Using RAP in the Superpave Mix Design System

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  – Senior Program Officer, NCHRP 9-12

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What is RAP?

**Reclaimed Asphalt Pavement**

- Old asphalt pavement that has been removed from the roadway by either milling or full-depth removal.
Why Use RAP?

• Economics
  – Components of RAP still have value
    • Particularly true of asphalt binder
    • Can reduce the amount of new asphalt binder in a mixture
      20% RAP with 5% asphalt content
      1% Savings in new asphalt binder
Considerations in Using RAP

• RAP Variability
  – Variability in the original pavement materials
    • multiple layers
    • different specifications

• Storage of RAP
  • RAP from different projects stored in same stockpile
  • GOK-pile
Determining RAP Properties

- Mix Design
  - Low RAP
    - Asphalt Content of RAP
    - Aggregate Gradation of RAP
    - RAP Specific Gravity
    - Consensus Aggregate Properties
  - High RAP
    - 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 % of RAP (greater than 20-25%)
Extraction and Recovery of RAP

• Solvent Extraction
  – ASTM D2172
  • Quantitative Extraction of Bitumen from Bituminous Paving Mixtures
    – Method A (Centrifuge) - most common
    – Method B (Reflux) - completely contained
    – Method E (Vacuum)

• Ignition Oven
Component Analysis of RAP

• After Extraction Procedure…
  – Determine the final mass of the sample and the amount of asphalt binder extracted
    • Determine asphalt content
  – Use extracted aggregate for further testing
    • Gradation
Determining Physical Properties of RAP 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
Determining Physical Properties of RAP Binder

- Recovery Procedures
  - AASHTO T319
    - Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt (HMA)
    - Modified version of SHRP procedure
AASHTO T319 Extraction and Recovery Procedure

• After assembly of extraction vessel, attach ends and add mixture (approximately 1000 grams)
• Rotate cylinder on its side for 5 minutes
AASHTO T319 Extraction and Recovery Procedure

- Pull effluent from vessel into first recovery flask
- Add more solvent and rotate vessel on its side for 10 minutes
- On successive washes, rotate vessel for 30 minutes
- Continue until the effluent achieves a light straw color
AASHTO T319 Extraction and Recovery Procedure

• Perform recovery using Rotavapor apparatus and modification to ASTM D5404

• Preferred solvents: n-propyl bromide, toluene/ethanol
RAP Aggregate Properties

• Gradation
  – ASTM D5444
    • Mechanical Size Analysis of Extracted Aggregate
  – More than one sample?
RAP Aggregate Properties

• Consensus Properties
  – Separate RAP aggregate into coarse (material retained on 4.75-mm) and fine fractions
  • Coarse Aggregate Angularity
  • Fine Aggregate Angularity
  • Flat and Elongated Particles
  • Sand Equivalent
    – Virgin aggregate only
RAP Aggregate Properties

• RAP Aggregate Specific Gravity
  – Method #1
    • Split extracted aggregate into coarse (+ 4.75-mm) and fine (- 4.75-mm) fractions
    • Determine the specific gravity of each size fraction
  – Method #2
    • Determine $G_{mm}$ of RAP (ASTM D2041)
    • Determine asphalt content of RAP
    • Calculate $G_{se}$ of RAP and use instead of $G_{sb}$ in volumetric calculations
RAP Aggregate Properties

• RAP Aggregate Specific Gravity
  – Method #2A
  • Determine $G_{mm}$ of RAP (ASTM D2041)
  • Determine asphalt content of RAP
  • Calculate $G_{se}$ of RAP
  • Assume asphalt absorption, $P_{ba}$, based on experience with materials
  • Calculate $G_{sb}$ of RAP aggregate
RAP Aggregate Properties

• RAP Aggregate Specific Gravity
  – Advantages - Method #1
    • Direct measure of specific gravity of RAP aggregate
  – Disadvantages - Method #1
    • Extraction (or ignition oven) procedure can change aggregate properties
    • Sample may still contain asphalt or solvent, making it difficult to accurately determine specific gravity
RAP Aggregate Properties

• RAP Aggregate Specific Gravity
  – Advantages - Method #2
    • $G_{se}$ easy to determine; more repeatable than $G_{sb}$ measurements
  – Disadvantages - Method #2
    • Use of $G_{se}$ instead of $G_{sb}$ artificially raises VMA
RAP Aggregate Specific Gravity

- Advantages - Method #2A
  - $G_{se}$ easy to determine; more repeatable than $G_{sb}$ measurements
  - Use of assumed $P_{ba}$ allows for determination of $G_{sb}$

- Disadvantages - Method #2A
  - Assumption of $P_{ba}$
## Summary Table – RAP Aggregate Specific Gravity

<table>
<thead>
<tr>
<th></th>
<th>RAP SpG Method 1</th>
<th>RAP SpG Method 2</th>
<th>RAP SpG Method 2a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Directly measure $G_{sb}$</td>
<td>Determine $G_{mm}$; Calculate $G_{se}$</td>
<td>Determine $G_{mm}$; Calculate $G_{se}$; Assume Absorption; Calculate $G_{sb}$</td>
</tr>
<tr>
<td><strong>Advantage(s)</strong></td>
<td>$G_{sb}$ is determined like virgin aggregates</td>
<td>$G_{se}$ is easy to determine; more repeatable than $G_{sb}$ measurements</td>
<td>Same as Method 2; Assumption of absorption allows determination of $G_{sb}$</td>
</tr>
<tr>
<td><strong>Disadvantage(s)</strong></td>
<td>Requires coarse and fine $G_{sb}$ determination; extraction or ignition oven procedure may change aggregate properties</td>
<td>Use of $G_{se}$ instead of $G_{sb}$ artificially raises VMA thus potentially decreasing effective asphalt and reducing durability</td>
<td>Absorption is an assumed value, needs validation</td>
</tr>
</tbody>
</table>
For Method #2A...

Determine best fit line by:

1. Performing RAP theoretical maximum specific gravity;
2. Calculating the RAP aggregate effective specific gravity; and
3. Determining the RAP aggregate bulk specific gravity.
Prepared RAP for $G_{mm}$ Determination

Dry each test sample to a constant mass in an oven at 230 ± 9 F.

While drying, break up the sample as with a standard $G_{mm}$ sample.

Mix well to re-coat the uncoated particles.
Difference Between RAP Gse and Gsb

The graph represents the difference between RAP Gse and Gsb. As RAP Gse increases, the difference (Gse - Gsb) decreases linearly. The graph shows a downward trend from approximately 0.080 (at 2.550 RAP Gse) to 0.040 (at 2.800 RAP Gse).
Difference in Mixture VMA Using RAP Gse and Gsb

25% RAP

Δ VMA

RAP Gse

We’re driven. www.asphaltinstitute.org
Effect of VMA on Laboratory Fatigue Life

Change of 10,500 cycles for 0.5% VMA change. Equals approx 12-20% lower fatigue life in this data.
RAP Aggregate Properties

- RAP Aggregate Specific Gravity

\[ G_{se}(RAP) = \frac{100 - P_b(RAP)}{G_{mm}(RAP)} - \frac{P_b(RAP)}{G_b(RAP)} \]

\[ G_{se}(RAP) = \frac{100 - 4.5}{2.545} - \frac{4.5}{1.02} \]

\[ G_{se}(RAP) = 2.738 \]

\[ G_{mm}(RAP) = 2.545 \]
\[ G_b(RAP) = 1.020 \]
\[ P_b(RAP) = 4.5\% \]
RAP Aggregate Properties

• RAP Aggregate Specific Gravity

\[ G_{sb}(RAP) = \frac{G_{se}(RAP)}{100 \times G_b(RAP)} + 1 \]

\[ G_{sb}(RAP) = \frac{2.738}{1.5 \times 2.738} + 1 \]

\[ G_{sb}(RAP) = 2.632 \]

- \( G_{mm}(RAP) = 2.545 \)
- \( G_b(RAP) = 1.020 \)
- \( P_b(RAP) = 4.5\% \)
- \( P_{ba}(RAP) = 1.5\% \)
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
RAP Binder Properties

• Tests on Recovered RAP Binder
  – Dynamic shear rheometer (DSR) at high temperature
    • Determine critical temperature ($T_c$) for original recovered binder
    • $T_c$ is determined where $G^*/\sin \delta = 1.00$ kPa for recovered RAP binder
• DSR at High Temperature (Original Recovered RAP Binder)
  – Determine $T_c$
  • Determine slope of stiffness-temperature curve as $\Delta \log (G^*/\sin \delta)/\Delta T$
  • Determine $T_c$ to nearest 0.1°C

$$T_c \text{ (High)} = \frac{\log(1.00) - \log(G_1)}{a} + T_1$$

G*/sin $\delta$ at specific temperature, $T_1$
Slope of stiffness-temperature curve
RAP Binder Properties

- Tests on Recovered RAP Binder
  - Perform RTFO aging on remaining sample of recovered RAP binder
    - No PAV aging is necessary
  - Perform DSR testing on RTFO-aged RAP binder
    - High, intermediate temperature
  - Perform BBR testing on RTFO-aged RAP binder
    - low temperature
Binder Grade Selection for RAP Mixtures

- 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)

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

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

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>Original</td>
<td>DSR $G^*/\sin \delta$</td>
<td>High 86.6</td>
</tr>
<tr>
<td></td>
<td>DSR $G^*/\sin \delta$</td>
<td>High 88.7</td>
</tr>
<tr>
<td></td>
<td>DSR $G^*\sin \delta$</td>
<td>Intermediate 30.5</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low -4.5</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low -1.7</td>
</tr>
<tr>
<td>RTFO</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>
Example
Desired Final Binder Grade: PG 64-22
RAP Percentage: 30%

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

\[
T_{\text{virgin (High)}} = \frac{64.0 - (0.30 \times 86.6)}{(1 - 0.30)} = 54.3
\]
Developing Blending Charts - Method A

Percentage of RAP

$T_{\text{critical}, \ C}$

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

52 58 64 70 76 82 88

54.3
## Developing Blending Charts - Method A

Virgin Binder Properties Required:

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Critical Temperature, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>DSR G*/sin δ</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>DSR G*/sin δ</td>
<td>High</td>
</tr>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High</td>
</tr>
<tr>
<td>PAV</td>
<td>DSR G*sin δ</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low</td>
</tr>
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<td></td>
</tr>
</tbody>
</table>

**Actual Grade**  PG 54-26  
**M320 Grade**   PG 58-28
Developing Blending Charts - Method A

• From the Example:
  – To achieve a final asphalt binder grade of PG 64-22...
    • Recovered RAP Binder Grade = PG 82-10
    • 30% RAP used in mixture

  ...the virgin asphalt binder needs to be PG 54-26 (PG 58-28)
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)

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

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

**Example**

**Desired Final Binder Grade:** PG 64-22

**Virgin and RAP Binder Properties:**

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Critical Temperature, C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Virgin Binder</td>
</tr>
<tr>
<td>Original</td>
<td>DSR G*/sin δ</td>
<td>High</td>
</tr>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High</td>
</tr>
<tr>
<td>PAV</td>
<td>DSR G*sin δ</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low</td>
</tr>
</tbody>
</table>

**PG Actual**
- **PG 60-29**
- **PG 58-28**
- **PG 86-11**
- **PG 82-10**
Example

Desired Final Binder Grade: PG 64-22

Known Virgin and RAP Binder Properties

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

\[ \% RAP \text{ (High)} = \frac{64.0 - 60.5}{86.6 - 60.5} = 13.4\% \]
Developing Blending Charts - Method B

RAP Percentage Required to Achieve Final Blend:

<table>
<thead>
<tr>
<th>Aging</th>
<th>Property</th>
<th>Temp.</th>
<th>PG 64-22</th>
<th>PG 70-28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>DSR G*/sin δ</td>
<td>High</td>
<td>13.4%</td>
<td>36.4%</td>
</tr>
<tr>
<td>RTFO</td>
<td>DSR G*/sin δ</td>
<td>High</td>
<td>10.8%</td>
<td>32.5%</td>
</tr>
<tr>
<td>PAV</td>
<td>DSR G*sin δ</td>
<td>Intermediate</td>
<td>66.3%</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>BBR S</td>
<td>Low</td>
<td>57.6%</td>
<td>23.7%</td>
</tr>
<tr>
<td></td>
<td>BBR m-value</td>
<td>Low</td>
<td>40.5%</td>
<td>5.8%</td>
</tr>
</tbody>
</table>
Developing Blending Charts - Method B

• From the Example:
  – To achieve a final asphalt binder grade of PG 64-22...
  • Recovered RAP Binder Grade = PG 82-10
  • Virgin Binder Grade = PG 58-28

...the allowable RAP percentage is between 14% and 40%.
# Binder Grade Selection for RAP Mixtures

<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>

**Note on Stiffer RAP Binders**
What is the Effect of Stiffer RAP?

- Change in Critical Low Temperature

<table>
<thead>
<tr>
<th>RAP</th>
<th>PG xx-22, -16</th>
<th>PG xx-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>14%</td>
<td>+1.1</td>
<td>+2.6</td>
</tr>
<tr>
<td>15%</td>
<td>+1.2</td>
<td>+2.8</td>
</tr>
<tr>
<td>25%</td>
<td>+2.2</td>
<td>+4.8</td>
</tr>
<tr>
<td>26%</td>
<td>+2.4</td>
<td>+5.0</td>
</tr>
<tr>
<td>40%</td>
<td>+3.8</td>
<td>+7.8</td>
</tr>
</tbody>
</table>
Handling RAP During the Mix Design Process

• Handling RAP in the Lab
  – Recommended RAP Heating Procedure
    • 110°C (230°F) for 2 hours (max)
    • Suitable for 1-2 kg batches
    • Higher temperature or longer time may affect properties of some RAP
  – Virgin Aggregate
    • Heat to 10°C above mixing temperature
Lab Performance Testing
Shear Modulus (Stiffness)

High Stiffness RAP with PG64-22 40C and 10Hz

G*, ksi

RAP Content

0% RAP
10% RAP
20% RAP
40% RAP
Permanent Deformation

High Stiffness RAP with PG52-34 58C

Est. Rut Depth, mm

RAP Content

- 10%
- 20%
- 40%
• As RAP content increases…
  …shear modulus (stiffness) increases…
  …permanent deformation decreases…
  …fatigue life decreases…
  …low temperature stiffness increases…

• At low RAP content, effects are not significant
Incorporation of Reclaimed Asphalt Pavement in the Superpave System

– North Central Superpave Center (Purdue) and the Asphalt Institute
– Completed in 2000
Products

• Final Report
• Implementation Plan
• Guidelines for Agencies
  – NCHRP Report 452
• Proposed AASHTO procedure and specification changes
Products

• Modified Version of AASHTO TP2
  – Now AASHTO T319
  – Modifications allow for determination of gradation
  – More repeatable and accurate recovery procedure than Abson procedure
  • Comparable to Rotavapor procedure
• Procedure for Developing Blending Charts
  – Uses linear blending procedure
  – Uses critical temperature for DSR, BBR
  – RTFO aging of recovered binder improves accuracy of linear blending
    • PAV aging of recovered binder is not necessary
  – Valid up to 40% RAP
    • Some non-linearity noted at 40%
Research Recommendations

• RAP mixtures should be able to perform at least as well as virgin mixes.

• RAP aggregates need to be included in consensus properties and gradations.
  – Watch changes in aggregates due to extraction, ignition oven procedure
  – Exception: sand equivalent value.
Practical Considerations

• Mixtures with 15 to 20% RAP may become more common.
  – Blending charts may limit high RAP contents unless there are strong economic incentives.

• At high RAP contents, gradation and properties of RAP aggregate may limit amount of RAP used.
  – RAP variability may need to be controlled to meet production tolerances.
Summary of Mix Design Recommendations

• Component Analysis of RAP
  – Asphalt binder content
  – Aggregate gradation

• Determine Consensus Properties of RAP
  – Coarse Aggregate (Individual)
    • Coarse Aggregate Angularity
    • Flat and Elongated Particles
  – Fine Aggregate (Blend)
    • Fine Aggregate Angularity
Summary of Mix Design Recommendations

• Determine $G_{mm}$ of RAP
  – Calculate $G_{se}$
    • Assumed value of $G_b$
    • Use $G_{se}$ value to determine combined $G_{sb}$ of aggregate blend **OR**
  • Assume $P_{ba}$ to estimate $G_{sb}$ of RAP aggregate
Summary of Mix Design Recommendations

• Determine Virgin Asphalt Binder Grade
  – Dependent on…
  • Project requirements
  • Desired RAP %
    – No change in binder grade (15% RAP or less)
    – One grade softer (16-25% RAP)
    – Use blending charts (more than 25% RAP)

Determine RAP Binder “True” Grade
Thanks!