Tech Brief

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SUMMARY AND DISCLAIMERS

The purpose of this Tech Brief is to describe the use of recycled concrete aggregate (RCA) in concrete paving mixtures and identify considerations for its use in highway infrastructure. The document is intended for highway agency and contractor engineers.

The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. This document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies. However, compliance with applicable statutes or regulations cited in this document is required.

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ADVANCING CONCRETE PAVEMENT TECHNOLOGY SOLUTIONS

USE OF RECYCLED CONCRETE AGGREGATE IN CONCRETE PAVING MIXTURES

INTRODUCTION

Recycled concrete aggregate (RCA) is produced by removing, crushing, and processing hardened concrete. It can be substituted for virgin aggregate in a variety of both bound and unbound uses. Concrete pavement is an excellent source of RCA, because it is generally comprised of high-quality source materials that have previously met state agency specifications.

As virgin aggregate sources and landfill space become limited, use of RCA is becoming increasingly attractive for both environmental and economic reasons (Cackler 2018). While RCA is often utilized in unbound applications, RCA has also been successfully used in new concrete paving mixtures in both laboratory studies and in new pavement construction projects.

Over the past several decades, more than 100 pavement projects have been constructed in the United States using RCA as either a full or partial replacement for coarse aggregate, fine aggregate, or both in concrete paving mixtures (Snyder et al. 1994, Reza and Wilde 2017). Most of these pavements have exhibited satisfactory performance over several decades, and a number of these pavements are still in service today.

In addition, several projects have served to identify limitations with use of RCA and have guided advancements in design and construction processes to improve performance. Overall, when RCA is properly evaluated and considered in mixture design and proportioning, RCA concrete has been found to provide durable performance with accompanying sustainability benefits (Reza and Wilde 2017).

The fundamental principles guiding design and batching of a durable RCA mixture that meets the agency's specifications do not differ from those utilized for conventional concrete mixtures. However, some additional considerations may be needed to ensure suitable performance, and differences in RCA and RCA concrete properties should be considered during the mixture design and development processes. The performance of a pavement should not be compromised when aiming to improve sustainability (FHWA 2007).

This Tech Brief provides information about the effective use of RCA in new concrete mixtures, including characterization of RCA, the expected impacts of RCA on concrete properties and durability performance, and current procedures for proportioning concrete pavement mixtures using RCA. After that, this Tech Brief presents information about pavement design using RCA, along with considerations for RCA production and use. Finally, this Tech Brief briefly describes example projects that illustrate the successful use of RCA in new concrete pavements.

CURRENT USE OF RCA IN CONCRETE MIXTURES

In 2016, a two-part benchmarking survey on the use of RCA was conducted (Cackler 2018). Information regarding the current use of RCA, as well as barriers and challenges to increased use, was solicited from state highway agencies (SHAs) and industry stakeholders. Findings indicated that production of RCA was common on most projects when existing concrete pavement was removed, and opportunities existed to use larger volumes of RCA.

The survey also revealed that most agencies had less stringent requirements for RCA if it was sourced from their own infrastructure. Use of RCA in unbound applications was found to be a common practice, with use in unbound base being the predominant use at the time of the survey.

Both agency and contractor respondents were interested in increasing the use of RCA, although several barriers or challenges to increased use were cited. These included regulatory barriers, a lack of guidance on how to use RCA without compromising performance, and a lack of guidance on how to mitigate potential environmental concerns.

Lack of technical information has historically been cited as a barrier to increased use of RCA in new concrete mixtures. However, recent publications developed with support from the Federal Highway Administration (FHWA) and others may enable use of RCA in other applications.

For example, the 2016 benchmarking survey results (published in 2018) were used with input from agency and industry stakeholders in the development of *Recycling Concrete Pavement Materials: A Practitioner's Reference Guide* (Snyder et al. 2018), along with a series of supporting technical briefs and webinars (Snyder and Cavalline 2016, Cavalline 2016, Snyder 2017, Cavalline 2017, Fick 2017, Snyder 2018a/b, Cavalline 2018a/b). Much of this guidance focused on use of RCA in unbound applications, although some guidance was presented to assist with using RCA in new concrete paving mixtures.

Concrete pavements that have reached the end of their service lives provide high-quality, reliable sources of aggregate that, when used in new concrete pavement applications, can improve the sustainability of the transportation system and preserve natural resources and existing landfill space (Snyder et al. 2018). Currently available processing technologies allow RCA to be produced on site (or near site), reducing hauls and making RCA a readily available resource for contractors to utilize in new concrete.

If allowed flexibility, contractors can determine the most economical use of RCA produced on each individual project. Information on project selection and scoping is presented by Snyder et al. 2018.

RCA BASICS

The Recycling Process

The quality of RCA is highly dependent upon the quality of the source concrete. Concrete obtained from agency infrastructure is typically of good quality, has already met agency specification requirements, and typically has a known performance history. Concrete from multiple sources or unknown sources should only be used to produce RCA if a thorough investigation and appropriate testing indicates that the RCA will be of suitable quality for the intended application. This is because variability in the source concrete properties can result in undesirable variability in the RCA concrete properties.

RCA production should be a controlled process (Fick 2017). RCA can be produced on site using a mobile crusher, on site using a stationary crusher (which may be moved one or more times due to project staging), or off site using a stationary facility. Typically, mobile on-site processing equipment is only utilized for base and fill uses. Stationary on-site processing or off-site processing is typically used to produce RCA for use in new concrete mixtures. Stationary processing facilities are commonly used for projects in urban areas or in other areas that may have such a facility.

The recycling process begins with breaking and removing the existing pavement. Large amounts of undesirable material such as asphalt overlays and asphalt patching material should be removed (and recycled separately later) prior to breaking, removing, and transporting the concrete pavement slabs. Torches and cutters may be required to separate reinforced slabs and to remove exposed steel. Slab fragments are then sent to the primary crusher, where most steel is separated and initial crushing occurs.

Several different types of crushers are available, including jaw crushers, impact crushers, and cone crushers. The type and size of the crusher utilized will determine the quantity of the coarse RCA produced, the gradation of the RCA produced, and the quantity of fines generated. Jaw crushers usually accept larger feed (24 inches or more) and tend to produce fewer fines than other types of crushers; they are often selected for primary crushing operations. Impact crushers tend to crush both mortar and aggregate (producing more fines) and use a smaller feed size of 12 inches or less (Fick 2017); they are more commonly used in secondary crushing operations.

After the primary crusher, the material is screened. Joint sealant and other light materials can be separated at the primary screen using air blowing, heavy media separation, or another method. Depending on the gradation specified, crushed material from the primary crusher may be screened and sent to a secondary crushing process. Crushing of clean, good quality concrete pavement will produce roughly 1 to 2 percent of the material finer than the No. 200 sieve, although additional fines may be introduced to the RCA when excavators scrape underlying foundation material while removing broken concrete (Fick 2017).

In addition to crushers and screens, other equipment typically used for RCA processing includes conveyors and equipment to produce and manage stockpiles. RCA stockpiles should be kept clean and free of deleterious substances such as organic material, soil, and other construction materials and debris. Stockpiles should be managed in a way that reduces the chance of segregation and contamination, as well as any adverse environmental impacts due to rainwater runoff from the stockpiles, such as a high pH (Cavalline 2018b).

Project staging may impact the availability of RCA; therefore, project staging and equipment production rates should be considered to ensure RCA is available for use when needed. If staging does not allow RCA production in sufficient quantities for demand throughout the project, aggregate demand can be met with virgin material (Fick 2017). Additional information on the production process for RCA, including strategies for establishing and maintaining production operations, is provided in Snyder et al. 2018 and Fick 2017.

Characteristics of RCA and Qualification Testing

RCA characteristics typically differ slightly from those of virgin aggregates. RCA particles are comprised of both the natural aggregate used to produce the source concrete as well as adhered (or reclaimed) mortar from the source concrete (Figure 1).

The differences between RCA properties and virgin aggregate properties are typically driven by the characteristics and volume of adhered mortar, which is lighter and more porous than the aggregate fraction. The high porosity of mortar increases the absorption capacity of RCA in direct proportion to the volume of adhered mortar. The volume of the mortar fraction of the RCA depends on the quality of the source concrete as well as the crusher type and particle size being produced. Smaller sized fractions of RCA usually comprise higher volumetric percentages of adhered mortar, and some particles can consist of only mortar.

In addition to driving increased water absorption, the mortar fraction of RCA is also responsible for a lower unit weight that needs to be considered in mixture proportioning. The mortar fraction has also been shown to be more susceptible to abrasion, and some agencies have increased the percentage of allowable abrasion loss from that recommended in the AASHTO T 96 test for RCA (Snyder et al. 2018). As a crushed material, RCA often has a more angular shape and a rougher texture than many virgin aggregates, and particularly gravels, which tend to be more rounded and smooth.

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Figure 1. RCA produced from interstate highway pavement (left) and polished sawcut face of RCA concrete showing residual mortar (lighter paste area) on coarse RCA particles with new mortar darker in color (right)

Despite these differences, characterization of RCA is performed in a similar manner to that for virgin aggregates. Many agencies require RCA to meet the same quality requirements as those for other aggregates. Typical qualification tests include gradation and abrasion according to AASHTO T 96 (2002). Sources that may potentially be affected by alkali-silica reaction (ASR) and D-cracking should receive additional attention, including testing in accordance with AASHTO R 80 (2017).

Some agencies have additional requirements, particularly for RCA produced from non-agency sources. These qualification tests may include limits on contaminants and potentially deleterious substances. Recommended limits on contaminants are provided by the American Concrete Pavement Association (ACPA 2009).

Sulfate soundness tests should not be utilized for RCA qualification due to unusual mass losses (caused by chemical interaction between the sulfates and cement paste) not representative of the actual durability performance of the RCA (ACPA 2009). Alternative soundness tests suitable for qualification of RCA are described in AASHTO M 319 (2015).

Influence of RCA on Constructability (Fresh Properties)

RCA concrete can be batched, mixed, transported, and placed using the same methods as conventional concrete. However, differences in several RCA characteristics relative to those of natural aggregate (described in the previous section) can result in differences in some plastic concrete properties. The effects of RCA on the fresh properties of concrete are described below and summarized in Table 1.

Workability and Water Demand

Compared to mixtures using virgin aggregates, RCA mixtures typically exhibit increased water demand and reduced workability. This is primarily due to RCA's higher absorption, angular shape, and relatively rougher surface. Additionally, increased slump loss can occur due to chemical reactions between hydrated cement and the calcium hydroxide contained in RCA.

Use of smaller-sized RCA fractions will increase the impact of RCA on workability, given the surface area is greater and the finer-sized RCA often has a greater proportion of adhered mortar (Obla et al. 2007). Studies have shown that, for an RCA concrete mixture to produce the same workability of a conventional mixture, approximately 5 percent additional water may be needed if only coarse RCA is utilized (Mukai et al. 1979), and approximately 10 to 15 percent additional water may be needed if both coarse and fine RCA are utilized (Buck 1973).

Table 1. Effects of RCA on plastic concrete properties

Property/Characteristic	Range of Expected Changes from Similar Mixtures using Virgin Aggregates	
	Coarse RCA Only	Coarse and Fine RCA
Water demand	Greater	Much greater
Air void system	Similar	Increased (reported air content will include air in the source concrete paste)
Unit weight	Slightly lower	Lower
Finishability	Slightly more difficult	More difficult
Bleeding	Slightly less	Less
Finishing characteristics	Similar	May be harsher to finish
Setting time	May be accelerated	May be accelerated

Sources: After FHWA 2007, ACI 2001

Provisions to mitigate reduced workability can be implemented during RCA production, stockpiling, proportioning, and delivery as follows:

- The selection and use of crushing equipment and operating practices can be done with the goals of decreasing dust and reducing the angularity and surface texture of the RCA. Washing or air blowing can also remove excess dust from the RCA.
- The moisture content of RCA can be maintained at high levels prior to batching using sprinkler systems. This can reduce water absorption and accompanying slump and workability loss after batching.
- Mixture proportions can be adjusted to improve workability by increasing paste content (increasing both water and cementitious materials, while maintaining the w/cm ratio) or by incorporating water-reducing admixtures (WRAs) (and often high-range WRAs) to obtain the desired slump at a lower w/cm ratio. Some research has suggested that the water demand of RCA concrete can be reduced by 12.5 percent by use of fly ash (at a 20 percent substitution rate) and a superplasticizer (Saravan Kumar and Dhinakaran 2012). If fine RCA is to be utilized in lieu of virgin fine aggregate, the ACPA recommends limiting the content to 30 percent to help avoid workability issues (ACPA 2009).
- If excessive slump loss occurs on site and is noted prior to placement, retempering of the concrete with additional water should be avoided so that the desired w/cm ratio is not exceeded.

Air Void System

The air void system of RCA concrete includes the entrained air in the new mortar, as well as the entrained air of the original source concrete mortar. Therefore, air content measured using the pressure method may be higher than expected. For example, Hansen and Narud (1983) found that the air content of RCA concrete is up to 0.6 percent greater than that of companion non-RCA mixtures.

If free of contaminants, RCA should not significantly influence the ability of air entraining admixtures to support development of a suitable entrained air system. However, care should be taken to minimize organic contaminants, as the presence of organic material (including asphalt cement) can influence the development of the entrained air system, and especially its variability, when certain types of air entraining admixtures are used. For example, vinsol resin air entraining admixtures are highly affected by organic contaminants, while synthetic air entraining admixtures are less affected (Ramachandran 1996).

Care should be exercised when determining the air content of RCA concrete. The pressure method is sensitive to the porosity of the aggregate, and the aggregate correction factor should be applied in accordance with ASTM C231 (Cuttell et al. 1997). The volumetric method of air content testing should be utilized instead of the pressure method for mixtures with high absorption RCA (Katz 2003, ACPA 2009).

Unit Weight

The specific gravity of RCA is typically less than that of natural aggregates since the mortar fraction of the RCA is less dense than the virgin aggregate portion of the RCA and contains some of the porosity and entrained air void system of the source concrete. This results in RCA concrete tending to have a slightly lower unit weight than that of conventional concrete mixtures.

The extent of the decrease in unit weight depends on many factors, including the type of RCA utilized (coarse and/or fine aggregate), the percent replacement utilized, the specific gravities of the components of the source concrete, and the mortar fraction content of the RCA. In general, unit weights of RCA concrete mixtures tend to be 10 to 15 percent lower than those of similar conventional concrete mixtures (Hansen and Narud 1983, Hansen 1986).

Bleeding and Finishability

Bleeding is often reduced in RCA mixtures, likely due to the increased absorption of the RCA (Mukai et al. 1979, Hansen and Narud 1983). The angularity and texture of coarse RCA has not been shown to significantly influence the finishability of concrete. However, inclusion of fine RCA results in a harsher mixture that is more challenging to finish (ACPA 2009, Yrjanson 1989).

As with conventional mixtures, the paste content of an RCA mixture also influences its finishability. Finishing of RCA concrete is not significantly affected if mechanical finishing equipment is utilized, as is typical in most paving applications.

Setting Time

Use of RCA may reduce concrete set times. This phenomenon is likely due to the presence of hydrated cement and the calcium hydroxide contained within the RCA and the resulting effects on the hydration of the new cementitious materials. Studies of concrete containing RCA, produced from crushed, returned, ready-mixed concrete, found that, absent the use of set-retarding admixtures, RCA concrete had initial and final set times roughly 30 to 60 minutes shorter than those of the concrete control mixture (Obla et al. 2007).

Influence of RCA on Hardened Properties of Concrete

RCA has been used to produce paving concrete with adequate mechanical properties and good durability (ACPA 2009, Snyder et al. 2018). However, the physical and mechanical characteristics of RCA are often different from those of natural aggregate, which can result in differences in hardened concrete properties. These impacts should be considered during the mixture design stage.

The effects of RCA on the properties of hardened concrete are described below and summarized in Table 2.

Strength

The strength of RCA concrete is affected by the same factors that affect the strength of conventional concrete. These factors include the w/cm ratio, cementitious materials used, temperature and moisture conditions during placement and curing, and age of concrete. Typically, RCA concrete exhibits the same strong correlation between the w/cm ratio and strength as conventional mixtures. However, using RCA in a concrete mixture often results in lower concrete strength than would be obtained with a comparable mixture containing virgin aggregates. This reduction in strength is attributed to microcracks that may exist in RCA particles due to the crushing process and the presence of weak and/or porous mortar in the RCA (Behera et al. 2014).

As such, the quantity and quality of adhered mortar has been shown to play an important role in the strength of RCA concrete (Hansen and Narud 1983). The production process should be designed and controlled to ensure the mortar content of the RCA does not adversely affect strength to an unacceptable degree.

Using fine RCA may result in greater strength reductions (especially at high replacement levels) than using coarse RCA, because fine RCA typically comprises more adhered mortar and less natural aggregate. One strategy to mitigate the impact of RCA on strength and other properties is by blending RCA with virgin aggregates, which effectively reduces the quantity of adhered mortar included in the new concrete mixture.

The shape and texture of the RCA will also influence the aggregate/paste bond and strength of the RCA concrete mixture. Unwashed, dusty RCA will also have reduced bond strength and, subsequently, lower concrete strength. Washing and air-blowing of RCA to remove dust can mitigate this issue.

The influence of RCA on the flexural and splitting tensile strength of RCA concrete has been shown to be dependent on the quality of the source concrete and the surface characteristics of the RCA, rather than on the replacement level (Malesev et al. 2010). Some studies have indicated that RCA concrete can achieve higher splitting tensile strength, possibly due to the improved bond between saturated RCA and the new paste, along with the contributions of the RCA particle angularity and possible chemical reactions between the RCA concrete and the paste (Abou-Zeid and McCabe 2002).

Table 2. Effects of RCA on hardened concrete properties and mitigation approaches in concrete paving

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

CTE = coefficient of thermal expansion
Sources: Adapted from ACI 2001, FHWA 2007, and Hansen 1986

Strength reductions due to the use of RCA can be compensated for by adjusting the w/cm ratio while utilizing WRAs to help achieve the desired workability (Reza and Wilde 2017). In addition to assisting with workability issues, prewetting of RCA before batching can help offset strength reductions by supporting the enhanced hydration benefits associated with the mechanisms of internal curing (ACPA 2009, ACI 2001).

Another approach to mitigate strength reductions is to utilize RCA as only a fraction of the natural aggregate (Xiao et. al 2005). Cuttell et al. (1997) identified RCA concrete pavements with increased strengths, attributing those to a low w/cm ratio and limiting the fine RCA to 25 percent. Use of RCA fines can be reduced or eliminated if reduced strength is an issue (Hansen 1986, Obla et al. 2007).

Again, variability in the source concrete used to produce RCA can cause variability in the RCA concrete strength and other properties (ACI 2001). Use of a consistent source of pavement concrete with a known performance history helps ensure acceptable variability.

Modulus of Elasticity and Poisson's Ratio

In general, the reclaimed mortar in RCA has a lower elastic modulus than most natural aggregate. Therefore, using RCA typically lowers the stiffness of concrete (Xiao et al. 2012). The volume of adhered mortar included in a mixture depends on the crusher types used and particle sizes produced, as well as the RCA replacement level (ACPA 2009).

For example, Bekoe et al. (2010) found that the modulus of elasticity decreased 10 percent when a 50 percent RCA replacement level was used, while Limbachiya et al. (2012a) observed a 35 percent reduction in elastic modulus where 100 percent RCA was used. In another study by the Building Contractors Society of Japan (1978), reductions in modulus of elasticity for concrete produced with coarse RCA only ranged from 10 to 33 percent, while concrete produced with both fine and coarse RCA had a drop in elastic modulus ranging from 25 to 40 percent.

In the limited number of studies on Poisson's ratio in the literature, it has been reported that minimal difference exists between that of RCA concrete and conventional concrete mixtures. Published values of Poisson's ratio of RCA concrete have ranged from 0.15 to 0.23 (Sofi et al. 2012). A study by Verian et al. (2013) found no correlation between the level of RCA replacement and the Poisson's ratios of concrete mixtures.

Volumetric Stability and Coefficient of Thermal Expansion

Drying shrinkage is associated with a decrease in volume of hardened concrete due to capillary moisture loss. The drying shrinkage of RCA concrete is often greater than that of conventional concrete since it contains both the residual mortar adhered to the RCA and new mortar. Higher mortar content mixtures typically result in greater shrinkage (Yang et al. 2008, Domingo-Cabo et al. 2009). Use of finer fractions of RCA, with their corresponding increase in residual mortar content, has been linked to relatively high increases in shrinkage when compared to similar mixtures containing virgin aggregates (ACI 2001, ACPA 2009).

Measures used to reduce drying shrinkage in conventional concrete mixtures, such as reducing paste content, lowering the w/cm ratio, and using appropriate amounts of some supplementary cementitious materials (SCMs), are also effective for reducing RCA concrete shrinkage. Specifically, use of fly ash and WRAs have been shown to be effective in reducing the amount of drying shrinkage in RCA concrete (Zhu and Wu 2010, Xiao et al. 2012).

Good construction practices should also be used for RCA concrete, just as they should be for conventional concrete. These include ensuring appropriate placement conditions (including temperature and humidity) and providing suitable curing.

The coefficient of thermal expansion (CTE) has been found to be an influential property in mechanistic-empirical design of rigid pavements (AASHTO 2008). The CTE of RCA concrete is linked to the CTE of the source concrete and the relative volumes of reclaimed natural aggregate and total mortar (reclaimed plus new). If the CTE is of interest for design purposes, testing to determine the CTE of the source concrete in accordance with AASHTO T 336 should be performed (AASHTO 2019).

Bond Strength

In continuously reinforced concrete paving applications, there should be adequate bond strength between concrete and reinforcing steel. A limited number of studies have been performed on the bond of RCA concrete with reinforcing steel. In general, the bond strength of RCA concrete with reinforcing steel has been found to be like that of conventional concrete (Fathifazl 2008, Choi and Kang 2008) or slightly lower (Butler et al. 2011).

Potential Durability

The durability of concrete refers to its ability to perform satisfactorily under the demands of the exposure conditions it is subjected to during its service life. This includes a concrete element's ability to withstand the ingress of water and aggressive agents, its ability to resist deterioration due to external stresses from freezing and thawing and abrasion, and its resistance to materials-related distresses such as alkali-aggregate reactivity (AAR) and D-cracking.

Some RCA concrete pavements have exhibited reduced durability performance compared to conventional concrete with the poorer performance often attributed to the microstructural damage to the RCA imparted during production, the porous nature of the aggregate, and the high absorptive characteristics of the RCA (Behera et al. 2014). However, many studies have also shown mixture design and proportioning strategies can be used to ensure satisfactory RCA concrete durability performance. Strategies used to improve conventional concrete pavement durability, such as the use of a low w/cm ratio and inclusion of SCMs, have been found to improve the microstructure of RCA concrete as well (Limbachiya et al. 2012a/b).

Permeability

Like most concrete, the permeability of RCA concrete is heavily influenced by the quality of the interfacial transition zone (ITZ) between the paste and the aggregate. Due to the nature of RCA containing both original aggregate and adhered mortar, new RCA concrete contains three ITZs: between the original aggregate and original paste, between the original aggregate and new paste, and between the original adhered paste and the new paste. In short, RCA concrete typically contains more paste and a greater volume of ITZs than conventional concrete and is therefore more permeable (Etxeberria 2004).

The increase in RCA concrete's permeability can vary widely, depending on many factors, including the permeability of the source concrete used to produce the RCA, the RCA replacement rate, and the w/cm ratio of the new concrete. Research suggests that RCA concrete can have up to 500 percent more permeability than conventional concrete (FHWA 2007, ACI 2001, Hansen 1986). However, conventional practices commonly used to reduce permeability in conventional concrete mixtures can be successfully used with RCA mixtures.

Researchers have suggested that lower strength and higher permeability of RCA concrete can be mitigated by reducing the w/cm ratio value by 0.05 to 0.10 (Rasheeduzzafar 1984). Another approach is to use a reduced amount (lower replacement percentage) of RCA.

Freeze-Thaw Resistance

Like conventional concrete, the quantity of air entrained in the RCA concrete, as well as the quality of the air void system, plays a key role in freeze-thaw performance. Air voids contained in both the adhered mortar in the RCA and within the new mortar contribute to the freeze-thaw durability of RCA concrete. If the mortar adhered to the RCA does not contain a well-dispersed entrained air system of adequate volume and spacing, it may not be sufficient to resist freeze-thaw stresses, and freeze-thaw damage could initiate in the RCA. Use of known sources of concrete to produce RCA can help ensure the RCA has a suitable entrained air void system in the adhered mortar.

The entrained air within the source concrete used to produce the RCA, as well as the entrained air of the new concrete, should be considered during the mixture design and trial batching phases. Field studies have indicated that RCA concrete can provide suitable freeze-thaw performance (Hansen 1986, Dhir et al. 1999, Gokce et al. 2011).

Abrasion Resistance

As mentioned previously, the mortar fraction of RCA has been shown to provide lower resistance to abrasion than most virgin aggregate sources, although abrasion resistance can vary greatly with the source properties and RCA production techniques (Yrjanson 1989, Adams and Jayasuriya 2019). Abrasion of the RCA during batching can result in production of additional fines that can impact the workability and finishability of the mixture.

The resistance of RCA concrete pavement to surface wear and aggregate polishing depends on the characteristics of the RCA mixture, construction, and traffic loads. The RCA may become exposed through grinding and/or wear, but it will not necessarily polish and become slippery. If virgin aggregate used in the source concrete is not associated with skid resistance issues, it is likely that the RCA concrete will not cause such issues either.

Alkali Aggregate Reactivity and D-Cracking

The susceptibility of RCA concrete to AAR depends on the remaining reactivity of the aggregates contained in the source concrete as well as the reactivity of new aggregates introduced into the mixture. If the source concrete used to produce the RCA was affected by AAR, the reaction may continue when the RCA is used in new concrete. The potential future expansion partially depends on the extent of the alkali-aggregate reaction completed while the original concrete was in service. If the reactive silicates in the RCA have been previously consumed (or nearly so), the residual expansion that may occur in the new RCA concrete may be limited, particularly if no new reactive silicates are introduced to the system (Snyder et al. 2018).

The crushing process may result in exposure of new, unreacted (or partially reacted) material in the RCA. These surfaces will be exposed to the paste of the new concrete, and that may increase the potential for an AAR-susceptible RCA to undergo new or accelerated reactions. In this sense, fine aggregate may pose a greater AAR risk than coarse RCA. One mitigating factor associated with the use of RCA is that the total volume of potentially reactive virgin aggregates is reduced (ACPA 2009).

AASHTO R 80, a voluntary, non-binding standard, provides a protocol for assessing the risk of ASR given materials, structures, and exposure conditions (AASHTO 2017). Traditional methods of evaluating aggregates for AAR susceptibility can be applied to RCA (Li and Gress 2006, Adams et al. 2013), and traditional methods of mitigating ASR, such as use of low-calcium fly ash or slag, can also be used in the new RCA concrete mixture (ACPA 2009). Petrographic analysis (for both AAR and D-cracking) can provide insights into the potential risk in using the source concrete as RCA.

Use of conventional approaches to mitigate AAR, such as SCMs and lithium compounds, are also recommended for RCA concrete (ACPA 2009). Blending of RCA aggregates with conventional aggregates has also been successfully used as a strategy to mitigate the potential for AAR. Several RCA pavements have been constructed using ASR-affected or -susceptible source concrete as RCA. Mitigation measures such as SCMs and low w/cm ratios were utilized in many of these pavements, and most have provided suitable performance (Snyder et al. 2018, ACPA 2009).

D-cracking is an aggregate-related distress, where stresses from freezing and thawing of saturated aggregates with susceptible pore system characteristics cause cracking. Use of RCA containing aggregates susceptible to D-cracking can result in distress in the new concrete, although RCA will contain a lower volume of original coarse aggregate because particles contain both aggregate and attached mortar. A field study of a pavement constructed using RCA with D-cracking-susceptible aggregates showed satisfactory performance, and no evidence of additional D-cracking after 35 years of service (Zeller 2016).

Mixture Design using RCA

Qualification Testing

When qualifying RCA for use in new infrastructure projects, many agencies have found success by ensuring that RCA meets the same requirements as virgin aggregate (FHWA 2007, Snyder et al. 2018). However, RCA exhibits several unique qualities that could also be considered, and some additional specification provisions unique to RCA are recommended.

ACPA (2009) suggests limiting contaminants to the following: asphalt concrete to 1 percent by volume (although if RCA is to be used in the lower lift of two-lift pavements, 30 percent or more has been present in successful applications), gypsum to 0.5 percent by weight, glass to 0 percent, and chlorides to 0.6 lb/yd^3. Agencies should also consider waiving the magnesium and sodium sulfate soundness tests (if required), since results of these tests for RCA are unreliable due to chemical reactions between the cement paste and the test sulfate solutions (ACPA 2009).

If the source concrete may be susceptible to ASR, testing of the materials in accordance with AASHTO R 80 is recommended (AASHTO 2017). Processing techniques such as washing and air blowing should be specified to minimize dust and contaminants in the RCA to ensure these deleterious materials do not affect water demand or concrete strength.

Proportioning

Proportioning of RCA concrete does not differ significantly from the procedures used for conventional concrete. The absolute volume mixture proportioning method detailed in ACI 211 (voluntary standard, ACI 1991, Reapproved 2009), ACI 325.14R-17 (voluntary standard, ACI 2017), and similar approaches based on this method, have been successfully utilized. Adequate material characterization of the RCA should be performed prior to designing mixtures and performing preliminary batching and testing. These tests should include gradation, specific gravity, and absorption. When proportioning, the lower specific gravity of RCA should be considered.

As discussed previously, a lower w/cm ratio may be needed to achieve the target properties for RCA concrete, particularly when using variable RCA. Use of SCMs has been shown to improve the performance of RCA concrete by supporting enhanced hydration, which helps to compensate for the relatively weak ITZ component of the RCA and the new ITZ (Limbachiya et al. 2012a/b). SCMs, such as Class F fly ash, slag-cement, or lithium nitrate admixtures, should also be included in the mixture if the potential for ASR exists.

To achieve the desired workability, users may choose to increase the paste content, particularly if fine RCA is to be used in the mixture. One successful strategy utilized to achieve a target slump is to increase the paste content of the mixture while holding the w/cm ratio constant, rather than just increasing the water content (ACPA 2009, ACI 2001).

Proportioning of the aggregates should be evaluated in a combined approach, using tools such as the Tarantula curve, the Shilstone workability-coarseness chart, or the gradation envelope required by the Illinois Tollway (revised 2016). In general, success has been achieved using up to 100 percent RCA as the coarse aggregate. However, the fine aggregate replacement rate should be limited to roughly 30 percent (ACPA 2009). If the RCA may be susceptible to materials-related distresses, such as AAR or D-cracking, the incorporation of coarse RCA can be reduced to a lower percentage to reduce the risk of damage (Snyder et al. 1994).

The unique nature of RCA can make it challenging to predict the impact of RCA use on concrete mixture performance. Recent research has aimed to help establish correlations and provide a better understanding of RCA concrete. Adams and Jayasuriya (2019) performed a statistical study using data from more than 100 peer-reviewed studies of RCA concrete conducted from 1988 through 2018, focusing on the impact of RCA properties and other mixture characteristics on RCA concrete mechanical properties, including compressive strength, elastic modulus, flexural strength, and splitting tensile strength. Findings of this study resulted in development of an RCA concrete mixture design procedure based on models and relationships determined through the statistical study, as well as recommendations by the American Concrete Institute (ACI) (including ACI 302, a voluntary, non-binding standard, which provides design recommendations for flatwork and slabs).

Steps in the process developed by Adams and Jayasuriya (2019) include determining an effective w/cm ratio, identifying an appropriate RCA replacement level, determining an aggregate-to-cement ratio, selecting aggregate size, selecting minimum requirements for cement contents based on ACI 302 guidance (ACI 2004), and, finally, determining mixture proportions for concrete materials. Adams and Jayasuriya (2019) also recommend laboratory batching be performed using a two-stage mixing procedure developed by Tam et al. (2005), although other approaches can be used.

A mixture proportioning method that accounts for the residual mortar on the RCA was developed by Fathifazl et al. (2009). This method, called the equivalent mortar volume (EMV) method, ensures that the resulting new RCA mixture contains a mortar content equal to that of the comparable conventional concrete mixture.

Advantages of this mixture proportioning method include improved workability, improved fresh and hardened properties, and a reduction in the amount of cement and fine aggregate needed in the RCA concrete mixture. This method also ensures that use of different RCA replacement levels does not result in changes in total mortar content. One disadvantage to the EMV method is that it is only intended for use with coarse RCA (Abbas et al. 2009).

To design a mixture using the EMV method, the proportions of a mixture containing only virgin aggregates are determined using a conventional mixture design method of the designer's choice. The method provides a means to develop an RCA mixture using two constraints: (1) the volume of the total mortar contained in the RCA concrete equals the volume of mortar in the virgin aggregate concrete, and (2) the total volume of coarse virgin aggregate in the RCA mixture equals the volume of coarse aggregate in the virgin aggregate concrete.

The EMV method includes equations to assist the designer in computing required volumes and weights of oven-dried coarse RCA and virgin coarse aggregates. Once these quantities are calculated, the method provides equations to compute the volumes and weights of water, cement, and fine aggregates. These equations account for the measured residual mortar content of the RCA and the measured specific gravities of the original virgin aggregate contained in the RCA and the new virgin aggregate. Using the EMV method, a maximum permissible RCA residual mortar content can be computed such that 100 percent of the coarse virgin aggregate can be replaced with coarse RCA, while ensuring that the fresh and hardened properties of the RCA are like those of the virgin aggregate mixture (Fathifazl et al. 2009).

Regardless of the mixture design and proportioning approach selected, the characteristics of the RCA concrete should be determined, and trial batches should be produced and tested. The material inputs used for the pavement design should be confirmed prior to production mixing and construction.

CONSIDERATIONS FOR PAVEMENT DESIGN USING RCA CONCRETE

Use of RCA concrete can be an economical, sustainable approach to construction of concrete pavements. As stated previously, the decision to use RCA should not adversely impact the performance of the pavement (FHWA 2007). As described in this technical brief, RCA affects fresh and hardened material properties and both the mechanical and durability performance characteristics of the concrete; therefore, these parameters should be considered during the design phase.

Given that trial batching of RCA concrete is generally not an option prior to the design phase, estimates of the required design inputs based on anticipated RCA concrete material properties should be used. For mechanistic-empirical pavement design, suggested inputs are presented in Table 3.

Table 3. Suggested inputs for mechanistic-empirical rigid pavement design using RCA concrete

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

CRCP = continuously reinforced concrete pavement
M-EPDG = *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice*. AASHTO July 2008 Interim Edition.

If a lower strength and modulus of elasticity are anticipated with the RCA concrete, the design pavement thickness may increase slightly over the design thickness of a non-RCA concrete pavement. For continuously reinforced concrete pavements (CRCPs) utilizing RCA mixtures, the reinforcement requirements may also change due to the lower strength and elastic modulus (Snyder 2018a). Additional structural design considerations are presented in ACPA 2009.

The increased shrinkage and potentially different thermal characteristics of RCA concrete should also be considered in design of RCA concrete pavements. Changes to these properties can result in larger joint movements, which may need to be accommodated by using more extensible joint sealant materials or with changes (typically reductions) in the panel dimensions (Snyder 2018a).

The increased shrinkage of RCA concrete also causes greater pavement warping stresses than in conventional concrete when other factors are held constant. Means to reduce these stresses, including reducing slab panel dimensions, can be incorporated into design (ACPA 2009).

Other practices such as incorporation of adequate drainage provisions and appropriate joint details should also be included in the design to ensure the long-lasting performance of both RCA and conventional concrete pavements.

RCA PRODUCTION AND USE CONSIDERATIONS

Selection of the crusher is important in determining the characteristics of the RCA produced. Jaw crushers tend to be effective primary crushers, capable of removing reinforcing steel or dowels from the material while producing fewer fines than other crushers. Impact and cone crushers tend to be more capable of removing mortar, resulting in RCA with properties more like the original concrete's coarse aggregate (ACPA 2009).

Although agencies have found that small amounts of contaminant material in the RCA (such as joint sealant, oil, or other pavement surface contaminants) can be incorporated into RCA concrete mixtures without adversely affecting performance, excessive amounts of contaminants should be avoided (NHI 1998). ASTM C33 (2013), a voluntary standard, provides limits on deleterious substances, as do many agency specifications.

RCA stockpiles should be monitored to ensure the stockpiles are kept free from contamination and segregated, and that the moisture content is controlled. Information about stockpile management is provided in Snyder and Cavalline 2018 and in Cavalline (2018b). Stockpiles should be wetted, and the RCA should be maintained in a high moisture state to reduce potential water absorption problems and rapid changes in workability during paving.

EXAMPLE PROJECTS

Use of RCA in Concrete Pavement

Colorado State Highway 470 (C-470) serves as the southwest portion of the Denver Metro area's beltway. More than 100,000 vehicles use a 12.5-mile stretch of C-470 per day between I-25 and Wadsworth Boulevard, with traffic volumes projected to increase 40 percent by 2035. The C-470 Express Lanes Project included the addition of three express lanes (two westbound and one eastbound) and full reconstruction of a portion of the existing pavement and a concrete overlay where elevations and cross slopes allowed. All existing concrete removed as part of the work, which included mainly segments of the pavement, was crushed to produce RCA used on the project.

A portable crushing plant stationed on or near the site was used to produce the RCA (Figure 2).

Daniel Pearsall, provided by Castle Rock Construction, with reuse permission

Figure 2. Crushing plant used to produce RCA for use in new RCA concrete pavement on C-470 in Colorado

Crusher locations were chosen to minimize the haul of the aggregate to the on-site batch plants. The crushing process included a jaw crusher (primary) and a cone crusher (secondary). The crushing operation produced 86,000 tons of 1½-inch nominal maximum size coarse RCA, which was used in the mixture for 926,000 square yards of concrete paving, along with another RCA that was used as the unbound base for the pavement.

The coarse RCA was used in the new concrete mixture as a 38 percent replacement (by volume) for conventional coarse aggregate, with the design mixture having an average 28-day flexural strength of 700 psi. The RCA concrete pavement was completed in the fall of 2019 and consisted of three driving lanes plus shoulders and buffer lanes (width varied, up to approximately 72 feet wide) over a length of 12.5 miles (926,584 square yards).

Use of RCA in this project provided cost savings to the owner, as well as the sustainability benefits achieved by not hauling existing material off site and hauling virgin material back to the site. In the contractor's experience, if the RCA is prewetted before mixing, they have had very good results using RCA in new concrete on this and other projects. For this project, the RCA stockpile was sprinkled to ensure the material was prewetted before adding it to the mixer. However, the contractor indicated that on other projects they have also had success putting the RCA through a log washer to prewet it prior to mixing.

Use of Fine and Coarse RCA in Interstate Concrete Shoulders

Completed in 2016, the Georgia Department of Transportation (GDOT) I-16 project included 56 miles of truck lane replacement and new inside and outside shoulder construction (Figure 3).

The existing 10-inch thick concrete slab (constructed during the 1960s and 1970s) was crushed at a nearby stationary facility to produce RCA for use in the new concrete shoulders. Trial batches using 100 percent RCA as fine and coarse aggregate produced a mixture that was too sticky, so a natural sand was blended with the RCA to improve workability. The final mixture used for the RCA concrete shoulders included 81.1 percent RCA and 18.9 percent natural sand.

The contractor adapted mixtures and production processes to account for slump loss over different haul distances. Overall, this approach allowed recycling of 100 percent of the removed concrete (providing economic and environmental benefits) and provided confidence to GDOT in use of RCA in new concrete shoulder applications (Geary et al. 2016).

Use of RCA in Lean Concrete Base

The California Department of Transportation (Caltrans) I-710 project in Los Angeles consisted of rehabilitating a 3.5-mile stretch of highway with five lanes in each direction (Figure 4).

The existing jointed plain concrete pavement (JPCP), originally constructed in the 1960s, was removed and mostly replaced with JPCP with rapid strength concrete (RSC). A small section of about 700 feet was replaced with CRCP using RSC due to work being done on a weekend-closure schedule (Rapoport 2020).

The existing concrete pavement was crushed and combined with the existing Class III permeable aggregate base to produce an aggregate product comprising approximately 75 to 80 percent crushed concrete pavement and approximately 20 to 25 percent base. This RCA/aggregate blend was used to provide 100 percent of the coarse and fine aggregate in a new lean concrete base. It was also used as a new Class III permeable base to achieve "zero concrete waste" of the old pavement on the project.

The contractor reported no issues with the RCA used in the new lean concrete base or in the new Class III permeable base. Completed in 2020, this project was also the first CRCP pavement in Caltrans District 7 and was constructed over 55 hours of extended weekend closures showing that RCA mixtures can be used in projects with short timeframes.

CONCLUSIONS

RCA can be incorporated into new concrete paving mixtures as evidenced by pavements that have provided satisfactory service over typical design service lives. Although the RCA can impact fresh and hardened properties of concrete, basic mixture design and proportioning techniques can be used to readily address these impacts. RCA durability concerns can be addressed through typical aggregate testing and screening protocols.

Georgene Geary, GGfGA, used with permission

Figure 3. Concrete shoulders using RCA on I-16 in Georgia

Michael Roe, Flatiron, used with permission

Figure 4. RCA used in lean concrete base on I-710

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