Understanding Development and Implementing the Multiple Stress Creep Recovery (MSCR) Test as a Specification Parameter

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Problem: High Temperature Binder Criteria

- Does $G^*/\sin \delta$ reflect rutting performance of modified binders?
  - General anecdotal data says no.
Mississippi SPS – 9 Project

- I 55, 3 binders same mix design, 2 years and 2.4 million ESAL’s
  - 58-22 exhibited 7 mm of rutting.
  - 64-22 exhibited 3 mm of rutting.
  - 76-22 exhibited no rutting.
Modified Binders Affect Performance

- Study same mix different binders.

PG 63-22 mod. no rutting

PG 67-22 unmod. 15mm rutting
High Temperature Binder Criteria

What is Rutting?

- Rutting is the plastic deformation of a mix caused by heavy traffic loads.
- This is a high strain failure in the pavement. It is a non-linear response.
- Linear criteria of the binder are not likely to correlate with failure.
Current spec, $G^*$ and $\delta$ are measured in the linear visco-elastic range.

For viscous materials flow is linear even under high stress and high strain.

For polymer networks the binder response is not linear for high stress and high strain.
Rutting in Asphalt Layer

Movement and rotation of aggregate creates very high strain in the binder.

Review of the Multi-Stress Creep and Recovery Work
Aggregate reorientation during Rutting
Why Superpave Plus Specs.

- The existing SHRP specifications do not identify the performance characteristics of modified binders.
- The existing specifications do not have a criteria for fatigue or durability.
- Agencies look to other tests to identify modifiers
  - Elastomeric polymer modifiers are desired
Problem Statement

- Provide Users a High Temperature Binder Spec Blind to Modification
- Provide Users with alternatives to the empirical Superpave Plus tests
  - Elastic Recovery
  - Ductility/ Force Ductility
  - Toughness and Tenacity
- Approach: Develop AASHTO/ASTM Standard Practice for Superpave Plus Specifications
  - Use existing equipment - DSR
    - Multiple Stress Creep Recovery
Previous studies of High Temperature Binder Properties

NCHRP 9-10

- Repeated Shear Creep
  - Analogous to mixture test (RSCH)
  - Performed in DSR
    - Controlled shear stress (i.e., 25 Pa or 300 Pa)
    - 100 cycles
    - 1-second load, 9-second rest per cycle
    - High test temperature (HT-?)
  - Response: permanent shear strain ($\gamma_p$) or strain slope
Repeated Shear Creep

NCHRP 9-10: PG 82 Binders

Repeated Shear Creep (70°C, 300Pa)

Perm. Shear Strain, %

0 2 4 6 8 10 12 14

0 200 400 600 800 1000

Time, seconds
# Repeated Shear Creep

<table>
<thead>
<tr>
<th>Binder</th>
<th>$G^*/\sin \delta$</th>
<th>$\gamma_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 82 Ox</td>
<td>15.27</td>
<td>11.6%</td>
</tr>
<tr>
<td>PG 82 SBS-r</td>
<td>13.22</td>
<td>2.4%</td>
</tr>
<tr>
<td>PG 82 PE-s</td>
<td>13.10</td>
<td>6.9%</td>
</tr>
</tbody>
</table>
# High Temperature Binder Criteria
## Initial Mix Study

Table 1. Asphalt Binders Selected for This Study.

<table>
<thead>
<tr>
<th>Asphalt Binder</th>
<th>Continuous Grade</th>
<th>Trade Name</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG70-22</td>
<td>PG71.8-23.0</td>
<td>N/A</td>
<td>Citgo Asphalt refining Co. supplied for ALF, Lab. No B6267</td>
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<tr>
<td>PG70-28</td>
<td>PG74.1-28.2</td>
<td>Air Blown</td>
<td>Trumbull and Owens Corning supplied for ALF, Lab No. B6281</td>
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<tr>
<td>PG58-40</td>
<td>PG64.4-42.3</td>
<td>Elvaloy</td>
<td>Mathy Testing Services</td>
</tr>
<tr>
<td>PG58-40</td>
<td>PG61.9-41.3</td>
<td>Stylink</td>
<td>Koch Materials</td>
</tr>
</tbody>
</table>
Mix tests and performance

[Graph showing APA Testing with different materials and their performance over temperature C.
Key:
- 70-22
- Air Blown
- Stylink
- Elvaloy]
Mix test and performance

Hamburg Rutting 10000 cycles Dry

- Stylink
- 70-22
- Air Blown
- Elvaloy
- Expon. (Stylink)
- Expon. (70-22)
- Expon. (Air Blown)
- Expon. (Elvaloy)
FINDINGS

- APA and Hamburg are failure tests.
- Binder properties measured in the linear range cannot correlate with non-linear mix tests.
- Polymer chains will slip under high stress.
- Pavement response must be determined to relate binder to mix.
Jnr of the binder from Rut Tester
Study with multiple stresses

The Stylink shows the most sensitivity to stress going from the most rut resistance to the least.

Non-Recoverable Compliance Jnr

Stress Pa

control
Elvaloy
Koch
AB
High Temperature Binder Criteria

- New criteria non recoverable compliance is based on binder creep testing at several stress levels.
- Determine the average unrecovered stain and recovery cycles and then divide the stress level of the test by the average unrecovered strain.
Testing for development of a New High Temperature Binder Test

- Evaluation test criteria:
  - Perform multiple stress levels on the same sample at reduced number of cycles.
  - Stress levels: 25, 50, 100, 200, 400, 800, 1600, and 3200, 6400, 12800, 25600 Pa.
  - Run 10 cycles at each stress level no rest periods
  - Total cycles per test 110.
Determination of $\text{J}_{\text{nr}}$

$\text{J}_{\text{nr}} = \frac{\gamma_{u}}{\tau}$

$\gamma_{u}$ = Avg. un-recovered strain

$\tau$ = applied stress during creep kPa

$\text{J}_{\text{nr}}$ = non-recoverable compliance
MSCR and Rutting

• What is the relationship of $J_{nr}$ to Rutting?
  • The relationship was determined with many field and lab studies using many modified and neat binders.
  • During Specification development many stress levels were evaluated in the test.
<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
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<tr>
<td>AZ</td>
<td>CRM</td>
<td>70-22</td>
<td>PG</td>
<td>70-22</td>
<td>Control</td>
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<td>SBS</td>
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<td>+</td>
<td>Fiber</td>
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<td>70-22</td>
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<td>SBS</td>
<td>64-40</td>
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<td>Air</td>
<td>Blown</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>TP</td>
<td></td>
</tr>
</tbody>
</table>

**7 Asphalt Binders**
ALF Loading

- The pavement was heated to a constant 64°C.
- The FHWA ALF uses an 18,000 lbs wheel load with no wheel wonder.
- The speed is 12 MPH.
  - This is an extreme loading condition far more severe than any actual highway.
Relationship between $G^*/\sin \delta$ and ALF rutting

Existing SHRP specification has poor relationship to rutting for modified systems.
Relationship between Jnr and ALF rutting 25.6kPa

y = 4.7357x - 1.1666
R^2 = 0.8167

MSCR can adjust for field conditions and has excellent relations to performance.
Dry Hamburg Testing
Dry Hamburg Testing

- Testing is done dry to eliminate the effect of moisture damage.
- 158 lbs load with a steel wheel.
Hamburg Rut testing MinnRoad mixes
Tested at multiple temps

\[ y = 0.3976x - 0.2894 \]
\[ R^2 = 0.9646 \]
<table>
<thead>
<tr>
<th>Binder</th>
<th>Modification</th>
<th>Formulation</th>
<th>Continuous PG grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 58-28</td>
<td>None</td>
<td>NA</td>
<td>60.4-29.8</td>
</tr>
<tr>
<td>PG 64-22</td>
<td>None</td>
<td>NA</td>
<td>66.1-23.5</td>
</tr>
<tr>
<td>PG 70-22</td>
<td>None</td>
<td>NA</td>
<td>71.5-25.0</td>
</tr>
<tr>
<td>PG 70-22 SBR</td>
<td>SBR Latex</td>
<td>3% BASF NX-1118 SBR solids</td>
<td>70.9-25.7</td>
</tr>
<tr>
<td>PG 70-28 SBS</td>
<td>SBS with sulfur cross linking</td>
<td>2% Kraton 1116, 1% Kraton 1118 + 0.1% sulfur</td>
<td>72.2-30.3</td>
</tr>
<tr>
<td>PG 70-28 ELV</td>
<td>Elvaloy® + PPA</td>
<td>2.1% Elvaloy® AM + 0.3% PPA</td>
<td>72.3-30.1</td>
</tr>
<tr>
<td>PG 70-28 SBS/EB</td>
<td>SBS with sulfur cross linking + EntiraBond 120</td>
<td>(1% Kraton 1116, 0.5% Kraton 1118 + 0.1% sulfur) + 1.2% EntiraBond®12</td>
<td>71.5-29.2</td>
</tr>
<tr>
<td>PG 76-28 ELV</td>
<td>Elvaloy® + PPA</td>
<td>2.6% Elvaloy® AM + 0.4% PPA</td>
<td>77.2-30.8</td>
</tr>
<tr>
<td>PG 76-22 SEAL</td>
<td>Sealoflex® + PPA</td>
<td>2.8% SBS + 0.4% PPA</td>
<td>81.9-27.5</td>
</tr>
</tbody>
</table>
Hamburg Rutting 9 binders one mix, multiple temps, Jnr 12.8 kPa

\[ y = 0.1663x - 0.3701 \]

\[ R^2 = 0.8454 \]
Kentucky 70-22 Study

- Kentucky PG 70-22 Study (1996)
  - Evaluate PG 70-22 asphalt binders produced by different methods
    - SBS (2)
    - SBR
    - Gel
    - Select Crude
  - I-64 near Winchester
    - Duplicate 1-mile test sections using each asphalt binder
    - Asphalt binder and mixture testing
Effect of Binder G*/sin δ on Mixture Permanent Shear Strain

\[ y = 19270.79e^{-0.09x} \]

\[ R^2 = 0.42 \]
Effect of Binder $J_{nr}$ on Mixture Permanent Shear Strain

$y = 8633.20e^{0.58x}$

$R^2 = 0.71$
Statistical Comparison by Binder Groups

- **Group A**
  - 322
    - Average $J_{nr} = 0.195$
    - Average $\gamma_p = 9,750$ microstrain

- **Group B**
  - 330, 328
    - Average $J_{nr} = 0.580$
    - Average $\gamma_p = 12,125$ microstrain

- **Group C**
  - 326, 324
    - Average $J_{nr} = 1.78$
    - Average $\gamma_p = 17,250$ microstrain
Miss I55 6yr rut Jnr 3.2 kPa

\[
y = 0.2907x + 0.1297
\]

\[R^2 = 0.7499\]

<table>
<thead>
<tr>
<th>binder</th>
<th>mod</th>
<th>true grade</th>
<th>6 yr</th>
<th>Jnr 3.2 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrapave SBR</td>
<td>70-27</td>
<td>4.5</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Styrelf SB</td>
<td>77-29</td>
<td>2</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>GTR 80 SBS</td>
<td>75-29</td>
<td>1.5</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td>Sealoflex SBS</td>
<td>82-27</td>
<td>3</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Multigrade</td>
<td>72-24</td>
<td>5</td>
<td>2.13</td>
<td></td>
</tr>
<tr>
<td>Cryo Rubber</td>
<td>75-28</td>
<td>7</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>70-24</td>
<td>11</td>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>
Effect of Gradation on Rutting

\[ y = 0.1654x - 0.3805 \]
\[ R^2 = 0.83 \]

\[ y = 0.0776x - 0.1829 \]
\[ R^2 = 0.80 \]

\[ y = 0.0425x - 0.1175 \]
\[ R^2 = 0.81 \]
High Temperature Binder Criteria

- Linear binder tests will not correlate with high temperature mix failure test unless the binder is a viscous fluid at those temps.
- To accurately address mix failure non-linear binder properties have to be evaluated.
- Creep & Recovery testing of the binder at different stress levels is needed to describe binder properties in the non-linear range.
Affect of Jnr on Rutting

- Reducing $J_{nr}$ by half typically reduced rutting by half.
- This affect is seen on ALF sections and Hamburg Rut Testing.
- But most importantly this is seen on the Mississippi I 55 sections.
Determination of a Specification criteria.

- The existing binder specification works very well for neat binders.
- The grading for neat binders should not change.
- Establish new $J_{nr}$ criteria based on response of neat binders at their continuous grade temp.
- Evaluate the binders near the end of their linear range. Most neat binders remain linear up to 3.2 kPa stress.
## Evaluation of Straight run binders

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Name</th>
<th>Grade</th>
<th>true grade</th>
<th>Temp</th>
<th>Jnr 3.2kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALF 6727</td>
<td>Control</td>
<td>70-22</td>
<td>72.7-74.2</td>
<td>72.7</td>
<td>4.39</td>
</tr>
<tr>
<td>BBRS3</td>
<td>straight</td>
<td>64-22</td>
<td>66.1-27.3</td>
<td>66.1</td>
<td>4.18</td>
</tr>
<tr>
<td>MN county rd 112</td>
<td>neat Valero</td>
<td>58-28</td>
<td>60.8-33.4</td>
<td>60.8</td>
<td>3.68</td>
</tr>
<tr>
<td>MN county rd 112</td>
<td>neat Citgo</td>
<td>58-28</td>
<td>59.5-29.8</td>
<td>59.5</td>
<td>5.30</td>
</tr>
<tr>
<td>MN county rd 112</td>
<td>AshlandM</td>
<td>58-28</td>
<td>60.7-31.4</td>
<td>60.7</td>
<td>4.30</td>
</tr>
<tr>
<td>Minn Road</td>
<td>straight</td>
<td>58-28</td>
<td>61.8-30.8</td>
<td>61.8</td>
<td>3.03</td>
</tr>
<tr>
<td>Miss I-55</td>
<td>CSL</td>
<td>67-22</td>
<td>68.3-25.1</td>
<td>68.3</td>
<td>2.67</td>
</tr>
<tr>
<td>Shandong</td>
<td>straight</td>
<td>64-22</td>
<td>64.4-23.5</td>
<td>64.4</td>
<td>4.44</td>
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<tr>
<td>BBRS3</td>
<td>straight</td>
<td>70-22</td>
<td>71.4-24.8</td>
<td>71.4</td>
<td>4.81</td>
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<tr>
<td>BBRS3</td>
<td>straight</td>
<td>58-28</td>
<td>61.3-30</td>
<td>61.3</td>
<td>4.00</td>
</tr>
<tr>
<td>MD project</td>
<td>straight</td>
<td>64-28</td>
<td>64.8-29.6</td>
<td>64.8</td>
<td>4.59</td>
</tr>
<tr>
<td><strong>average</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>4.13</strong></td>
</tr>
</tbody>
</table>
Polymer modified binders have shown significant sensitivity to the applied stress.
The existing SHRP binder specification does not identify this issue.
Compliance values increase with temperature and stress. The rate of increase with stress increases with increased temperature.
Affect of Temp and Stress on Jnr

In neat binders a grade bump by temp will more than double the Jnr value.

Some neat binders will maintain their compliance value well beyond the 3.2 kPa stress.

Grade bumping by increases in PG grade temp have forced suppliers to use very soft base binders and high degree of polymer modification to meet wide temperature ranges and the 2.2 kPa for the RTFOT.

This has made some polymers very stress sensitive.
Grade bumping recommendation

- All testing should be done at the environmental grade temp one shift factor does not work for polymer binders.
- The standard grade should be based on the Jnr value of existing neat binders 4.5.
- For high traffic the Jnr value should be reduced by half at the grade temp to 2.0.
- For standing traffic the Jnr value should be reduced by half again 1.0.
New high Temp Spec

- PG 64 (Standard, Heavy, Very heavy, Extreme) based on traffic.
  - PG 64S-XX $J_{nr} \leq 4.5$
  - PG 64H-XX $J_{nr} \leq 2.0$
  - PG 64V-XX $J_{nr} \leq 1.0$
  - PG 64E-XX $J_{nr} \leq 0.5$
NuStar Rutting Study Dry
Hamburg WI E10 fine mix

\[ y = 0.4848x - 0.3131 \]

\[ R^2 = 0.9586 \]
MSCR What is % Recovery

- MSCR $J_{nr}$ addresses the high temperature rutting for both neat and modified binders, but many highway agencies require polymers for cracking and durability.
- The MSCR % Recovery measurement can identify and quantify how the polymer is working in the binder.
What is % Recovered Strain

\[ \gamma_p = \text{Peak strain} \]

\[ \gamma_r = \text{recovered strain} \]

\[ \gamma_u = \text{un-recovered strain} \]

\[ \% \text{ recovery} = (\frac{\gamma_r}{\gamma_p}) \times 100 \]
Blending of binders and polymers

Jnr, % recovery study

- PG 64-22 Base asphalt
- 4 % SBS polymer
  - Radial
  - Linear
- 0.5% PPA
- 2 blending temperatures
Polymer network effects response and temperature effects.

4 binders same base asphalt all with 4% SBS polymer. 2 with .5% PPA all have different properties.
MSCR does a far better job of distinguishing between binders

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Continuous Grade</th>
<th>Polymer</th>
<th>PPA</th>
<th>Temp C</th>
<th>$J_{nr}$ 3.2kPa</th>
<th>ER</th>
<th>% Recovery 3.2kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>66.7-24.1</td>
<td>0</td>
<td>64C</td>
<td>3.12</td>
<td>5</td>
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<td>LC 4</td>
<td>75.7-22.3</td>
<td>4% SBS</td>
<td>0</td>
<td>70C</td>
<td>1.85</td>
<td>73.8</td>
<td>19.2</td>
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<td>LC P4</td>
<td>81.2-22.2</td>
<td>4% SBS</td>
<td>0.50%</td>
<td>70C</td>
<td>1.06</td>
<td>93.8</td>
<td>28.4</td>
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<td>LOP 4</td>
<td>76.6-25.2</td>
<td>4% SBS from Concentrate</td>
<td>0</td>
<td>70C</td>
<td>1.18</td>
<td>86</td>
<td>40.3</td>
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<tr>
<td>LOP 4P</td>
<td>81.6-24.5</td>
<td>4% SBS from Concentrate</td>
<td>0.50%</td>
<td>76C</td>
<td>2.35</td>
<td>83</td>
<td>37.02</td>
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</tbody>
</table>

Fluorescence Micro-graphs at 250 magnification show changes in Morphology

Discreet polymer particles LC 4

More uniform dispersion some bulking

polymer strands developing LC 4P

More uniform dispersion almost cross-linked

LOP 4

LOP 4P
Experiment Design
Time Temperature study

Incompatible 67-22 base binder mixed with 4% linear SBS elemental sulfur as a cross linker.

<table>
<thead>
<tr>
<th>Blending Time, hours</th>
<th>2 h</th>
<th>4 h</th>
<th>6 h</th>
<th>6 h + x-linking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blending Temperature, °C</td>
<td>188</td>
<td>200</td>
<td>188</td>
<td>200</td>
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<tr>
<td>M320 High Temp DSR</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>UDOT Elastic Recovery</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>MSCR Test</td>
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<td>UV Microscopy</td>
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<td>X</td>
<td>X</td>
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</table>
Changes in % Recovery MSCR test with Processing

Recommended Min % Recovery Jnr .5 to 1
Recommended Min % Recovery Jnr 1 to 2
Fluorescence Micro-graphs at 250 magnification

- Discreet polymer particles
- Polymer strands developing
- More uniform dispersion almost cross-linked

188 2h
188 4h
200 2h
200 4h
Fluorescence Micro-graphs at 250 magnification

- Polymer strands developing
- More uniform dispersion almost cross-linked
- 188 6h + x-link
- 200 6h + x-link
BRRS Study Relationship between Jnr and % recovery MSCR test.

% recovery 3.2kPa

SBS Elva 70-28
Elvaloy 70-28
SBS 70-28
SBR 70-22
Ergon 76-22
Elvaloy 76-28

64V,70S
64V, 70H, 76S
64V, 70S
58V, 64H, 70S
70V, 76H, 82S
70V, 76H, 82S
Crumb Rubber study

% recovery vs Jnr for different AMM samples:
- AMM 1 76-28
- AMM 2 76-28
- AMM 3 76-22
- AMM 4 76-22
- AMM 5 70-28
- AMM 6 70-22
MSCR % recovery can be added to validate polymer modification.

\[ y = 29.371x^{-0.2633} \]

High elasticity

Poor elasticity
Validate Polymer Modification

PG 76-22 Binders: MSCR3200

Recovery = 29.37*J_{nr}^{-0.26}

\[ y = 29.82x^{-0.39} \]

\[ R^2 = 0.54 \]
The new specification should be based on the non-recoverable compliance on the binder.

All testing should be done at the pavement environmental grade temp to reflect response at actual operating temperatures.

The test should be run at two stress levels 0.1 and 3.2 kPa ten cycles at each level. A comparison would be made to check how stress sensitive the binder is.

Grade bumping should be done by halving the Jnr value.
Conclusions

- MSCR can identify how the polymer, binder and processing will affect performance in one simple test.
- The use of PPA and x-linker seem to work together to improve the performance properties of the binder as opposed to being used individually.
Thanks!