Recycled Concrete Aggregates: Current Practice, Implementation Challenges and New Guidance

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RCA Increases Pavement Sustainability

- RCA can be used in bound and unbound applications in concrete paving projects.
- Increased use of RCA will address several challenges:
  - dwindling landfill space and increased disposal costs
  - increased demand for aggregates
  - reduced availability and longer hauls for virgin aggregates
- Use of RCA provides reduced environmental impacts due to:
  - conservation of materials
  - reduced emissions associated with production of virgin aggregates and hauling
  - reduced construction traffic
- Use of RCA can reduce project cost and schedule
- RCA can potentially improved pavement performance

Source: Phillip Lamoureux, FHWA Western Federal Lands
Production and Reuse of RCA
<table>
<thead>
<tr>
<th>Construction Byproduct</th>
<th>Production</th>
<th>Beneficial Reuse</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled asphalt pavement (RAP)</td>
<td>107 million tons</td>
<td>102.1 million tons</td>
<td>4.9 million tons</td>
</tr>
<tr>
<td></td>
<td>(EPA 2020)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycled concrete aggregates (RCA)</td>
<td>405.2 million tons</td>
<td>334.0 million tons</td>
<td>71.2 million tons</td>
</tr>
<tr>
<td></td>
<td>24.2 (6%) – construction waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>381.0 (94%) – demolition waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(EPA 2020)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quarry fines</td>
<td>484 million tons</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(Willet 2021a and 2021b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCA fines</td>
<td>101.3 million tons</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(EPA 2018 data @ 25% fines production estimate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids recovered from diamond grinding</td>
<td>0.284 million tons</td>
<td>0.10 million tons</td>
<td>0.184 million tons</td>
</tr>
<tr>
<td></td>
<td>(IGGA 2021 and Dufalla et al. 2015, IGGA 2020 annual grinding estimate @ 100 tons fines/lane mi with 35% beneficial reuse rate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids recovered from diamond grooving</td>
<td>0.006 million tons</td>
<td>0.002 million tons</td>
<td>0.004 million tons</td>
</tr>
<tr>
<td></td>
<td>(IGGA 2021 and Dufalla et al. 2015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrodemolition materials</td>
<td>36 million square feet of deck area hydrodemolished per state since practices began</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>(Simmons et al. 2020)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
National production and reuse

Million Tons of Material Produced

- RAP
- RCA from construction waste
- RCA from demolition waste
- RCA fines
- Quarry fines
- Diamond grinding solids
- Diamond grooving solids

- 484 Million Tons
- 381 Million Tons
- 101.3 Million Tons
- 107 Million Tons
- 24.2 Million Tons
End uses for crushed concrete

- Used as aggregate base: 65.5%
- Used as fill: 6.5%
- Used in new concrete mixtures: 9.7%
- Used in asphalt concrete: 7.6%
- Used as high-value rip rap: 3.2%
- Other uses: 7.6%

After Van Dam et al. 2015, from USGS 2000 after T.A. Deal 1997
Characteristics of RCA and RCA Concrete
## Properties of RCA

<table>
<thead>
<tr>
<th>Property</th>
<th>Virgin Aggregate</th>
<th>RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape and Texture</td>
<td>Well-rounded; smooth to angular/rough</td>
<td>Angular with rough surface</td>
</tr>
<tr>
<td>Absorption Capacity</td>
<td>0.8% – 3.7%</td>
<td>3.7% – 8.7%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.4 – 2.9</td>
<td>2.1 – 2.4</td>
</tr>
<tr>
<td>L.A Abrasion</td>
<td>15% – 30%</td>
<td>20% – 45%</td>
</tr>
<tr>
<td>Sodium Sulfate</td>
<td>7% – 21%</td>
<td>18% – 59%</td>
</tr>
<tr>
<td>Magnesium Sulfate</td>
<td>4% – 7%</td>
<td>1% – 9%</td>
</tr>
<tr>
<td>Chloride Content</td>
<td>0 – 2 lb/yd³</td>
<td>1 – 12 lb/yd³</td>
</tr>
</tbody>
</table>
Properties of Concrete with RCA

MN 4-1 (Recycled)

MN 4-2 (Control)

Photos from Mark Snyder, PERC
### Fresh Properties of Concrete Containing RCA

<table>
<thead>
<tr>
<th>Property</th>
<th>Coarse RCA</th>
<th>Coarse and Fine RCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workability</td>
<td>Similar to slightly lower</td>
<td>Slightly to significantly lower</td>
</tr>
<tr>
<td>Finishability</td>
<td>Similar to more difficult</td>
<td>More difficult</td>
</tr>
<tr>
<td>Water bleeding</td>
<td>Slightly less</td>
<td>Less</td>
</tr>
<tr>
<td>Water demand</td>
<td>Greater</td>
<td>Much greater</td>
</tr>
<tr>
<td>Air content</td>
<td>Slightly higher</td>
<td>Slightly higher</td>
</tr>
</tbody>
</table>
## Influence of RCA on Hardened Properties of Concrete

<table>
<thead>
<tr>
<th>Property</th>
<th>RCA used as Coarse Aggregate</th>
<th>RCA used as Coarse and Fine Aggregate</th>
<th>Potential Adjustments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>0% to 24% less</td>
<td>15% to 40% less</td>
<td>Reduce w/cm ratio</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>0% to 10% less</td>
<td>10% to 20% less</td>
<td>Reduce w/cm ratio</td>
</tr>
<tr>
<td>Strength variation</td>
<td>Slightly greater</td>
<td>Slightly greater</td>
<td>Increase average strength compared to specified strength</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>10% to 33% less</td>
<td>25% to 40% less</td>
<td>This may be considered a benefit with regard to cracking of slabs on grade</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0% to 10% lower</td>
<td>5% to 15% lower</td>
<td>None recommended</td>
</tr>
<tr>
<td>CTE</td>
<td>0% to 30% greater</td>
<td>0% to 30% greater</td>
<td>Reduce panel sizes</td>
</tr>
<tr>
<td>Drying shrinkage</td>
<td>20% to 50% greater</td>
<td>70% to 100% greater</td>
<td>Reduce panel sizes</td>
</tr>
<tr>
<td>Creep</td>
<td>30% to 60% greater</td>
<td>30% to 60% greater</td>
<td>Typically not an issue in pavement applications</td>
</tr>
<tr>
<td>Bond strength</td>
<td>Similar to conventional concrete, or slightly less</td>
<td>None recommended</td>
<td></td>
</tr>
<tr>
<td>Permeability</td>
<td>0% to 500% greater</td>
<td>0% to 500% greater</td>
<td>Reduce w/cm ratio</td>
</tr>
</tbody>
</table>
Bound and Unbound Uses of RCA
Uses of Recycled Concrete Aggregate in Pavement Applications

- PCC pavement
- Single and Two-Lift
- HMA pavement

- Subbase
  - Unbound
  - Stabilized
- Fill material
- Filter material
- Drainage layer
Unstabilized Subbases/Backfill

- Most common application for RCA in U.S.
- Application used by 38+ of 44 states using RCA in U.S.
  - Some believe it outperforms virgin aggregate as an unstabilized subbase!
- Some level of contaminants is tolerable.

- On-grade recycling reduces time, cost, and hauling impacts (fuel, traffic)

Photo: Gary Fick, Transtec
Cement-stabilized and Lean Concrete Subbases

- Stabilization helps to prevent migration of crusher fines, mitigates high pH runoff
- Physical and mechanical properties of the RCA must be considered in the design and production of cement-stabilized subbases
Use of RCA in Lean Concrete Bases

- Caltrans - use of all old pavement resulted in a “Zero Concrete Waste” project
- Completed in 2020
- Constructed over 55 hours of extended weekend closures
- Demonstrated that RCA mixtures can be used in projects with short timeframes

Source: Caltrans
Concrete Mixtures

- RCA can be (and has been) incorporated as the primary or sole aggregate source in new concrete pavements.
- Used in the U.S. concrete mixtures since the 1940s
  - Roadway surfaces, shoulders, median barriers, sidewalks, curbs and gutters, building/bridge foundations
    and even structural concrete.
- Common in the lower lift of two-lift concrete pavements in Europe.

Photos: Andy Naranjo, TxDOT (top), CP Tech Center (bottom)
RCA in Two-Lift Construction

- **Iowa US 75 Reconstruction (1976)**
  - 60-40 RCA and RAP in 7-in lower lift; 23 ft wide
  - All virgin in 4-in top lift; 24 ft wide
  - Provided more than 40 years of service!

- **Austrian Standard Practice since late 1980s**
  - A-1 (Vienna-Salzburg)
  - 19-cm (7.5-in) lower lift (RCA and RAP), 3-cm (1.5-in) upper lift fines to stabilize foundation (100 percent PCC recycled)
  - Overall project savings >10 percent

  - Using recycled materials, particularly in lower lift, is now standard
Use of RCA in Concrete Pavement

- Colorado State Highway 470 (C-470) – SW portion of Denver’s beltway
- 100,000 vehicles per day expected to increase 40% by 2035
- 12.5 miles – addition of 3 express lanes + full reconstruction of existing pavement
- All existing pavement removed used to produce RCA on-site
- 86,000 tons of 1½ inch nominal max coarse RCA used in concrete mixture for 926,000 SY of pavement

Source: Castle Rock Construction Company
Conclusions of 2006 Field Study of RCA Pavements in Service

- Need to treat RCA as “engineered material” and modify mix and structural designs accordingly
  - Reduce w/c
  - ASR mitigation
  - Reduced panel lengths
  - Other modifications as needed

- Mortar contents are generally higher for RCA
  - Varied with aggregate type, crushing process
  - Higher mortar contents often had more distress – may need to control reclaimed mortar content
Paving with RCA Concrete Mixtures

- Batching, mixing, delivery, placement and finishing techniques can be similar to those used for virgin aggregate concrete mixtures.
- Concerns with water demand and premature stiffening:
  - Limiting or eliminate fine RCA
  - Presoak RCA
  - Chemical and mineral admixtures
- Contaminants can lead to air entrainment problems.

*Fresh and hardened properties of RCA PCC might be different from virgin aggregate PCC.*

User must understand the RCA that will be used.... Characterization is key!
Guidance for Use of RCA
Guidance on Use of RCA prepared as part of Concrete Recycling Initiative (2018)

Ch. 1: Introduction to Concrete Pavement Recycling
Ch. 2: Economics and Sustainability
Ch. 3: Project Selection and Scoping
Ch. 4: Using RCA in Pavement Base Products
Ch. 5: Using RCA in Unbound Aggregate Shoulders
Ch. 6: Using RCA in Concrete Paving Mixtures
Ch. 7: Mitigating Environmental Concerns

92 pages of useful technical information, many case studies, and up-to-date implementation guidance
Tech Brief: Use of RCA in Concrete Paving Mixtures

- Prepared as part of FHWA Cooperative Agreement with CP Tech Center

- Updated guidance to build upon 2018 Practitioner’s Reference Guide

- Guidance for:
  - Characterizing RCA
  - Influence of RCA on concrete properties
  - Mixture design approaches
  - Production and use considerations
  - Example projects
Tech Brief

- Characteristics of byproducts
- Provides information on handling and processing needed for reuse
- Recommends how to evaluate construction byproducts for reuse in bound and unbound applications
- Describes potential impacts of reusing each byproduct in specific applications
- Presents a protocol for characterizing and assessing byproducts for reuse
- Provides recommendations for qualification-, preconstruction- and construction-phase tests for the byproduct materials and applications (bound/unbound bases, fills, concrete mixtures)
- Describes design and construction considerations and ways to protect the environment
Planning, Scoping, and Construction Considerations
Project Selection and Scoping

- Includes checklist of considerations for use of RCA in different applications
  - Materials considerations
  - Production considerations
  - Other considerations

- Structured around a flowchart showing typical project selection and scoping process

Potential Recycling Project Identified
Characterization of the Source Concrete
Production Options for RCA
Economics
Other Factors
Project Scoping Completed
## Project Selection and Scoping

Checklist of considerations for use of RCA in different applications

<table>
<thead>
<tr>
<th>RCA use</th>
<th>Materials considerations</th>
<th>Production Considerations</th>
<th>Other considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>New RCA concrete and stabilized base materials</td>
<td>Sources</td>
<td>Processing options</td>
<td>Project staging</td>
</tr>
<tr>
<td></td>
<td>Specifications</td>
<td>Hauling</td>
<td>Costs</td>
</tr>
<tr>
<td>Unbound bases and drainage layers</td>
<td></td>
<td>Crusher types</td>
<td>Environmental</td>
</tr>
<tr>
<td>Filter material around drainage structures</td>
<td></td>
<td>Production rates/storage</td>
<td>considerations</td>
</tr>
<tr>
<td>Fill (beneficial reuse of fines) not in pavement structure</td>
<td></td>
<td>QA/QC</td>
<td>Permitting</td>
</tr>
</tbody>
</table>

! Highly simplified table shown here! See Reference Guide for all details…
Mitigating Environmental Concerns

- Legislative and regulatory considerations
- Overview of potential environmental concerns
  - water quality
  - air quality
  - noise/local impacts
  - waste generation

Mitigating environmental concerns during project planning and design
- Focus on water quality issues

Mitigating environmental concerns during construction
- Strategies for mitigating issues on-site
Evaluation for Use
Practical considerations

● **Availability**
  ○ Project-specific (project-produced byproducts)
  ○ Proximity to a producer (e.g. quarry, C&D waste recycling facility)
  ○ Phasing should be considered
    ■ Immediate need, handling/storage capacity, ways to maximize use

● **Consistency**
  ○ Function of quality of the source material, processing/handling techniques
  ○ Characterization of materials is essential to understand properties and consistency

● **Economic factors**
  ○ Difference in cost between using byproduct vs. using virgin material
Recent Advancements in RCA Characterization

- ACI CRC 2019 P0027:
  Effective Characterization of RCA for Concrete Applications
  (PI – Jiong Hu, UNL, Co-PI Tara Cavalline, UNC Charlotte)

- Improved existing tests and developed new tests:
  - Modified residual mortar content (RMC) test
    - improved thermal shock method
  - Modified Aggregate crushing value (ACV) test
    - strength characterization
  - Aggregate freeze-thaw test
    - able to differentiate the air-entrainment level of parent concrete
  - Portable handheld XRF
    - can be used for chemical characterization and residual mortar determination
Mixture Proportioning Using RCA

- Proportioning does not differ significantly from procedures from conventional concrete
- ACI 211 and similar approaches have been successfully used for decades
  - Adequate characterization of RCA is key
  - Trial batching and testing is a must
- Lower w/cm is often needed to meet concrete property targets
- Use of SCMs improves performance of RCA concrete by supporting enhanced hydration → helps compensate for relatively weak interfacial transition zone (ITZ) of RCA
- Use of Class F fly ash, slag, or lithium nitrate admixtures should also be used if the potential for ASR exists.
Recent Developments in RCA Mixture Proportioning

- **NJIT Method** (Adams and Jayasuriya 2019)
  - Statistical study using data from more than 100 peer-reviewed studies of RCA concrete
  - Linked RCA properties and mixture characteristics to RCA concrete mechanical properties (compressive/flexural strength, elastic modulus)
  - Developed a new RCA concrete mixture design procedure based on models developed as part of this study, along with recommendations from ACI 302.

**Overview of NJIT RCA Mixture Proportioning Method**

- Step 1 – Approximate effective w/cm ratio
- Step 2 – Approximate RCA replacement level
- Step 3 – Determine aggregate-to-cement ratio
- Step 4 – Finalize material ratios
- Step 5 – Select aggregate size
- Step 6 – Select minimum requirements for cement contents
- Step 7 – Determine mixture proportions for concrete materials
Recent Developments in RCA Mixture Proportioning

- **UN-L Method**
  - Mamirov 2021, and Hu et al. 2022
  - Based on particle packing and excess paste theory
  - ACI CRC Project 2019 P0027: Effective Characterization of RCA for Concrete Applications

![Flowchart of RCA Mixture Proportioning Process](chart.png)

- **Start**
  - Perform ASTM C29* and ASTM C136
  - Individual packing degrees
  - Characteristic diameters

- **Run The Modified Toufar Model**
  - Proportions of coarse and fine aggregates (optimum blend)

- **Design a concrete mix with a minimum excess paste-to-aggregate ratio of 0.120**.
  - Void content in the blend
  - Bulk density of the blend

- **Perform the Combined void content test (Modified ASTM C29*)**

- **Perform the Box Test for a concrete mix**
  - Yes: Optimum pavement concrete mixture
  - No: Passed?
    - Yes: Optimum pavement concrete mixture
    - No: Increase the excess paste-to-aggregate ratio after each failure of the mix to pass the Box Test (if needed)

* - the test is performed by means of the vibration plus pressure compaction method
** - increase the excess paste-to-aggregate ratio after each failure of the mix to pass the Box Test (if needed)
### Considerations for Pavement Design Using RCA Concrete

<table>
<thead>
<tr>
<th>Input Type</th>
<th>Input</th>
<th>RCA used as Coarse Aggregate</th>
<th>RCA used as Coarse and Fine Aggregate</th>
<th>Recommended Test Protocol and/or Additional Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PCC</strong></td>
<td>Poisson’s ratio</td>
<td>Similar to mixture with virgin aggregates</td>
<td></td>
<td>ASTM C469</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>Select based on user preferences</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unit weight</td>
<td>0% to 10% lower</td>
<td>5% to 15% lower</td>
<td>AASHTO T 121</td>
</tr>
<tr>
<td><strong>PCC</strong></td>
<td>CTE</td>
<td>0% to 30% greater</td>
<td>0% to 30% greater</td>
<td>AASHTO T 336</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>Thermal conductivity</td>
<td>0% to 40% lower (Bravo et al. 2017)</td>
<td></td>
<td>ASTM E1952</td>
</tr>
<tr>
<td></td>
<td>Heat capacity</td>
<td>Somewhat higher (Damdelen et al. 2014)</td>
<td></td>
<td>ASTM D2766</td>
</tr>
<tr>
<td><strong>PCC</strong></td>
<td>Aggregate type</td>
<td>Select based on actual or expected aggregate source</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cementitious material content</td>
<td>Select based on actual or expected concrete mixture design</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PCC</strong></td>
<td>Cement type</td>
<td>Select based on actual or expected cement source</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>w/cm ratio</td>
<td>Select based on actual or expected concrete mixture design</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Curing method</td>
<td>Select based on agency recommendations and practices</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reversible shrinkage (%)</td>
<td>Estimate using agency historical data or select M-EPDG defaults</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time to develop 50% of ultimate shrinkage</td>
<td>Estimate using agency historical data or select M-EPDG defaults</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Strength and Modulus</strong></td>
<td>Elastic modulus</td>
<td>10% to 33% lower than mixture with virgin aggregates</td>
<td>25% to 40% less than mixture with virgin aggregates</td>
<td>ASTM C469</td>
</tr>
<tr>
<td></td>
<td>Flexural strength</td>
<td>Mixture can be designed to meet specified strength with reduced w/cm ratio</td>
<td></td>
<td>AASHTO T 97</td>
</tr>
<tr>
<td></td>
<td>Indirect tensile strength (CRCP only)</td>
<td>Mixture can be designed to meet specified strength with reduced w/cm ratio</td>
<td></td>
<td>AASHTO T 198</td>
</tr>
</tbody>
</table>
CP Tech Center has a concrete recycling website with links to many resources

https://cp-techcenter.org/concrete-recycling/
Acknowledgements

- Peter Taylor – Director, CP Tech Center at Iowa State University
- Mark Snyder – PERC
- Gary Fick - Transtec
- Jiong Hu and Miras Mamirov – University of Nebraska-Lincoln
- Arindam Dey – UNC Charlotte
- Castle Rock Construction – Amy Brooks and Matt Fonte
- Georgene Geary – GGfGA
- Caltrans – Dulce Rufino Feldman
- Flatiron – Michael Roe
- Southwest ACPA – Charles Stewart
Extra slides
Using RCA in Pavement Base Products

**Unbound aggregate base applications**

- Performance concerns
  - Structural issues
  - Drainage issues
- Qualification testing
  - General
  - Gradation
  - Other tests (abrasion, soundness, etc.)
- Subbase design and construction considerations
- Concrete pavement design considerations
- Environmental considerations

**Bound (stabilized) base applications**

- Lean concrete subbase and cement-stabilized subbase
- Asphalt concrete and asphalt-stabilized subbase

Includes example projects for each application
Using RCA in Unbound Aggregate Shoulders

• Constructability considerations
  • particle degradation during roll-down
  • moisture-density control
  • other concerns

• Qualification testing
  • gradation
  • Absorption
  • LA abrasion/MicroDeval
  • unconfined compression
  • other tests

• Examples and Case Studies
Using RCA in Paving Mixtures

- **Constructability considerations**
  - Fresh properties

- **Pavement design considerations**
  - Hardened properties

- **Developing concrete mixture designs using RCA**
  - Qualification Testing
  - Proportioning

- **Examples and Case Studies**
  - D-cracking aggregate
  - ASR
  - Continuously reinforced concrete pavement
Mixture Design Using RCA

- Qualification testing
  - Agencies report success when ensuring RCA meets same requirements as virgin aggregates
  - Contaminant limits (ACPA 2009):
    - Asphalt concrete: < 1% by volume (although 30% or more has been successfully used in lower lift of 2-lift paving applications)
    - Gypsum: < 0.5% by weight
    - Glass: 0%
    - Chlorides 0.6 lb/cy
  - Waive magnesium and sodium sulfate soundness tests since RCA results are unreliable - reaction between cement paste and test solutions
Use of RCA in Concrete Pavement

- Coarse RCA used as 38% replacement for natural aggregate
- Other RCA used in unbound base for the pavement
- Benefits
  - Cost savings to owner on price of material
  - Reduced hauling of existing material off-site and hauling new material on-site
- Contractor’s experience:
  - Make sure material is prewetted before adding to the mixer
  - Log washers have been successfully used to prewet RCA prior to mixing

Source: Castle Rock Construction Company
Log Washer

Developed in 1890s –
Used in the mining industry
to remove clay from gravel,
ores, crushed stone to
improve the quality of the
material feed

Source: Matt Fonte, Castle Rock Construction Company
Use of RCA in Interstate Concrete Shoulders

- Georgia DOT I-16 project – 56 miles
- Truck lane replacement plus new inside and outside shoulder construction
- Existing 10-inch slab crushed at nearby stationary facility
- Trial batches used 100% RCA as fine and coarse aggregate but were too sticky
- Final mixture blended some natural sand to improve workability
- Final mixture 81.1% RCA and 18.9% natural sand
- Approach allowed recycling of 100% of removed concrete
- GDOT gained confidence in use of RCA for shoulders

Source: Georgene Geary, GGfGA
Use of RCA in Lean Concrete Bases

- Caltrans I-710 project in Los Angeles
- Rehabilitation of 3.5-mile stretch with 5 lanes in each direction
- Existing JPCP removed and mostly replaced with rapid strength JPCP, 700 foot section of rapid strength CRCP constructed, weekend-closure schedule
- Existing pavement crushed and combined with existing aggregate base
  - 75-80% RCA plus 20-25% original aggregate base
- This blend was used as 100% of the coarse and fine aggregate in the new lean concrete base mixture
- Also used in new permeable base

Source: Caltrans
Factors to consider when comparing costs

<table>
<thead>
<tr>
<th>Cost of the Virgin Material</th>
<th>Cost of the Construction Byproduct</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Material costs (either virgin aggregate or binder)</td>
<td>• Cost to take material to a crushing facility (if produced on site)</td>
</tr>
<tr>
<td>• Cost to haul to site</td>
<td>• Cost of hauling material to the site (if produced off site)</td>
</tr>
<tr>
<td>• Cost to place and compact (for unbound uses)</td>
<td>• Cost of blending material and hauling (if applicable)</td>
</tr>
<tr>
<td>• Cost to handle/store/manage (for bound uses)</td>
<td>• Cost of crushing and screening a material produced on site (if</td>
</tr>
<tr>
<td>• Cost to haul away existing or unsuitable materials</td>
<td>applicable)</td>
</tr>
<tr>
<td>• Cost of existing or unsuitable material disposal</td>
<td>• Cost of placement and compaction of the material (for</td>
</tr>
<tr>
<td></td>
<td>unbound uses)</td>
</tr>
</tbody>
</table>

- Production costs for lower-grade applications (unbound base/fill) may be lower than production costs for higher-grade applications (bound bases/new concrete)

- Key to cost savings:
  - Consider use of byproducts early in project bidding or delivery phases
    - Challenges can be addressed/cost savings potentially passed on
  - Allow contractor flexibility in establishing operations
Flowchart! Characterization and Assessment for Use

Byproduct used as Aggregate

Tests to Support Use in Base or Fill
- Gradation (AASHTO T 27)
- Contaminants (visual, or per AASHTO M 319)
- Uniformity should be evaluated by reviewing the variability of the characterization test results. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.
- Optimum moisture and maximum dry density (AASHTO T 134)

Tests to Support Use in Concrete
- Gradation (AASHTO T 27)
- Contaminants (visual, or per AASHTO M 319)
- Uniformity should be evaluated by reviewing the variability of the characterization test results. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.

Byproduct used as SCM

Tests to Support Use in Base or Fill
- Contaminants (visual, or per AASHTO M 319)
- Uniformity should be evaluated by reviewing the variability of the characterization test results. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.

Tests to Support Use in Concrete
- Contaminants (visual, or per AASHTO M 319)
- Uniformity should be evaluated by reviewing the variability of the characterization test results. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.

Recommended Tests for Qualification/Preconstruction Stage

Tests of Byproduct Material

- Gradation (AASHTO T 27)
- Contaminants (visual, or per AASHTO M 319)
- Uniformity should be evaluated by reviewing the variability of the characterization test results. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.
- Optimum moisture and maximum dry density (AASHTO T 134)
Flowchart! Characterization and Assessment for Use

Byproduct used as Aggregate

- Tests to Support Use in Base or Fill
  - Compressive strength (ASTM C593 and/or D1632)
  - Freeze-thaw durability (ASTM C593 and/or D560)
  - Maximum dry density and optimum moisture content (ASTM D698 or D1557)
  - Compacted density (ASTM D1556 and/or D3877)
  - Volumetric stability (ASTM D3877)
  - Resilient modulus (AASHTO T 307)

- Tests to Support Use in Concrete
  - Assess the potential for Alkali-Aggregate Reactivity using AASHTO R 80
  - Assess the susceptibility of the material to D-cracking using ASTM C666 (only if by-product material was not previously assessed using AASHTO T 103 or the hydraulic fracture test).

Byproduct used as SCM

- Tests to Support Use in Base or Fill
  - Strength development (AASHTO T 22 / T 97)
  - Unrestrained volume change (AASHTO T 160 or T 334) or restrained volume change (AASHTO T 363)

- Tests to Support Use in Concrete

Recommended Tests for Qualification/Preconstruction Stage

Tests of Application Containing Byproduct Material

- Resilient modulus (AASHTO T 307)
- Shear strength (static triaxial and repeated triaxial loading, at optimal moisture content and saturated conditions)
Flowchart! Characterization and Assessment for Use

- **Byproduct used as Aggregate**
  - Tests to Support Use in Base or Fill
    - Resilient modulus (AASHTO T 307)
    - Shear strength (static triaxial and repeated triaxial loading, at optimal moisture content and saturated conditions)
  - Tests to Support Use in Concrete
    - Assess the potential for Alkali-Aggregate Reactivity using AASHTO R 80
    - Assess the susceptibility of the material to D-cracking using ASTM C666 (only if by-product material was not previously assessed using AASHTO T 103 or the hydraulic fracture test).

- **Byproduct used as SCM**
  - Tests to Support Use in Base or Fill
  - Tests to Support Use in Concrete
    - Compressive strength (ASTM C593 and/or D1632)
    - Freeze-thaw durability (ASTM C593 and/or D560)
    - Maximum dry density and optimum moisture content (ASTM D698 or D1557)
    - Compacted density (ASTM D1556 and/or D3877)
    - Volumetric stability (ASTM D3877)
    - Resilient modulus (AASHTO T 307)
    - Strength development (AASHTO T 22 / T 97)
    - Unrestrained volume change (AASHTO T 160 or T 334) or restrained volume change (AASHTO T 363)
Flowchart: Characterization and Assessment for Use

Tests of Application Containing Byproduct Material

- Recommended Tests for Delivery or Construction
  - Tests to Support Use in Base or Fill
    - Compacted density (AASHTO T 310, AASHTO T 191, ASTM D2167)
  - Tests to Support Use in Concrete
    - Workability (AASHTO T 119 / TP 129 / TP 137)
    - Air content (AASHTO T 152 or T 196)
    - SAM number (AASHTO TP 118)
    - Strength (AASHTO T 22 / T97)

Byproduct used as Aggregate

- Tests to Support Use in Base or Fill
  - Compacted density (AASHTO T 310, AASHTO T 191, ASTM D2167)
  - Workability (AASHTO T 119 / TP 129 / TP 137)
  - Air content (AASHTO T 152 or T 196)
  - SAM number (AASHTO TP 118)
  - Strength (AASHTO T 22 / T97)

Byproduct used as SCM

- Tests to Support Use in Base or Fill
  - Optimum moisture and maximum dry density (AASHTO T 134)
  - Compacted density (AASHTO T 310, AASHTO T 191, ASTM D2167)
- Tests to Support Use in Concrete
  - Workability (AASHTO T 119 / TP 129 / TP 137)
  - Air content (AASHTO T 152 or T 196)
  - SAM number (AASHTO TP 118)
  - Strength (AASHTO T 22 / T97)
Environmental Impacts

● Consider during Qualification/Preconstruction
  ○ Review agency regulations, specifications, permitting
  ○ Identify and address any environmental considerations

● Many byproducts contain small amounts of heavy metals and contaminant materials

● Water quality should be protected on and near the site

● RAP and RCA can produce high-pH runoff, leachate with contaminants

● Although levels can be greater than those acceptable in drinking water, research has shown runoff or leachate can be readily diluted, mitigated, or captured in nearby environmental systems (bioswales) or typical stormwater BMPs
  ○ RAP - Cosentino et al. 2003, Townsend and Brantley 1998, Brantley and Townsend 1999
  ○ RCA - Snyder et al. 2018

Photo: Dwayne Stenlund, MnDOT
Processing, Handling, and Storage

● Typically use equipment and methods like (or the same as) conventional materials

● Stockpile management
  ○ Appropriate stockpile management to ensure contaminants are not introduced
    ■ RCA - limiting stockpiles to a single source of material to support consistency
      ● Guidance in Snyder et al. (2018)
    ■ RAP – processes and techniques exist to support blending of material from multiple sources to achieve uniform composition (Hoppe et al. 2015).
      ● Sampling and testing of RAP in West (2015).

● Mitigate environmental impacts
  ○ Manage high pH runoff (BMPs, setbacks from receiving waters)
  ○ Snyder et al. (2018) provides strategies for protecting air, water quality, reducing noise

Photo: Tom Cackler