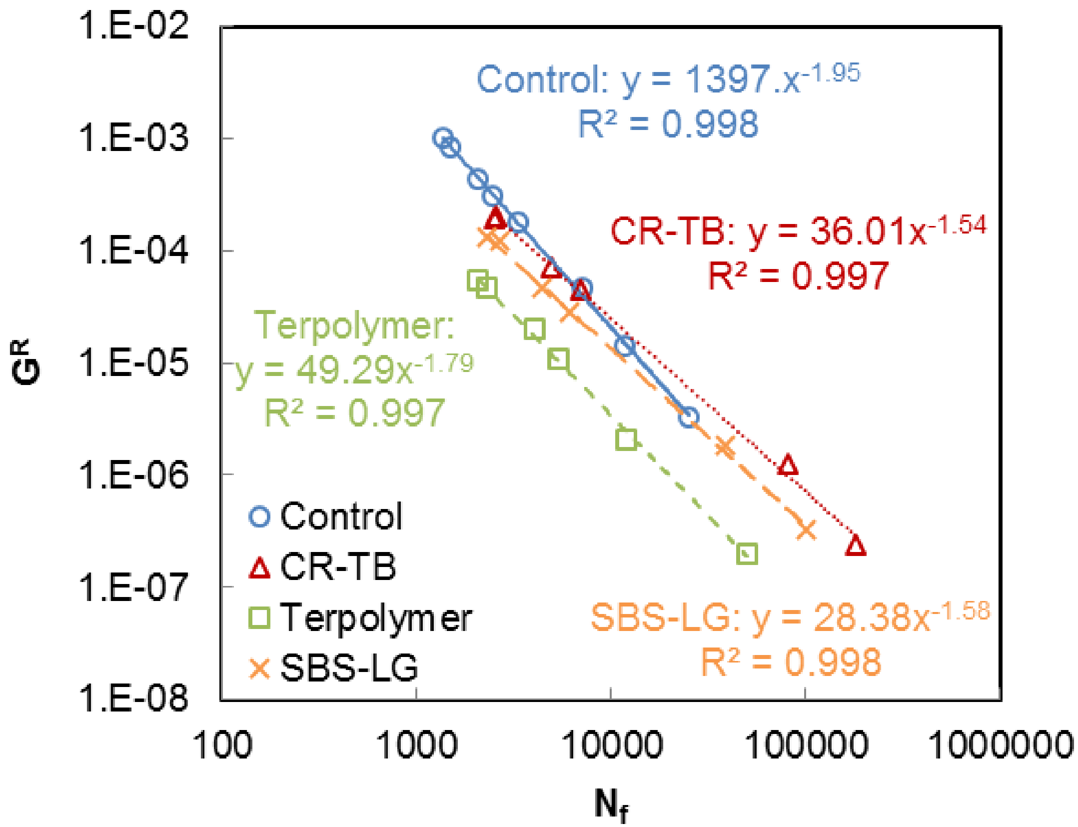
Assessment of Performance Predictions using New Failure Definition & Criterion

- Materials
  - FHWA-ALF Control, CR-TB, Terpolymer and SBS-LG binders
- Experiments
  - LAS at 3 Constant Shear Amplitude Rate (CSR)
  - Time Sweep
    - ✓ Controlled Displacement (CD)
    - ✓ Controlled Stress (CS)



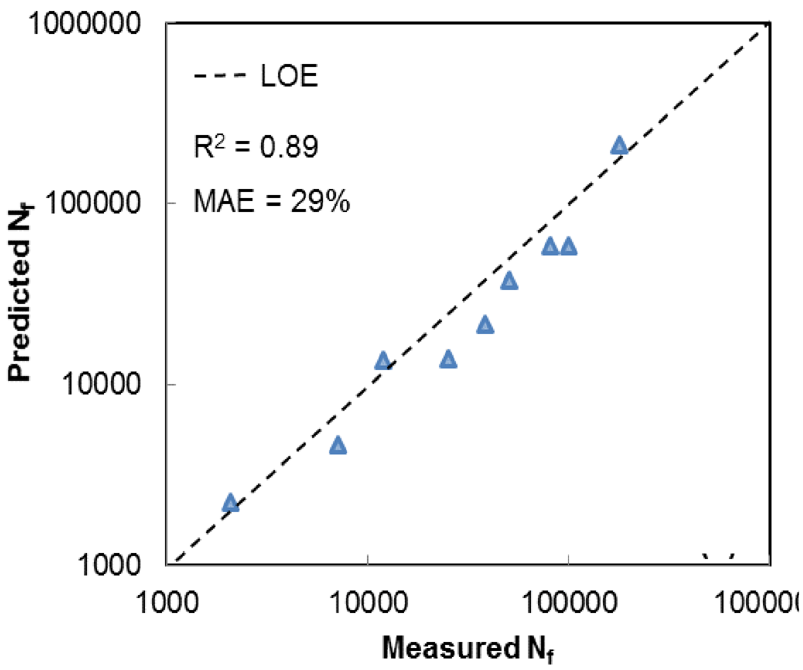


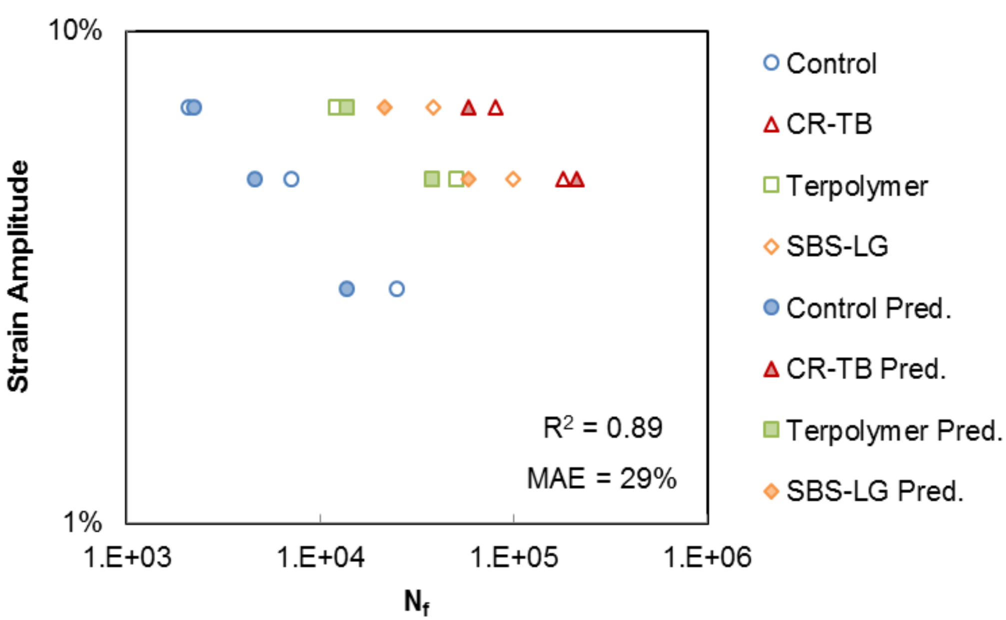
Comparison of Failure Criteria



Prediction of TS from LAS

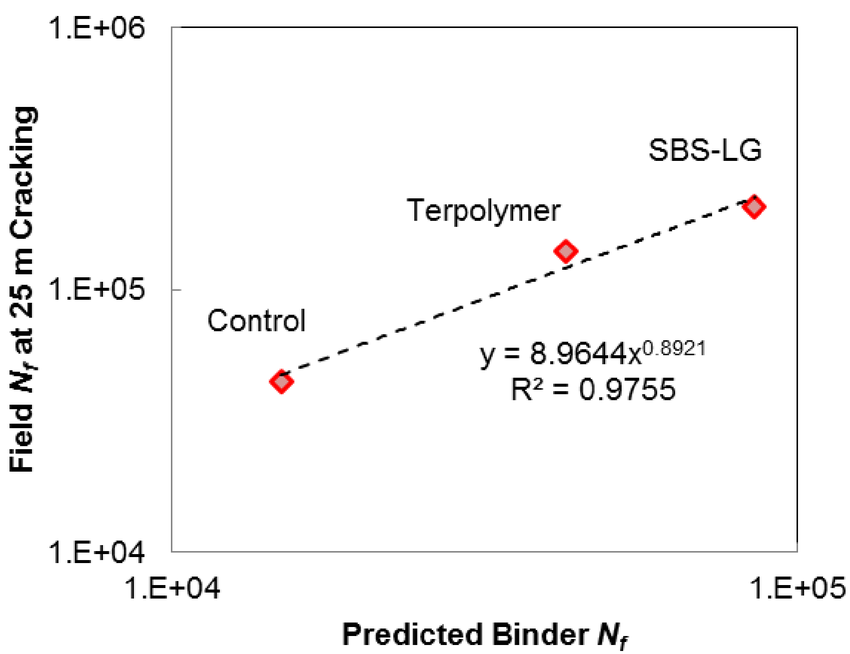
- Requires multiple LAS tests with varying CSRs





Field Validation

- Layered viscoelastic analysis conducted using mixture |E*| coupled with ALF conditions to determine tensile strain in bottom of asphalt layer
  - Binder to mix strain ratio of 80 used to predict N_f
    - ✓ S-VECD combined + failure criterion
- Reasonable correlation between binder and field except for CR-TB
  - CR-TB demonstrated highest binder N_f
  - CR-TB contained both SBS and tire rubber modification



Conclusions & Future Research

- Conclusions
  - Peak in stored PSE can be used to define failure in the LAS test
  - Relationship between G^R and N_f can be incorporated into S-VECD model for improved performance prediction
- Future Research
  - More extensive mixture validation
  - Investigation of temperature effects
  - Consideration of nonlinearity

Thank you!

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  - Farinaz Safaei
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