Characterization of Recycled Concrete Aggregates for Reuse in Rigid Pavements
Michigan Department of Transportation (MDOT)

Minnesota Department of Transportation (Mn/DOT)

MTU Tomasini Fund

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RCA is old concrete that has been removed, crushed, and sized for reuse.

Old aggregates as well as old mortar and some unhydrated cement.

RCA can contain contaminants.

RCA differs depending on crushing process.
RCA use in concrete goes back to post WWII Europe

MDOT was pioneer of RCA use in rigid pavements in the USA in 1980’s
- 1050 lane-km constructed
- Moratorium for use in rigid pavements in 1991

Costs from landfill, transportation, and quality aggregates has brought issue back into play

Sustainability
I-94 West of Kalamazoo, Michigan, USA

- JPCP after 10 years
- Shrinkage cracking
- Wide joints and cracks
- Low load transfer
Some RCA Issues for Reuse in Concrete Surface Layer

- Varied crushing processes and high fines
- D-cracking and Material-related distress potential
  - High alkalinity of water runoff
- Leachates (calcium) and high pH for base material
- High absorption (mortar / unhydrated cement)
- Less volumetric stability
  - Shrinkage, creep, and carbonation
LABORATORY STUDY

- Aggregate Characterization
  - Absorption capacity
  - Specific gravity

  Using three methods

- Address RCA in comparison with virgin aggregate concrete
  - Hardened air content
  - Shrinkage (drying, autogenous, and restrained)
Coarse Aggregate Sources

- Natural aggregates
  - Crushed gravel
- RCA (with original aggregate type)
  - RCA limestone
  - RCA blast furnace slag
  - RCA crushed gravel
  - Recycled RCA crushed gravel (3G/Twice recycled)
- Fine aggregate → natural sands
DIFFERENCES IN ABSORPTION CAPACITY AND POROSITY

- Standard ASTM C127
  - 24-hour absorption
  - Visual assessment of SSD → High variability
- Helium Pycnometer and envelope density analyzer (EDA)
  - Automated
  - Assess water absorption?
- Image Analysis
Image Analysis - Aggregate Thin Sections

Surface porosity

Internal porosity

Using Impregnated resins with specified viscosities
**Image Analysis**

- Imaging software to assess
  - Pore sizes
  - Locations
  - Distribution

- Leads into future research in moisture diffusivity and poromechanics
Natural aggregates void of larger Feret’s diameter

Number of voids much lower in natural aggregates
Surface Porosity by Multiple Methods

- Image Analysis matches He Pyc / EDA
- Does ASTM C127 capture porosity/AC for highly porous aggs?

\[ A = \frac{n}{G_B} \]
0.42 water-to-cement ratio
- No SCMs
362 kg cement per m³ of concrete
72% bulk volume of aggregate to vol. of concrete
- Paving mixes high in coarse aggregate content
Air entrained (target= 6.5%, range of 5.5 – 8.5%)
Target slump 50mm
- Monitor fresh properties over time
**Fresh Properties**

- Measured slumps consistently higher than expected for RCA concretes
  - Met specs for natural aggregate concretes
- Slump loss was more dramatic in RCA concrete
  - Shorter window of workability
  - Harsh mixes with poorer consolidation
  - Superplasticizers helped to some degree
- Fresh air content specification difficult to meet
RCA occupies same bulk volume
Contains more void space
Moisture / chloride movement

**Hardened Air Content**

- RCA
- Contains more void space
- Moisture / chloride movement

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<table>
<thead>
<tr>
<th></th>
<th>Air Content in RCA Mortar Fraction</th>
<th>Air Content in New Mortar</th>
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</thead>
<tbody>
<tr>
<td>Crushed Gravel</td>
<td><img src="#" alt="Bar Chart" /></td>
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</tr>
<tr>
<td>Slag RCA</td>
<td><img src="#" alt="Bar Chart" /></td>
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<tr>
<td>Limestone RCA</td>
<td><img src="#" alt="Bar Chart" /></td>
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<tr>
<td>Crushed Gravel RCA</td>
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</table>
RCA concretes showed better air void system connectivity in general
Dependent on old concrete’s quality
Counterintuitive

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Void Frequency</th>
<th>Within Criteria</th>
<th>Specific Surface Area (mm(^{-1}))</th>
<th>Within Criteria</th>
<th>Spacing Factor (mm)</th>
<th>Within Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed Gravel</td>
<td>0.187</td>
<td>N</td>
<td>16.3</td>
<td>N</td>
<td>0.303</td>
<td>N</td>
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<tr>
<td>Slag RCA</td>
<td>0.339</td>
<td>Y</td>
<td>18.4</td>
<td>N</td>
<td>0.237</td>
<td>N</td>
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<tr>
<td>Limestone RCA</td>
<td>0.522</td>
<td>Y</td>
<td>23.8</td>
<td>N</td>
<td>0.140</td>
<td>Y</td>
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<td>Crushed Gravel RCA</td>
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<td>Y</td>
<td>29.8</td>
<td>Y</td>
<td>0.153</td>
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</table>
Porous interfacial transition zones (ITZ)

Ettringite filled pores of 3G concrete samples
  - Good performance of 3G concrete

Microcracking in old mortar from crushing process
  - Reduced fracture resistance
Some evidence of multiple ITZs
1-D shrinkage
- ASTM C 157
- Sealed (autogenous)
- Unsealed
- Difference is drying shrinkage

Stored at constant relative humidity, then switched after 1 year, then every 30-45 days
Shrinkage in concrete is dominated by capillary surface tension mechanisms.

As water leaves pore system, curved menisci develop, creating reduction in RH and "vacuum" within the pore fluid.
VOIDS IN CONCRETE

- RCA concrete contains higher percentage of entrained air through gel pores
- Affects concrete durability and structural properties
Capillary stresses present in pores with radii between 2-50 nm

C-S-H makes up ~70% of hydration product

Majority of capillary stresses present in C-S-H network
Drying Shrinkage in RCA Concrete

- Thought to be a driving force in deterioration of JPCPs in many cases
  - Higher amount of capillary pores from attached mortar
  - Unhydrated cement particles
- Previous pavement design methods have not taken this into account
- Pavement mechanics are now being utilized to capture effects
Significantly higher for RCA concrete

Capillary porosity exists in RCA and new mortar

Crushing
Restrained Shrinkage Strains
While drying shrinkage is higher in RCA concretes ...

- Increased creep characteristics of RCA concrete can relax strains at early ages
- At later ages, creep is less effective in controlling strain magnitudes and deflections

Rigid pavement is restrained from dowels, tie bars, slab-base friction/bonding, and self-weight
Due to this semi-porous nature of concrete
- Moisture can get in and out of pores
- Due to simplicity of pavement geometry, typically through surface

Below depth of 50-100mm in concrete slab
- Moisture content is nearly saturated and consistent

Top 50-100mm varies with rain events, ambient relative humidity, wind, etc.
- Leads to highly non-linear moisture gradients in slab
Moisture Loss Effects

- Occurs through both self-desiccation and drying
  - Both cause volumetric changes
  - Autogenous (self-desiccatcion) happens throughout concrete
  - Drying shrinkage is a gradient within concrete
- Drying shrinkage and warping are linked
  - Tied to gel pores and smaller capillary pores
  - Differential drying shrinkage – permanent
  - Warping – reversible portion of shrinkage
Stresses induced by environmental loading can be enough to crack a slab.

Slab corners can be unsupported.

Changing boundary conditions.

Change in primary failure mechanism.

Premature fatigue failure.

Top-down cracking from combined environmental and traffic loading.
Drying Shrinkage Leading to Slab Deformation

- Warping and built-in curling issues can lead to alternative fatigue cracking development
- Gaps under slab corners
  - Interaction with external loads
Volume Change Components in the Mechanistic-Empirical Pavement Design Guide (MEPDG)

- Total Equivalent Temperature Difference
- Equivalent Temperature Gradient (ETG)
- Built-in Curl (BIC)
  - Temperature Gradient
  - Moisture Gradient
  - Construction Curl
  - Differential Drying Shrinkage
    - Creep
TEMPERATURE SHIFT DUE TO BUILT-IN CURL

- Shift can be large enough to never “curl down”
Portion of shrinkage is reversible

Assumed to be 50% in MEPDG

Mindness and Young, (1981.) *Concrete*. Prentice Hall, Englewood Cliffs, NJ.
Some research in Europe from 1940-1975

40-70% of shrinkage is reversible

Mortars stored in water for an extended cure had complete shrinkage reversibility

The mechanism is not well understood

Neville hypothesized that C-S-H gels form bonds when they are in close proximity during drying phase

When the concrete is again exposed to moisture, these bonds swell, but hold the matrix together

- Preventing shrinkage from being fully reversible
Others hypothesize that a portion of irreversible shrinkage is related to microcracking.

During the shrinkage phase, microcracks are formed and open.

During swelling, cracks close either partially or fully.

Because these cracks cannot be reversed, some portion of drying shrinkage is believed to be irreversible.


% Reversible by Agg Type

Initially low humidity (50% RH)
Initially high humidity (100% RH)

Percent reversible shrinkage

- Virgin
- Slag RCA
- Limestone RCA
- Gravel RCA
- Twice recycled
- Lightweight

Initially low humidity (50% RH):
- % R1 dry cure
- % R2 dry cure
- % R3 dry cure

Initially high humidity (100% RH):
- % R1 wet cure
- % R2 wet cure
Non-linear model for equivalent temp. difference due to drying shrinkage in concrete pavements

Warping model

\[ ETG_{warp} = \frac{\phi \gamma \omega \varepsilon \alpha h_s [ -3h( -4 + \pi ) - 20h_s + 6\pi h_s ](1 - \mu) }{2h^2 \alpha} \]

Differential Drying Shrinkage model

\[ ETG_{DDS} = \frac{(1 - \phi) \gamma \omega \varepsilon \alpha h_s [ -3h( -4 + \pi ) - 20h_s + 6\pi h_s ](1 - \mu) }{2h^2 \alpha} \]
WARPING & DDS - DESIGN AIDS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>h</td>
<td>25cm</td>
</tr>
<tr>
<td>h_s</td>
<td>7.5cm</td>
</tr>
<tr>
<td>w/c</td>
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</tr>
<tr>
<td>φ</td>
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<tr>
<td>ε_{su}</td>
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</table>
HOW THIS AFFECTS CONCRETE PAVEMENTS IN AUSTRALIA

- Non-linear model for equivalent temp. difference due to drying shrinkage
HOW THIS AFFECTS CONCRETE PAVEMENTS IN AUSTRALIA

- For RCA concretes
- Higher drying shrinkage
- More change in coastal regions
**SIGNIFICANCE OF HIGH LEVELS OF PERMANENT DIFFERENTIAL DRYING SHRINKAGE?**

- Poor curing → High irreversible drying shrinkage
  - Leads to high levels of built-in curling in JPCP
  - Essentially causes equivalent temperature shift for specific climatic location

- MEPDG captures this effect to some degree
  - Only predicts transverse fatigue cracking

- To account for fatigue as transverse, longitudinal, or corner cracking →
Mechanistic rigid pavement analysis tool

Predict fatigue cracking at multiple locations
- Transverse, longitudinal, corner cracking
- Top-down or bottom-up

Site-specific conditions, traffic, materials
EBITD = Equivalent Built-in Temperature Difference

For temperature differences, °C = 5/9 °F

For San Francisco climate, traffic, soils, etc.
LOW LOAD TRANSFER AND 3.7M JOINT SPACING

EBITD 0°F

Relative Damage Level

Longitudinal Edge

Transverse Joint
RCA Conclusions

- More unpredictable fresh and hardened properties using RCA in concrete
  - Need to account for existing air content in RCA
- RCA concrete shows higher drying shrinkage, but better creep characteristics
  - Account for some factors in mechanistic design methods
  - Creep may be advantageous in restrained pavements
- Must understand differences and plan for multi-generational use → Promote Sustainable Practices
RCA in PVTs Conclusions

- Past pavement design/analysis has not taken moisture warping into consideration directly
  - Not site-specific design
  - MEPDG attempts to account for this ... unsuccessfully

- Amount of reversible warping can be controlled
  - Macro-level → curing conditions, w/c ratio, SCMs
  - Affects nano/micro-level → C-S-H gel spacing, micro-cracking
  - RCA concretes show no difference with virgin agg concretes

- Now have ability to capture these effects in pavement design, analysis, and construction practices
Cost savings for right projects
  - Typically urban with crushing on-site
  - Michigan environmental policy to use RCA if up to 10% greater cost than virgin aggregates
Knowledge and control of original project aggs
Lower cement content can yield good performance
Design adjustments to accommodate differences
  - Joint spacing, thickness, limited restraint, materials?
  - Two-lift construction?
THANK YOU ... ANY QUESTIONS?