Concrete Pavement Recycling

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What is Concrete Recycling?

- Breaking, removing and crushing hardened concrete from an acceptable source.
- Old concrete pavements often are excellent sources of material for producing RCA.
- ***Concrete pavements are 100% recyclable!***

In-Place Concrete Recycling

- When RCA is to be used in a subbase layer of the roadway and/or shoulders, production can be accomplished using an in-place concrete recycling train.

Recycling Ready-Mixed Concrete

- Approximately 5% of the 445 million cubic yards of ready mixed concrete produced in the U.S. each year is returned to the concrete plant.
- Recycling this material, as with recycling any existing concrete material, presents sustainable benefits, including reduction of landfill use and virgin aggregate use.

Reasons for Concrete Recycling

- Dwindling landfill space/increasing disposal costs
  - 50000 U.S. landfills accepting PCC in 1980
  - 5000 U.S. landfills accepting PCC in 2000
- Rapidly increasing demand for aggregates with limited resources
- Sustainability
  - Conservation of materials
  - Potential reduced environmental impact due to reduced construction traffic, reduced landfill
  - Cost savings
- Potential for improved pavement performance
- A proven technology – it works!

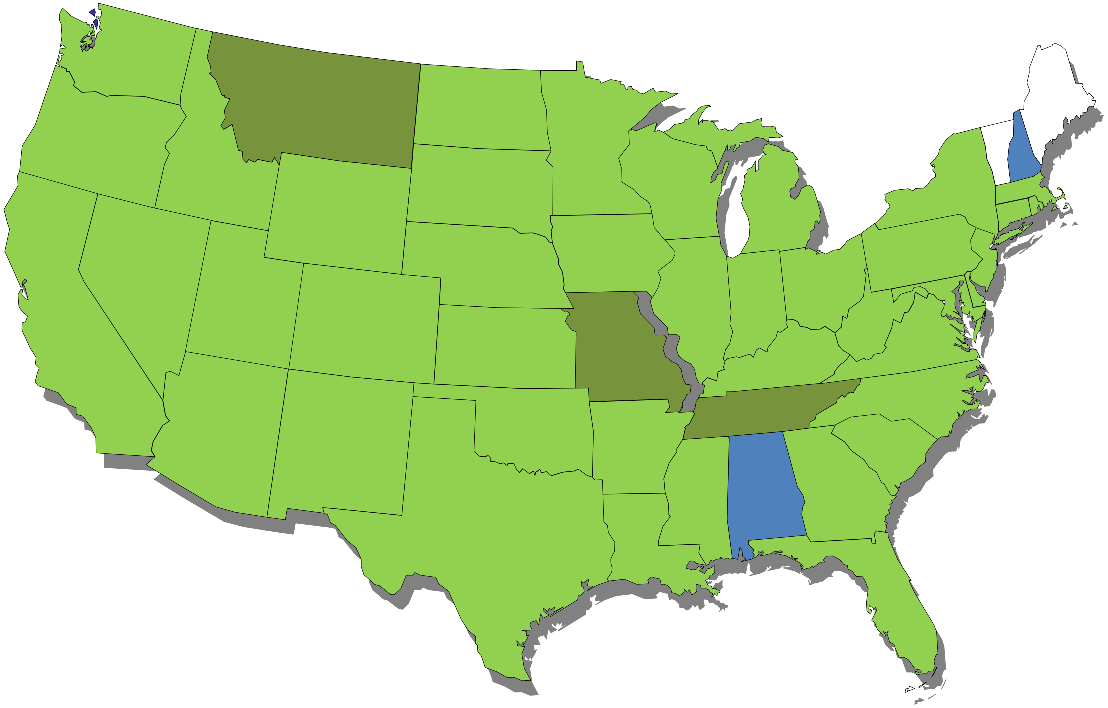
Potential Pavement Performance Improvements

- Foundation stability; angular, rough texture and secondary cementing action.
- Concrete strength; partial substitution of RCA for virgin fine aggregate may increase concrete compressive strength.

Concrete Recycling: A Proven Technology!

At least 44!

~~41~~ of 50 states allow use of RCA in various applications (FHWA, 2004)



Uses of Recycled Concrete Aggregate

- 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 41 states using RCA in U.S. (FHWA 2004)
  - Some believe it outperforms virgin aggregate as an unstabilized subbase!
- Some level of contaminants is tolerable.

Cement-stabilized and Lean Concrete Subbases

- Stabilization helps to prevent migration of crusher fines, dissolution and transport of significant amounts of calcium hydroxide.
- Physical and mechanical properties of the RCA must be considered in the design and production of cement-stabilized subbases.

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.

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 (exposed virgin aggregate), fines to stabilize foundation (100 percent PCC recycled)
  - Overall project savings >10 percent
  - More than 75km (47 miles) between 1991 and 1994; two-lift construction using recycled materials is now standard

Concrete Mixtures (cont.)

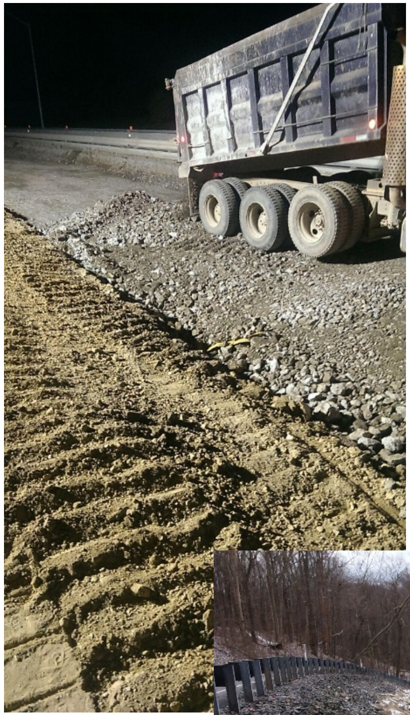
- Batching, mixing, delivery, placement and finishing techniques can be similar to those used for virgin aggregate concrete mixtures.
- Concerns with water demand and premature stiffening:
  - Limiting or eliminate fine RCA
  - Presoak RCA
  - Chemical and mineral admixtures.
- Contaminants can lead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

Other Applications

- RCA is an economical and highly stable material that is well-suited for granular fill applications.
- Most states allow the use of RCA for erosion control ("rip-rap") or slope stabilization.
- Soil stabilization, pipe bedding, landscape materials, railroad ballast, agricultural soil treatment, treatment of acidic lake waters, masonry blocks, artificial reefs, etc.

Pennsylvania Experience

225,000+ tons in CY 2016, various applications



Photos courtesy of Ben LaParne, PennDOT D2-0

SUSTAINABILITY CONSIDERATIONS IN CONCRETE RECYCLING

Sustainability Benefits

Concrete recycling addresses sustainability “Triple Bottom Line”:

- Environmental benefits (well-documented)
  - Conservation of aggregates
  - Reduction of landfill use
  - Reduction of greenhouse gases, sequestration of carbon
- Societal benefits (well-documented)
  - Reduced land use and reduced impact to landscape
- Economic benefits (not always apparent)
  - Metals recovery
  - Fuel savings due to reduced haul distances
  - Reduced disposal costs
  - Extension of landfill life
  - Potential tax credits, other incentives

Quantifying Sustainability Benefits

Measurement tools can be used to quantify sustainability benefits, weigh alternatives and facilitate decision-making.

- Economic Analysis
  - Life Cycle Cost Analysis, LCCA
- Environmental Assessment
  - Life Cycle Assessment, LCA
- Rating Systems
  - INVEST
  - Greenroads
  - Envision
  - Others

Incorporate recycling activities into these tools to quantify sustainability benefits

Economic Analysis

- Lifecycle Cost Analysis (LCCA) quantifies economic cost over the lifetime of a project.
  - FHWA RealCost
  - Does NOT quantify environmental or societal benefits associated with recycling.

- Initial construction, future maintenance and rehabilitation, and end of life considered.
- Cost savings from recycling concrete can include:
  - Lower initial costs for recycled aggregates
  - Lower hauling costs
  - Reduced tipping fees
  - Salvage value of project, if recycled
    - Avoid double-counting

Environmental Impacts

Recycling is inherently a beneficial practice, but must mitigate potential adverse environmental impacts

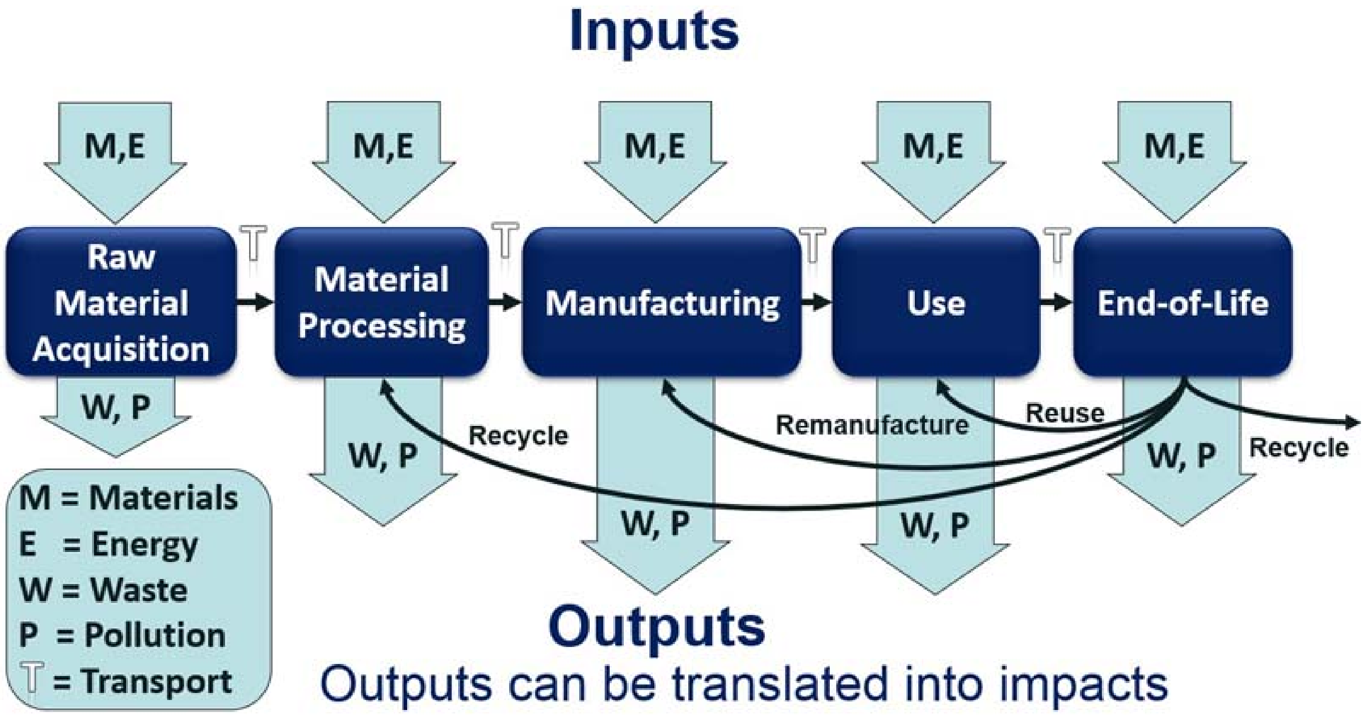
- Water quality
  - Contaminants in runoff and drainage
  - Alkalinity, chemical contaminants, other
  - Transported sediments

Often identified as key concern by state agencies

- Air quality
  - Equipment emissions
  - Fugitive dust
- Noise
  - Additional processing, handling
- Waste generation and disposition
  - Solids, wastewater, slurries, residuals

Environmental Assessment

- Lifecycle Analysis (LCA) quantifies impact of a product or process on the environment over the life cycle.



(from FHWA, Kendall 2012)

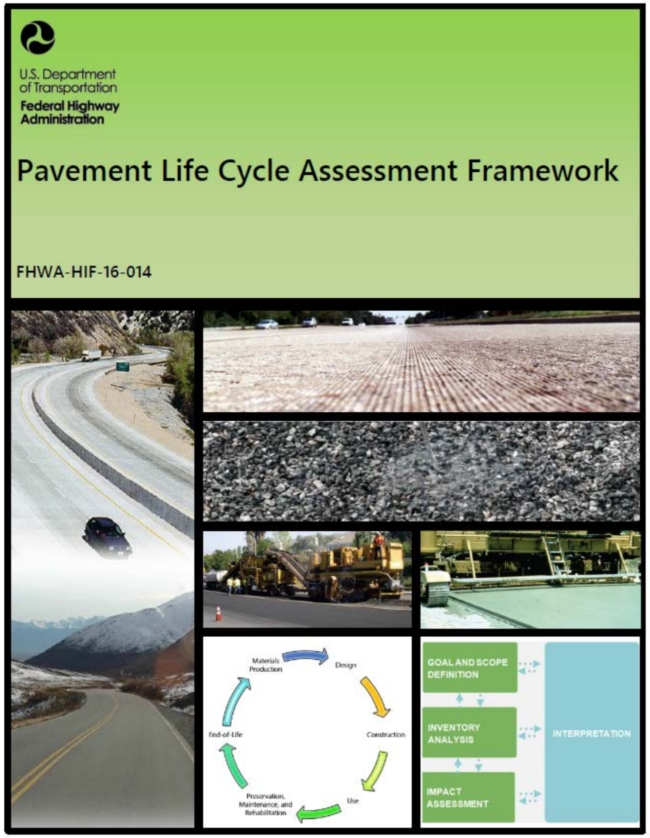
  – Quantifies environmental impacts
  – Societal and economic impacts quantified to some extent

Life Cycle Assessment (LCA)

- ISO 14140 and 14044
- LCA software programs include Athena, SimaPro, or TRACI
- Level of detail required makes LCA project-specific
- Comparisons are only possible with equivalent bounding assumptions.

NEW from FHWA:

Pavement Life Cycle Assessment Framework



Example Cost Savings and Environmental Benefits: Illinois Tollway Data

- 32-miles of I-88 Extension (2005)
  - Rubblized in place as base for new PCCP
  - $29.5 million savings (2015 dollars)
    - Savings from elimination of excavation, reduced purchase and haul of natural aggregate, reduced thickness over stiffer base
- Congestion Relief and Move Illinois Programs (2008 – 2016)
  - 3.4M tons of recycled concrete aggregate used base
    - Material cost savings from RCA: $20,530,000
    - Avoided hauling cost (@$7.50/ton): $25,500,00
    - Avoided haul fuel consumption: 529,000 gallons
    - 12,258,000 lbs of CO_2 not emitted!

Source: Steve Gillen (Illinois Tollway) from 2016 Internal Tollway Document

Quantifying Sustainability

- Beltline Highway – Madison, WI
  - 1.5 mile segment of Beltline Highway reconstructed using a variety of recycled materials, including RCA
  - RCA used in base course or embankment fill
  - 9,870 CY of RCA produced from onsite material utilized, crushed and graded onsite
  - Additional RCA sourced from offsite
    - Source concrete qualified for use using WisDOT's specifications
    - Require AASHTO T96 abrasion testing for off-site materials
  - LCCA indicated cost savings of approximately $130,000 at initial construction from use of RCA
  - LCA quantified lifetime environmental impact reductions of:

    Energy use (13% reduction), water consumption (12% reduction),

    CO_2 emissions (13% reduction), and hazardous waste (9% reduction) (Bloom et al. 2016)

Performance of Pavements Constructed using RCA in PCC

There have been a few notable (and well-publicized) failures ….

- Deterioration of mid-panel cracks in JRCP
- Design issues (undoweled joints, panel length, foundation type, etc.)

…. *but performance has generally been very good!*

No structural problems have been reported with the use of RCA in foundation layers.

Reconstruction Example: Texas I-10

- Houston, TX between I-45 & Loop 610W
- 1995 Reconstruction – 6 CL miles
- Original CRCP built in 1968
- 10 Lanes + HOV

2007 Photo

No Virgin Aggregates Used for New Concrete:

100% RCA (Coarse & Fine)

8” CRCP

6” CSB

Original

14” CRCP

3” ASB

6” LTS

11” CRCP

1” BB

Reconstruct and Unbonded Overlay

D-Crack Reconstruction Example: US 59, Worthington, MN

- 1st major recycle of "D-cracked" concrete into new concrete
- Original 1955 pavement – 16 centerline miles reconstructed in 1980
  - 100% coarse RCA (3/4-in top size) used in new pavement
  - Fines used for 1-in cap on subbase
  - Edge drains added
  - 3000+ vpd, ~8 percent heavy commercial

- Rehabilitated in 2000 – DBR, grind, reseal joints
- **No recurring D-cracking**

MnDOT estimated savings of 27% total project costs and 150,000 gallons of fuel.

ASR Reconstruction Example: I-80, Pine Bluffs, Wyoming

- 1985 Reconstruction:
  - 65 percent coarse RCA, 22% fine RCA
  - Low-alkali (<0.5%) cement, 30% Class F flyash, w/c = 0.44
  - 4400 ADT in 1985 (30 - 40% heavy)

- 2004 Rehabilitation:
  - DBR, grind, joint reseal
- 2006 ADT: 8000 vpd (30-40% heavy)

- **No significant evidence of recurring ASR until recently.**

Performance Case Study: U.S. 52 – Zumbrota, MN (27-ft JRCP) after 22 years of service

Test and Value	MN 4-1 (Recycled)	MN 4-2 (Control)
Transverse Joint Spalling, % Joints	81	100
Avg. Faulting between Panels, in	0.04	0.04
Avg. Joint Width, in	0.47	0.43
Longitudinal Cracking, ft/mile	90	0
Transverse Cracking, % Slabs	92	24
Deteriorated Transverse, cracks/mile	201	42
Total Transverse Cracks/mile	211	47
PSR	3.0	3.8
IRI, in/mile	102	60
Tensile Strength, psi	350	360
Compressive Strength, psi	6500	7400
Young's Modulus, psi	4.4E6	6.3E6
Aggregate Top Size, inches	1.0	1.5
Average VSTR, cm^3/cm^2	0.2902	0.3264
Total Mortar Content (New + Recycled), %	74	52
Coefficient of Thermal Expansion, F $degrees^{-1}$	6.9	6.6

Effects of RCA, Panel Length on Cracking (Section, L/ℓ, % Cracked Panels)

(from FHWA, 1997)

- Granular Base Sections
  - CT1-1, 16.6, 66%
  - CT1-2, 15.2, 93%
  - MN1-1, 7.3, 1%
  - MN1-2, 7.3, 0%
  - MN2-1, 8.2, 84%
  - MN4-1, 7.8, 88%
  - MN4-2, 8.2, 22%
  - WI1-1, 4.4, 8%
  - WI1-2, 4.6, 2%
  - WY1-1, 4.3, 0%
  - WY1-2, 4.3, 0%
- Stabilized Base Sections
  - KS1-1, 5.5, 0%
  - KS1-2, 5.5, 0%
  - MN3-1, 5.0, 2%

Long panels (L/ℓ > 6) with RCA generally experienced more cracking than when natural aggregate was used.

There was no apparent effect on shorter panels.

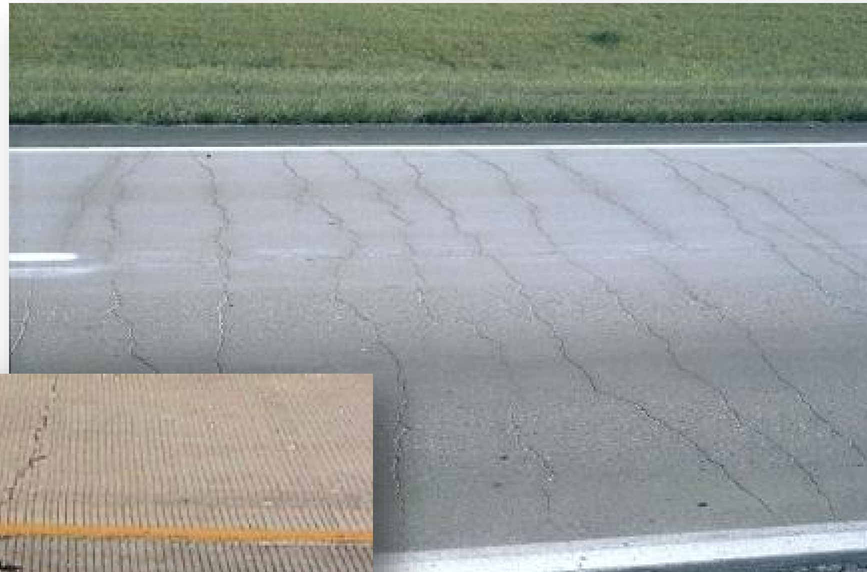
2006 Study Conclusions

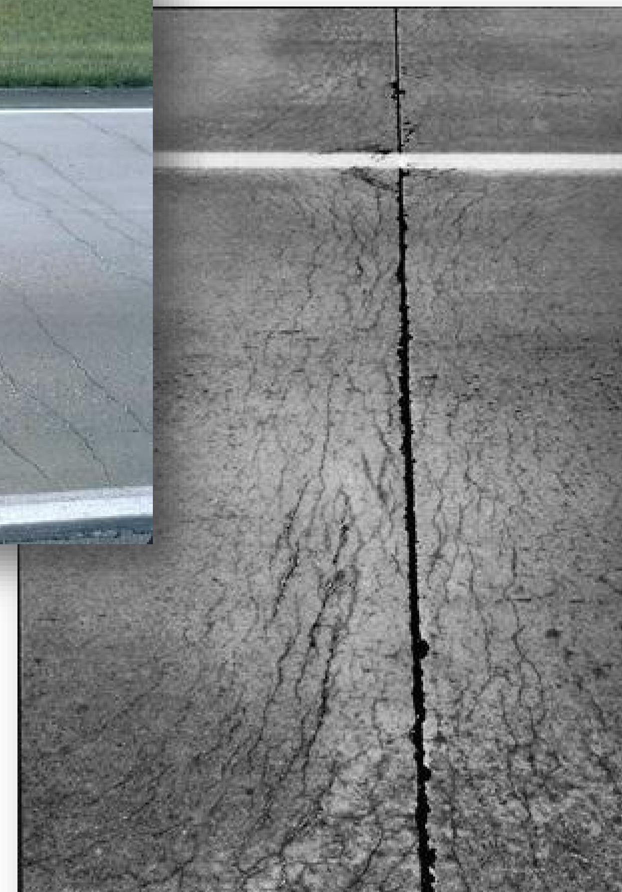
- Need to treat RCA as "engineered material" and modify mix and structural designs accordingly
  - Reduce w/c
  - ASR mitigation
  - Reduced panel lengths
  - Other modifications as needed.
- Mortar contents are generally higher for RCA
  - Varied with aggregate type, crushing process
  - Higher mortar contents often had more distress – may need to control reclaimed mortar content

Production of RCA

- Typical steps:
  - Evaluation of source concrete.
  - Pavement preparation.
  - Pavement breaking and removal.
  - Removal of embedded steel.
  - Crushing and sizing.
  - Beneficiation.
  - Stockpiling.
- In-place concrete recycling
- Recycling of returned ready-mixed concrete.

Evaluation of Source Concrete

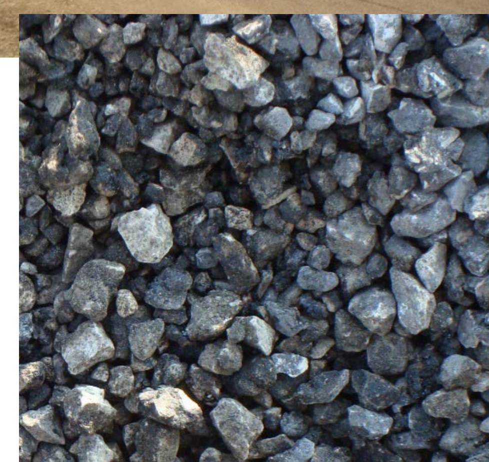




Known sources vs. unknown sources?

Pavement Preparation

RCA for concrete mixtures might require more pavement preparation than for other uses.



- Removal of joint sealant:
  - Cutting tooth sealant plow
  - Removal during production
- Removal of asphalt patches, overlays and shoulders?
  - Some European countries allow up to 30% RAP in new concrete paving mixtures (two-lift construction).
  - IL Tollway use of FRAP in two-lift paving

Pavement Breaking

- Main purpose: size material for ease of handling, transport – typically 18 – 24 inches, max dimension
- Also aids in debonding concrete and any reinforcing steel.
- “Impact breaker” is most common breaking method.
- Production: 1,000+ yd^2/hr

Pavement Breaking and Removal

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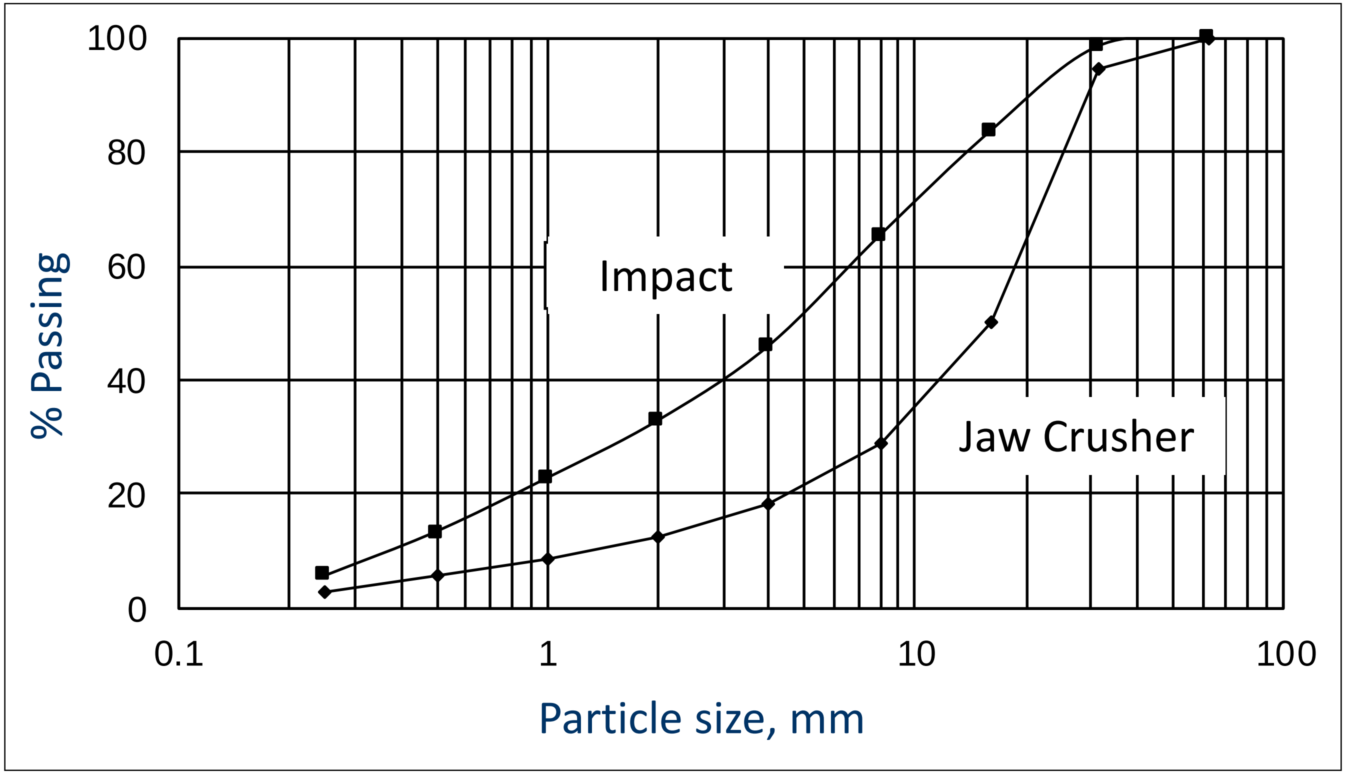
Removal of Embedded Steel

- Typically during break-and-remove
- Can also follow crushing operations
  - Electromagnets
  - Manual removal

- Standard crushing, sizing and stockpiling equipment.
- Yield loss = 0 – 10% (varies with many factors).
- Three main crusher types: jaw, cone, and impact.
  - Tell contractor desired gradation/result
  - Contractor to select crushing process for desired gradation and material properties.



Effects of Crushing Technique and Natural Aggregate Type on RCA Reclamation Efficiency

Process	Reclamation Efficiency		
	RCA Type		
	Limestone	Gravel	Granite
Jaw-Jaw-Roller	71	73	**87**
Jaw-Cone	73	80	76
Impact-Impact	**44**	63	53

Environmental Challenges from Crushing Concrete

- Silica dust (concrete)
- Asbestos (demolition debris – not paving PCC)

Example concrete crushing dust suppression system (photo courtesy of Duit Construction).

Stockpiling

- Stockpile coarse RCA using same equipment, techniques as for virgin material.
- Protect fine RCA stockpiles from moisture
  - Secondary cementing
- RCA stockpile runoff is initially highly alkaline
  - Leaching of calcium hydroxide
  - Runoff alkalinity rapidly decreases

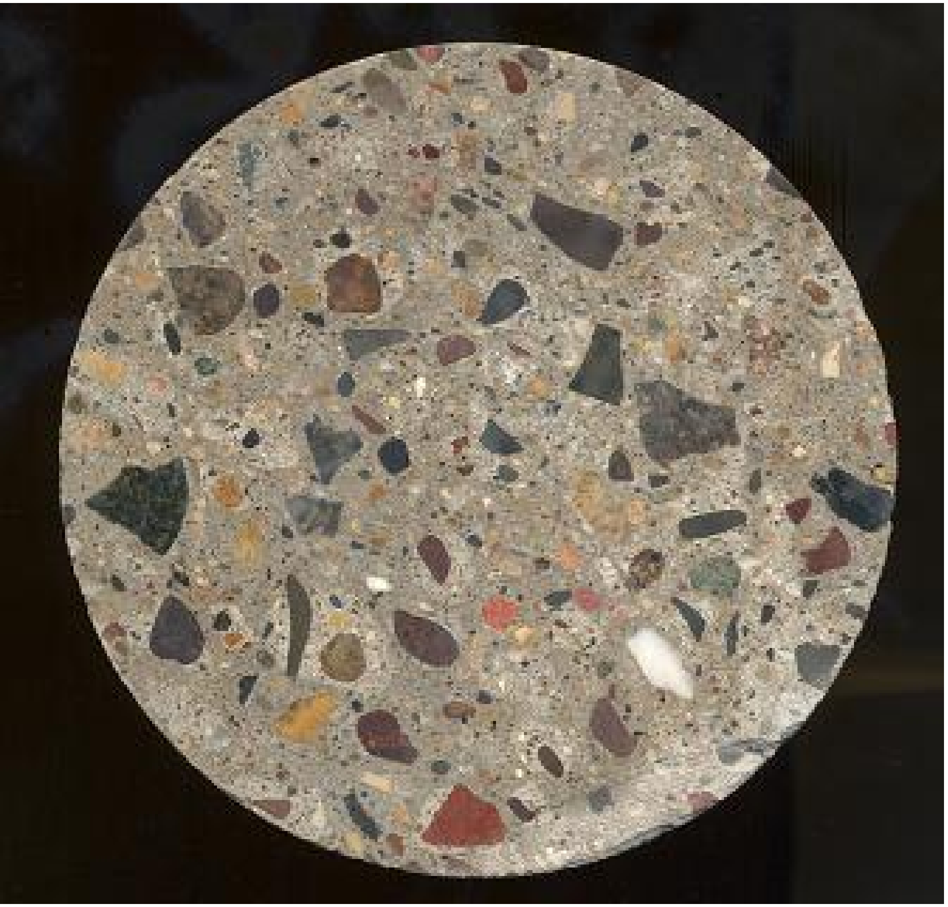
Properties of RCA

Property	Virgin Agg.	RCA
Shape and Texture	Well–rounded; smooth to angular/rough	Angular with rough surface
Absorption Capacity	0.8% – 3.7%	3.7% – 8.7%
Specific Gravity	2.4 – 2.9	2.1 – 2.4
L.A Abrasion	15% – 30%	20% – 45%
Sodium Sulfate	7% – 21%	18% – 59%
Magnesium Sulfate	4% – 7%	1% – 9%
Chloride Content	0 – 2 lb/yd^3	1 – 12 lb/yd^3

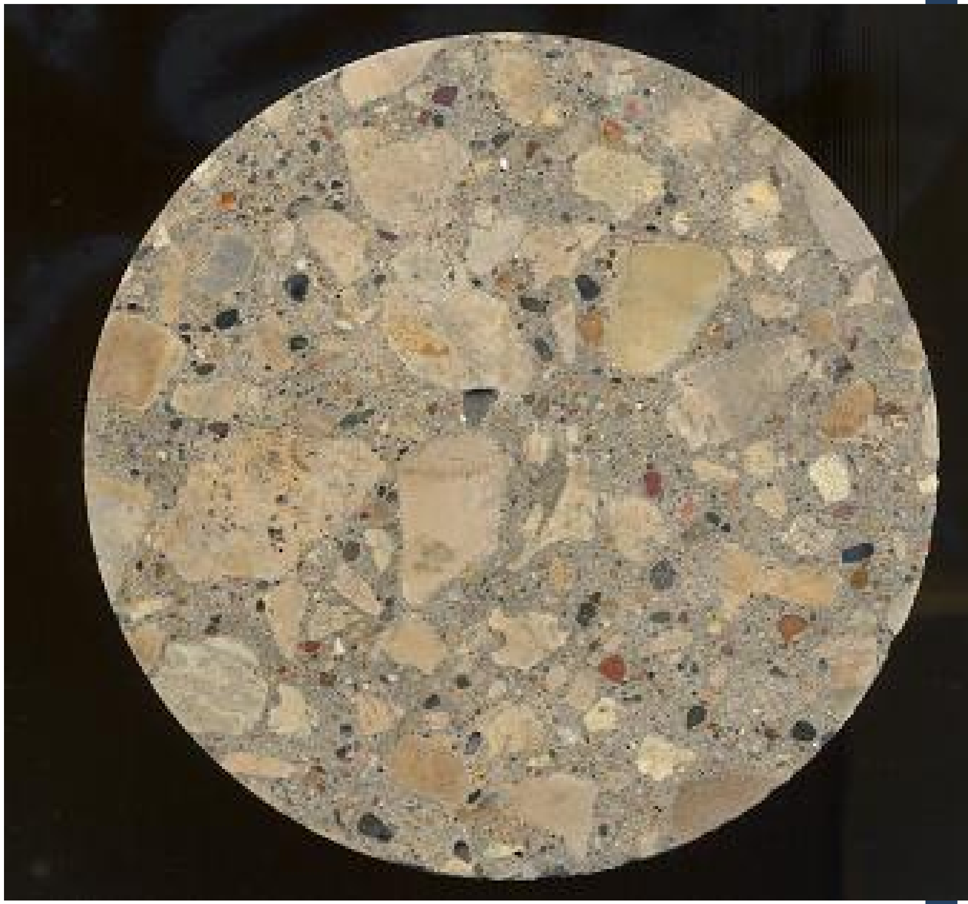
Effect of Particle Size on RCA Properties (after Fergus, 1980)

Sieve size	Percent retained	Bulk specific gravity	Percent Absorption
1.0 in. (25 mm)	2	2.52	2.54
¾ in. (19 mm)	22	2.36	3.98
½ in. (12.5 mm)	33	2.34	4.50
⅜ in. (9.5 mm)	18	2.29	5.34
No. 4 (4.75 mm)	25	2.23	6.50
Weighted average	100	2.31	5.00

Properties of Concrete with RCA
(Hint: it's all about the mortar …)



MN 4-1 (Recycled)



MN 4-2 (Control)

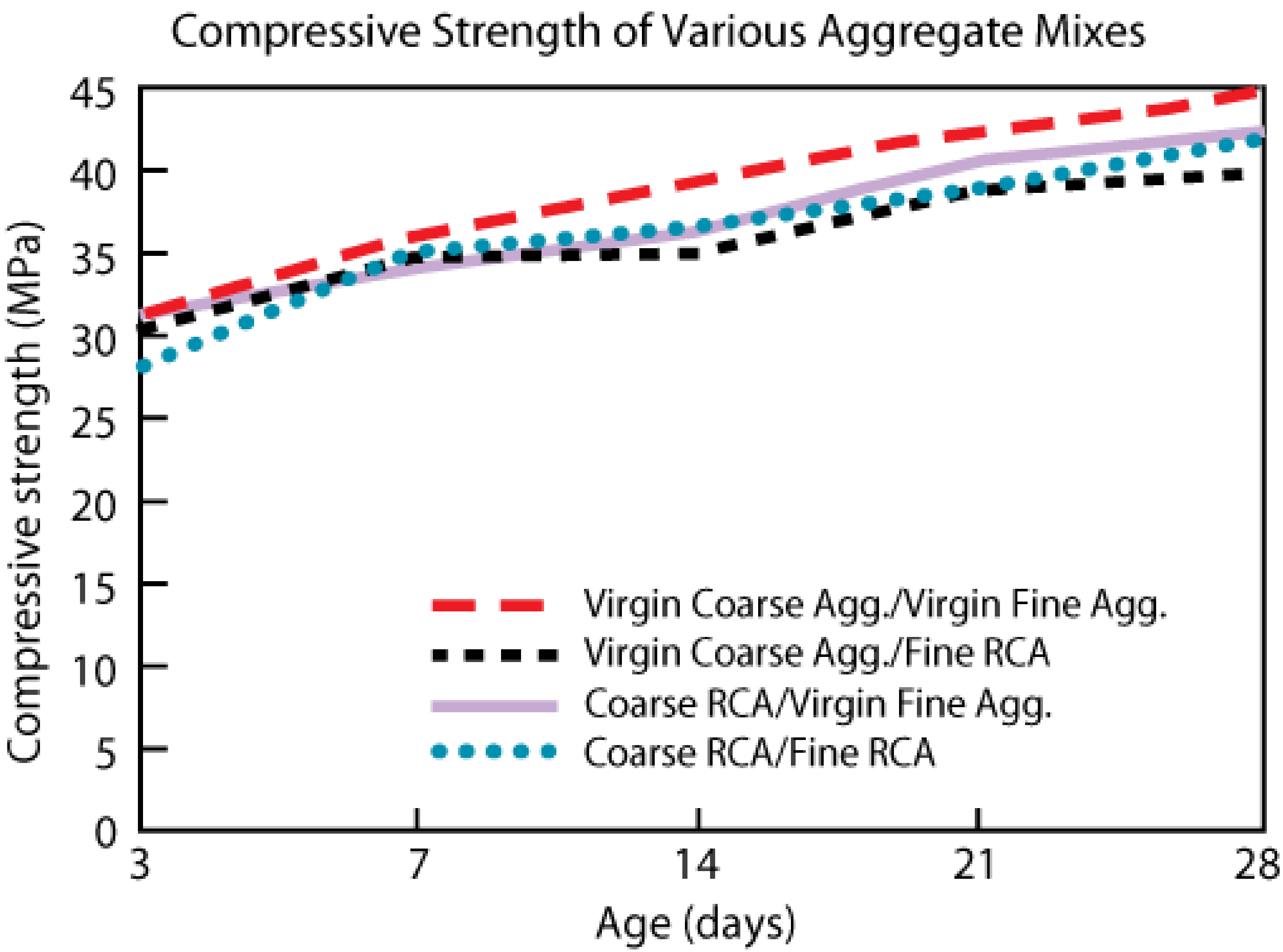
Fresh (Plastic) Properties

Property	Coarse RCA	Coarse and Fine RCA
Workability	Similar to slightly lower	Slightly to significantly lower
Finishability	Similar to more difficult	More difficult
Water bleeding	Slightly less	Less
Water demand	Greater	Much greater
Air content	Slightly higher	Slightly higher

Hardened Properties

Property	Coarse RCA	Coarse and Fine RCA
Compressive strength	0% to 24% less	15% to 40% less
Tensile strength	0% to 10% less	10% to 20% less
Strength variation	Slightly greater	Slightly greater
Modulus of elasticity	10% to 33% less	25% to 40% less
CTE	0% to 30% greater	0% to 30% greater
Drying shrinkage	20% to 50% greater	70% to 100% greater
Creep	30% to 60% greater	30% to 60% greater
Permeability	0% to 500% greater	0% to 500% greater
Specific gravity	0% to 10% lower	5% to 15% lower

Hardened Properties



Source: Dr. Moon Won, Univ. of Texas

Effects of RCA and Mix Design on Strength and Thermal Properties

(after FHWA, 1997)

Project	CT		KS		MN1		WY		MN4	
Section	**RCA**	**Natural**	**RCA**	**Natural**	**RCA**	**Natural**	**RCA**	**Natural**	**RCA**	**Natural**
w/cm	0.40	0.45	0.41	0.41	0.47	N/A	**0.38**	**0.44**	**0.44**	**0.47**
% Fine RCA:	0	0	**25**	**0**	0	0	**22**	**0**	0	0
f'c (psi)	**5690**	**5130**	7210	6340	6860	6740	**7060**	**6480**	**6210**	**6900**
E (10^6 psi)	4.60	4.76	5.12	5.20	5.25	5.95	5.01	5.32	5.13	6.06
α (10^{-6}/°F)	6.4	5.9	**5.8**	**5.2**	6.2	6.3	**7.4**	**6.0**	6.4	6.2

Reducing w/cm and/or adding some RCA fines often resulted in RCA concrete mixtures with improved properties!

Durability and other Properties

Property	Coarse RCA	Coarse and Fine RCA
Freeze-thaw durability	Depends on air voids	Depends on air voids
Sulfate resistance	Depends on mixture	Depends on mixture
ASR	Less susceptible	Less susceptible
Carbonization	Up to 65% greater	Up to 65% greater
Corrosion rate	May be faster	May be faster

RECOMMENDATIONS FOR USING RCA

RCA Production Considerations

- Consider RCA an “engineered material”; test thoroughly.
- Determine material properties and quality (before recycling, if possible)
- Consider product type/quality requirements
  - Gradation requirements will determine crushing equipment selection
  - Maximize reclamation?
  - Minimize reclaimed mortar?
- Give contractor options for determining the most cost-effective point for recycling
- Stockpile management plan (contamination, moisture)

Recommendations: Use in Subbases

- AASHTO M319
- Quality requirements (Saeed and Hammons, 2008)
- Grade according to subbase function
  - Free-draining
  - Dense-graded
  - See ACPA EB204P

Test Criteria for RCA Unbound Subbase Applications

(after Saeed and Hammons, 2008)

Tests and Test Parameters											
	Traffic	High		Med.		High		Low		Med.	Low
	Moisture	High	Low	High	Low	High	Low		High		Low
	Climate	Freeze				Nonfreeze		Freeze	Nonfreeze		
Micro-Deval Test (percent loss)		< 5 percent			< 15 percent				< 30 percent		< 45 percent
Tube Suction Test (dielectric constant)		≤ 7			≤ 10				≤ 15		≤ 20
Static Triaxial Test (Max. Deviator Stress)	OMC, σ_c = 5 psi (35 kPA)	> 100 psi (0.7 MPa)			> 60 psi (0.4 MPa)				> 25 psi (170 kPa)		Not required
	Sat., σ_c = 15 psi (103 kPA)	≥ 180 psi (1.2 MPa)			≥ 135 psi (0.9 MPa)				≥ 60 psi (410 kPa)		Not required
Repeated Load Test (Failure Deviator Stress)	OMC, σ_c = 15 psi (103 kPA)	≥ 180 psi (1.2 MPa)			≥ 160 psi (1.1 MPa)				≥ 90 psi (620 kPa)		Not required
	Sat., σ_c = 15 psi (103 kPA)	≥ 180 psi (1.2 MPa)			≥ 160 psi (1.1 MPa)				≥ 60 psi (410 kPa)		Not required
Stiffness Test (Resilient Modulus)		≥ 60 ksi (0.4 MPa)			≥ 40 ksi (275 kPa)				≥ 25 ksi (170 MPa)		Not required

Note: Low traffic: < 100,000 ESALs/year; Medium traffic: 100,000 to 1,000,000 ESALs/year; High traffic: 1,000,000 ESALs/year.

Recommendations: Use in Subbases Preventing Drainage Structure Clogging

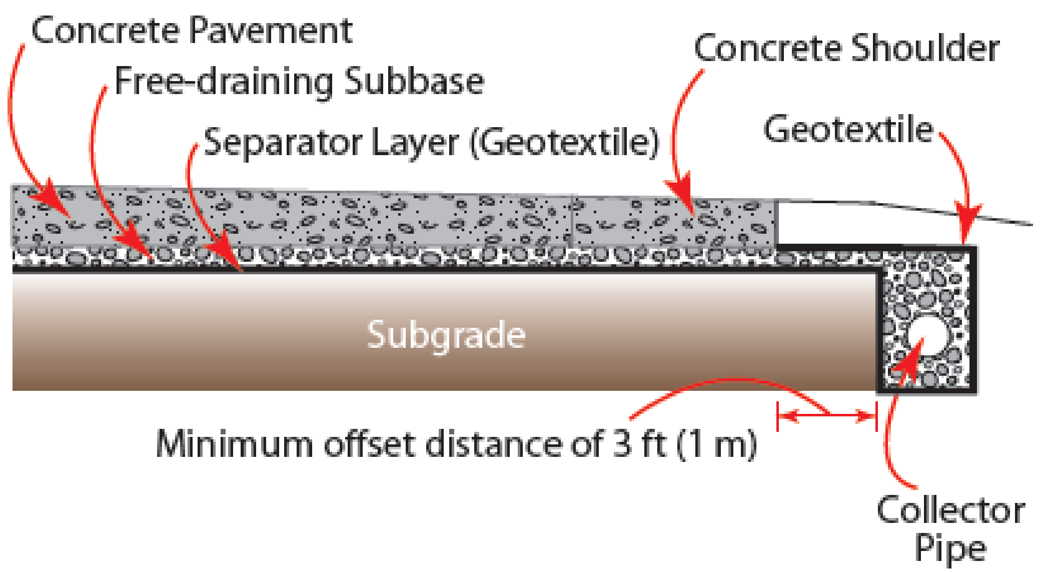
- All RCA is capable of producing precipitate and insoluble residue (“crusher dust”)
  - Potential increases with surface area (smaller particles)
- Usually no problem below drains or in undrained layers
- In drained layers, you could get infill of drain pipes and/or clogging of rodent screens.

Effects of $Ca(CO_3)_2$ and Crusher Dust on Drainage Systems

Photo credits: Iowa DOT and PennDOT

Preventing Drainage Structure Clogging

- Minimize use of RCA fines.
- Crush to eliminate reclaimed mortar
- Blend RCA and virgin materials
- Use largest practical RCA particle sizes.
- Consider washing RCA to reduce insoluble residue (crusher dust) deposits.
- Use high-permittivity fabric
- Wrap trench, not pipe
- Consider daylighted subbase



Recommendations: Pavement Structural Design

- RCA Subbase:
  - Consider possible stiffening of RCA subbase and adjust panel length, thickness as required
- RCA Slab:
  - Consider CTE and shrinkage
    - Adjust panel length
    - Adjust sealant reservoir dimensions and sealant materials
    - Higher reinforcing quantities (CRCP, JRCP)?
  - Reduced aggregate interlock potential
    - LTE may require dowels
  - Evaluate abrasion resistance (surface friction and wear)

Recommendations: RCA in Mixture Design

- AASHTO MP16-13
- Quality Requirements and Properties
  - Generally the same as for PCC with virgin aggregate
  - Exception: sulfate soundness (unreliable for RCA)
- Materials-Related Distress
  - Alkali-silica reactivity
    - Lithium
    - Class F fly ash and/or slag cement
    - Limit RCA fines
    - Reduce water access (joint sealing, drains, etc.)
  - D-cracking
    - Reduce coarse aggregate top size
    - Reduce moisture exposure
  - Test effectiveness of all treatments before construction!

Recommendations:
RCA in Mixture Design Proportioning

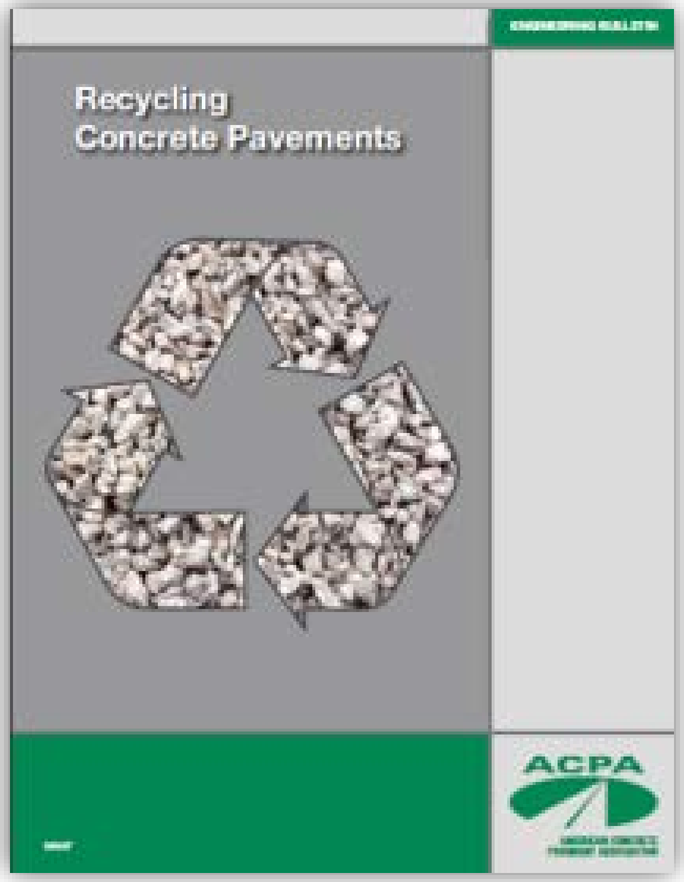
- Consider Specific Gravity and Absorption Capacity
- Consider higher strength variability
- To maintain workability, add 5 – 15% water

OR

- Use admixtures (chemical and/or mineral)
- Verify air content requirements (adjust for air in reclaimed mortar)
- Trial mixtures are essential

Resources: ACPA EB043P

- Production of RCA
- Properties and Characteristics of RCA
- Uses of RCA
- Properties of Concrete Containing RCA
- Performance of Concrete Pavements Constructed Using RCA
- Recommendations for Using RCA
- Appendices:
  - Guidelines for Removing and Crushing Existing Concrete Pavement
  - Guidelines for Using RCA in Unstabilized (Granular) Subbases
  - Guidelines for Using RCA in Concrete Paving Mixtures
  - Relevant AASHTO/ASTM Standards
  - Glossary of Terms and Index



Resources: CP Tech Center Deployment Plan

A Technology Deployment Plan for the Use of Recycled Concrete Aggregates in Concrete Paving Mixtures

National Concrete Pavement Technology Center

Final Report
June 2011

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Federal Highway Administration
(through DTFH61-06-H-00011, work plan 27)
National Concrete Pavement Technology Center
Sponsored Research Fund

- Use of RCA in concrete mixtures is not common, but implementation efforts are underway.
- Report outlines barriers to implementation (perceptions, lack of experience, risk, etc.) and recommends approaches to overcoming them.
- Report available at: http://www.intrans.iastate.edu/reports/RCA%20Draft%20Report_final-ssc.pdf

- **Also: FHWA Technical Advisory TT 5040.37: Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement**

- **New CPTech Center Guide Document due in 2017!**

Acknowledgments

- American Concrete Pavement Association
- Applied Research Associates, Inc. (formerly ERES Consultants)
- Tara Cavaline, University of North Carolina – Charlotte
- Federal Highway Administration
- Gary Fick, Trinity Construction Management Services, Inc.
- Jim Foringer, PennDOT District 11-0
- Steve Gillen, Illinois State Toll Highway Authority
- Todd Hanson, Iowa Department of Transportation
- Ben LaParne, PennDOT District 2-0
- Mike Lipps, Duit Construction
- Maria Masten, Minnesota Department of Transportation
- Jeff Roesler, University of Illinois at Urbana-Champaign
- Jeff Sturtevant, Prof. David Gress and the University of New Hampshire Recycled Materials Resource Center (RMRC)
- Moon Won, Texas DOT and University of Texas

Questions?