New Tools for Assessing & Characterizing High RBR Asphalt Concrete Mixtures

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FHWA Binder ETG
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Outline

- NCHRP 9-58 Objectives & Research Plan
- Preliminary Phase II Tools
  - Recycling Agent Dosage Selection Method
  - Rejuvenating Effectiveness & Its Evolution
  - Binder Availability from Recycled Materials
- Next Steps
NCHRP 9-58: The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios

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NCHRP 9-58 Objectives

- Assess effectiveness of RAs to:
  - restore blended binder rheology
  - improve mixture cracking performance at optimum dosage rates

- Evaluate the evolution of RA effectiveness

- Recommend evaluation tools
NCHRP 9-58 Research Plan

**PHASE I**
Identification of Gaps in Knowledge on RA Use with High RBRs

- **Task 1.** Gather Information
- **Task 2.** Design Laboratory Experiment
- **Task 3.** Document Results in First Interim Report

**PHASE II**
Investigation of Effectiveness of RAs in Restoring Binder Rheology, Development of Blending Protocol, and Associated Mixture Performance

- **Task 4.** Conduct Laboratory Experiment
- **Task 5.** Design Field Experiment and Document Results in Second Interim Report

**PHASE III**
Validation of RA Use in Mixtures with High RBRs

- **Task 6.** Conduct Field Experiment
- **Task 7.** Propose Revisions to AASHTO Specifications and Test Methods
- **Task 8.** Develop Training Materials and Best Practices and Deliver Workshop
- **Task 9.** Document Results in Final Report
RECYCLING AGENT DOSAGE SELECTION METHOD
SELECT MATERIALS

- Target and base binder PG grade
- RAP and/or RAS source(s)
- Recycling Agent (RA)
- RAP and/or RAS Recycled Binder Ratio (RAPBR/ RASBR)
Extract and recover binder from RAP and/or RAS source(s)

Prepare recycled binder blends:
• With no RA (control)
• With low RA dosage
• With high RA dosage
CONDUCT LAB TESTS

Obtain high PG grade (PGH) and low PG grade (PGL) per AASHTO M320:

• Target binder
• Recycled binder blend with no RA (control)
• Recycled binder blend with low RA dosage
• Recycled binder blend with high RA dosage
SELECT DOSAGE

Plot original & RTFO PGH, S- & m-controlled PGL vs. RA dosage for all blends

Establish linear regression equations

Select RA dosage in 0.5% increments to meet target binder PGL using warmer PGL regression line

Verify PGH of selected dosage vs. target binder PGH using colder PGH regression line

Meets target PGH?

NO

\[ \Delta \text{ dosage in 0.5\% increments to meet PGH & maintain PGL} \]

YES

Report selected dosage & PG grade

*For RAS mixtures, if selected dosage >5.5%, replace virgin binder with 50% RA and add other 50%.
0.3 RBR (PG 64-22 | 0.1 TxBRAP | 0.2 TxBMWAS | T1)

- Original G*/sin(d)
- RTFO G*/sin(d)
- PAV m-controlled
- PAV S-controlled

- $y = -1.7x + 85.1$
- $y = -1.8x + 81.8$
- $y = -1.3x - 16.0$
- $y = -0.7x - 28.5$

- A (4.5, -22)
- B (4.5, 73)

$\Delta Tc = 10.0$

Target Grade: 70-22
Actual Grade: 73-22

Selected Dosage: 4.5%
0.5 RBR (64-22 | 0.25 TxBRAP | 0.25 TxBTOAS | T1)

- Original G*/sin(d)
- RTFO G*/sin(d)
- PAV m-controlled
- PAV S-controlled

Equations:
- y = -1.8x + 102.3
- y = -2.2x + 100.5
- y = -2.1x - 1.3
- y = -1.0x - 23.3

Points:
- B (9.5, 79)
- C (11.5, 75)
- A (9.5, -22)
- D (11.5, -26)

ΔTc = 11.0
ΔTc = 9.0

Target Grade: 70-22
Actual Grade: 75-26

Selected Dosage: 11.5%
## DOSAGE SELECTION

<table>
<thead>
<tr>
<th>Virgin</th>
<th>RBR</th>
<th>RAP</th>
<th>RAS</th>
<th>RA</th>
<th>Opt Dosage</th>
<th>Field Dosage</th>
<th>ΔTc @ Opt</th>
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<tbody>
<tr>
<td>64-22 TX</td>
<td>0.3</td>
<td>0.1 TX</td>
<td>0.2 TX MWAS</td>
<td>T1</td>
<td>4.5</td>
<td>2.7</td>
<td>10</td>
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<tr>
<td>64-22 TX</td>
<td>0.3</td>
<td>0.1 TX</td>
<td>0.2 TX MWAS</td>
<td>A1</td>
<td>5.5</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>64-22 TX</td>
<td>0.4</td>
<td>0.4 TX</td>
<td>-</td>
<td>T1</td>
<td>7.5</td>
<td>-</td>
<td>8</td>
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<tr>
<td>64-22 TX</td>
<td>0.4</td>
<td>0.4 TX</td>
<td>-</td>
<td>A1</td>
<td>9.5</td>
<td>-</td>
<td>7</td>
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<tr>
<td>64-22 TX</td>
<td>0.5</td>
<td>0.25 TX</td>
<td>0.25 TX MWAS</td>
<td>T1</td>
<td>7.5</td>
<td>-</td>
<td>9</td>
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<tr>
<td>64-22 TX</td>
<td>0.5</td>
<td>0.25 TX</td>
<td>0.25 TX TOAS</td>
<td>T1</td>
<td>11.5</td>
<td>-</td>
<td>9</td>
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<tr>
<td>64-28 NH</td>
<td>0.4</td>
<td>0.4 TX</td>
<td>-</td>
<td>A1</td>
<td>6.0</td>
<td>-</td>
<td>4</td>
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<tr>
<td>64-28 NH</td>
<td>0.5</td>
<td>0.25 TX</td>
<td>0.25 TX TOAS</td>
<td>T1</td>
<td>12.5</td>
<td>-</td>
<td>5</td>
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<tr>
<td>64-28P NV</td>
<td>0.5</td>
<td>0.25 TX</td>
<td>0.25 TX TOAS</td>
<td>T1</td>
<td>11.0</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>64-28P NV</td>
<td>0.3</td>
<td>0.3 NV</td>
<td>-</td>
<td>T2</td>
<td>1.5</td>
<td>2.0</td>
<td>3</td>
</tr>
<tr>
<td>64-28P NV</td>
<td>0.3</td>
<td>0.3 NV</td>
<td>-</td>
<td>A2</td>
<td>2.0</td>
<td>2.0</td>
<td>2</td>
</tr>
</tbody>
</table>

- 0.5% increments
- Restore PGL, then meet PGH (if possible) & maintain PGL
- High ΔTc ??
- Aging effects – using optimum w/G-R @ 0, 20, 40hr PAV
RA ADDITION VS. REPLACEMENT

• Current Practice
  – 100% replacement
  – OK at low RA dosage
  – Coating issues at high RA dosage (5.5%A1)

• Example: 0.5 RBR (0.25TXRAP + 0.25TXRAS + 12.5%T1)
  – 100% addition: \( P_b = 4.9\% \)
  – 100% replacement: \( P_b = 4.3\% \)
  – 0.6% reduction in \( P_b \) (coating issues)
  – Max% for replacing?
COATABILITY EVALUATION (NCHRP 9-53)

Coarse Aggregate Fraction VS. Coarse Foamed Loose Mix Fraction

Water

Soak under water for 1 hour

Water

Coatability Index (CI): relative difference in SSD water absorption
Higher CI = better aggregate coating
COATABILITY: W/RAP 100% ADD, W/RAS 50/50 ADD/REPLACE
DOSAGE SELECTION – BASE BINDER TYPE
DOSAGE SELECTION – RA TYPE

- 0.3 RBR (0.1 TX RAP, 0.2 TX MWAS, 64-22)
- 0.4 RBR (0.4 TX RAP, 64-22)
- 0.3 RBR (0.3 NV RAP, 64-28P)

Optimum Dosage

T1  A1  T1  A1  T2  A2

BBRAtε

0%  3%  6%  9%  12%  15%

T1  A1  T1  A1  T2  A2

RA Type
DOSAGE SELECTION – RAS TYPE

0.5 RBR (0.25 TX RAP, 64-22, T1)

Optimum Dosage

- 9% for TX MWAS
- 15% for TX TOAS

BBRATe

- 9 for TX MWAS
- 6 for TX TOAS
RA Dosage Selection – Mortar Verification

![Graph showing the relationship between temperature and high temperature for different binder and mortar experiments.](image)

- **Virgin 64-28P + 0.3 RBR**
- **Virgin 64-28P + RA (A2) + 0.3 RBR**
- **Virgin 64-28P + RA (T2) + 0.3 RBR**
- **Virgin PG64-22 + 0.286 RBR**
- **Virgin PG64-22 + RA (T1) + 0.286 RBR**

- **Binder Experiment** represented by red circles
- **Mortar Experiment** represented by white circles
RA Dosage Selection – Mortar Verification

Low Temperature (°C)


Virgin 64-28P + 0.3 RBR
Virgin 64-28P + RA (A2) + 0.3 RBR
Virgin 64-28P + RA (T2) + 0.3 RBR
Virgin PG64-22 + 0.286 RBR
Virgin PG64-22 + RA (T1) + 0.286 RBR

Temperature (°C)

Binder Experiment
Mortar Experiment
RA Dosage Selection – Mixture Validation - $M_R$

**Graph Description:**
- **X-axis:** Various conditions and categories of recycled materials.
- **Y-axis:** Resilient Modulus (ksi).
- **Legend:**
  - Cores @ 1 Year
  - Cores - @ const.
  - LTOA
  - STOA

**Conditions and Modulus Values:**
- **Target**
- **Recycled Control**
- **Recycled w/T1 @ FLD (2.7%)**
- **Recycled w/T1 @ FLD (64-28)**
- **Recycled w/T1 @ OPT (2.5%)**
- **Recycled w/T1 @ OPT (TOAS)**
- **Recycled w/A1 @ OPT (4.5%)**
- **Recycled w/A1 @ OPT (5.5%)**

**Analysis:**
- The graph compares the resilient modulus for different recycled materials and conditions, showing variability and trends across the categories.
RA Dosage Selection – Mixture Validation - SCB

Flexibility Index (FI)

- Target
- Recycled Control
- Recycled w/T1 @ FLD (2.7%)
- Recycled w/T1 @ FLD (64-28)
- Recycled w/T1 @ (3.5%)
- Recycled w/T1 @ OPT (4.5%)
- Recycled w/A1 @ OPT (5.5%)
- Recycled w/T1 @ OPT (TOAS)
RA Dosage Selection – Mixture Validation S-VECD

![Graph showing strain vs. predicted number of cycles to failure for different mixtures.](attachment://image.png)
RA Dosage Selection – Mixture Validation LVECD

- Target
- Recycled Control
- Recycled w/T1@FLD

Graph showing the number of failure points over months with different materials.
RA Dosage Selection – Mixture Validation UTSST

UTSST Resistance Index

- TX Target LMLC: 388
- TX Target RPMLC: 118
- TX Recycled Control LMLC: 46
- TX Recycled Control RPMLC: 17
- TX Recycled w/T1 LMLC: 78
- TX Recycled w/T1 RPMLC: 2
REJUVENATING EFFECTIVENESS & ITS EVOLUTION
Overall G-R Results

0.3 RBR (0.1 RAP & 0.2 RAS)

Target Binder ≤ Recycled Blends @ opt RA < Recycled Blend no RA

Error bar: standard deviation of 2 replicates

Target Binder ≤ Recycled Blends @ opt RA < Recycled Blend no RA
Black Space Diagram

0.3 RBR (0.1 RAP & 0.2 RAS)
- Target Binder, 70-22
- Recycled Blend, 64-22, 5.5% A1
- Control Blend, 64-22, No RA
- Recycled Blend, 64-22, 4.5% T1

Log $G^*$ (Pa) @ 15°C, 0.005 rad/s

Phase Angle (degree) @ 15°C, 0.005 rad/s

BLOCK CRACKING

NO BLOCK CRACKING
PAV Hours to reach G-R Damage Curve

0.3 RBR (0.1 RAP & 0.2 RAS)

<table>
<thead>
<tr>
<th>Blend</th>
<th>Damage Onset (180 kPa)</th>
<th>Significant Cracking (450 kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Binder 70-22</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>Control 64-22 No RA</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Recycled 64-22 4.5% T1</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Recycled 64-22 5.5% A1</td>
<td>16</td>
<td>23</td>
</tr>
</tbody>
</table>

**Significant Improvements**

Target Binder > Recycled Blends @ opt RA > Recycled Blend no RA
Rejuvenating Effectiveness (RE)

- Normalized difference in log(G-R) for recycled blend @ opt RA vs. target binder & recycled blend no RA
RE Evolution with PAV Aging

The “rejuvenating” effect of RA decreased with PAV aging
BINDER AVAILABILITY FROM RECYCLED MATERIALS
Problem Statement

- How much RAP binder is available and blends with the virgin binder during the mixing process?

- DOTs assume 100% of RAP binder will be active and become part of the mix - 100% RAP binder availability – not realistic
  - a portion of RAP binder participates in the mixing process – Active RAP binder
  - a portion of RAP binder forms a stiff coating around the RAP aggregate and produces “black rock” – Inactive RAP binder

- Partial binder availability – realistic
  - Effect on performance?
Objective

- Develop a procedure to **quantify** RAP binder availability
  - % active RAP binder
  - % inactive RAP binder
- Evaluate the effect of recycling agents (RAs) on RAP binder availability
The amount of binder needed to coat the aggregate depends on:

- total binder content in the mix (AC%)
- aggregate gradation

Each aggregate size will have a different binder content. For a fixed AC% the binder content in each aggregate size will also remain fixed.

For HMA mix with 4.5% binder content:

Binder contents on 3/8, #4, and (#8,30) fractions are 2.7, 4.0, and 6.1%, respectively.
Binder Availability Methodology

Virgin Mix
1. Mix virgin binder & aggregate
2. Sieve loose mix
3. Determine \( P_b \) of material retained in sieve # 4 using the ignition oven

Labeled as Reference \( P_b \)
* constant for specific mixture

RAP Mix
1. Mix virgin binder & aggregate + RAP
2. Sieve loose mix

Labeled as \( RAP' P_b \)
* varied based on RAP used
**Example Binder Availability Calculation**

**Virgin Mix**
- 3/8
- #4
- #8, 30

**RAP Mix**
- 3/8
- #4 RAP
- #8, 30

(RAP $P_b = 4.5\%$)

**P$_b$ Values**

<table>
<thead>
<tr>
<th>Virgin Mix</th>
<th>RAP Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_b = 2.7%$</td>
<td>$P_b &lt; 2.7%$</td>
</tr>
<tr>
<td>$P_b = 4.0%$</td>
<td>$P_b &gt; 4.0%$</td>
</tr>
<tr>
<td>$P_b = 6.0%$</td>
<td>$P_b &lt; 6.0%$</td>
</tr>
</tbody>
</table>

**Total $P_b = 4.5\%$**

**Total $P_b = 4.5\%$**

RBR = 0.3
Virgin Mix

Reference $P_b = 4.0\%$

RAP Mix with 0.3RBR

$RAP' P_b = 4.0\%$

$RAP' P_b = 7.3\%$

$(70\%*\text{Reference } P_b + 30\%*\text{Distributed RAP } P_b)$

$(70\%*\text{Reference } P_b + 100\%*\text{RAP } P_b)$

Virgin

Virgin

Virgin

Virgin binder

Virgin Aggregate

100\% Available

Perfect Blending

Partial availability

assuming linear relationship

0\% Available

Black Rock

Virgin binder

Virgin binder

RAP

RAP

RAP

RAP binder

(Virgin binder + RAP binder (All active binder))

RAP binder

(RAP binder (Inactive binder))
Preliminary Verification

- Produce Artificial RAP (#4 agg. + virgin binder)
  - RAP 1: no aging
  - RAP 2: 5 days @ 110°C
  - RAP 3: 10 days @ 110°C
  - RAP 4: 10 days @ 110°C plus 3 days at 150°C

- 0.3 RBR

- Artificial RAP binder content: 4.5%
- Mixture total binder content: 4.5%
Preliminary Verification

Reference $P_b = 4.0\%$

RAP’ $P_b$:
- 4.0%: 100% Availability
- 7.3%: 0% Availability

RAP’ (1) $P_b = 4.0\%$
RAP’ (2) $P_b = 4.5\%$
RAP’ (3) $P_b = 5.1\%$
RAP’ (4) $P_b = 6.0\%$
0.3 RBR

TX & NH RAP binder contents are 4.7% and 4% respectively

Mixture Total binder content: 4.5%
Next Steps

- G-R Thresholds based on Climate
  - Change $T \neq 15^\circ C$
  - Change $f \neq 0.005$ rad/s
  - Change Thresholds
  - Change Aging Durations to Reach Thresholds

- Binder Availability
  - Different size RAP
  - MWAS & TOAS
  - Higher RBRs
  - Degree of Blending (DOB)

- Binder Compatibility

- Additional Field Projects – NV, IN, MO?, DE?
Motivation – High Recycled Binder Ratio (RBR)

Economic & Environmental Benefits
- Natural Resources
- Energy
- Emissions

Engineering Concerns
- Compactibility
- Stiffness & Embrittlement
- Cracking Resistance
Mitigation – Recycling Agent (RA)

**BENEFITS**

- **Engineering**
  - Reduced Stiffness, Improved Compactibility
  - Improved Cracking Resistance

- **Economic**

**REMAINING ISSUES**

- **Engineering**
  - Reduced Embrittlement
  - Aging

- **Blending**

- **Mixture Performance**
Field Projects

Environmental Zones
- Wet-Freeze
- Dry-Freeze
- Dry-N Freeze
- Wet-No Freeze

MO 2016: 0.45 RBR
RA: T1

IN 9/15: 0.4, 0.5 RBR
RA: T2

NV 9/15: 0.3 RAPBR
RAs: T2 + A2

TX 6/14: 0.3 RBR
RA: T1
TX (Expanded) & NV Field Materials

- **TX:** PG 64-22 + 0.3 RBR (0.1 RAP+0.2 MWAS) + 2.7% Tall Oil T1 (Target=PG 70-22)
- +0.4 RBR w/RAP only, **0.5 RBR** balanced RAP/RAS
- + Aromatic Extract A1
- + NH PG 64-28 & NV PG 64-28P
- + TX TOAS & NH RAP

- **NV:** PG 64-28P + 0.3 RBR (0.3 RAP) + 2.0% Tall Oil T2 & + 2.0% Tall Oil A2 (Target=PG64-28)
Laboratory Tests – BINDER & MORTAR

- PG - BOTH
- G-R
Laboratory Tests - MIXTURE

- **Stiffness**
  - $M_R \text{ @ } 25 ^\circ \text{C}$
  - $E^*$

- **Cracking Resistance**
  - SCB
  - S-VECD
  - UTSST
RA Dosage Selection – Mortar Verification

- **Binder Testing**
  - Base 64-22 + 0.28 RBR (0.1 TX RAP + 0.18 TX MWAS)
  - Base 64-22 + T1 + 0.28 RBR (0.1 TX RAP + 0.18 TX MWAS)

- **Mortar Testing**
  - Base 64-22 + 0.18 RBR (TX MWAS)
  - Base 64-22 + T1 + 0.18 RBR (TX MWAS)

*ΔTC (°C) [m-value Critical Temp - Stiffness Critical Temp]*

- Could not be tested.
RA Dosage Selection – Mortar Verification

- Binder Testing
- Mortar Testing

<table>
<thead>
<tr>
<th>Binder Testing</th>
<th>Mortar Testing</th>
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<tbody>
<tr>
<td>RAP</td>
<td>Target 64-28P</td>
</tr>
<tr>
<td>3.4</td>
<td>3.6</td>
</tr>
<tr>
<td>-3</td>
<td>4.5</td>
</tr>
<tr>
<td>2.4</td>
<td>2.9</td>
</tr>
<tr>
<td>0</td>
<td>10.5</td>
</tr>
<tr>
<td>5.8</td>
<td>7.1</td>
</tr>
</tbody>
</table>

ΔTC (°C) = m-value Critical Temp - Stiffness Critical Temp
The “rejuvenating” effect of RA decreased with PAV aging.
RE Evolution with PAV Aging

0.5 RBR (0.25 RAP & 0.25 RAS)
- Recycled Blend, 64-22, MWAS, 7.5% T1
- Recycled Blend, 64-22, TOAS, 11.5% T1
- Recycled Blend, 64-28, TOAS, 12.5% T1

Target Binder, 70-22

Rejuvenating Effectiveness vs PAV Aging Time (hours)

Control Blend, no RA

0% 20% 40% 60% 80% 100% 120% 140%

0 20 40
Change in CA with PAV Aging

0.3 RBR (0.1 RAP & 0.2 RAS)
- Target Binder, 70-22
- Control Blend, 64-22, No RA
- Recycled Blend, 64-22, 4.5% T1
- Recycled Blend, 64-22, 5.5% A1

Recycled Blends @ opt RA = Recycled Blend no RA
G-R Hardening Sensitivity

0.3 RBR (0.1 RAP & 0.2 RAS)

○ 70-22 ○ 64-22, No RA ● 64-22, T1 (4.5%) □ 64-22, A1 (5.5%)

Recycled Blends @ opt RA > Recycled Blend no RA