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

Haifang Wen
Kun Zhang
Washington State University

Fouad Bayomy
and Ahmed Muftah
University of Idaho

FHWA Mix ETG,
Oklahoma City, OK
Sept 17, 2015
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.
Results and Discussion

- **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.

![Dynamic Modulus Test Results](image-url)
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.

![Fracture Work Density (psi)](chart1)

- Vertical Failure Deformation (inch)

![Vertical Failure Deformation (inch)](chart2)
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?

![Fracture Work Density (psi)](a)

![Vertical Failure Deformation (inch)](b)
Results and Discussion

- Bottom-up cracking fatigue model

\[ N_f = 3.75 \times 10^{-5} \left( \frac{1}{\varepsilon_t} \right)^{0.147} (FWD)^{1.92} h^{0.135} \]
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.

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

\[y = 0.98x \quad R^2 = 0.42\]
Results and Discussion

- Procedures of performance-related empirical mix design
  - Selection of low temperature PG of virgin binder for a mix with RAP.

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

  - (1) Design a control mix without RAP using target PG of virgin binder.
  - (2) Estimate FWD\text{\_low} of the control mix.
  - (3) Design a RAP mix to meet volumetrics specification by using target high temperature grade of virgin binder with any low temperature PG.
  - (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

Haifang Wen
Kun Zhang
Washington State University

FHWA Mix ETG,
Oklahoma City, OK
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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
  - RAP binder *mobilization and transfer to virgin aggregate*
  - Mechanical blending between RAP binder and virgin binder
  - Diffusion between RAP binder and virgin binder

(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>RAP Aggregate Percent Passing, %</th>
<th>RAP Binder Content</th>
<th>Gsb of RAP Aggregate</th>
<th>True PG of RAP Binder</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>South Idaho RAP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 95 88 68 54 43 33 21 14 9.4</td>
<td>4.9%</td>
<td>2.583</td>
<td>85.2-16.8</td>
</tr>
<tr>
<td><strong>POE RAP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 97 89 63 43 31 23 17 13 8.9</td>
<td>4.4%</td>
<td>2.777</td>
<td>83.8-18.3</td>
</tr>
</tbody>
</table>

- **Sieve Size (mm)**
  - 19.0 12.5 9.5 4.75 2.36 1.18 0.6 0.3 0.15 0.075
**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>Percent Passing, %</td>
<td>100 95 84 62 47 35 26 16 9 5.5</td>
<td>----</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>4.0</td>
</tr>
<tr>
<td>VMA, %</td>
<td>14.5</td>
<td>14 min</td>
</tr>
<tr>
<td>VFA, %</td>
<td>73</td>
<td>65-75</td>
</tr>
<tr>
<td>Dust-to-Asphalt Ratio</td>
<td>1.2</td>
<td>0.6-1.2</td>
</tr>
<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>Percent Passing, %</td>
<td>100 93 79 50 33 24 17 13 8 4.8</td>
<td>----</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>4.0</td>
</tr>
<tr>
<td>VMA, %</td>
<td>14.2</td>
<td>14 min</td>
</tr>
<tr>
<td>VFA, %</td>
<td>72</td>
<td>65-75</td>
</tr>
<tr>
<td>Dust-to-Asphalt Ratio</td>
<td>1.1</td>
<td>0.6-1.6</td>
</tr>
<tr>
<td>PG of Target Binder</td>
<td>64-28</td>
<td></td>
</tr>
</tbody>
</table>
Materials and Experiments-Mixing Scheme Design

Heat virgin aggregate (VA) for two hours, and heat virgin binder (VB) and RAP (if in mix design) separately for one hour to mixing temperature

Mix VA and VB for 3 min.

Mix VA and RAP for 3 min. (Mix A)

Mix VA and RAP first for 3 min.

Mix VA and RAP with VB for 3 min. (Mix E and F)

Mix VA and VB for 3 min. (Mix B)

Mix VM and RAP separately to room temperature

Immediately mix virgin mix with RAP for 3 min. (Mix C)

Immediately mix VA and RAP for 3 min. (Mix D)

Cool down blended mix to room temp.

Heat VM and RAP separately at compaction temp for total 2.5 hours

Mix VM and RAP for 3 min. at room temp. (Mix B)

Cool down virgin mix (VM) and RAP separately to room temperature

Mix VM and RAP by Spatula (Mix A)

Heat blended mix for 2.5 hours at compaction temp.

Compact mixes by gyratory compactor to the height of 115 mm.

Cool down compacted samples by fan to room temp.

Heat in Oven

VM and RAP
## 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</td>
</tr>
<tr>
<td>Mix B</td>
<td>PG 64-34</td>
<td>PG 58-34</td>
<td>26%</td>
<td>Diffusion</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

- Rheological properties: dynamic modulus (DM) values
  - Difference was profound at intermediate level
  - RAP mixes has comparable DM values so that diffusion was most dominant stage to affect DM values.
Dynamic Modulus Values at Different Levels

**Idaho High Level (-20°C, 20 Hz)**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Dynamic Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>19121</td>
</tr>
<tr>
<td>B</td>
<td>22173</td>
</tr>
<tr>
<td>C</td>
<td>23529</td>
</tr>
<tr>
<td>D</td>
<td>21528</td>
</tr>
<tr>
<td>E</td>
<td>21695</td>
</tr>
<tr>
<td>F</td>
<td>21419</td>
</tr>
</tbody>
</table>

**POE-High Level (-20°C, 20 Hz)**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Dynamic Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>17869</td>
</tr>
<tr>
<td>B</td>
<td>18963</td>
</tr>
<tr>
<td>C</td>
<td>19829</td>
</tr>
<tr>
<td>D</td>
<td>19482</td>
</tr>
<tr>
<td>E</td>
<td>20153</td>
</tr>
<tr>
<td>F</td>
<td>20524</td>
</tr>
</tbody>
</table>

**Idaho-Intermediate Level (20°C, 1 Hz)**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Dynamic Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2,197</td>
</tr>
<tr>
<td>B</td>
<td>2,814</td>
</tr>
<tr>
<td>C</td>
<td>2,814</td>
</tr>
<tr>
<td>D</td>
<td>2,952</td>
</tr>
<tr>
<td>E</td>
<td>1,917</td>
</tr>
<tr>
<td>F</td>
<td>3,288</td>
</tr>
</tbody>
</table>

**POE-Intermediate Level (20°C, 1 Hz)**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Dynamic Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2435</td>
</tr>
<tr>
<td>B</td>
<td>2,823</td>
</tr>
<tr>
<td>C</td>
<td>2,891</td>
</tr>
<tr>
<td>D</td>
<td>2,656</td>
</tr>
<tr>
<td>E</td>
<td>2,095</td>
</tr>
<tr>
<td>F</td>
<td>2,684</td>
</tr>
</tbody>
</table>
Results and Discussion

- Rheological properties: *creep compliance*
  - At a high temperature or reduced time, control mix E has highest creep compliance, while control mix F has similar creep compliance with all four RAP mixes.
  - Again, RAP mixes has comparable creep compliance values and diffusion is most dominating blending stages.
Creep Compliance Values at -10°C

South Idaho RAP Mixes

Creep Compliance (1/Pa) @ -10℃

Creep Time (s)

POE RAP Mixes

Creep Compliance (1/Pa) @ -10℃

Creep Time (s)
Results and Discussion

- Facture 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.
Results and Discussion

- **Facture performance: IDT test at 68ºF**
  - 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](image1)

![POE RAP Mixes](image2)
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
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

- Facture performance: *IDT test at 14°F*
  - No significant difference among mixes
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.
Thank you!