Using RAP in Asphalt Mixtures

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Asphalt Institute

Workshop: Modified Asphalt in a RAP World
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    • Michael Arasteh, AOTR

• Member Companies of the Asphalt Institute
  • Technical Advisory Committee
Terminology

• Grade Bumping
  • Increasing the required high temperature grade of an asphalt binder for a given project so that the asphalt binder has sufficient stiffness to account for traffic loading and temperature.
  • Often requires the use of a modified asphalt binder to achieve higher grade.
  • Target distress: rutting
Terminology

• Grade Dumping
  • Using a softer asphalt binder in conjunction with RAP/RAS to meet a specific final (blended) asphalt binder grade.
  • May not require the use of a modified asphalt binder.
  • Target distress: cracking
“The use of recycled materials, particularly reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS), conserve raw materials and reduce overall asphalt mixture costs....”

• Survey Scope
  • Asphalt mix producers from all 50 states represented
  • 228 companies/branches with 1,185 plants represented
Figure 2: Comparison of Tons of RAP Accepted and Tons of RAP Used (Million Tons)

Source: NAPA Information Series 138, 2015
RAP Usage in the USA (2009-14)

Source: NAPA Information Series 138, 2015
Figure 6: Estimated Average %RAP by State

Source: NAPA Information Series 138, 2015
Determining RAP Properties

• Mix design
  • Low RAP (usually < 25% of total aggregates)
    • Asphalt Content of RAP
    • Aggregate Gradation of RAP
    • RAP Specific Gravity
    • Consensus Aggregate Properties
  • High RAP (usually ≥ 25%)  
    • All of the above
    • Asphalt binder physical properties
Extraction and Recovery Procedures

• Extraction
  • Determine asphalt content of RAP
  • Determine RAP aggregate gradation
  • Necessary for mix design

• Recovery
  • Determine asphalt binder physical properties
  • Necessary for blending charts
    • Usually for high RAP mixtures
    • Need to offset stiffer RAP with softer binder
Recovery procedures

- Conducted after extraction procedure
- ASTM 1856
  - Recovery of Asphalt from Solution by Abson Method
- ASTM D5404
  - Recovery of Asphalt from Solution Using the Rotavapor Apparatus
• Recovery procedures
  • AASHTO T319
    • Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt (HMA)
    • Modified version of SHRP procedure
    • Tumbles mix and solvent together
    • Performs extraction and recovery
Current Recommended Setup
RAP Binder Properties

- Physical properties of RAP binder
  - Used to construct blending charts
  - Characterize at high, intermediate, and low temperatures
RAP Binder Properties

• After recovery...
  • Ensure that there is sufficient material for testing (minimum 50 grams)
  • Perform binder classification testing in accordance with AASHTO M320
    • Rotational Viscosity
    • Flash Point
    • Mass Loss

Not Needed
• Test in accordance with the procedures in AASHTO M320 with the following notes:
  • No flash point, rotational viscosity, or Original DSR testing
  • Perform RTFO aging (AASHTO T240) but no mass loss needed
  • Test the RTFO-aged recovered asphalt binder using AASHTO T315 at two or more temperatures to determine the critical temperature where the $G^*/\sin \delta$ value exactly meets 2.20 kPa.
Recovered RAP Binder Properties

• Test in accordance with the procedures in AASHTO M320 with the following notes:
  • Do not conduct PAV aging on the recovered asphalt binder.

  • Test the RTFO-aged recovered asphalt binder at two or more temperatures to determine the critical temperature where the $G \sin \delta$ value exactly meets 5000 kPa.

  • Test the RTFO-aged recovered asphalt binder at two or more temperatures to determine the critical temperature where the BBR Stiffness value exactly meets 300 MPa and where the BBR m-value exactly meets 0.300.
• “Why conduct RTFO aging on a recovered RAP asphalt binder?”

• Research conducted as part of the NCHRP 9-12 project indicated that by RTFO-aging the recovered RAP binder before testing, any residual solvent left from the recovery procedure would be removed and the linear blending chart approach better matched actual measured values.
RAP Binder Properties

• DSR at high temperature (RTFO-Aged Recovered RAP binder)
  • Determine $T_c$
  • Determine slope of stiffness-temperature curve as $\Delta \log \left( \frac{G^*/\sin \delta}{\Delta T} \right)$
  • Determine $T_c$ to nearest 0.1C

$$T_c \text{ (High)} = \frac{\log(2.20) - \log(G_1)}{a} + T_1$$

$G^*/\sin \delta$ at specific temperature, $T_1$

Slope of stiffness-temperature curve
Determining Continuous Grade Temperature ($T_c$)

$T_c = T_1 + \left[ \frac{\log(2.20) - \log\left(\frac{G^*_1}{\sin \delta_1}\right)}{\log\left(\frac{G^*_1}{\sin \delta_1}\right) - \log\left(\frac{G^*_2}{\sin \delta_2}\right)} \times (T_1 - T_2) \right]$

Where

- $T_c =$ critical temperature (in this case, the critical high temperature)
- $T_1 =$ lower of the two test temperatures, °C, where the $G^*/\sin \delta$ value $\geq 2.20$ kPa
- $T_2 =$ higher of the two test temperatures, °C, where the $G^*/\sin \delta$ value $< 2.20$ kPa
- $G^*_1/\sin \delta_1 =$ $G^*/\sin \delta$ value at temperature $T_1$, kPa
- $G^*_2/\sin \delta_2 =$ $G^*/\sin \delta$ value at temperature $T_2$, kPa
## TABLE 2: Recovered RAP Binder Properties (Example)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Test Property</th>
<th>Temperature, °C</th>
<th>Test Value</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTFO-aged</td>
<td>DSR G*/sin δ</td>
<td>70, 76, 82, 88</td>
<td>15.97, 7.38, 3.50, 1.71 kPa</td>
<td>≥ 2.20 kPa</td>
</tr>
<tr>
<td></td>
<td>DSR G*sin δ</td>
<td>28, 25</td>
<td>4492, 6486 kPa</td>
<td>≤ 5000 kPa</td>
</tr>
<tr>
<td></td>
<td>BBR Stiffness</td>
<td>-12, -18</td>
<td>280, 534 MPa</td>
<td>≤ 300 MPa</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>-12, -18</td>
<td>0.303, 0.254</td>
<td>≥ 0.300</td>
</tr>
</tbody>
</table>
Recovered RAP Binder Properties

\[ T_{c, \text{high}} = 82 + \left[ \frac{\log(2.20) - \log(3.50)}{\log(3.50) - \log(1.71)} \times (82 - 88) \right] = 85.9 \]

- \( T_{c, \text{high}} = 85^\circ\text{C} \) (calculated value = 85.9\(^\circ\text{C}\))
- \( T_{c, \text{int}} = 28^\circ\text{C} \) (calculated value = 27.1\(^\circ\text{C}\))
- \( T_{c, S} = -22^\circ\text{C} \) (calculated value = -22.6\(^\circ\text{C}\))
- \( T_{c, m} = -22^\circ\text{C} \) (calculated value = -22.3\(^\circ\text{C}\))
• Developing Blending Charts
  • Method A - Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)
    • Binder Grade Required by the Project - **KNOWN**
    • Recovered RAP Binder Properties - **KNOWN**
    • Percentage of RAP in Mixture - **KNOWN**
    • Virgin Binder Properties/Grade - **UNKNOWN**
Binder Grade Selection for RAP Mixtures

- Developing Blending Charts
  - Method A - Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)

\[ T_{\text{virgin}} = \frac{T_{\text{blend}} - (% \text{RAP} \times T_{\text{RAP}})}{1 - \% \text{RAP}} \]

- \( T_{\text{virgin}} = \) Tc of virgin binder
- \( T_{\text{blend}} = \) Tc of blended binder (desired)
- \( T_{\text{RAP}} = \) Tc of recovered RAP binder
- \( % \text{RAP} = \) percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)
**Example**

Desired Final Binder Grade: PG 64-22

RAP Percentage: 30%

**RAP Binder Properties:**

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Critical Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High 86</td>
</tr>
<tr>
<td></td>
<td>DSR G* sin δ</td>
<td>Intermediate 31</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low -14</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low -11</td>
</tr>
<tr>
<td></td>
<td>PG Actual</td>
<td>PG 86-11</td>
</tr>
<tr>
<td></td>
<td>M320</td>
<td>PG 82-10</td>
</tr>
</tbody>
</table>
Developing Blending Charts - Method A

\[ T_{\text{Virgin}} = \frac{T_{\text{Blend}} - (\% RAP \times T_{\text{RAP}})}{(1 - \% RAP)} \]

where:
- \( T_{\text{Virgin}} \) = critical temperature of the virgin asphalt binder
- \( T_{\text{Blend}} \) = critical temperature of the blended asphalt binder (final desired)
- \( \% \text{RAP} \) = percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)
- \( T_{\text{RAP}} \) = critical temperature of recovered RAP binder
\[ T_{\text{Virgin}} = \frac{64 - (0.30 \times 86)}{1 - 0.30} = 54.6 \]

Table 5: Estimated Critical Temperatures of Virgin Asphalt Binder

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Critical Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>PAV</td>
<td>DSR G*sin δ</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>-26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>-27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG</td>
<td>Actual</td>
</tr>
<tr>
<td></td>
<td>M320</td>
<td>PG 55-27</td>
</tr>
<tr>
<td></td>
<td>Actual</td>
<td>PG 58-28</td>
</tr>
</tbody>
</table>
Developing Blending Charts - Method A

DSR High Temperature

![Graph](image)

- Critical Temperature ($T_{critical}$) as a function of the Percentage of RAP.
DSR Intermediate Temperature

The graph shows the relationship between the critical temperature ($T_{\text{critical}, \ C}$) and the percentage of RAP (Recycled Asphalt Pavement). The critical temperature increases with the percentage of RAP, as indicated by the line on the graph. At 22.4% RAP, the critical temperature is approximately 22.4°C.
BBR Low Temperature (S)
Developing Blending Charts - Method A

BBR Low Temperature (m-value)
Developing Blending Charts - Method A

• From the Example:
  • To achieve a final asphalt binder grade of PG 64-22, we need
    • Recovered RAP Binder Grade = PG 82-10
    • 30% RAP used in mixture
    • Virgin Asphalt Binder Grade = PG 58-28 (continuous PG 55-27)

70% of PG 58-28 + 30% of RAP PG 82-10 = 100% of PG 64-22
Binder Grade Selection for RAP Mixtures

- Developing Blending Charts
  - Method B - Blending with a Known Virgin Binder Grade (RAP Percentage Unknown)
    - Binder Grade Required by the Project - KNOWN
    - Recovered RAP Binder Properties - KNOWN
    - Percentage of RAP in Mixture - UNKNOWN
    - Virgin Binder Properties/Grade - KNOWN
Binder Grade Selection for RAP Mixtures

- Developing Blending Charts
  - Method B - Blending with a Known Virgin Binder Grade (RAP Percentage Unknown)

\[
\% \text{RAP} = \frac{T_{\text{blend}} - T_{\text{virgin}}}{T_{\text{RAP}} - T_{\text{virgin}}}
\]

- \( T_{\text{virgin}} = \) Tc of virgin binder
- \( T_{\text{blend}} = \) Tc of blended binder (desired)
- \( T_{\text{RAP}} = \) Tc of recovered RAP binder
- \( \% \text{RAP} = \) percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)
## Developing Blending Charts - Method B

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Temp. Range</th>
<th>Virgin Binder</th>
<th>RAP Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>DSR G*/sin δ</td>
<td>High</td>
<td>61</td>
<td>n/a</td>
</tr>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High</td>
<td>61</td>
<td>86</td>
</tr>
<tr>
<td>PAV</td>
<td>DSR G* sin δ</td>
<td>Intermediate</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low</td>
<td>-32</td>
<td>-14</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low</td>
<td>-29</td>
<td>-11</td>
</tr>
<tr>
<td>PG</td>
<td>Actual</td>
<td></td>
<td>PG 61-29</td>
<td>PG 86-11</td>
</tr>
<tr>
<td></td>
<td>M320</td>
<td></td>
<td>PG 58-28</td>
<td>PG 82-10</td>
</tr>
</tbody>
</table>
Example

Desired Final Binder Grade: PG 64-22

Known Virgin and RAP Binder Properties

\[
\%\text{RAP} = \frac{T_{\text{blend}} - T_{\text{virgin}}}{T_{\text{RAP}} - T_{\text{virgin}}}
\]

\[
\%\text{RAP (High)} = \frac{64 - 61}{86 - 61} = 12\%
\]
Developing Blending Charts - Method B

DSR High Temperature

- T_{critical}, C
- 12%, 32%

Percentage of RAP
Developing Blending Charts - Method B

DSR Intermediate Temperature

\[ T_{\text{critical}} \quad ^\circ C \]

- 13
- 16
- 19
- 22
- 25
- 28
- 31
- 34

- 0%
- 20%
- 40%
- 60%
- 80%
- 100%

Percentage of RAP

- 62%

\[ T_{\text{critical}} \quad ^\circ C \] vs. Percentage of RAP
Developing Blending Charts - Method B

BBR Low Temperature (S)

Graph showing the relationship between the percentage of RAP and the critical temperature ($T_{\text{critical}}$) in Celsius (°C). The graph indicates:

- At 28% RAP, the critical temperature is approximately -18°C.
- At 55% RAP, the critical temperature is approximately -12°C.

The graph ranges from 0% to 100% RAP on the x-axis and from 0°C to -24°C on the y-axis.
Developing Blending Charts - Method B

BBR Low Temperature (m-value)

![Graph showing the relationship between percentage of RAP and critical temperature, with specific points at 11% and 38% RAP marked on the graph.](image-url)
# Developing Blending Charts - Method B

## RAP Percentage Required to Achieve Final Blend

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Temp. Range</th>
<th>PG 64-xx</th>
<th>PG 70-xx</th>
<th>PG xx-22</th>
<th>PG xx-28</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High</td>
<td>≥12%</td>
<td>≤32%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>PAV</td>
<td>DSR G*sin δ</td>
<td>Intermediate</td>
<td>---</td>
<td>---</td>
<td>≤62%</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low</td>
<td>---</td>
<td>---</td>
<td>≤55%</td>
<td>≥28%</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low</td>
<td>---</td>
<td>---</td>
<td>≤38%</td>
<td>≥11%</td>
</tr>
</tbody>
</table>
From the example:

- To achieve a final asphalt binder grade of PG 64-22, we need
  - Recovered RAP Binder Grade = PG 82-10
  - Virgin Binder Grade = PG 58-28
- The allowable RAP percentage is between 12% and 32%
  - Increases to 38% maximum if the final binder grade could also meet for a PG 70-22
If RAP is a Black Rock...

- Blending chart premise is invalid.
- Mix properties/ behavior depend on virgin binder only.
- How to evaluate?
  - Analyze mixture properties.
Three Treatments

• **Case A** = virgin binder with virgin aggregate plus extracted RAP aggregate.
• **Case B** = virgin binder with RAP
• **Case C** = virgin binder physically blended with recovered RAP binder.

• Aggregate gradation and source constant.
• Three RAP stiffness
• Two virgin binders (PG58-34, PG 64-22)
• Total binder volume constant.
Black Rock Analysis

• Case A represents “black rock.”
• Case B represents standard practice.
• Case C represents total blending.

• If no blending occurs:
  
  \[ \text{Case A} = \text{Case B} \]

• If partial blending occurs:
  
  \[ \text{Case A} < \text{Case B} < \text{Case C} \]

• If total blending occurs:
  
  \[ \text{Case B} = \text{Case C} \]
NCHRP 9-12 Black Rock Study

64-22 CT 10% RAP

Plastic Shear Strain vs. Cycles

Cycles

Plastic Shear Strain

A

B

C
RSCH Test @58C, 64-22 CT, 40%

Plastic Shear Strain vs. Cycles

Case A
Case B
Case C

NCHRP 9-12 Black Rock Study
Primary Findings

- Blending does occur to an appreciable extent.
- Concept of blending charts is reasonable.
**NCHRP 9-12 Binder Effects**

<table>
<thead>
<tr>
<th>RAP Source</th>
<th>RAP %</th>
<th>PG 52-34</th>
<th>PG 64-22</th>
<th>PG 52-34</th>
<th>PG 64-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
<td>53-33</td>
<td>66-26</td>
<td>52-28</td>
<td>64-22</td>
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<td>FL</td>
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<td>57-33</td>
<td>69-26</td>
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<td>66-29</td>
<td>73-22</td>
<td>64-28</td>
<td>70-22</td>
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<tr>
<td>CT</td>
<td>10</td>
<td>57-33</td>
<td>69-25</td>
<td>52-28</td>
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<td>63-29</td>
<td>72-21</td>
<td>58-28</td>
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<td>40</td>
<td>70-24</td>
<td>78-19</td>
<td>70-22</td>
<td>76-16</td>
</tr>
</tbody>
</table>
NCHRP 9-12 Binder Effects

BBR Stiffness: Arizona RAP
PG 52-34 Blends

BBR Stiffness: Arizona RAP
PG 64-22 Blends

BBR m-value: Arizona RAP
PG 52-34 Blends

BBR m-value: Arizona RAP
PG 64-22 Blends
NCHRP 9-12 Binder Effects Study

ΔTc, degrees

0 10 20 30 40 50

RAP Binder in Blend, %

PG 52-34, FL RAP
PG 52-34, CT RAP
PG 52-34, AZ RAP
CT RAP (from NCHRP 9-12)

ΔTc, degrees

RAP Binder in Blend, %

PG 52-34
PG 64-22
CT RAP (from NCHRP 9-12)

Estimated $\Delta T_c$

- RAP Binder, %

- RAP Binder, %

PG 52-34
PG 64-22
• Key Findings
  • Linear blending chart concept is valid
    • Some non-linearity noted at higher RAP percentage (40%)
  • Rotavapor recovery procedures preferred
    • Significantly different response with Abson
    • Solvent left in recovered binder?
  • RTFO age the recovered RAP binder
    • PAV aging not needed
  • Linear estimation of $\Delta T_c$ may not be accurate
    • Error at low RAP%
    • More work needed
Effect of Testing Variability

• Variability in test results can come from three sources
  • Materials
  • Sampling
    • Controlled by good sampling practices
  • Testing
    • Variability in RAP extraction/recovery procedure
    • Variability in recovered binder test procedures
## Effect of Testing Variability

<table>
<thead>
<tr>
<th></th>
<th>Kentucky</th>
<th></th>
<th></th>
<th>Florida</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>64°C</td>
<td>70°C</td>
<td>76°C</td>
<td>Tc, °C</td>
<td>64°C</td>
<td>70°C</td>
<td>76°C</td>
<td>Tc, °C</td>
</tr>
<tr>
<td>Rep 1</td>
<td>21.76</td>
<td>9.23</td>
<td>4.06</td>
<td>86.0</td>
<td>7.10</td>
<td>3.10</td>
<td>1.42</td>
<td>78.6</td>
</tr>
<tr>
<td>Rep 2</td>
<td>24.24</td>
<td>9.60</td>
<td>4.01</td>
<td>85.3</td>
<td>7.11</td>
<td>3.07</td>
<td>1.39</td>
<td>78.4</td>
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<tr>
<td>Rep 3</td>
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<td>11.55</td>
<td>5.01</td>
<td>87.4</td>
<td>7.79</td>
<td>3.37</td>
<td>1.51</td>
<td>79.0</td>
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<tr>
<td>Ave.</td>
<td>24.43</td>
<td>10.13</td>
<td>4.36</td>
<td>86.2</td>
<td>7.33</td>
<td>3.18</td>
<td>1.44</td>
<td>78.7</td>
</tr>
<tr>
<td>1s</td>
<td>2.27</td>
<td>1.02</td>
<td>0.46</td>
<td>0.9</td>
<td>0.32</td>
<td>0.13</td>
<td>0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>1s%</td>
<td>9%</td>
<td>10%</td>
<td>11%</td>
<td>1%</td>
<td>4%</td>
<td>4%</td>
<td>4%</td>
<td>0.3%</td>
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<tr>
<td>d2s</td>
<td>6.41</td>
<td>2.88</td>
<td>1.30</td>
<td>2.5</td>
<td>0.91</td>
<td>0.38</td>
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<tr>
<td>d2s%</td>
<td>26%</td>
<td>28%</td>
<td>30%</td>
<td>3%</td>
<td>12%</td>
<td>12%</td>
<td>10%</td>
<td>1%</td>
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</tbody>
</table>
Effect of Testing Variability

• Notes
  • Single-laboratory variability associated with AASHTO T319 procedure
    • Multi-lab variability yet to be determined
  • No intermediate or low temperature evaluation determined
  • AASHTO procedures describe asphalt binder testing variability
    • Virgin (tank) asphalt binder
    • Expect variability to increase with recovery procedure
Effect of Testing Variability

• Notes
  • Errors mitigated by RAP percentage used
    • Lower RAP percentage minimizes errors due to variability
  • Mix designers may want to add tolerance to final blended grade to account for variability
    • e.g. use target $T_c$ values for final blend of 66°C and -24°C instead of 64°C and -22°C
Testing Recovered RAS Binders

- Post-consumer (Tear-Off) Shingles
  - Very stiff recovered binder compared to typical recovered RAP binder
  - Some operational changes may be needed to recovery procedure
    - Quantity needed for recovery is less
      - 20-25% asphalt binder content
    - Higher temperature post-recovery to remove binder from recovery flask
• Recovered RAS Binder Properties
  • Typical high temperature $T_c \geq 120^\circ C$
    • Can’t test using many DSRs (particularly water bath units)
  • Typical low temperature $T_{c,S}$ much lower than $T_{c,m}$
    • Not unusual to see temperature difference of 20°C between $T_{c,S}$ and $T_{c,m}$
    • Can’t test at passing/failing temperatures
      • Temperature to get $m$-value close to 0.300 causes Stiffness to be too low to test (excess deflection)
<table>
<thead>
<tr>
<th>ACTION</th>
<th>RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Change in Binder Grade</td>
<td>15% or less</td>
</tr>
<tr>
<td>One Grade Lower</td>
<td>16 - 25%</td>
</tr>
<tr>
<td>Use Blending Charts</td>
<td>&gt;25%</td>
</tr>
</tbody>
</table>
• Effect of Mix Variables on Fatigue Life
  • Relationships exist between the fatigue resistance of asphalt mixtures and volumetric composition
    • Fatigue resistance increases with increasing volume of effective binder (VBE)
      • assuming no change in design compaction, design air voids and in-place air voids.
    • Fatigue resistance increases with increasing N_{design}
      • assuming no change in VBE, design air voids and in-place air voids.
    • Fatigue resistance increases with decreasing in-place air voids (increasing compaction)
      • Assuming no change in VBE, design air void content, and N_{design}. 
Importance of VMA

• VMA is the volume of the voids in a compacted aggregate sample to accommodate asphalt and air.
  • Assure sufficient binder coating
  • Maintain 4% Air voids
Volumetrics – VMA

Volume of air plus effective asphalt expressed as a percentage of the total mixture volume

\[ \text{VMA} = \frac{V_a + V_{be}}{V_{mb}} \times 100 \]
Grade Dumping Scenarios

• High RAP + Unmodified Asphalt Binder
  • Final blend may be same as premium grade
    • e.g. PG 58-28 + 40% RAP (PG 82-22) produces a PG 70-28
    • Is this the same as a mix using virgin PG 70-28?
  • Consider why the premium grade is used
    • Rutting
    • Cracking
    • Durability
  • Lab Performance Testing
Grade Dumping Scenarios

• Medium-High RAP + Modified Asphalt Binder
  • Same premium binder grade required
  • Replacement RAP binder content results in less polymer concentration than 100% virgin mix
    • 30% RAP replacement binder content means 30% less polymer concentration in mix
    • Is there a significant effect?
# Fatigue Study: Asphalt Binders

<table>
<thead>
<tr>
<th></th>
<th>Jnr-3.2</th>
<th>Rec-3.2</th>
<th>FD Ratio</th>
<th>ER</th>
<th>δ</th>
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<td>737</td>
<td>0.104</td>
<td>79.8</td>
<td>0.55</td>
<td>83</td>
<td>64.3</td>
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<tr>
<td>748</td>
<td>0.636</td>
<td>38.6</td>
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<td>73</td>
<td>74.5</td>
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<tr>
<td>736</td>
<td>0.490</td>
<td>32.9</td>
<td>0.33</td>
<td>65</td>
<td>73.6</td>
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<td>735</td>
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<td>0.34</td>
<td>68</td>
<td>72.3</td>
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<tr>
<td>733</td>
<td>0.366</td>
<td>24.7</td>
<td>0.29</td>
<td>65</td>
<td>75.1</td>
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</table>
MSCR – Non-Recoverable Compliance ($J_{nr}$)

$$J_{nr} = \frac{\text{Unrecovered Shear Strain}}{\text{Applied Shear Stress}}$$

Unrecovered Shear Strain

- Cycle 1 Unrecovered (permanent) strain
- Cycle 2 Unrecovered (permanent) strain
- Cycle 3 Unrecovered (permanent) strain

Time, seconds

Strain

0 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80

0 5 10 15 20 25 30 35 40
MSCR – Non-Recoverable Compliance ($J_{nr}$)

$J_{nr} = \frac{\text{Unrecovered Shear Strain}}{\text{Applied Shear Stress}}$

$J_{nr} = \frac{0.197}{0.1 \text{ kPa}} = 1.97 \text{ kPa}^{-1}$

Cycle 1 Unrecovered (permanent) strain
MSCR – Non-Recoverable Compliance ($J_{nr}$)

**0.1 kPa Shear Stress**

**Recovery = 100% * Peak Strain – Unrecovered Strain**

Peak Strain

Recovery = 100% * \(rac{0.300 - 0.197}{0.300} = 34.3\%

Cycle 1 Unrecovered (permanent) strain

Time, seconds
## Fatigue Study: Asphalt Binders

<table>
<thead>
<tr>
<th></th>
<th>Jnr-3.2</th>
<th>Rec-3.2</th>
<th>FD Ratio</th>
<th>ER</th>
<th>$\delta$</th>
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</thead>
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<td>38.6</td>
<td>0.37</td>
<td>73</td>
<td>74.5</td>
</tr>
</tbody>
</table>

- Same Base Binder
- Same Modifier
- Different Concentration
- 30% less polymer
Fatigue Study: Asphalt Binders

Same base binder; Same modifier; Different concentration

Rec-3.2, %

Jnr-3.2, kPa⁻¹
Flexural Beam Fatigue Fixture
Flexural Beam Fatigue Test
Fatigue Study: Effect of Modifier Concentration

**ASTM 4760 4-point Flexural Fatigue**

**Cycles x Stiffness Analysis**

**20°C Test Temperature**

- 737 Mix
- 737 Binder
- 748 Mix
- 748 Binder

- $y = 1.03E+22x - 5.88E+00$
  - $R^2 = 9.98E-01$
- $y = 8.69E+20x - 5.60E+00$
  - $R^2 = 9.33E-01$
- $y = 8.45E+20x - 5.56E+00$
  - $R^2 = 9.93E-01$
- $y = 1.20E+19x - 5.33E+00$
  - $R^2 = 1.00E+00$
## Fatigue Study: Effect of Modifier Concentration

### Binder Strain (E-06)

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<thead>
<tr>
<th>Binder</th>
<th>22,500</th>
<th>30,000</th>
<th>40,000</th>
<th>50,000</th>
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<tr>
<td>737</td>
<td>1.61E+05</td>
<td>3.45E+04</td>
<td>7.37E+03</td>
<td>2.23E+03</td>
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<tr>
<td>748</td>
<td>8.86E+04</td>
<td>1.91E+04</td>
<td>4.13E+03</td>
<td>1.26E+03</td>
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<tr>
<td>Ratio 748/737</td>
<td>55%</td>
<td>56%</td>
<td>56%</td>
<td>57%</td>
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### Mix Strain (E-06)

<table>
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<th>450</th>
<th>600</th>
<th>800</th>
<th>1000</th>
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<td>737</td>
<td>2.33E+06</td>
<td>5.35E+05</td>
<td>8.19E+04</td>
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<td>748</td>
<td>1.61E+06</td>
<td>3.05E+05</td>
<td>4.98E+04</td>
<td>2.09E+04</td>
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<tr>
<td>Ratio 748/737</td>
<td>69%</td>
<td>57%</td>
<td>61%</td>
<td>93%</td>
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Fatigue Study: Effect of Modifier Concentration

- **Caveats**
  - Lab fatigue testing only
  - Single mixture
  - Single modifier/binder combination

- Reinforces the need for mixture performance testing
<table>
<thead>
<tr>
<th>Binder</th>
<th>RAP</th>
<th>RAP%</th>
<th>ΔTc</th>
<th>Cycles</th>
<th>S₀, MPa</th>
<th>φ₀, deg.</th>
<th>S''</th>
<th>DE, J/m³</th>
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<td>2.1</td>
<td>129,106</td>
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<td>0.2</td>
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<td>108</td>
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<td>0.0</td>
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### NCHRP 9-12 Mixture Effects Study

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<th>STOA (800 ms)</th>
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<th>RAP%</th>
<th>ΔTc</th>
<th>Cycles</th>
<th>$S_0$, MPa</th>
<th>$\phi_0$, deg.</th>
<th>$S''$</th>
<th>DE, J/m³</th>
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</thead>
<tbody>
<tr>
<td>PG 52-34</td>
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NCHRP 9-12 Mixture Effects Study
Kentucky RAP-RAS Study

- Bullitt
- Grant
- Robertson
- Fleming
# Kentucky RAP-RAS Mixtures

<table>
<thead>
<tr>
<th>Property</th>
<th>Bullitt</th>
<th>Fleming</th>
<th>Grant</th>
<th>Robertson</th>
<th>Control</th>
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<tbody>
<tr>
<td>NMAS, mm</td>
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<td>9.5</td>
<td>9.5</td>
<td>9.5</td>
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<tr>
<td>VMA, %</td>
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<td>76</td>
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<tr>
<td>$G_{mm}$</td>
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<td>2.464</td>
<td>2.457</td>
<td>2.452</td>
<td>2.521</td>
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<tr>
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<tr>
<td>RAS, %</td>
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<td>3</td>
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<td>0</td>
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<td>Asphalt Content (AC), %</td>
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<td>Virgin AC, %</td>
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<td>5.0</td>
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<td>PG 52-34</td>
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<td>PG 64-22</td>
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# Kentucky RAP-RAS Mixtures

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<td>VFA, %</td>
<td>66</td>
<td>74</td>
<td>76</td>
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<tr>
<td>G&lt;sub&gt;mm&lt;/sub&gt;</td>
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<tr>
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<td>3.5</td>
<td>5.1</td>
<td>5.6</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Virgin AC, %</td>
<td>3.0</td>
<td>4.2</td>
<td>5.0</td>
<td>4.2</td>
<td>5.4</td>
</tr>
<tr>
<td>RAP AC, %</td>
<td>0.12</td>
<td>0.09</td>
<td>0.00</td>
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<tr>
<td>RAS AC, %</td>
<td>0.13</td>
<td>0.10</td>
<td>0.11</td>
<td>0.12</td>
<td>0</td>
</tr>
<tr>
<td>Recycled Binder Ratio</td>
<td>0.25</td>
<td>0.19</td>
<td>0.11</td>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>Virgin Asphalt Grade</td>
<td>PG 58-28</td>
<td>PG 58-28</td>
<td>PG 52-34</td>
<td>PG 52-34</td>
<td>PG 64-22</td>
</tr>
</tbody>
</table>
Kentucky RAP-RAS: Bullitt

![Graph showing shear modulus (G*, Pa) vs. angle of rotation (δ, degrees) for different materials: PG 58-28 RTFO, PG 58-28 PAV20, RAP, RAS, and Mix. The graph illustrates the material stiffness and angular behavior.](image-url)
<table>
<thead>
<tr>
<th>ACTION</th>
<th>RAP</th>
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<tbody>
<tr>
<td>No Change in Binder Grade</td>
<td>15% or less</td>
</tr>
<tr>
<td>One Grade Lower</td>
<td>16 - 25%</td>
</tr>
<tr>
<td>Use Blending Charts</td>
<td>&gt;25%</td>
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</tbody>
</table>
• Asphalt Institute MS-2 Guidance
  • The “RAP Percentage” is a “RAP Binder Percentage”
    • Developed before fractionation and assuming RAP would have asphalt contents similar to virgin asphalt mixtures
    • Not intended for RAS or a combination of RAP and RAS
  • The use of blending charts/equations is the most robust and responsible approach to using RAP
    • Characterizes RAP binder properties
    • Can provide a continuous grade of RAP and virgin asphalt binders
• Asphalt Institute MS-2 Guidance
  • For mixtures using 15-25% RAP, the standard recommendation is to select one grade softer (high and low temperature)
    • Mix designer may choose to use blending charts/equations at any time, subject to agency approval.
      • Could be important if 20% RAP doesn’t indicate that a grade change is needed.
AASHTO M323: Binder Selection Guideline for RAP Mixtures

- Asphalt Institute MS-2 Guidance
  - For mixtures using more than 25% RAP, blending charts/equations should definitely be used
    - Linear blending becomes unstable as RAP binder content approaches 40%
    - Virgin binder grade added should, in no case, be more than two grades softer than the binder grade that would be used in an 100% virgin mixture for that location and application
• Asphalt Institute MS-2 Guidance
  • Projects requiring a modified asphalt binder grade should use a modified virgin asphalt binder to work in the RAP mixture
    • Not as much a concern if the reason for specifying a modified binder grade is for rutting resistance
    • Much more of a concern if the reason for specifying a modified binder grade is for cracking resistance/durability
    • Recognize that the addition of RAP – if unmodified – will lower the total polymer content of the mix, even if a modified virgin binder grade is used
• Asphalt Institute MS-2 Guidance
  • When properly designed and constructed mixes containing 20-25% RAP have historically performed successfully in service. Regardless of the information provided by blending charts/equations, mix designers may want to assess performance through mix tests.
  • Blending that occurs between RAP and WMA may be different
    • Performance testing also recommended
Durability and Recycled Materials

• A few words about durability and recycled materials (e.g., RAP and RAS)...
  • Understand effects of materials
    • Adding age-hardened asphalt binder with reduced relaxation to mix in some proportion
    • “The very high binder viscosities that can potentially exist in aged pavements could contribute significantly to surface cracking by preventing any healing from occurring at the pavement surface during hot summer weather.” ~ NCHRP Report 567
A few words about durability and recycled materials (e.g., RAP and RAS)...

- Understand effects of materials
  - Properly account for amount of recycled binder that is available for use by the mix (i.e., how well is it actively blended?)
    - Can lead to under-asphalted mixes
  - If using premium asphalt binders, consider impact of added aged binder
    - Reduction in polymer loading?

- Mix performance testing
## Selected NM Paving Projects: 2010-12

<table>
<thead>
<tr>
<th>Specified</th>
<th>UTI</th>
<th>PG 58-28</th>
<th>PG 64-22</th>
<th>PG 64-28</th>
<th>PG 70-22</th>
<th>PG 70-28</th>
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<tr>
<td>PG 70-22</td>
<td>92</td>
<td>3</td>
<td>11</td>
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<td>1</td>
<td>5(3)</td>
<td>3(5)</td>
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<td>PG 76-28</td>
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<td></td>
<td></td>
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</tbody>
</table>

### Notes:
- UTI: Ultra-temperature index (temperature at which the material acts as a solid)
- PG X-XX: Grade of asphalt paving mix
- Numbers indicate the percentage range of the material in the pavement mix.
- (3) indicates the number of specimens tested for the specified grade.
Thanks!