Linear Viscoelastic Behavior of Asphalt Binders At Low Temperatures

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Outline

- Background
- Objective
- Approach
  - How?
  - Why?
- Data Collection and Analysis
- Conclusion
Objective

To Evaluate The Linear Viscoelastic Behavior Of Asphalt Binders At Low Temperatures
Approach—How?

- Apply Different Stress Levels and Study the Effect on Relaxation Modulus
- Apply Different Strain Levels and Study the Effect on Relaxation Modulus
- Apply Different Strain Rates and Study the Effect On Failure Stress/Strain Rate
Mathematically

- **Non-Linear Viscoelastic if:**
  - Relaxation Modulus (Stiffness)

  \[ E(T) = f(t, \sigma \text{ or } \varepsilon) \]

- **Linear Viscoelastic if:**
  - Relaxation Modulus (Stiffness)

  \[ E(T) = f(t) \text{ only} \]
Approach—Why?

To Explain:

– Why is there a difference between the relaxation modulus calculated using the BBR compliance data and the DTT stress-strain data?

• As Observed by Marasteanu and Anderson
Problem Statement

PG70-22 Oxd.

Relaxation Modulus, MPa

Time, s

BBR Hopkins and Hamming

DTT Thor Smith’s Formula
Thor Smith’s Formula

\[ E(t) = F(t) \left[ 1 + \frac{d \log F(t)}{d \log(t)} \right] \]

Where,

- \( E(t) \) = Relaxation Modulus, MPa
- \( F(t) \) = Secant Modulus, MPa = Stress/Strain
Hopkins and Hamming

\[
\int_{0}^{\infty} G(t) \cdot J(t - \tau) d\tau = t
\]

Numerical Solution Of The Above Convolution Integral
Possible Explanations

- Equipment Differences
- Numerical Errors
- Sample Geometry
- Non-Linearity
- Other
Materials and Methods

- Asphalt Binders
  - AI – Five PG 76-22 Binders
  - ALF – Styrelf, Novophalt
  - LUDO – 581 (BlackMax)
  - Lamont – Section 6
  - Oxidized PG70-22
  - SHRP Core – AAA-1 and AAM-1
- Test Temperature – PG Low Grade Temp.
Test Methods

- **BBR**
  - Creep Compliance Measured
  - Relaxation Modulus **Computed** Using Improved Hopkins and Hamming Method

- **DTT**
  - Creep Compliance Measured
  - Relaxation Modulus **Measured**
  - Failure Data (Stress Strain Curve) **Measured**
  - Relaxation Modulus **Computed** Using Thor Smith’s Formula
Typical BBR with DTT - Creep

**BBR with DTT**

- **Strain, %**
- **Time, s**

**25 N Creep Load**

- **REP 1**
- **REP 2**
- **REP 3**

**120 N/min**

**0**

**0.1**

**0.2**

**0.3**

**0.4**

**0.5**

**0.6**

**0.7**

**0**

**50**

**100**

**150**

**200**

**250**

**300**
BBR Vs. DTT – Creep Data

![Graph showing creep stiffness over time for BBR and DTT](image)
Typical Stress Relaxation - DTT

AAA-1, PAV, -18°C

Ramp Rate = 10%/min

Stress, MPa

Time, s
BBR Vs. DTT – Relaxation

[Graph showing relaxation modulus over time for BBR-Creep to Rlx (Improv H&H), DTT-Rlx-Strain to 0.75% @ 3%/min, and DTT-Relax]
Repeatability

AAM-1, -12°C

![Graph showing relaxation modulus over time for REP 1 and Rep 2.](image)
Linearity Check – Creep Loads

BBR with DTT

Ref: BBR Load = 0.980N

Time, s

Load, N

- 5N
- 10N
- 25N
- 60N
Linearity Check – Creep Loads

Husky Lyodminster 150/200A

\[ \sigma_0 = 1.82 \text{MPa (65N)} \]

\[ \sigma_0 = 0.7 \text{MPa (25N)} \]

\[ \sigma_0 = 0.28 \text{MPa (10N)} \]

\[ \sigma_0 = 0.14 \text{MPa (5N)} \]
Linearity Check – Creep Stiffness

ALF Styrelf PAV

- BBR-0.012MPa
- DTT-0.14MPa
- DTT-0.28MPa
- DTT-0.7MPa
- DTT-1.82MPa
Linearity Check – Relaxation Strains

AAM-1 At -6°C

Ramp Rate = 10%/min
Linearity Check-Relaxation....

AAM-1, -6°C

Time, s

Relaxation Modulus, MPa

0.6%
0.8%
1.0%
1.1%
Linearity Check – Relaxation

AAA-1, -18°C

Relaxation Modulus, MPa

Time, s
Linearity Check - Relaxation

581 At -30°C

Relaxation Modulus, MPa

Ramp Strain Rate = 10%/min

Time, s
Linearity Check - Failure

![Graph showing linearity check failure with various temperature data points.](image)
Linearity Check - Failure

The graph shows the relationship between $\sigma/\dot{\varepsilon}$ (MPa·s) and $t$ (s) for different temperatures: -24°C (diamonds), -21°C (squares), -18°C (triangles), -15°C (crosses), and -12°C (circles). The data points are plotted on a log-log scale, indicating a linear relationship within the range shown. The graph refers to PAV Aged Sample AAM-1.

The failure criterion is indicated by a horizontal line, where the intersection with the trend lines suggests the point of failure for each temperature condition.
BBR Vs. DTT – Failure Data

AI-095 - PG76-22

![Graph showing relaxation modulus vs. time for BBR-Creep and DTT-Fail-3.0%/min](image)
BBR Vs. DTT – Failure Data

AI-095 - PG76-22

Relaxation Modulus, MPa

Time, s

BBR-Creep

DTT-Fail-0.3%/min
All Combined-Summary

- BBR
- DTT Strain = 1.1%
- DTT Strain = 0.8%
- DTT Strain = 0.6%
- DTT Const. Strain Rate

Husky Black Max 581
T = -30°C
Other Variables

![Graph showing relaxation modulus vs. time for various tests: BBR-Creep, DTT-Fail-3.0%/min-St. Line fit—dLN F(t)/dLN(t), and DTT-Fail-3.0%/min-3rd order Poly fit.](image)
Thor Smith’s Formula

\[ E(t) = F(t) \left[ 1 + \frac{d \log F(t)}{d \log (t)} \right] \]

Where,
E(t) = Relaxation Modulus, MPa
F(t) = Secant Modulus, MPa = Stress/Strain
Correct Method to Convert

- Take the derivative of the stress-strain curve
  - Fit a Power Law to the True Stress vs True Strain Curve

\[
E (t) = \frac{d \sigma}{d \varepsilon}
\]

\[
\sigma = K (\varepsilon)^n
\]

\[
\frac{d \sigma}{d \varepsilon} = K \cdot n \cdot (\varepsilon)^{n-1}
\]
PG70-22 Oxd.

Relaxation Modulus, MPa

Time, s
Findings

- BBR and DTT produce identical results
- Flexure and Uniaxial geometry produce the same results
- Non-Linearity was not found at the PG grade temperatures
- When Converting Stress-Strain Curves From the DTT into Relaxation Modulus
  - Use True Stress Vs True Strain
  - Use the Derivative of the True Stress vs True Strain
Test for The Audience

- What is one other thing we learned about the DTT that is not always apparent?
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