Performance-based Design Method of Asphalt Mixes that Contain Reclaimed Asphalt Pavement (RAP)

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Issues related to usage of high RAP

- Availability
- Variability
- Cracking potential
- Extraction and recovery of RAP binder
- Blending mechanism not fully understood
- Lack of performance tests or associated cost
- ..........
Outline

- Introduction
- Materials and Experiments
- Results & Discussion
- Conclusions

Introduction

- Aged binder in RAP increased brittleness of mixes, resulting in susceptibility to pavement cracking.
- Softer virgin binder is used based on RAP binder replacement ratio:
  - <17%, no adjustment.
  - 17%~30%, one grade lower.
  - >30%, blending chart is used; complete blending is assumed, which may not be always reasonable.
- Current mix design is based on volumetric properties, not performance-related.
Results of PG of Recovered Binder

- **North RAP Binder: PG 75.8-23.6 (PG70-22)**

<table>
<thead>
<tr>
<th></th>
<th>PG of Recovered North RAP binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>High Temperature</td>
<td>76.9</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>-22.7</td>
</tr>
</tbody>
</table>

- **South RAP Binder: PG 85.2-16.8 (PG82-16)**

<table>
<thead>
<tr>
<th></th>
<th>PG of Recovered South RAP binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>High Temperature</td>
<td>85.3</td>
</tr>
<tr>
<td>Low Temperature</td>
<td>-17.0</td>
</tr>
</tbody>
</table>

Materials and Experiments

- **North mixes**
  - N0, N17, N30, N50, and NF30
- **South mixes**
  - S0, S17, S26, S50, and SF26

<table>
<thead>
<tr>
<th>North Mixes</th>
<th>PG of Virgin Binder</th>
<th>South Mixes</th>
<th>PG of Virgin Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>58-28 (Target)</td>
<td>S0</td>
<td>70-28 (Target)</td>
</tr>
<tr>
<td>N17</td>
<td>58-28</td>
<td>S17</td>
<td>70-28</td>
</tr>
<tr>
<td>N30</td>
<td>52-34</td>
<td>S26</td>
<td>64-34</td>
</tr>
<tr>
<td>N50</td>
<td>52-34 (40-34*)</td>
<td>S50</td>
<td>58-34 (58-40*)</td>
</tr>
<tr>
<td>NF30</td>
<td>52-34</td>
<td>SF26</td>
<td>64-34</td>
</tr>
</tbody>
</table>
Materials and Experiments

- Short-term and long-term aging
- Dynamic modulus test
- Rutting resistance
  - Flow number test
- Fatigue cracking resistance
  - Indirect tensile test (IDT) at 68°F.
  - Bottom-up cracking resistance: fracture work density.
  - Top-down cracking resistance: vertical failure deformation.
- Thermal cracking resistance
  - IDT at 14°F.
  - Fracture work density.

Fracture Work Density

- Bottom-up fatigue cracking - fracture work from Indirect tensile test at 68°F (Wen et al. 2011)
Vertical Failure Deformation

- Top-down cracking – vertical failure deformation (Wen et al. 2015)

Results and Discussion

- **Mix Design**- North mixes (blue) & South mixes (red)
  - Mixes contain up to 50 percent RAP could be produced and satisfy the specification requirements of volumetrics.
  - However, inclusion of RAP could significantly change the volumetrics of asphalt mixes, which could affect mix performance.
Results and Discussion

- Dynamic modulus test-North mixes:
  - Binder grade adjustment did not offset the stiffening effects of RAP binder.

- Dynamic modulus test-South mixes
  - Dynamic modulus values of S0, S17, and S50 mixes are close to each other, and significantly higher than those of S26 and SF26, e.g. at 70°F.
Results and Discussion

- Rutting resistance-flow number test
  - Mix with low percentage RAP (17% in this study) has similar flow number to control mix.
  - Mixes with high RAP (>17%) has increased flow number, with higher resistance to rutting.
  - Again, binder grade adjustment did not offset the stiffening effects of RAP binder.

Results and Discussion

- Fatigue Cracking Resistance-North mixes
  - Target PG of binder is PG58-28.
  - Have comparable resistance to bottom-up and top-down fatigue cracking.
Results and Discussion

- Fatigue Cracking Resistance-South mixes
  - Target PG of binder is PG70-28.
  - S0 and S17 performed identically, and significantly better than S26, S50, and SF26.
  - Loss of polymerization?

\begin{align*}
N_f &= 3.75 \times 10^{-5} \left( \frac{1}{E_t} \right)^{0.147} (FWD)^{1.92} h^{0.135}
\end{align*}

Results and Discussion

- Bottom-up cracking fatigue model

\begin{align*}
\text{Predicted } N_f \quad \text{N0} &\quad 131,297 \\
\text{N17} &\quad 113,515 \\
\text{N30} &\quad 94,387 \\
\text{N50} &\quad 121,165 \\
\text{NF30} &\quad 124,420
\end{align*}

\begin{align*}
\text{Predicted } N_f \quad \text{S0} &\quad 116,022 \\
\text{S17} &\quad 105,736 \\
\text{S26} &\quad 58,150 \\
\text{S50} &\quad 72,888 \\
\text{SF26} &\quad 72,735
\end{align*}
Results and Discussion

- Summary of fatigue cracking resistance
  - Fatigue cracking resistance with low percentage of RAP, e.g. 17%, was comparable to that of control mix.
  - Effects of high percentage RAP (>17%) on fatigue cracking depended on target PG of virgin binder.
    - Low target PG of virgin binder, e.g. PG 58-28: bumping down the grade of virgin binder for high RAP mixes did not affect fatigue resistance, e.g. North mixes.
    - High target PG of virgin binder, e.g. PG 70-28: bumping down the grade of virgin binder for high RAP mixes compromised the fatigue resistance, e.g. South mixes.
  - Recommend to keep the high temperature grade of target binder to avoid elimination or reduction of degree of polymer modification.

Results and Discussion

- Low temperature thermal cracking resistance
  - Inclusion of RAP affected thermal cracking performance of asphalt mixes, but was mix-specific.
  - Cracking performance tests shall be considered in mix design.
Results and Discussion

- Performance-related empirical mix design
  - Based on fracture work at 14°F.
  - Predicted model was moderately effective.

\[
FWD_{low} = 9.437 + 0.179P_{RAP} - 5.209AV + 6.690VMA + 1.475PG_{virgin\_low} - 0.513PG_{virgin\_high}
\]

Results and Discussion

- Procedures of performance-related empirical mix design
  - Selection of low temperature PG of virgin binder for a mix with RAP.
    - (1) Design a control mix without RAP using target PG of virgin binder.
    - (2) Estimate \(FWD_{low}\) of the control mix.
      \[
      FWD_{low} = 9.437 + 0.179P_{RAP} - 5.209AV + 6.690VMA + 1.475PG_{virgin\_low} - 0.513PG_{virgin\_high}
      \]
    - (3) Design a RAP mix to meet volumetrics specification by using target high temperature grade of virgin binder with any low temperature PG.
      \[
      PG_{virgin\_low} = (FWD_{low} - 9.437 + 0.179P_{RAP} + 5.209AV - 6.690VMA + 0.513PG_{virgin\_high}) / 1.475
      \]
    - (4) Determine the low temperature PG of the virgin binder based on above equation.
  - Thermal cracking resistance is safeguarded, but binder extraction, recovery, grading of RAP binder, and performance tests of RAP mixes are not needed.
Conclusions

- Inclusion of RAP could significantly affect volumetrics of asphalt mix.
- Inclusion of RAP could improve rutting resistance, regardless of grade bumping.
- Inclusion of low percentage (<17%) of RAP does not affect fatigue cracking resistance, and the effect of inclusion of high percentage (>17%) of RAP on fatigue cracking resistance depended on target PG of binder.
- Inclusion of RAP also affected the thermal cracking performance of asphalt mixes, but was mix-specific.
- A performance-related mix design method was developed to guarantee thermal cracking resistance.

Investigation of Effects of Different Blending Stages on Mix Performance: A WCAT Study

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Investigation of Blending Mechanisms for RAP Binder and Virgin binder

- The production of asphalt mix in asphalt plant greatly affects the blending between RAP binder and virgin binder

Introduction

- Three blending stages between RAP binder and virgin binder during production
  - \textit{RAP binder mobilization} and transfer to virgin aggregate
  
  \begin{figure}[h]
  \centering
  \includegraphics[width=0.3\textwidth]{image1.png}
  \caption{RAP Binder Mobilization}
  \end{figure}

  \begin{figure}[h]
  \centering
  \includegraphics[width=0.3\textwidth]{image2.png}
  \caption{Mechanical Blending}
  \end{figure}

  - \textit{Mechanical blending} between RAP binder and virgin binder

  \begin{figure}[h]
  \centering
  \includegraphics[width=0.3\textwidth]{image3.png}
  \caption{Mechanical Blending}
  \end{figure}

  - \textit{Diffusion} between RAP binder and virgin binder

  \begin{figure}[h]
  \centering
  \includegraphics[width=0.3\textwidth]{image4.png}
  \caption{Diffusion}
  \end{figure}

  (After Rad 2013)
Objectives of Study

- Propose a laboratory mixing scheme to distinguish the three blending stages.
- Study the effect of each blending stage on rheological and fracture performance properties of the study mixtures.
- Identify the primary mechanisms of blending of RAP binder and virgin binder.

Materials and Experiments

- RAP Characterization
  - South Idaho RAP
  - POE RAP

<table>
<thead>
<tr>
<th></th>
<th>RAP Aggregate Percent Passing, % Sieve Size (mm)</th>
<th>RAP Binder Content</th>
<th>G₀ of RAP Aggregate</th>
<th>True PG of RAP Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Idaho RAP</td>
<td>19.0 12.5 9.5 4.75 2.36 1.18 0.6 0.3 0.15 0.075</td>
<td>4.9%</td>
<td>2.583</td>
<td>85.2-16.8</td>
</tr>
<tr>
<td>POE RAP</td>
<td>19.0 12.5 9.5 4.75 2.36 1.18 0.6 0.3 0.15 0.075</td>
<td>4.4%</td>
<td>2.777</td>
<td>83.8-18.3</td>
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</tbody>
</table>
Materials and Experiments

• Mix Design
  ■ RAP binder replacement ratio: 26%

<table>
<thead>
<tr>
<th>South Idaho RAP Mixes</th>
<th>Sieve Size (mm)</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19.0</td>
<td>12.5</td>
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<tr>
<td>Percent Passing, %</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>Optimum Binder Content, %</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>Air Voids, %</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>VMA, %</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>VFA, %</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Dust-to-Asphalt Ratio</td>
<td>1.2</td>
<td></td>
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<tr>
<td>PG of Target Binder</td>
<td>70-28</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POE RAP Mixes</th>
<th>Sieve Size (mm)</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Percent Passing, %</td>
<td>100</td>
<td>93</td>
</tr>
<tr>
<td>Optimum Binder Content, %</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Air Voids, %</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>VMA, %</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>VFA, %</td>
<td>72</td>
<td></td>
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<tr>
<td>Dust-to-Asphalt Ratio</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>PG of Target Binder</td>
<td>64-28</td>
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Materials and Experiments-Mixing Scheme Design

<table>
<thead>
<tr>
<th>Mixes</th>
<th>Virgin Binder of South Idaho RAP Mixes</th>
<th>Virgin Binder of POE RAP Mixes</th>
<th>RAP Replacement</th>
<th>Blending Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix A</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Minimal Diffusion Only</td>
</tr>
<tr>
<td>Mix B</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Diffusion Only</td>
</tr>
<tr>
<td>Mix C</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Mechanical Blending +Diffusion</td>
</tr>
<tr>
<td>Mix D</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Binder Mobilization +Mechanical Blending +Diffusion</td>
</tr>
<tr>
<td>Mix E</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>0%</td>
<td>NA</td>
</tr>
<tr>
<td>Mix F (Target Mix)</td>
<td>PG 70-28</td>
<td>PG 64-28</td>
<td>0%</td>
<td>NA</td>
</tr>
</tbody>
</table>
Materials and Experiments-Mixing Scheme Design

<table>
<thead>
<tr>
<th>Mixes</th>
<th>Virgin Binder of South Idaho RAP Mixes</th>
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<th>RAP Replacement</th>
<th>Blending Stages</th>
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</thead>
<tbody>
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<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Minimal Diffusion Only</td>
</tr>
<tr>
<td>Mix B</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Diffusion Only</td>
</tr>
<tr>
<td>Mix C</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Mechanical Blending + Diffusion</td>
</tr>
<tr>
<td>Mix D</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Binder Mobilization + Mechanical Blending + Diffusion</td>
</tr>
<tr>
<td>Mix E</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>0%</td>
<td>NA</td>
</tr>
<tr>
<td>Mix F (Target Mix)</td>
<td>PG 70-28</td>
<td>PG 64-28</td>
<td>0%</td>
<td>NA</td>
</tr>
</tbody>
</table>
Materials and Experiments

- Make samples
  - 4% air void
  - Short-term and long-term aging
- Rheological performance evaluation
  - Dynamic modulus in indirect tensile (IDT) mode
  - Creep compliance
- Fracture performance evaluation
  - IDT test at 68°F
    - Bottom-up fatigue cracking resistance: fracture work density.
    - Top-down fatigue cracking resistance: vertical failure deformation.
  - IDT test at 14°F
    - Thermal cracking resistance: fracture work density.
Results and Discussion

- Fracture performance: **IDT test at 68°F**
  - IDT strength at 68°F
    - IDT strength of RAP mixes were **higher** than control mix E with the same PG of virgin binder, and **lower** than control mix F with target PG of virgin binder.
    - Blended binder in RAP mixes dictated the strength.
    - Diffusion is the dominating blending effect between RAP binder and virgin binder.

![South Idaho RAP Mixes](chart1.png)

![POE RAP Mixes](chart2.png)

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- Fracture performance: **IDT test at 68°F**
  - Fracture work density-bottom-up fatigue cracking resistance.
    - RAP mixes B, C, and D have comparable fracture work density
    - Keep high PG of target PG is beneficial

![South Idaho RAP Mixes](chart3.png)

![POE RAP Mixes](chart4.png)
Results and Discussion

- Facture performance: **IDT test at 68°F**
  - Vertical failure deformation-ductility of the mixes
    - Values of RAP mixes are close to control mix with same PG of virgin binder
    - Relatively soft binder controls the ductility of the mix.
    - Keep high PG of target PG is beneficial

- **South Idaho RAP Mixes**

- **POE RAP Mixes**

Results and Discussion

- Facture performance: **IDT test at 14°F**
  - IDT strength at 14°F
    - South Idaho RAP mixes: Same trend as IDT strength of 68°F
    - POE RAP mixes: No significant difference between mixes, except Mix A and Mix F. The effect of aggregate properties on low temperature fracture performance is more apparent.
    - Diffusion dominates the behavior of RAP mixes compared to RAP binder transfer and mechanical blending.
Results and Discussion

- Fracture performance: *IDT test at 14°F*
  - No significant difference among mixes

![Fracture Work Density (Pa)](image)

Conclusions

- Diffusion was the most dominant in affecting rheological and fracture properties of RAP mixes.
- Relatively softer binder controls ductility of the mix, and active blended binder dictates the strength of mixes at intermediate temperature.
Background

- Established through partnership between
  - Washington State Department of Transportation (WSDOT),
  - Washington Asphalt Paving Association (WAPA), and
  - Washington State University (WSU)

- Funding also contributed by National Science Foundation (NSF)
Board Members

- Tom Baker, State Bridge Engineer, WSDOT
- Jeff Carpenter, State Design Engineer, WSDOT
- Tom Gaetz, Executive Director, WAPA
- Keith Metcalf, Deputy Chief Engineer, WSDOT
- Dave Gent, Technical Director WAPA
- Haifang Wen, WSU, Director

Members
Industry service

- WCAT is AASHTO accredited
  - Binder PG Grading, Extraction and Recovery, MSCR
  - Mix Design and Verification
- Binder Tests
  - RAP Binder Extraction and Recovery
  - Asphalt Content of Compacted Bituminous Mixtures using Ignition Oven or Solvent
  - Dynamic Shear Rheometer
  - Bending Beam Rheometer
  - Rolling Thin Film Oven
  - Pressure Aging Vessel
  - Rotational Viscometer (Brookfield)
  - Multiple Stress Creep and Recovery (MSCR)

Industry service

- Mix performance tests
  - Hamburg Wheel Tracking (APA Jr.)
  - Indirect Tensile Test – fatigue and thermal cracking
  - Dynamic Modulus Test - stiffness
  - Static Creep Test (Flow Time) - rutting
  - Repeated Load Test (Flow Number) – rutting
  - Modified Lottman – moisture damage
  - Studded Tire Machine
Thank you!