Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios

46th Ohio Asphalt Paving Conference

February 3, 2021
MOTIVATION & CONCERN for High Recycled Binder Ratio (RBR) = High RAP and/or RAS

- OH in 2019
  - 19.4M tons HMA/WMA
  - 6.3M tons RAP
  - 12k tons RAS
- materials savings = $2.3M

- Workability
- Compaction
- Performance w/Aging
NCHRP 9-58 Objectives

- **High RBR** = 0.3 – 0.5
- Assess effectiveness of recycling agents at selected dose to
  - partially restore binder rheology
  - improve mixture cracking performance without adversely affecting rutting resistance
- Evaluate the **evolution of recycling agent effectiveness** with aging
- Recommend **evaluation tools**
9-58 Binder Blend Evaluation Tools

- **DSR** for PGH, G-R, $T_{\delta=45}$

$$G-R = \frac{G^* (\cos \delta)^2}{\sin \delta} @ 15^\circ C, 0.005 \text{ rad/sec}$$

$T_{\delta=45^\circ}$ for $G'=G'' @ 10 \text{ rad/sec}$

- **BBR** for $\Delta T_c$

$$\Delta T_c @ PAV20 = T_s - T_m$$
Black Space Evaluation with Aging/Recycling

![Graph showing phase angle (degrees) vs. log of G* (Pa) with zones for block cracking, transition, and no block cracking.]

- BLOCK CRACKING ZONE
- TRANSITION ZONE
- NO BLOCK CRACKING ZONE

- More Aging
- Aging
- Recycling
- Rejuvenation
9-58 Mixture Evaluation Tools

- **HWTT/APA** for \( N_{12.5} \)
- **E** for \( G-R_m \) @ 20°C, 5Hz
- **I-FIT** for FI
- **BBR_m** for \( S_m \) and \( m\)-value_m
- **UTSST** for \( CRI_{Env} \)
9-58 Materials

**RAP**
- TX
- NH
- NV
- IN
- WI
- DE

**RAS**
- TX MWAS, TOAS
- CA TOAS
- IN MWAS
- DE MWAS

**Base Binder**
- A1, A2
- P
- T1, T2
- V1, V2, V3
- B1, B2

**Recycling Agents**
- TX
- NV
- IN
- WI
- DE

**Virgin Aggregates**

**Rejuvenated Mixture**

**Rejuvenated Blend**

TX PG 64-22 (-4.6), PG 70-22P (-4.9)
- NH PG 64-28 (+1.4)
- NV PG 64-28P (-3.6)
- IN PG 64-22 (-1.2), PG 58-28 (-8.0)
- MN PG 58-28 (0.0)
- WI PG 58-28 (-3.4), PG 52-34 (+0.4)
- DE PG 64-28 (+0.1)
9-58 Field Projects

NV 9/15
0.15, 0.33 RAPBR
Recycling Agents T2, A2

TX 6/14
0.28 RBR
Recycling Agent T1

WI 9/16
0.22, 0.31 RAPBR
Recycling Agent V2

IN 9/15
0.32, 0.42 RBR
Recycling Agent T2

DE 12/16
0.33, 0.41 RBR
Recycling Agent T2

Environmental Zones
- Wet-Freeze
- Dry-Freeze
- Dry-No Freeze
- Wet-No Freeze
Draft AASHTO Standard Practice for 0.3-0.5 RBR + Recycling Agent

- Component Materials Selection & Proportioning Guidelines
- Recycling Agent Dose Selection & Incorporation Methods
- Binder Blend Rheological Evaluation Tools
- Mixture Performance Evaluation Tools
- RAP Binder Availability Factor
Component Materials Selection & Proportioning

- **Base Binder**
  - PGH < 64°C
  - $\Delta T_c @ PAV20 > -3.5°C$

- **RAP**
  - PGH < 100°C
  - $\Delta T_c @ PAV20 > -7.5°C$

- **RAS**
  - PGH < 150°C

- **RBR** ≤ 0.5
  - $(R_{APBR} + R_{ASBR})$

- **RAS_{BR}** ≤ 0.15
Component Materials Selection
(TX PG 64-22 w/ $\Delta T_c = -4.6$, IN PG 64-22 w/ $\Delta T_c = -1.2$)

0.28 RBR (0.1 TX RAP + 0.18 TX MWAS)

<table>
<thead>
<tr>
<th>Base Binder</th>
<th>$\Delta T_c$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX 64-22</td>
<td>-4.6</td>
</tr>
<tr>
<td>TX T1</td>
<td>-9</td>
</tr>
<tr>
<td>TX A1</td>
<td>-8</td>
</tr>
<tr>
<td>TX V1</td>
<td>-8</td>
</tr>
<tr>
<td>TX B</td>
<td>-6</td>
</tr>
<tr>
<td>IN 64-22</td>
<td>-4.6</td>
</tr>
<tr>
<td>IN T1</td>
<td>-4</td>
</tr>
<tr>
<td>IN A1</td>
<td>-3</td>
</tr>
<tr>
<td>IN V1</td>
<td>-3</td>
</tr>
<tr>
<td>IN B</td>
<td>-5</td>
</tr>
</tbody>
</table>

Binder Blends
Component Materials Selection (WI PG 58-28, PG 52-34)

> 7 after STOA
Recycling Agent Dose Selection & Incorporation

- Match Continuous PGH = BALANCED

\[ %RA = (PGH_{Blend} - PGH_{Target}) / \text{Slope Rate} \]

\[ PGH_{Blend} = (RAP_{BR} \times PGH_{RAP}) + (RAS_{BR} \times PGH_{RAS}) + (BB_{BR} \times PGH_{Base}) \]

*1.82 for tall oils, vegetable oils, bio-based oils, 1.38 for aromatic extracts

- < Max without sacrificing rutting resistance & economical
- Dose as % of total binder (base + recycled) by replacement
Materials Proportioning / Balance

\[ PGH_{Blend} = (BB_{BR} \times PGH_{Base}) + (RAP_{BR} \times PGH_{RAP}) \]
### Materials Proportioning / Balance

\[ PGH_{Blend} = (R_{AP} \times PGH_{RAP}) + (R_{AS} \times PGH_{RAS}) + (BB \times PGH_{Base}) \]

\[ \%RA = (PGH_{Blend} - PGH_{Target}) / 1.82 \]

<table>
<thead>
<tr>
<th>Base Binder</th>
<th>RAP</th>
<th>RAS</th>
<th>RA Dose</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX PG 64-22</td>
<td>0.25 TX RAP</td>
<td>0.25 TX TOAS</td>
<td>19.4</td>
<td>UNBALANCED</td>
</tr>
<tr>
<td></td>
<td>0.4 TX RAP</td>
<td>0.1 TX TOAS</td>
<td>13.5</td>
<td>High Dose</td>
</tr>
<tr>
<td></td>
<td>0.4 TX RAP</td>
<td>0.1 TX MWAS</td>
<td>10.9</td>
<td>High Dose</td>
</tr>
<tr>
<td></td>
<td>0.4 NH RAP</td>
<td>0.1 TX MWAS</td>
<td>7.3</td>
<td>High Dose</td>
</tr>
<tr>
<td>MN 58-28</td>
<td>0.4 NH RAP</td>
<td>0.1 TX MWAS</td>
<td>4.6</td>
<td>Acceptable Dose</td>
</tr>
</tbody>
</table>
## Binder Blend Rheological Evaluation

<table>
<thead>
<tr>
<th>T &amp; Aging Conditions</th>
<th>Test</th>
<th>Parameter</th>
<th>Suggested Performance Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T&lt;sub&gt;high&lt;/sub&gt;</strong> Unaged, Short-Term</td>
<td>DSR</td>
<td>PGH</td>
<td>Target Climate</td>
</tr>
<tr>
<td><strong>T&lt;sub&gt;int&lt;/sub&gt;</strong> Track w/Aging</td>
<td>DSR</td>
<td>G-R</td>
<td>≤ 180 kPa after 20-hr PAV</td>
</tr>
<tr>
<td></td>
<td>DSR</td>
<td>T&lt;sub&gt;δ=45°&lt;/sub&gt;</td>
<td>≤ 32° after 20-hr PAV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>≤ 45° after 40-hr PAV</td>
</tr>
<tr>
<td><strong>T&lt;sub&gt;low&lt;/sub&gt;</strong> Long-Term</td>
<td>BBR</td>
<td>ΔT&lt;sub&gt;c&lt;/sub&gt;</td>
<td>≥ -5.0 after 20-hr PAV</td>
</tr>
</tbody>
</table>

Short-Term Aging = RTFOT; Long-Term Aging = PAV @ 100°C
G-R Black Space (WI PG 58-28, PG 52-34)
Crossover Temperature ($T_d=45^\circ$) @ 10 rad/sec

Determination by T Sweep

Preliminary Thresholds

$y = 0.001x^{3.545}$  
$R^2 = 0.929$

Note: $T_d=45^\circ$ in this study was obtained from mastercurves and time-temperature superposition.
# Mixture Performance Evaluation

<table>
<thead>
<tr>
<th>T &amp; Aging Conditions</th>
<th>Test</th>
<th>Parameter</th>
<th>Suggested Performance Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T\textsubscript{high}</strong></td>
<td>HWTT or APA</td>
<td>(N_{12.5})</td>
<td>(\geq 5000) for PG 58-XX</td>
</tr>
<tr>
<td><strong>Short-Term</strong></td>
<td></td>
<td></td>
<td>(\geq 7500) for PG 64-XX (cold)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\geq 10,000) for PG 64-XX (warm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\geq 15,000) for PG 70-XX</td>
</tr>
<tr>
<td><strong>T\textsubscript{int}</strong></td>
<td>E*</td>
<td>G-(R_m)</td>
<td>(\leq 8000) MPa after STOA</td>
</tr>
<tr>
<td><strong>Track w/Aging &amp;</strong></td>
<td>I-FIT</td>
<td>FI</td>
<td>(\leq 19,000) MPa after LTOA</td>
</tr>
<tr>
<td><strong>Short-Term</strong></td>
<td>BBR(_m)</td>
<td>(S_m, m\text{-value}_m)</td>
<td>(\leq) Utah threshold after STOA</td>
</tr>
<tr>
<td><strong>T\textsubscript{low}</strong></td>
<td>UTSST</td>
<td>CRI(_{Env})</td>
<td>(\geq 17) after LTOA</td>
</tr>
</tbody>
</table>

Short-Term Aging = STOA = 2hr @ 135°C; Long-Term Aging = LTOA = 5d @ 85°C
$N_{12.5}$ (WI PG 58-28) 

Min. 5,000 cycles for PG 58-XX climate

$N_{12.5} > 5000$ for PG 58-XX
G-Rm Black Space
WI PG 58-28, PG 52-34

< 8000 MPa after STOA
< 19,000 MPa after LTOA
FI (WI PG 58-28, PG 52-34) ≥ 7 after STOA
$S_m, m\text{-value}_m$ (WI PG 58-28, PG 52-34)

**Diagam Description:**
- **Low severity cracking (1 year)**: This area indicates materials that are at a low risk of cracking within the first year.
- **Likely to Crack**: Indicates materials that are at a high risk of cracking.
- **At Risk**: Indicates materials that are at an intermediate risk of cracking.
- **Not Likely to Crack**: Indicates materials that are unlikely to crack.

**Legend:**
- **DOT Control 0.22 RBR**
- **Recycled 0.31 RBR (PG 52-34)**
- **Rejuvenated 0.31 RBR (1.2%) V2**
- **Rejuvenated 0.31 RBR (5.5%) V2**
- **Rejuvenated 0.5 RBR (9%) V2**
CRI_{Env} \ (WI \ PG \ 58-28, \ PG \ 52-34) \ > \ 17 \ after \ LTOA
RAP Binder Availability

- **Binder Availability Factor (BAF)**
  
  measured binder content of #4 fraction in RAP mixture as compared to that for virgin mixture

  \[
  RAPBAF = -0.010 \times PGH_{\text{RAP}} + 1.771 \text{ for } 150^\circ \text{C mixing}
  \]

- **Degree of Activity (DoA)**

  IDT TS of 100% RAP after 4hrs @ 140°C, 170°C & SGC compaction

  \[
  DoA (\%) = 100 \times \frac{TS (T)}{\text{max } TS}
  \]
## RAP Binder Availability

<table>
<thead>
<tr>
<th></th>
<th>NCHRP 09-58 (BAF)</th>
<th>RILEM (DoA)</th>
<th>FHWA (DWT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>Considers interaction of RAP &amp; virgin materials</td>
<td>Requires only RAP</td>
<td>Requires only RAP</td>
</tr>
<tr>
<td></td>
<td>Performance testing not required</td>
<td>Utilizes simple performance testing &amp; relevant conditioning temperatures</td>
<td>Performance testing not required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Captures effects of gradation &amp; effective binder content</td>
<td></td>
</tr>
<tr>
<td><strong>Limitations</strong></td>
<td>Requires ignition oven</td>
<td>Includes testing @ multiple temperatures</td>
<td>Requires SGC with modified control software</td>
</tr>
<tr>
<td></td>
<td>Uses specific type &amp; size of RAP &amp; virgin materials</td>
<td>Requires comparison of results for multiple RAP sources</td>
<td>No agreement with other methods</td>
</tr>
<tr>
<td></td>
<td>Only considers total binder content</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Additional Results

❑ Representative Binder Blending
  ■ mortar results indicate complete blending “over” estimates both PGH & PGL

❑ Chemical Compatibility
  ■ DSC results show recycling agents shift $T_g$ colder
  ■ AFM results indicate recycling agents increase & aging decreases molecular mobility
  ■ FTIR results show carbonyl compounds in recycling agents that thus require the use of CA$_g$

❑ Recycling Agent Classification/Effectiveness
  ■ Bulk
  ■ Microstructure
Recycling Agent Classification/Effectiveness
Recycling Agent Classification/Effectiveness

- **Base Binder (DE PG 64-28)**
- **Recycled 0.5 RBR**
- **Rejuvenated 0.5 RBR (13.5%) A1**
- **Rejuvenated 0.5 RBR (8%) B1**
- **Rejuvenated 0.5 RBR (10.5%) B2**
- **Rejuvenated 0.5 RBR (11%) P**
- **Rejuvenated 0.5 RBR (8.5%) T1**
- **Rejuvenated 0.5 RBR (9%) V2**
- **Rejuvenated 0.5 RBR (8%) V3**

The graph shows the relationship between CA growth and G-R parameter (kPa) for different recycling agents.
Recycling Agent Classification/Effectiveness

Binder Embrittlement Parameter (BEP) = \( \log[(G - R_{RTFO} \times G - R_{PAV40}) \times (G - R/CA_g HS)^2] \)

Lower BEP = More effective RA
Recycling Agent Classification/Effectiveness - Microstructure
Recycling Agent Classification/Effectiveness

Rejuvenation Index (RI) = \( \frac{\int_{0}^{40} E_{RAP}(x)dx \cdot \int_{0}^{40} WPT\ Energy_{RAP}(x)dx}{\int_{0}^{40} E_{Rej}(x)dx \cdot \int_{0}^{40} WPT\ Energy_{Rej}(x)dx} \)

Higher RI = More effective RA
Recycling Agent Classification/Effectiveness

• Must utilize CA_g
• BEP captures oxidation & rheological stiffening, embrittlement
• RI captures aging resistance & roughness/inhomogeneity
• Recycling Agent Classification
  – P = only SOFTENER w/poor compatibility despite low CA_g
  – A = sufficient REPLENISHER for some combos @ higher dose
  – V & B = EMULSIFIER to compatabilize, oxidize but less rheological effect
  – T = EMULSIFIER that is more sensitive to aging, more volatile (early gen)

• Specifications for blends & characterization with aging needed
Implementation & Future Research

- TxDOT BMD with High RBR
- Capturing Durability of High RBR Mixtures (NCHRP 09-65)
  - Moisture Susceptibility
  - Aging
- Field Demonstration Projects with High Recycling Agent Dose
- NAPA Practical Guide
- Recycling Agent Classification
- Binder Availability & Blending
THANK YOU!

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TTI, UNH, UNR, Gayle King
TX, NV, IN, WI, DE DOTs, APAs, & Contractors
Recycling Agent Manufacturers
Crossover Temperature \( (T_{\delta=45^\circ}) @ 10 \text{ rad/sec} \)

(TX PG 64-22 w/ \( \Delta T_c = -4.6 \), NH PG 64-28 w/ \( \Delta T_c = +1.4 \))

[Graph showing crossover temperature data]
• RA reduces both PGH & PGL
• Complete blending "over" estimates both PGH & PGL
# Chemical Compatibility

## Highlights

<table>
<thead>
<tr>
<th>Rejuvenation</th>
<th>Tools/Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_g$ Inflection &amp; $T_g$ End shift to <strong>colder</strong> $T$</td>
<td>Modulated DSC/WRI</td>
</tr>
<tr>
<td>Strong RA-asphaltene polar interaction, <strong>no breaking of agglomerates</strong></td>
<td>SAR-AD/WRI</td>
</tr>
<tr>
<td>Some RA include carbonyl-containing chemical groups that <em>confound CA calculation</em></td>
<td>FT-IR/TTI</td>
</tr>
<tr>
<td>Microstructural changes suggest <strong>increased molecular mobility</strong></td>
<td>AFM/TAMU Q</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aging</th>
<th>Tools/Partner</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA can experience chemical changes with aging</td>
<td>FT-IR/TTI</td>
</tr>
<tr>
<td>Microstructural changes suggest <strong>decreased molecular mobility</strong></td>
<td>AFM/TAMU Q</td>
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</table>
Black Space Evaluation with Aging/Recycling

Aging Index = $\log \left( \frac{G-R_{PAV40}}{G-R_{RTFO}} \right)$
Microstructure Quantification

More %associations = Less homogeneity

More energy = More roughness
Microstructure & Nanomechanical Properties

![Graph showing the relationship between DMT modulus (MPa) and percent of phase associations (%). The graph includes data points for Unaged, RTFO, 20-hours PAV, and 40-hours PAV samples. The R² value is 0.8.]
MIXTURE PERFORMANCE
Literature Review

- Recycled binders partially available
  - binder content
  - source (aging)
  - %
  - virgin binder grade & recycling capacity
  - additive type, dose, & incorporation method
  - mixing temperature
  - storage time, temperature
  - gradation
  - RAP binder more available

- Different methods to estimate recycled binder availability.

  - **RAP (32 refs):** 16% to 96%

  - **RAS (4 refs):** 36% to 61%

  - **RAP + RAS (6 refs):** for 15% RAP + 5% RAS
    - RAP: 40-60%
    - RAS (MWAS): 20-40%
    - RAS (TOAS): <20%
Prepare Mixtures with SPECIFIC Virgin Materials, Determine Binder Content by Ignition Oven

**Virgin Mixture**
- Mix virgin binder & aggregate

**RAP Mixture**
- Mix virgin binder & aggregate + RAP

**Sieve loose mixture**

**Determine** $P_b$ of material retained on No. 4 sieve using the ignition oven

**Labeled as** $Reference\ P_b$
- constant for specific mixture

**Labeled as** $RAP'\ P_b$
- varies based on RAP source
RILEM (DoA)

Condition 100% RAP for 4hrs @ 160°F, 212°F, 285°F, 340°F, 375°F;
Compact in SGC;
Test in Indirect Tension ($S_T$, $CT_{Index}$)

\[
DoA (\%) = 100 \times \frac{X_{RAP}(T, test)}{\text{max } X_{RAP}}
\]

\[
X_{RAP} = S_T \text{ per Tex-226-F}
\]

OR

\[
= CT_{Index} \text{ per Tex-250-F}
\]