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

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LAS Test Procedure

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

Fatigue Law: \( N_f = A(\gamma_0)^B \)

- **Strong Pavement** (\( \gamma_0 = 2.5\% \))
- **Weak Pavement** (\( \gamma_0 = 5.0\% \))
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

Increasing Temperature

- Adhesive Failure
- Cohesive Cracking
- Flow
S-VECD Analysis

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

\[ C = \frac{\tau^{\text{damaged}}}{\gamma^R (= \tau^{\text{undamaged}})} \]

\[ \gamma^R = |G^*|_{LVE} \cdot \gamma \]

\[ C = \frac{|G^*|_{\text{damaged}}}{|G^*|_{LVE}} \]

Linear viscoelastic stress response

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

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

where \( \gamma^R = \text{pseudostrain} \)
and \( \alpha = \text{material dependent constant} \)
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

\[ C = 1 - C_1 D^{C_2} \]

\[ N_f = A \gamma^B \]

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

![Graph showing stress versus number of loading cycles for modified and unmodified materials](image)
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

\[ W^R_s = \frac{1}{2} \tau_p \cdot \gamma_p^R = \frac{1}{2} \cdot C \cdot (\gamma_p^R)^2 \]

\[ W^{R}_{total} = \frac{1}{2} \cdot \tau_{undamaged} \cdot \gamma_p^R = \frac{1}{2} \cdot (\gamma_p^R)^2 \]

\[ W_r^R = W^R_{total} - W^R_s = \frac{1}{2} \cdot (1 - C) \cdot (\gamma_p^R)^2 \]
Pseudostrain Energy Analysis

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

![Graph showing stored PSE and released PSE vs. number of cycles](image1.png)

![Graph showing max WR_s vs. phase angle Nf](image2.png)

- R² = 0.99
- Mean Absolute Error = 5.38%
Kraton Polymer Results

![Graph showing Shear Stress vs. Time for different modified PG64-22 samples.](image)

- **Frequency Sweep**
  - Unmodified -PP
  - + 3% SBS
  - + 3% SBS Crosslinked
  - + 7.5% SBS Crosslinked

- **Amplitude Sweep**
  - Shear Stress (Pa)
  - Time (sec)
  - Stored PSE
  - Time (s)

**Key Observations**
- The modified samples exhibit higher shear stress compared to the unmodified sample.
- The crosslinked samples show a peak in stored PSE at around 200 s.
Failure Criterion

- Necessary for performance prediction
  - Material integrity at failure dependent on loading history

- $G^R = \text{averaged rate of pseudo strain energy release during the fatigue test until failure}$
  - Relationship between $G^R$ and $N_f$ independent of loading history

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

*TS = time sweep
Failure Criterion

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

\[ G^R = a \cdot (N_f)^b \]

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

\[ p = 1 - \alpha \cdot C_2 + \alpha \]

\[ k = \frac{1}{2} \cdot C_1 \cdot \left| G^* \right|_{LV}^2 \cdot q \left( \frac{C_2}{p} \right)^{\frac{1}{b+1}} \]

\[ q = \frac{f \cdot 2^\alpha}{(1-\alpha \cdot C_2 + \alpha)(C_1 \cdot C_2)^\alpha \left| G^* \right|_{LV}^{2\alpha}} \]

\[ y = 936.4x^{-1.98} \]

\[ R^2 = 0.999 \]
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

- Control: $y = 1397x^{-1.95}$, $R^2 = 0.998$
- CR-TB: $y = 36.01x^{-1.54}$, $R^2 = 0.997$
- Terpolymer: $y = 49.29x^{-1.79}$, $R^2 = 0.997$
- SBS-LG: $y = 28.38x^{-1.58}$, $R^2 = 0.998$
Prediction of TS from LAS

- Requires multiple LAS tests with varying CSRs

Graphs showing the relationship between measured and predicted fatigue life with slopes and errors indicated.
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

Graph showing:
- Field $N_f$ at 25 m Cracking vs. Predicted Binder $N_f$
- Control
- Terpolymer
- SBS-LG

Equation: $y = 8.9644x^{0.8921}$
$R^2 = 0.9755$
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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