Role ofBinders
in Pavement Performance

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Outline

- Binder rheology modeling
- Role of binders in mixture rheology modeling
- A universal phenomenological model
- Damage resistance modeling
Why discuss binder effects on pavement performance?

- Pavements are built with Asphalt Mixtures, not binders!
- But, we select binders before mixture is even designed.
- This requires understanding the range of binder effects on specific mixture behaviors.
- **Effective binder specification should probably be based on a scale of mixture performance.**
Rheology of Asphalt Binders
Before and after Field Aging

Thermal Cracking / Fatigue / Rutting
Effect of Modification on Asphalt Rheology
Effect of Fillers

Phase Angle, degrees

Red. Frequency, log rad/s

Filler Type
- Calcite
- Quartz
- None

G*, log Pa

0 1 2 3 4 5 6 7 8 9 10
Binder Modeling Efforts

- **Linear Visco-Elastic Models**
  - 1950’s: van der Poel
  - 1960’s: Jongepier and Kuilman, Dobson
  - 1980’s: de Bats et al., Maccarrone
  - 1990’s: Christensen, Anderson, Marasteanu

- Recent attempts to include nonlinearity / modified binders / Aging
  - 2000’s: Zeng et al. (Strain dependency)
  - 2000’s: Witczak et al. (Aging effects)
  - 2000’s: Damage Resistance Characterization
Reality:
A Very Complex Material
Asphalt + Rocks + Air Voids

Very, very complex composite
Advanced Technology
Combined Digital Image/ X-Ray

New Tools
We Can determine Film Thickness Distribution

Can be very Precise
Binder to Mixture Stiffness Relations- Not a new Topic - Empirical

- Hukelom and Klomp Relations 50s - 60s:
  \[ S_m = S_b \left[ 1 + \left( \frac{2.5}{n} \frac{C_v}{1-C_v} \right) \right] \]
  where \( n = f(S_b) \)

- Bonnaure’s relations 70s:
  - If \( S_b \) is between 5.0 MPa and 1.0 GPa
    \[ \log(S_m) = \frac{\beta_4 + \beta_3}{2} (\log(S_b) - 8) + \frac{\beta_4 - \beta_3}{2} |\log(S_b) - 8| + \beta_2 \]
  - If \( S_b \) is between 1.0 GPa and 3.0 GPa
    \[ \log(S_m) = \beta_2 + \beta_4 + 2.0959(\beta_1 - \beta_2 - \beta_4)(\log(S_b) - 9) \]
Binder to Mixture Stiffness
Fundamental (Micro-mechanical)

- Paul’s Equation and the Law of Mixtures
- Hashin and Shtrikman’s Arbitrary Phase Geometry Model
- Hashin’s Composite Sphere Model
- Christensen and Lo’s Solution for Generalized Self Consistency Scheme

\[
\frac{1}{c_1} + \frac{c_2}{G_1} \leq G^* \leq G_1 c_1 + G_2 c_2
\]

\[
G_L^* = G_1 + \frac{c_2}{G_2 - G_1} \left( \frac{6(K_1 + 2G_1)c_1}{G_2 - G_1} + \frac{5G_1(3K_1 + 4G_1)}{5G_1(3K_1 + 4G_1)} \right)
\]

\[
G_L^* = \frac{G_m}{1 + c(1 - \eta)\gamma_1^{1/2}}
\]

\[
G_U^* = G_m \left( 1 + c(\eta - 1)\gamma_1^{1/2} \right)
\]

\[
A \left( \frac{G^*}{G_m} \right)^2 + 2B \frac{G^*}{G_m} + C = 0
\]
Most Recent Models – AASHTO 2002 and after

- Empirical-Witczak et al. (1976 – 2001)
  - Last 25 years. The latest version of this model is based on 1,429 mixture testing data on 149 asphalt mixtures.
  - Included in The 2002 AASHTO Design guide

Using same formulation for binder and mixtures

Illustration of $G^*$ master-master curve

- $G^*_{g}$
- $G^*_{e}$
- $G^*_{g}$
- $G^*_{e}$
- $G^*_{e} = 0$
- $G^*_{e} > 0$

Frequency (Hz)
Rheology (G*) Formulation
Fitted model (Phenomenological)

\[ G^* = G^*_e + \frac{G^*_g - G^*_e}{1 + (f_c / f')^k} \frac{m_e}{k} \]  \[ \text{[7]} \]

- \( G^*_e = G^* (f \rightarrow 0) \), equilibrium complex modulus,
- \( G^*_g = G^* (f \rightarrow \infty) \), glassy complex modulus,
- \( f_c \) = location parameter, (temperature effects)
- \( f' \) = reduced frequency, (speed effects)
- \( k, m_e \) = shape parameters, dimensionless.
- (Aging effects)
Phase Angle Formulation

\[
\delta = 90I - (90I - \delta_m) \left[ 1 + \left( \frac{\log(f_d/f')}{{R_d}} \right)^2 \right]^{-m_d/2}
\]  \[11\]

- \(\delta_m\) = phase angle constant, the value at \(f' = f_d\),
- \(f_d\) = location parameter,
- \(R_d, m_d\) = shape parameters,
- \(I = 0\) for mixtures;
- \(I = 1\) when \(f' > f_d\) and \(I = 0\) when \(f' < f_d\) for binders.
Mixture SST FSCH-- $G^*$ data
(PG76-22 binder, Limestone agg.)
Temperature and Strain Shift Factors

\[
\log \frac{a_T(T)}{a_T(T_0)} = - \frac{c_1(T-T_0)}{c_2 + (T-T_0)} \tag{14}
\]

\[ T_0 = \text{reference temperature (52C)}, \]
\[ c_1, c_2 = \text{constants}. \]

\[
\log \frac{a_\gamma(\gamma)}{a_\gamma(\gamma_0)} = - \frac{d_1(\gamma-\gamma_0)}{d_2 + (\gamma-\gamma_0)} \tag{15}
\]

\[ \gamma_0 = \text{reference strain (0\%)} , \]
\[ d_1, d_2 = \text{constants}. \]
Binder and mixture

$G^*$ master-master curves

![Graph showing binder and mixture $G^*$ master-master curves]
Binder and mixture
Phase angle - $\delta$ - master curves
Binder and mixture temperature shift factors

![Graph showing binder and mixture temperature shift factors. The graph plots logaT against Temperature (C). The graph includes two lines: a red dashed line labeled 'Binder fit' and a blue dashed line labeled 'Mix fit.' The graph shows a downward trend as temperature increases.]
Binder and mixture strain shift factors

Binder fit
Mix fit

Binder/Mixture Strain (%)
## Evaluation of Errors

<table>
<thead>
<tr>
<th>Items</th>
<th>Max Error</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Binder</td>
<td>Mixture</td>
</tr>
<tr>
<td>log G(^*)</td>
<td>0.2644</td>
<td>0.2972</td>
</tr>
<tr>
<td>δ (degree)</td>
<td>8.4</td>
<td>13.8</td>
</tr>
<tr>
<td>log a(_T)</td>
<td>0.0516</td>
<td>0.2058</td>
</tr>
<tr>
<td>log a(_γ)</td>
<td>0.0101</td>
<td>0.0188</td>
</tr>
</tbody>
</table>
If we have binder rheology model, can we predict mixture rheology?

Best “direct” approach is Finite Element Method
From Image to FEM

Binary Image

Finite Element Mesh

MATLAB
Experimental vs. FEM Estimated Mixture Stiffness

\[ G^* (\text{Pa}) \]

\[ \text{Frequency , Hz} \]

- Mix (FEM)
- Binder
- Mix I (Experiment)
- Mix II (Experiment)
Aggregate Interlock
Aggregate Interlock (cont’d)

Measured

$G^*$ (Pa)

Frequency, Hz

- Mix (FEM) w/ interlock
- Mix I (Experimental)
- Mix II (Experimental)
- Binder (RTFO)
Transition Zone
Transition Zone (cont’d)

![Graph showing G* (Pa) vs Frequency, Hz for 1B04 mixture. The graph includes different markers and lines for Mix (FEM), Binder, Mix I (Experiment), and Mix II (Experiment).]
How is modeling currently used in prediction performance?

Empirical Models are the Most Common
AASHTO 2002
Dynamic Modulus $/E^*/$Phase Angle, $\phi$

$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad \phi = \omega t_i$

Slide from Dr. Ray Bonaquist
AASHTO 2002 – (Witczak et al.)
Model for Plastic Strain \( (\varepsilon_p) \) – All Data

\[
\log \varepsilon_p = c_1 + c_2 \log N + c_3 \log No4 + c_4 \log No200 + c_5 \log \text{temp} + c_6 \log \text{th ei} + c_7 \log Va + c_8 \log vfa + c_9 \log \text{th fr} + c_{10} \log \text{Dev st} + c_{11} \log \text{visc t} + c_{12} (\log N)^2 + c_{13} (\log No4)^2 + c_{14} (\log \text{thei})^2 + c_{15} (\log Va)^2 + c_{16} (\log \text{temp})^2
\]

\( c_1 = 22.083, \quad c_2 = 0.5083, \quad c_3 = 38.131, \quad c_4 = -11.297, \quad c_5 = 44.16, \)
\( c_6 = -111.539, \quad c_7 = 0.4515, \quad c_8 = 0.6739, \quad c_9 = 3.5783, \quad c_{10} = 0.7, \)
\( c_{11} = -0.0825, \quad c_{12} = -0.0349, \quad c_{13} = -12.456, \quad c_{14} = 5.69, \quad c_{15} = 31.219, \)
\( c_{16} = -10.468 \)

\( R^2 = 71.8\% \)
\( Se/Sy = 0.537 \)
\( N = 4995 \)
How important is effect of Binder in typical mixture?

1. Rheology
2. Damage Resistance
Sensitivity to temperature:
Ratio of $G^*$ at 46C to $G^*$ at 52C ($f=0.1$Hz)

Binder Change per 6C = 2.3
Mix Change per 6 C = 1.4
Sensitivity to **Traffic Speed** : Ratios of $G^*$ at 10 Hz to $G^*$ at 0.1 Hz ($T=52^\circ C$)

**Graph Details:**
- **Temperature (C)**: 52
- **Strain (%)**: 0.01
- **Binder Change per 100 Hz**: 18
- **Mix Change per 100 Hz**: 5

**Graph Legend:**
- Binder
- Aggregate Type
- Binder: PG82 (SBSr), PG82 (PE), PG82 (ss), PG82 (SBR)/(SBSi), PG76 (ET), PG76 (oxd), PG58 (SBSi), PG58 (SB), PG58 (oxd)
- Aggregate Type: AI Coarse, AI Fine, NCAT Coarse, NCAT Fine
Effect of **Traffic Speed**: Ratios of $G^*$ at 10 Hz to $G^*$ at 0.1 Hz ($T=\text{IT}$)

- **Temp (C) =**
- **Strain (%) =** 0.01

- **Binder Change per 100Hz =** 7.0
- **Mix Change per 100 Hz =** 3.0
Sensitivities to Temperature and Traffic Speed

- Mixture sensitivity to temperature is lower than binder.
  - Changing grade from PG-58 to PG-64 results in:
    - Binder G* increase by 230%
    - Mix G* increase by only 40 %

- Mixture sensitivity to traffic speed is also lower than binder.
  - Increasing speed from 0.5 mph to 50 mph results in:
    - Binder G* increase by 1800% (52 C), 700% (25 C)
    - Mix G* increase by only 500 % (52C), 300% (25C)
Mixture vs. Binder (G*)

Mixture G* (Kpa) = A*(Binder G^B (Pa))

<table>
<thead>
<tr>
<th>Mixture</th>
<th>A</th>
<th>B</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder 10% - Mixture 0.1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AI</td>
<td>504.66</td>
<td>0.5029</td>
<td>0.9756</td>
</tr>
<tr>
<td>NCAT</td>
<td>144.34</td>
<td>0.5536</td>
<td>0.9794</td>
</tr>
<tr>
<td>ALL</td>
<td>269.89</td>
<td>0.5282</td>
<td>0.918</td>
</tr>
</tbody>
</table>

Binder G* at 10Hz and 0.1Hz at 52C and IT (10%) (Pa)

Mixture at 10Hz and 0.1Hz at 52C and IT (0.1%) (KPa)
Simplified Binder to Mixture Relationships

Mixture $G^*$ (KPa) = $A^*[\text{Binder } G^*]^B$

Binder $G^*$ (1% strain) - Mixture $G^*$ (0.01% strain)

<table>
<thead>
<tr>
<th>Modifiers</th>
<th>A</th>
<th>B</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 82 SBSr</td>
<td>1865.2</td>
<td>0.4456</td>
<td>0.997</td>
</tr>
<tr>
<td>PG 82 PEs</td>
<td>1581.6</td>
<td>0.4982</td>
<td>0.984</td>
</tr>
<tr>
<td>PG 82 Oxd</td>
<td>391.66</td>
<td>0.5443</td>
<td>0.966</td>
</tr>
<tr>
<td>PG 82 SBR</td>
<td>121.37</td>
<td>0.6004</td>
<td>0.997</td>
</tr>
<tr>
<td>PG 76 Eter</td>
<td>1391.3</td>
<td>0.4393</td>
<td>0.975</td>
</tr>
<tr>
<td>PG 76 Oxd</td>
<td>210.48</td>
<td>0.5782</td>
<td>0.994</td>
</tr>
<tr>
<td>PG 58 SBSI</td>
<td>1347.9</td>
<td>0.4368</td>
<td>0.992</td>
</tr>
<tr>
<td>PG58 SB</td>
<td>674.26</td>
<td>0.4463</td>
<td>0.998</td>
</tr>
<tr>
<td>PG 58 Oxd</td>
<td>1004.4</td>
<td>0.4511</td>
<td>0.986</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td><strong>717.16</strong></td>
<td><strong>0.4928</strong></td>
<td><strong>0.898</strong></td>
</tr>
</tbody>
</table>
The Best Simplified Relationship

- Analyses of data (9 binders and 36 mixtures) indicate that the best model is:
  \[
  \text{Mix } G^* = 720 \times (G^* \text{ of Binder})^{0.50}
  \]

- This model could be used for estimating binder effects in pavement analysis and design of layer thickness.
- It should allow revision of binder grading to effective grades.
How do binders affect mix damage?

1. Rutting
2. Fatigue
Flexible Pavement Failures.

1. RUTTING
Mixture Rutting (log-log plot)

![Graph showing the relationship between permanent strain and number of cycles for different aggregate types and stresses.](image-url)
Damage Testing for Rutting (Repeated Creep Test for Binders)

Creep Tests at 70C, 300 Pa shear stress
(Loading 1s Recovery 9s) 100 cycles

Accumulated Strain

Time (s)

Normal Scale

PG 82- Oxidized
PG82- PEs
PG-82- SBSr
Evaluation of Binder Effect on Mixture Rutting

Average of All Aggregates

Mix = 0.201 Binder + C

$R^2 = 0.6821$
Longitudinal Cracking In the Wheel Path – Alligator cracking

Fatigue
Mixture Fatigue Response

![Graph showing the response of mixture fatigue with number of cycles on the x-axis and stiffness on the y-axis. The graph includes lines for AI Coarse Average Fit, AI Fine Average Fit, NCAT Coarse Average Fit, and NCAT Fine Average Fit.]
Binder only
Fatigue Test Results (DSR)

Number of Cycles in the DSR

G*, Pa

Cycles

0.0E+00 2.0E+06 4.0E+06 6.0E+06 8.0E+06 1.0E+07 1.2E+07 1.4E+07 1.6E+07

100 1000 10000 100000 1000000

20000

400000
Correlation between Binder & Mixture Fatigue Lives

Mix = 0.198 Binder + C

$R^2 = 0.8412$
Findings from Damage Testing

- **Rutting Resistance**
  - On average, *the rule of 5 to 1* applies:
    - 100% change in binder resistance could result in only 20% change in mixture rutting resistance.

- **Fatigue Resistance**
  - Surprisingly, *the same rule of 5 to 1 can be applied*:
    - 100% change in fatigue life of binders results in 20% change in fatigue life of mixtures.

- Aggregate type and gradation can have significant influence on rutting and fatigue.
In summary

- **Binder rheology is important, but we need better methods to estimate effect on performance.**
- **Effective PG specification should be based on a scale of mixture behavior.**
Moisture Damage !
Adhesion Measurement

Schematic of Piston

Specimen Preparation
The relationship between the stress \( f \) and the time \( t \) when the plates move from \( d_0 \) to \( d_1 \) is given by:

\[
f = \frac{3\eta a^2}{4t} \left( \frac{1}{d_0^2} - \frac{1}{d_1^2} \right)
\]

- \( f \) = stress applied
- \( t \) = duration
- \( \eta \) = viscosity of adhesive
- \( a \) = radius of specimen
- \( d_0 \) = initial thickness of adhesive layer
- \( d_1 \) = thickness after time interval \( t \)
Hamburg Wheel Tracking Test

- Asphalt:
  - B1: Original PG 58-28 (RTFO)
  - B2: PG 64-28 Chemically Treated (RTFO)
  - B3: PG 64-28 w/ Elvaloy (RTFO)
  - B4: PG 64-34 w/ Elvaloy (RTFO)
  - B5: PG 70-28 w/ Elvaloy (RTFO)
- Aggregate: Limestone and Granite

*Testing Results and Pictures Provided by Mr. Reinke of the MTE Services, Inc.*
HWT Test Results

![Graph showing cycles to failure for different asphalt materials and binders: Limestone, Granite, Base, Acid, and Polymer.](image)

- **Limestone**
- **Granite**
- **Polymer**

**Asphalt**
- B1
- B2
- B3
- B4
- B5

**Cycles to Failure**

- 0
- 5000
- 10000
- 25000
- 50000
- 250000
- 500000
- 1000000
Linear Model Predicting the HWT Test results from Adhesion and Cohesion of Binder

$R^2 = 0.87$

Study will be Published in 2005 tRB