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Concrete Pavement Recycling and the Use of Recycled Concrete Aggregate in Concrete Paving Mixtures

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PROJECT TITLE
Concrete Pavement Recycling and the Use of Recycled Concrete Aggregate in Concrete Mixtures

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Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. The March 2016 MAP Brief provides information relevant to Track 12 of the CP Road Map: Concrete Pavement Sustainability.

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Introduction

Concrete pavement recycling is a relatively simple process that involves breaking, removing, and crushing hardened concrete from an acceptable source to produce recycled concrete aggregate (RCA) (see figure 1), a granular material that can be produced for any application for which virgin aggregate might be used (ACPA 2009).

Concrete recycling has been used extensively in Europe since the 1940s and in the U.S. since the 1970s (NHI 1998). Concrete recycling for paving applications is now performed in at least 41 states (FHWA 2004). Annual production of RCA in the U.S. from all sources (both pavements and demolition debris) was recently reported as about 140 million tons (CDRA 2014).

The recycling of paving materials (including concrete pavement) into new paving applications is supported by the Federal Highway Administration, which states that “reusing the material used to build the original highway system makes sound economic, environmental, and engineering sense” (FHWA 2002; also Hall et al. 2007, Van Dam et al. 2015).

Reasons for Concrete Pavement Recycling

There are many good reasons to recycle concrete pavement, including the increased demand for quality aggregates in the face of limited resources, the reduced availability of landfill space, and the adoption of sustainable construction practices. Economics is a component of sustainability, and concrete recycling offers the potential for major savings in the costs of aggregate, which comprises 20%–30% of the cost of pavement construction materials and supplies (Halm 1980) and 10%–15% percent of total construction costs (excluding engineering and right-of-way acquisition). Cost savings from concrete pavement recycling vary but have been reported to be as high as $5 million on a single project (CMRA 2008).

In addition, concrete pavement recycling is a smart and environmentally sustainable choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy, reduces greenhouse gas emissions, and captures carbon dioxide (CO_2) from the atmosphere. Concrete recycling can eliminate the need for mining or extracting new virgin aggregates, and can reduce haul distances and fuel consumption associated with both aggregate supply and concrete slab disposal.

Uses of RCA

RCA has been successfully used in many paving applications, including new concrete paving mixtures for single- or two-lift concrete pavements, HMA paving mixtures, bound and unbound subbase applications (e.g., cement-treated and granular base), drainage layers, fill


Figure 1. Photo of stockpiled coarse RCA

material, and more. Foundation layer and fill applications are most common for RCA produced from concrete pavements because of the ease of processing the materials on site (and resulting cost savings), the tolerance for minor contaminants (e.g., sealant materials, residual steel, etc.) in these applications, and the fact RCA typically provides a strong, stable subbase through the angular nature of particles and a degree of secondary cementing that takes place in the presence of moisture over time.

The drive for more sustainable pavements demands that consideration be given to using recycled materials in their highest possible use when it is feasible to do so (Van Dam et al. 2015). For example, a particular RCA may be of sufficient quality for producing a durable concrete paving mixture that might otherwise require transport of a high-quality, non-local aggregate (or even a more expensive high-quality local aggregate). A lower-quality local aggregate source might then be used (rather than the RCA) in the subbase layer. The cost-effectiveness of this approach must consider the costs of material handling, preparation for reuse, and transportation (from both monetary and environmental perspectives). Life-cycle cost analyses (LCCA) and life-cycle assessment (LCA) tools can help to determine the highest or "optimized" use of recycled materials (Van Dam et al. 2015).

Since the 1940s, RCA has been successfully used in concrete mixtures in the U.S. for roadway surfaces, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundations, and even structural concrete. One of the first applications of RCA in concrete paving mixtures was on U.S. Route 66 (Epps et al. 1980). Since that time, RCA has been used in the construction of hundreds of concrete pavement construction projects in the U.S. and around the world. Figure 2 presents a summary of the states that have used RCA in concrete paving mixtures. RCA concrete paving projects have included relatively low-volume roads (e.g., U.S. 75 in Iowa) and some very heavily traveled urban freeways (e.g., Interstate 10 near Houston, Texas). They also have included the recycling of pavements that were severely damaged by D-cracking or alkali-silica reactivity (ASR) damage into new concrete pavements. The use of RCA in the lower lift of two-lift concrete paving is common in some European countries (e.g., Austria) and is increasingly allowed in the U.S. (e.g., the recent Illinois Tollway reconstruction of I-90).

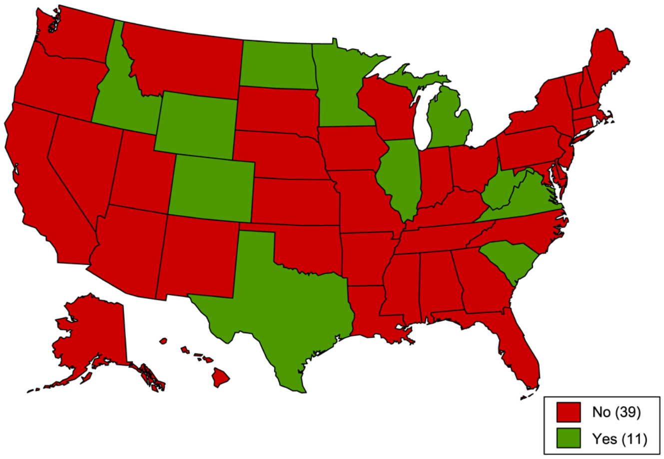

Figure 2. Map of states that have used RCA in new concrete paving mixtures (FHWA 2004)

RCA intended for use in concrete paving mixtures must be treated as an engineered material, with due consideration given to differences in physical and mechanical properties, such as absorption capacity, coefficient of thermal expansion, etc., and the impact that these differences have on the plastic and hardened properties of the resulting concrete. Consideration of these properties may result in the need to modify the concrete mix design through the use of chemical and/or mineral admixtures, different mix component proportions, and/or aggregate blending. They may also require the consideration of different pavement structural characteristics (i.e., thickness, panel dimensions, reinforcing, etc.). The need for mixture adjustments and design modifications are discussed briefly at the end of this document and extensively in ACPA 2009.

Performance of Pavements Constructed using RCA Concrete Mixtures

Snyder et al. (1994) identified nearly 100 RCA concrete paving projects in the U.S., including several where D-cracked or ASR-damaged pavements were recycled. Cuttell et al. (1997) evaluated the performance of nine of these projects with ages ranging from 6 to 15 years. Gress et al. (2007) re-evaluated these nine projects and two others in 2006.

Most of these projects, and the others that have since been built, have performed well and are considered successes. Some projects, however, have failed prematurely and have provided lessons in the design and construction of RCA concrete pavement details or have led to RCA concrete mixture design modifications to produce concrete properties and pavement performances similar to (and, in some cases, superior to) those of conventional concrete materials and pavements. For example, RCA concrete pavements constructed with longer (>20 ft) mesh-reinforced panels have often rapidly developed deteriorated mid-panel transverse cracks because the coarse RCA didn't provide as much potential (or durable) aggregate interlock across the crack. For similar reasons, undoweled RCA concrete pavements have sometimes developed faulting more quickly than their natural aggregate counterparts. Key findings and "lessons learned" from studies of RCA concrete paving projects that failed prematurely are presented in detail in Cuttell et al. (1997), FHWA (2004) and Gress et al. (2006), and are summarized in the Recommendations section of this brief.

Summaries of a few interesting and successful RCA concrete paving projects are presented below.

RCA from Composite Pavements Used in Two-Lift Pavements

US 75, Iowa - 1976

The Iowa DOT reconstructed a portion of U.S. 75 near Rock Rapids using two-lift paving in 1976, incorporating about 60% recycled concrete aggregate and 40% recycled asphalt pavement (from the original pavement) in the 9-inch lower lift and all virgin materials in the 4-inch top lift. Many of the long reinforced panels have developed transverse cracks, which have faulted due to failure of the reinforcing steel, but the pavement was otherwise in good condition in 2006 and is still in service today (see figure 3). The project is noteworthy because of the use of a significant quantity of recycled HMA (typically considered a contaminant in RCA concrete mixtures) in the lower paving lift.

Figure 3. U.S. 75 near Rock Rapids, IA in 2006 after 40 years of service and some rehabilitation

Austria – 1980s to present

A similar approach was taken in the renovation of the Austrian Salzberg-Vienna A-1 concrete motorway, which was also reconstructed in the late 1980s using two-lift construction and recycled concrete and HMA aggregate in the lower lift. The success of this project led to the adoption of two-lift paving using recycled materials in the lower lift as standard practice in Austria and an increasingly used construction technique in other European countries.

Illinois Tollway

The Illinois Tollway recently began to encourage the recycling of 100% of all existing pavement materials within the limits of their reconstruction projects on I-90 between Rockford and Chicago. Their current specifications allow for the use of both crushed concrete products and fractionated recycled asphalt pavement (FRAP) in the lower lift of two-lift concrete pavement.

CRCP Using 100 Percent RCA (Both Coarse and Fine)

I-10 near Houston, Texas - 1995

A 30-year-old section of I-10 CRCP was crushed to produce RCA that was used to provide 100% of the coarse and fine aggregate for the new CRCP mixture. The RCA was required to meet Texas DOT standards for concrete paving aggregate.

The contractor initially had difficulty in producing consistently workable concrete due to inadequate moisture control of the RCA stockpiles; this problem was remedied with the installation of improved stockpile sprinkler systems. There were also some problems with variability of strength, generally as a result of occasional very low test results. The contractor on this job was required to modify the mix design to produce higher average strengths and Texas DOT has since limited the use of fine RCA to less than 20% replacement of the total fine aggregate.

The relatively low elastic modulus of the RCA concrete is considered a key factor in the excellent performance of this project to date (see figure 4).

Figure 4. I-10 near Houston, TX in 2006 after 11 years of service (photo source: Prof. Moon Won)

RCA of Pavements with MRD

The following projects are notable as two of the first major projects to recycle D-cracked (MN) or ASR-damaged (WY) concrete back into new concrete pavement.

U.S. 59 near Worthington, MN (1980)

The 16-mile-long Minnesota project used coarse RCA (3/4-in top size) from the original severely D-cracked pavement to produce concrete for a new 8-in jointed plain concrete pavement with edge drains and a 13-16-14-19 ft skewed transverse joint pattern. The longer panels eventually developed transverse cracks and the undoweled joints faulted badly (both problems were addressed in a 2004 pavement rehab project), but the D-cracking did not recur (see figure 5).

Figure 5. 2006 photo of U.S. 59 near Worthington, MN (after 2004 rehabilitation and 26 years of service)

I-80 near Pine Bluff, Wyoming (1985)

By 1985, portions of I-80 in eastern Wyoming had developed severe ASR damage. Recycling this pavement to produce aggregate for a new 10-in JPCP concrete surface (with "randomly" spaced and undoweled skewed joints) was determined to be a feasible and economical rehabilitation solution. Extensive testing was performed to determine combinations of materials that would prevent the reoccurrence of ASR: 1) the use of a low-alkali Type II cement; 2) blending the coarse and fine RCA with high-quality virgin aggregates; and 3) using a Class F fly ash. There was little evidence of recurrent ASR in 2006 when a major pavement rehabilitation (dowel bar retrofit, diamond grinding and joint resealing) was performed to address developing joint faulting. However, some recurrent ASR was reported anecdotally in 2015 (approximately 30 years after the reconstruction using RCA).

Both of these pavements indicate that concrete mixtures containing RCA can produce long-lasting, good-performing concrete pavements, even when the RCA is produced from concrete with significant materials-related distress, provided appropriate steps are taken in mixture design and proportioning and materials processing.

Production of RCA

Following are the major steps in concrete pavement recycling:

- evaluation of the source concrete (to determine its suitability for various potential applications);
- preparation of the slab (e.g., removal and separate recycling of asphaltic materials, joint sealants, etc., as necessary for the intended application);
- breaking and removing the concrete;
- removal of any steel mesh, rebar, or dowels;
- crushing the concrete and sizing the RCA;
- treating the RCA to remove any additional contaminants (a process commonly known as beneficiation), if necessary; and
- stockpiling the RCA.

The same basic equipment used to process virgin aggregates also can be used to crush, size, and stockpile RCA (see figure 6). However, the selection of crushing processes can affect the amount of mortar that clings to the recycled aggregate particles and, therefore, the properties of the RCA (as is described later). Jaw crushers generally are more effective at producing higher quantities of coarse recycled aggregate, but the resulting RCA particles often contain relatively high amounts of reclaimed mortar, which usually increases aggregate absorption capacity. Impact crushers are more effective at removing mortar from natural aggregate particles, resulting in coarse RCA with properties that are more similar to virgin aggregate, but resulting in the production of lower amounts of coarse RCA from any given volume of processed concrete.

Figure 6. Typical concrete pavement recycling crushing and stockpiling operation

When being constructed in or near environmentally sensitive areas, stockpiles of RCA should be protected from precipitation or provisions should be made to capture and treat the runoff, which is initially highly alkaline due to the leaching of calcium hydroxide (a product of cement hydration) from the freshly crushed material. Runoff alkalinity usually decreases rapidly with time as the exposed calcium hydroxide is depleted. Exposure to precipitation may also result in some secondary cementation of previously unhydrated cement grains, which can cause the RCA particles to agglomerate, particularly for fine aggregate stockpiles.

Properties of RCA

RCA particles are comprised of reclaimed virgin aggregate, reclaimed mortar, or both. Concrete crushing processes generally produce relatively angular, rough-textured particles. The properties of a specific recycled concrete aggregate depend upon many factors, including the properties of the original concrete and the amount of reclaimed mortar in the RCA. Higher amounts of reclaimed mortar typically result in increasingly higher absorption, lower specific gravity, lower particle strength, and lower abrasion resistance than would be found in the included natural aggregate.

Table 1. Typical properties of natural and recycled concrete aggregate (after Snyder et al. 1994)

Property	Natural Aggregate	RCA
Absorption Capacity (%)	0.8–3.7	3.7–8.7
Specific Gravity	2.4–2.9	2.1–2.4
L.A. Abrasion Test Mass Loss (%)	15–30	20–45
Sodium Sulfate Soundness Test Mass Loss (%)	7–21	18–59
Magnesium Sulfate Soundness Test Mass Loss (%)	4–7	1–9
Chloride Content (lb/yd3)	0–2	1–12

RCA must generally meet the same requirements as virgin aggregate for the target application (e.g., concrete mixture, subbase layer, etc.). With proper care and process control, RCA generally can be produced to meet standard aggregate quality and grading requirements. Typical properties of natural aggregate and RCA are presented and compared in Table X. Sulfate soundness tests do not provide reliable tests for RCA (Hansen 1986) and are typically waived in favor of actual freeze-thaw testing (e.g., AASHTO T161).

RCA should be considered an engineered material for which the properties must be determined prior to use so that appropriate mixture design or construction adjustments can be made as required.

As noted in Table 1, high levels of chlorides have been found in RCA (especially in RCA with high reclaimed mortar content) produced from sources with long-term exposure to deicing chemicals. When RCA from such sources is to be used in concrete pavements and the chloride levels are high enough to be of concern epoxy-coated steel or other corrosion-resistant/non-corroding materials should be considered for use as tie bars and slab reinforcing (for jointed and continuous reinforced concrete pavements).

Properties of Concrete with RCA

When RCA is used to produce new concrete mixtures, its effect on the properties of those mixtures can range from minimal to significant, depending upon the nature, composition, and gradation of the RCA. Changes in mixture design and admixture usage can reduce (and sometimes eliminate) many differences in the properties of RCA concrete mixtures. (ACPA 2009)

Fresh (Plastic) RCA Concrete Properties

RCA particles tend to be angular and rough-textured, which can increase the harshness of fresh concrete mixtures. The shape and texture of coarse RCA particles generally does not cause significant workability problems, but the use of significant amounts of fine RCA can result in a very harsh, unworkable paving mixture. Fine RCA content is commonly limited to 30 percent or less replacement of natural sand to provide adequate workability. The use of pozzolanic and chemical admixtures can also improve mixture workability.

The higher absorption capacity of RCA (especially fine RCA) can lead to a rapid loss of workability. This probably can be successfully addressed by washing or wetting the aggregate and maintaining it in a moist condition until batching.

Hardened RCA Concrete Properties

Table 2 provides a summary of the ranges of typical changes in concrete properties that result from the use of RCA as a replacement for natural aggregate while holding all other factors constant (i.e., no compensating mixture adjustments are made). Mixture design modifications can partially offset or eliminate many of these differences (e.g., reducing w/(c+p) to offset reductions in strength or using fly ash in the mixture to decrease concrete permeability). Other differences (e.g., coefficient of thermal expansion and shrinkage) can be accounted for in the pavement structural design (e.g., modifications of panel dimensions and reinforcing).

Table 2. Typical properties of RCA concrete compared to similar mixtures comprising all natural aggregate (after ACI 2001, FHWA 2007 and Hansen 1986)

Property	Coarse RCA Only	Coarse and Fine RCA
Compressive Strength	0%–24% lower	15%–40% lower
Tensile Strength	0%–10% lower	10%–20% lower
Variability of Strength	Slightly greater	Slightly greater
Modulus of Elasticity	10%–33% lower	25%–40% lower
Coefficient of Thermal Expansion/ Contraction	0%–30% higher	0%–30% higher
Drying Shrinkage	20%–50% higher	70%–100% higher
Permeability	0%–500% higher	0%–500% higher
Specific Gravity	0%–10% lower	5%–15 % lower

It should be emphasized that concrete with adequate levels of compressive and flexural strength for paving and other applications can be produced even when virgin aggregates are completely replaced by RCA products.

RCA concrete can be highly durable provided that the mixture proportioning (including the use of chemical and mineral admixtures) is done properly and the construction (including concrete curing) is of good quality, even when the RCA is produced from concrete with D-cracking or alkali-silica reactivity (ASR) problems. D-cracked pavements have been successfully recycled into new concrete layers since at least the early 1980s by producing RCA coarse aggregate with a maximum size of ¾ inch or less (ACPA 2009). ASR-damaged pavement has also been successfully recycled into new concrete pavement through the use of Class F fly ash and/or slag cement, admixtures (e.g., lithium nitrate), and aggregate blending (i.e., limited or partial substitution for natural aggregate).

Sustainable Aspects of Concrete Recycling

The use of RCA can save money and time and reduce the environmental impact of concrete paving. Its use can potentially shorten project delivery as a result of expedited construction schedules due to reduced haul times. The potential for increased material transportation savings is even greater when there is no locally available aggregate and aggregate has to be trucked in from farther away. Expedited construction schedules result in fewer lane closures, which improve public safety. Public safety is also improved if processing of the aggregate is in close proximity to the project and there are fewer commercial vehicle-miles required for transport. Using RCA in new construction benefits the environment because it reduces the amount of material typically disposed of in landfills and conserves resources related to mining virgin aggregates.

Recommendations for using RCA

RCA Production

- Jaw crushers are effective at removing any embedded steel reinforcing or dowels and also tend to produce fewer fines than other types of crushers, which boosts the yield of coarse RCA. Impact and cone crushers are more effective at removing mortar to produce coarse RCA with properties that are similar to those of the original concrete aggregate (ACPA 2009).
- "Closed system" aggregate processing plants are preferred because they allow greater control over the aggregate particle size distribution and provide a more uniform finished material.
- Moisture control of stockpiles is essential in ensuring the production of uniform RCA concrete.

Use in PCC Mixtures

- In general, RCA products intended for use in new concrete pavements should meet the same quality requirements as virgin aggregate. RCA intended for use in high-quality concrete should be free of potentially harmful components. More than 90% of the material should be cement paste and aggregate. Small amounts of joint sealant material, motor oil and other pavement surface contaminants have not been found to cause problems in RCA used in concrete mixtures (FHWA 2007). RCA washing prior to batching is not generally required (except as needed to meet specification requirements limiting minus #200 material), but may be beneficial in reducing moisture absorption and associated mixture workability problems, and in enhancing paste-aggregate bond.
- Evaluate and test suspected ASR-affected and D-cracked sources to ensure that selected mitigation measures will effectively prevent recurrent problems. Techniques that may be effective in preventing recurrent ASR include: the use of Class F fly ash and/or slag cement in place of a portion of the cement; limiting the use of fine RCA; reducing concrete permeability through lower water content; the use of admixtures such as lithium nitrate; and reducing slab exposure to moisture (e.g., sealed joints, drainable base, subdrainage systems, etc.). Recurrent D-cracking may be prevented by reducing coarse RCA top size to 3⁄4 in. (19 mm) or less and by reducing slab exposure to moisture through the same techniques described above. (ACPA 2009).
- The basic proportioning of concrete containing RCA can be accomplished using the same procedures recommended for proportioning concrete containing only virgin aggregate.
    - To achieve similar workability to a conventional PCC mixture 5%–15% more water and/or a water-reducing admixture and/or the use of fly ash (substitution for Portland cement) may be required (FHWA 2007).
    - Additional cementitious material may be necessary to produce the required strength (FHWA 2007).
    - FHWA (2007) recommends a water-to-cementitious material ratio (w/cm) of 0.45 or less. However, many highway agencies are currently limiting w/cm to 0.42 or less for all concrete paving mixtures to provide a less permeable and more durable pavement.
    - The use of fine RCA should be limited to 30% of the total fine aggregate to avoid the production of a harsh mix.
    - There are no general limits on the use of coarse RCA in concrete paving mixtures and 100% coarse RCA

  has been successfully used in many projects, often with chemical and/or mineral admixtures or other mix proportioning adjustments to address potential workability issues. Limits on coarse RCA use have been imposed on some projects when the source concrete exhibited materials-related distress (e.g., D-cracking or ASR). (Snyder et al. 1994).
  - RCA substitutions for natural aggregate should be done volumetrically (rather than by weight) because of the generally lower specific gravity of RCA.

Pavement Structural Design

- Determine and consider the physical and mechanical properties of RCA concrete in the development of RCA concrete pavement design details.
  - Increased shrinkage and thermal response of concrete containing RCA can cause larger joint movements, requiring different sealant materials or reduced panel dimensions.
  - Reduced potential for aggregate interlock at transverse cracks in jointed, mesh-reinforced RCA concrete pavement may need to be offset with higher amounts of reinforcing.
  - Lower RCA concrete strength and elastic modulus may result in slightly increased pavement thickness requirements and different reinforcement requirements for continuously reinforced pavement.
- ACPA (2009) provides additional structural design guidelines and recommendations.

User Resources

The following resources provide guide specifications and detailed information concerning the production of RCA and its use in new concrete paving mixtures.

AASHTO MP 16-13 2013. Standard Specification for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete. American Association of State and Highway Transportation Officials. Washington, DC.

ACI 2001. Removal and Reuse of Hardened Concrete. ACI 555R-01. American Concrete Institute. Farmington Hills, MI. (currently under revision)

ACPA 2009. Recycling Concrete Pavements. Engineering Bulletin EB043P. American Concrete Pavement Association. Rosemont, IL.

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