Linear Amplitude Sweep Test: Binder Grading Specification and Field Validation

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Outline

1. Review of Questions raised last ETG meeting
2. Comparison to Field Performance
3. Use of the LAS as a Performance Grading Criteria
4. Review of Ruggedness Results
5. Conclusions and Recommendations
REVIEW OF CURRENT PROCEDURE
Fatigue Cracking

- **PG test (DSR |G*|sinδ)** is only based on small strain rheology, and does not consider damage resistance.
  - The advantages of many modifiers is manifested as “toughening” and enhancement of damage resistance.

- **Currently in PG+ spec Elastic Recovery and force ductility are used at intermediate temperatures.**
  - It is well recognized that ER is not considered to be a fatigue performance test. It is to indicate there is an elastomer polymer used.

- **The Linear Amplitude Sweep (LAS)** under AASHTO TP101 is introduced as a method of measuring “Damage Resistance”. It is performance-based assessment of binder fatigue resistance.
The “stepped” sweep was replaced with a “continuous” sweep.

- Simpler to run with most rheometers
Current LAS Failure Criteria
(As described in current updated Procedure 3/2014)

- AASHTO TP-101-12 uses VECD to calculate $N_f$ at 35% reduction in initial modulus ($C=0.65$)
- Alternative failure criteria based on peak stress can also be used to relate the ultimate failure criteria to material response indicator
ESTABLISHING RELATION TO FIELD PERFORMANCE
Effect of Traffic Volume and Binder Properties

• Fatigue damage can happen due to the following factors:
  – Poor binder fatigue resistance at specific strain levels
  – High traffic volume
  – Combination of both

• Analysis should consider traffic volume.
Recent WisDOT Study for Implementing the Linear Amplitude Sweep Results

Differences in failure criteria results

Relating Field Fatigue Damage to LAS (WisDOT Study)

• By comparing field performance to LAS results it was found that:
  – Best relation established when LAS performed at the project’s local required Climatic PG intermediate temperature (IT).
    ▪ Defined in LTPPBind Software with 98% Reliability Level
  – Considers variations in binder performance based on local climatic conditions.
  – Field damage was normalized to traffic (next slide)

Establishing DOT Specification

Considering Traffic Volume Variation

- Fatigue damage is function of \textit{traffic volume}.
  - Calculated traffic volume loading leading to \textit{equal damage} in all sections calculated
  - Damage levels from multiple surveys used to develop curves

More data points will be provided through pooled fund PG+ binder tests project
PROPOSED SPECIFICATION
PROCEDURE
Proposed Procedure

1. Perform LAS on binder at Climatic Intermediate specification temperature

2. Calculate LAS Nf at 2.5 and 5% strain
   - Binder strain assumed $\sim 50$ times pavement strain (Masad et al. 2001)
   - For “strong” pavement 500 $\mu$strain assumed ($\text{Binder strain}=0.025 = 2.5\%$)
   - For “weak” pavement 1000 $\mu$strain assumed ($\text{Binder strain}= 0.050 = 5.0\%$)

3. Compare to Nf limit corresponding to design ESALS (using MP-19 or Superpave Mix Design definitions)
Fatigue Law From LAS “A” and “B”
Two binders: 1: Modified, 2: Unmodified

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

For Strong Pavement (\( \gamma_0 = 2.5\% \))
Binder 1: H grade
Binder 2: S grade
Fatigue Law From LAS “A” and “B”
Two binders: 1: Modified, 2: Unmodified

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

For Weak Pavement (\( \gamma_0 = 5.0\% \))
Binder 1: S grade
Binder 2: S grade
Advantages of Proposed Specification

• Can be performed on same sample as used for Superpave M320 grading.

• Calculation is very simple: \( Nf = A(\gamma_0)^B \)

• Considers traffic levels (using MP-19 or DOTs definitions)

• Considers pavement layer stiffness
  – Asphalt layer < 4 “ : use 5.0% strain
  – Asphalt layer > 4 “ : use 2.5 % strain

• Using existing framework for AASHTO MP-19 can facilitate integration and adoption
VALID G* TESTING RANGE
Determination of LAS Valid Temperature-Stiffness Range

- Binders were tested at 5, 10, 15, 25, and 35°C
- Photographs were taken from cracked surface and side (to check for geometry change)
- Time-temperature superposition was checked for VECD damage curves
- Data collected in collaboration between UW-MARC (Dr. Hussain Bahia, Dr. Hassan Tabatabaee) and NCSU (Dr. Cassie Hintz)

- LTPP and MnROAD Binders Tested
  - LTPP 340901
  - LTPP 090962
  - LTPP 370901
  - LTPP 370903
  - LTPP 370962
  - MnROAD C33 (Acid Modified)
  - MnROAD C35 (Elastomer Modified)
Bulging vs. Stiffness

- A relationship was observed between binder stiffness and the apparent geometry change (bulging).

- Too much bulging

### At 10 rad/sec

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>300903</th>
<th>370903</th>
<th>C35</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>G*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 rad/sec (MPa)</td>
<td>10 rad/sec (MPa)</td>
<td>10 rad/sec (MPa)</td>
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<tr>
<td>35</td>
<td>0.41</td>
<td>0.67</td>
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<tr>
<td>25</td>
<td>2.14</td>
<td>4.50</td>
<td>2.39</td>
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<td>20</td>
<td>4.46</td>
<td>10.38</td>
<td>5.21</td>
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<td>15</td>
<td>8.76</td>
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<td>10</td>
<td>16.15</td>
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<tr>
<td>5</td>
<td>27.99</td>
<td>75.36</td>
<td>36.08</td>
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### At 10 Hz

<table>
<thead>
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<th>Temperature (°C)</th>
<th>300903</th>
<th>370903</th>
<th>C35</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>G*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 Hz (MPa)</td>
<td>10 Hz (MPa)</td>
<td>10 Hz (MPa)</td>
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<tr>
<td>35</td>
<td>1.49</td>
<td>2.44</td>
<td>1.38</td>
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<td>25</td>
<td>6.50</td>
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<td>20</td>
<td>13.90</td>
<td>30.99</td>
<td>15.21</td>
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<td>21.95</td>
<td>51.07</td>
<td>24.87</td>
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<tr>
<td>10</td>
<td>36.83</td>
<td>88.23</td>
<td>43.26</td>
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<tr>
<td>5</td>
<td>58.33</td>
<td>140.36</td>
<td>70.45</td>
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</tbody>
</table>
Applicable temperature Limits

- **LAS targets cohesive fracture-based crack propagation**
- At high temperatures geometry change and bulging initiates (observed in photos)
  - **Max Temperature:** $G^* > 10$ MPa at 10 Hz
    - Approximately 2.5 MPa at 10 rad/sec, based on binder
- At low temperatures excessive brittleness and adhesive failures occurs between DSR plates and binder specimen
  - **Min Temperature:** $G^* < 60$ MPa at 10 Hz
    - Approximately 25 MPa at 10 rad/sec, based on binder

*Easily determined from LAS standard frequency sweep step.*
Failure Parameter Within Applicable Temperature-Stiffness Range

- LTPP and MnROAD Binders Tested

![Graph showing the relationship between temperature and failure parameter.](Image)

**Legend:**
- 300903
- 340901
- 370903
- C35
- 90960

**Legend:**
- Increase in Testing Temperature (↑Temp)
- Increase in Failure Indicator (↑Nf)
Effects of Aging on Fatigue Life
Should we test RTFO or PAV?

Effect of Increasing $A$ with Age Level

Effect of Lower $B$ values (higher slope) with Age Level

Keep it consistent with M320: Test PAV
Collect more data for future
REVIEW OF RUGGEDNESS RESULTS
LAS Ruggedness Test (Review)

• Samples sent to 6 labs (listed alphabetically):
  – Asphalt Institute
  – FHWA Turner-Fairbanks
  – MTE Laboratories
  – North Carolina State University
  – University of Wisconsin
  – Utah DOT

• Ruggedness test plan and analysis was performed in accordance to ASTM E1169-12a “Standard Practice for Conducting Ruggedness Tests”

Rheometer Used:
• Anton Paar Smartpave
• TA ARES
• TA Discovery Hybrid 3
• Malvern Kinexus
Material and Method

- 3 binder types tested at at 19°C:
  - An RTFO aged Neat
  - An RTFO+PAV aged Neat
  - An RTFO+PAV aged Highly Polymer Modified

<table>
<thead>
<tr>
<th>Factor</th>
<th>Variable</th>
<th>Level 1</th>
<th>Level -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Sample Loading temperature</td>
<td>60°C</td>
<td>70°C</td>
</tr>
<tr>
<td>S</td>
<td>Strain Amplitude</td>
<td>0.95·(0.1 to 30%)</td>
<td>1.05·(0.1 to 30%)</td>
</tr>
<tr>
<td>F</td>
<td>Frequency Accuracy</td>
<td>9.5 Hz</td>
<td>10.5 Hz</td>
</tr>
<tr>
<td>P</td>
<td>Sample Placement Method</td>
<td>Mold</td>
<td>Pour</td>
</tr>
</tbody>
</table>
Review of Ruggedness Results

- Nf values from new analysis method (Damage at Peak Stress) were **rugged** (p-value > 0.05) against effects of:
  - Loading Temperature
  - Frequency
  - Strain Amplitude
  - Sample type (pour vs. pallet)

<table>
<thead>
<tr>
<th>Rugged?</th>
<th>F1-Loading Temp</th>
<th>F2-Strain Amplitude</th>
<th>F3-Frequency</th>
<th>F4-Sampling</th>
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<tbody>
<tr>
<td>Binder A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lab 1</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<td>Lab 2</td>
<td>Y</td>
<td>Y</td>
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<td>Lab 4</td>
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<td>Lab 5</td>
<td>Y</td>
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<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Binder B</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Lab 1</td>
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<td>Lab 4</td>
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<td>Y</td>
</tr>
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<td>Lab 5</td>
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<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Binder C</td>
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<tr>
<td>Lab 5</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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</table>
Conclusions and Recommendations

• The **Linear Amplitude Sweep test** (AASHTO RP 101) is shown to relate closely to observed field performance.
  – More data points needed to establish specification limits.

• Range of applicable temperatures and stiffness's defined.
  – **Superpave Intermediate PG** is suitable temperature for LAS test.
Next Steps

• Add additional field performance data to use in method shown for development specification Limits based on Mix Design categories (E-3, E-10, etc.) or AASHTO MP-19 framework (“S”, “H”, etc.).

• Draft a separate AASHTO procedure document for binder selection and specification limits.
  – Possibility exists to incorporate into current AASHTO M320 format
Acknowledgements

• This research was sponsored by the Asphalt Research Consortium (ARC), which is funded by FHWA and WRI.

• Dr. Cassie Hintz for her research and collaboration with MARC in finalizing the LAS procedure.

• Dr. Hassan Tabatabaee for contribution to LAS ruggedness testing and establishing relation to field performance.

• Special thanks to all participating laboratories in ruggedness program:
  – Asphalt Institute
  – MTE Laboratories
  – Utah DOT
  – FHWA Turner-Fairbanks
  – North Carolina State University
Image Analysis to Study Effect of Temperature on Failure Mechanism

PG intermediate temperature located in acceptable LAS Test Range

Easily determined from LAS standard frequency sweep step.
Addition of LAS to MP-19 Table

Table 1—Performance-Graded Asphalt Binder Specification

<table>
<thead>
<tr>
<th>Performance Grade</th>
<th>PG 46</th>
<th>PG 52</th>
<th>PG 58</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;46</td>
<td>&lt;52</td>
<td>&lt;58</td>
</tr>
<tr>
<td>Min pavement design temp, °C³</td>
<td>&gt;10</td>
<td>&gt;16</td>
<td>&gt;16</td>
</tr>
<tr>
<td></td>
<td>&gt;8</td>
<td>&gt;22</td>
<td>&gt;22</td>
</tr>
<tr>
<td></td>
<td>&gt;34</td>
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<td>&gt;40</td>
</tr>
<tr>
<td></td>
<td>&gt;6</td>
<td>&gt;28</td>
<td>&gt;28</td>
</tr>
<tr>
<td></td>
<td>&gt;46</td>
<td>&gt;40</td>
<td>&gt;40</td>
</tr>
<tr>
<td></td>
<td>&gt;10</td>
<td>&gt;34</td>
<td>&gt;34</td>
</tr>
<tr>
<td></td>
<td>&gt;46</td>
<td>&gt;34</td>
<td>&gt;34</td>
</tr>
</tbody>
</table>

Linear amplitude Sweep, TP101

- Grade “S”
  - Nf at 2.5 and 5% > 15,000
  - Test temp, °C

- Grade “H”
  - Nf at 2.5 and 5% > 19,000
  - Test temp, °C

- Grades “V” and “E”
  - Nf at 2.5 and 5% > 31,000
  - Test temp, °C

**Same traffic grades (S, H, …)**

Nf strain at 2 levels: “weak” or “strong”

Test at PG intermediate test temperature
Updated Analysis Method

• The following analysis is performed automatically once data is pasted into spreadsheet:

1. $\alpha$ is defined based on the slope of the frequency sweep (unchanged)

2. Calculate Damage for each increment as follows:

$$D(t) \approx \sum_{i=1}^{N} \left[ \pi \gamma_0^2 (C_{i-1} - C_i) \right]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}}$$

Where:

$$C(t) = \frac{|G^*(t)|}{|G^*|_{\text{initial}}}$$
3. C1 and C2 parameters are calculated by fitting the following equation to the C vs. Damage curve:

\[ C(t) = C_0 - C_1(D)^{C_2} \]
Updated Analysis Method

4. Define failure damage level:

\[ D_f = \left( \frac{C_1 - C \text{ at Peak Stress}}{C_1} \right)^{1/c_2} \]

5. Calculate A and B for \( N_f = A(\gamma_{\text{max}})^{-B} \)

\[ A = \frac{f(D_f)^k}{k(\pi C_1 C_2)^{\alpha}} \quad k = 1 + (1 - C_2)\alpha \]

and

\[ B = 2\alpha. \]
Analysis Spreadsheet

- Spreadsheet automatically calculates $A$, $B$, and $N_f$.

$$N_f = A(\gamma_{\text{max}})^{-B}$$