Behavior of Recycled Asphalt Pavement and Recycled Concrete Aggregate as Unbound Road Base

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Geological Engineering
Objective of Pool Fund Project

- Characterize properties of recycled concrete pavement (RCP) and recycled asphalt pavement (RAP) as unbound base
- Determine how RCA and RAP behave in the field and how to design pavements using these materials
- Both lab and field scale tests
  - Variability in material properties
  - Purity of materials
  - Control of material quality and best construction practices
  - Climatic effects and durability
  - Environmental suitability
## Project Tasks

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<td>New Mexico State</td>
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<td>ND State</td>
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<td>Oregon State</td>
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<td>Northern Illinois</td>
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<td>South Dakota</td>
<td>W 59-10</td>
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<td>Nebraska</td>
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Recycled Materials

- Recycled Asphalt Pavement (RAP)
- Recycled Pavement Material (RPM)
- Recycled Concrete Aggregate (RCA)
Objective of Today’s Presentation

- Characterize engineering properties of RCA and RAP as unbound road base without treatment/stabilization
- Assess influence of
  - compaction effort
  - compaction moisture content
  - freeze-thaw cycling
  on the stiffness of RCA and RAP as unbound road base
- Determine effect of varying RAP or RCA content on stiffness of natural aggregate used as unbound road base
Materials

- RCA: 7
- RAP: 7
- RPM: 2

Map showing states with RCA, RAP, and RPM materials.

- California
- Colorado
- Texas
- Minnesota
- Wisconsin
- Michigan
- New Jersey
- Ohio
Representative Materials

<table>
<thead>
<tr>
<th>Gradation</th>
<th>RCA</th>
<th>RAP</th>
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<tbody>
<tr>
<td>Coarser</td>
<td>Texas</td>
<td>Texas</td>
</tr>
<tr>
<td>Medium</td>
<td>Michigan</td>
<td>California</td>
</tr>
<tr>
<td>Finer</td>
<td>California</td>
<td>Minnesota</td>
</tr>
</tbody>
</table>

- Class 5 (Natural Aggregate)
Gradation: RAPs and Class 5

- RAP (TX)
- RAP (CA)
- RAP (MN)
- Class 5 (MN)

**Percent Finer (%)**

**Particle Size (mm)**

**RAP Lower Bound (Literature)**

**RAP Upper Bound (Literature)**
Gradation: RCAs and Class 5

![Graph showing gradation of RCAs and Class 5](image)

- RCA (TX)
- RCA (MI)
- RCA (CA)
- Class 5 (MN)

**RCA Lower Limit (Literature)**

**RCA Upper Limit (Literature)**

- Percent Finer (%)
- Particle Size (mm)
Test Method

- Resilient Modulus ($M_r$) Test

\[ M_r = \frac{d}{r} \]

where $\sigma_d$ = deviator stress, $\varepsilon_r$ = recoverable elastic strain
Resilient Modulus

Power Function:

\[ M_r = k_1 \theta^{k_2} \]

where \( \theta \) = bulk stress

\( k_1 \) and \( k_2 \) = fitting parameters

Summary Resilient Modulus (SRM)
Freeze-Thaw Cycling
 Freeze-Thaw Cycling

- Specimens
  - Prepared in same manner as resilient modulus specimens
  - Retained in freezer for 24 h
  - Thawed at room temperature for 24 h

- After last cycle, specimens extruded frozen and thawed inside resilient modulus cell

- Specimens subjected to 5, 10, 20 cycles
Temperature Records for RAPs and RCAs

- RAP
- RCA

Temperature (Celsius)

Time (Hours)

0 4 8 12 16 20 24

-30 -20 -10 0 10 20 30

Freezing
Thawing
RAPs: SRM vs F-T Cycles

Freeze and Thaw Cycles

Internal SRM (MPa)

- RAP (TX)
- RAP (CA)
- RAP (MN)
- Class 5 (MN)
RAPs: Normalized SRM vs F-T Cycles

Freeze and Thaw Cycles

SRM/N/SRM₀

RAPs:
- RAP (TX)
- RAP (CA)
- RAP (MN)
- Class 5 (MN)

AC=4%
AC=5%
AC=7%

Coarser
Medium
Finer
RCAs: SRM vs F-T Cycles

Freeze and Thaw Cycles

Internal SRM (MPa)

RCA (TX)
RCA (MI)
RCA (CA)
Class 5 (MN)
RCAs: Normalized SRM vs F-T Cycles

Freeze and Thaw Cycles vs \( \frac{SRM_N}{SRM_0} \)

- RCA (TX)
- RCA (MI)
- RCA (CA)
- Class 5 (MN)
Verification of RCA Behavior with Seismic Modulus Test

P- Wave Velocity

Constrained Modulus

Density, $\rho$

Length, $L$

$V_p$
RCAs: Constrained Modulus vs F-T Cycles

Constrained Modulus, (MPa) vs Freeze Thaw Cycles

- RCA (TX)
- RCA (MI)
- RCA (CA)
- Class 5 (MN)
Compaction Conditions
Effect of Density (Compaction Effort) and Compaction Moisture on Modulus
Density (Relative Compaction) Effect

Dry Unit Weight, (kN/m³)

Water Content (%)

OMC

95 % of MDU

90 % of MDU

85% of MDU
Effect of Relative Compaction on Modulus

![Graph showing the effect of relative compaction on modulus. The graph plots compaction effort (%) on the x-axis and internal SRM (MPa) on the y-axis. Different materials such as RAP (TX), RAP (CA), RAP (MI), RCA (TX), RCA (MI), and Class 5 (MN) are compared. The graph illustrates the decrease in internal SRM with increasing compaction effort.]
Summary Effect of Relative Compaction on Modulus

![Graph showing the effect of compaction effort on modulus of different materials.]

- **RAP**: 37% decrease
- **RCA**: 41% decrease
- **Natural Aggr**: 47% decrease

*Graph details:*
- **Y-axis**: Internal SRM (MPa)
- **X-axis**: Compaction Effort (%)
- **Legend**:
  - RAP
  - RCA
  - Class 5
Compaction Moisture Effect

![Graph showing the compaction moisture effect. The graph plots water content (%) on the x-axis and dry weight (kN/m³) on the y-axis. There is a peak at OMC (Optimum Moisture Content) with -2% and +2% deviation from OMC. The graph indicates that 95% of Modified Proctor is used.](image-url)
PSDs of RAPs and RCAs Used in Moisture Effects Testing

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**Graph 1:**
- **X-axis:** Particle Size (mm)
- **Y-axis:** Percent Finer (%)
- **Legend:**
  - RAP (OH)
  - RAP (TX)
  - RAP Lower Bound (Literature)
  - RAP Upper Bound (Literature)

**Graph 2:**
- **X-axis:** Particle Size (mm)
- **Y-axis:** Percent Finer (%)
- **Legend:**
  - RCA (OH)
  - RCA (CO)
  - RCA Upper Bound (Literature)
  - RCA Lower Bound (Literature)
Effect of Compaction Moisture on Modulus

- Coarser
- Finer
- Finer
- Medium

- RAP (TX)
- RAP (OH)
- RCA (CO)
- RCA (OH)

Internal SRM (MPa)

- 800
- 700
- 600
- 500
- 400
- 300
- 200
- 100

- - 2%
- OMC
- + 2%
Effect of Compaction Moisture on Normalized SRM

![Graph showing the effect of compaction moisture on normalized SRM.](image)
Summary of Compaction Moisture Effect on Normalized Modulus

- RCA 28% increase
- RAP 17% increase
- 7% decrease
- 29% decrease
Moisture Content Before and After Test

Water Content (%) vs. Internal SRM (MPa)

- RAP (TX)-Before
- RAP (TX)-After
- RAP (OH)-Before
- RAP (OH)-After

Coarser
Finer
RCA: Effect of Compaction Moisture on Modulus

![Graph showing the effect of water content on internal SRM (MPa) for RCA (CO) and RCA (OH) before and after compaction.](image-url)
Effect of RAP or RCA Content on Stiffness of Natural Aggregate Blends
## Materials Selected for Blends

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<tr>
<th>RAP</th>
<th>RCA</th>
<th>Natural Aggregate</th>
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<tbody>
<tr>
<td>California</td>
<td>Minnesota</td>
<td>Minnesota (Class 5)</td>
</tr>
<tr>
<td>Colorado</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PSD of RAPs and Class 5 Used in Blends

- Class 5 (MN)
- RAP (CA)
- RAP (CO)

Percent Finer (%)

Particle Size (mm)

RAP Lower Bound (Literature)

RAP Upper Bound (Literature)
PSD of RCA (MN) and Class 5 Used in Blends
Compaction Curves: RAP (CA) and RAP (CO) Blends

![Graph showing compaction curves for Class 5 (MN), Blend (50-50), and RAP (CA) and RAP (CO).]
Compaction Curve: RCA (MN) Blend

![Graph showing compaction curve for RCA (MN) blend. The graph plots water content (%)) against dry weight (kN/m³). There are three lines on the graph:

- Green triangles represent Class 5 (MN).
- Brown squares represent Blend (50-50).
- Red circles represent RCA (MN).]
SRM of Blends

![Graph showing the relationship between RAP or RCA (in %) and Internal SRM (MPa) for RAP (CA), RAP (CO), and RCA (MN).]
Results

![Graph showing results of RAP and RCA blends.]

- **RAP (CA)**
- **RAP (CO)**
- **RCA (MN)**

**SRM Blend/SRM Class 5**

- **RAP 68% increase**
- **RCA 30% increase**
Conclusions

- Freeze-thaw cycling reduces SRM of RAP and natural aggregate.
  - The modulus loss of RAP over 20 cycles is comparable to that of natural aggregate (i.e., 28% vs 21%).
  - RAP with finer gradation experienced more modulus loss, mostly in 1st 5 cycles.

- Consistent RCA trend with freeze-thaw cycling
  - Modulus decreases up to 5 cycles, then
  - Modulus increases up to 20 cycles
Conclusions continued

- Seismic modulus testing confirmed resilient modulus trend of RCA due to freeze-thaw:
  - A convenient non-destructive test to evaluate the effect of freeze-thaw cycling on RCA and natural aggregate.
  - Does not work with RAP.

- Reduction of relative compaction from 95% to 85% reduces the SRM of RAP, RCA and natural aggregate with comparable average rates (i.e., 37%, 41%, and 47%, respectively).
  - One RAP sample showed greater sensitivity.
Conclusions continued

- Increase of compaction moisture content from 2% dry to 2% wet of OMC (4% change) reduces the SRM of RAP and RCA by 40%.
  - RCA showed greater sensitivity than RAP.

- Blending recycled materials with natural aggregate result in intermediate modulus between the moduli of two materials.
  - Recycled materials has higher moduli than natural aggregate thus blends increase modulus.
Thank You

• Special thanks to:
  • Dr. Tuncer Edil
  • Dr. Craig Benson
  • Dr. Dante Fratta
  • Ozlem Bozyurt
  • Andrew Keene
  • Ryan Shedivy
Breakage process

Waste Pavement Material

Pavement constructed using recycled materials

Recycled Materials
Questions?
Results: Compaction Moisture Effect

Absorption (%) vs. Internal SRM (MPa)

- ▲ RCA (CO)
- ■ RCA (OH)

Legend:
- Finer
- Medium
Results: Compaction Moisture Effect

![Graph showing compaction moisture effect with data points for RCA (CO)-Before, RCA (CO)-After, RCA (OH)-Before, and RCA (OH)-After. The x-axis represents absorption (%) and the y-axis represents water content (%). The graph includes two labeled areas: Finer and Medium.]
Seismic Test Method

Voltage

$\begin{align*}
t_1 \\
t_2 \\
\text{Time, } t
\end{align*}$
Compaction Curves of Representative Materials

Dry Weight, (kN/m³)

Water Content (%)

Class 5 (MN)
RAP (MN)
RAP (CA)
RAP (TX)
RCA (CA)
RCA (MI)
RCA (TX)
The change in the fine percentage

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Before Compaction</th>
<th>After Compaction</th>
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<tbody>
<tr>
<td></td>
<td>Fines (%)</td>
<td>Fines (%)</td>
</tr>
<tr>
<td>RCA (CA)</td>
<td>0.97</td>
<td>2.52</td>
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<tr>
<td>RCA (CO)</td>
<td>7.59</td>
<td>7.80</td>
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<tr>
<td>RCA (MI)</td>
<td>0.80</td>
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<td>RAP (OH)</td>
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<tr>
<td>RAP (TX)</td>
<td>1.09</td>
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*Dry PSD before and after compaction