ENGINEERING BULLETIN

Recycling Concrete Pavements

EB043P

AMERICAN CONCRETE PAVEMENT ASSOCIATION

Recycling Concrete Pavements

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ACPA is the premier national association representing concrete pavement contractors, cement companies, equipment and materials manufacturers and suppliers. We are organized to address common needs, solve other problems, and accomplish goals related to research, promotion, and advancing best practices for design and construction of concrete pavements.

Keywords: AASHTO, ASTM, aggregate, alkali-aggregate reactivity (AAR), alkali-carbonate reactivity (ACR), alkali-silica reactivity (ASR), asphalt-treated subbase (ATB), base, beneficiation, carbonation, cement-treated subbase (CTB), cement-stabilized, coarse aggregate, cone crusher, crushed, daylighted, dense-graded, drainable, econocrete, edge drainage, fine aggregate, free-draining, gap-graded, geosynthetic, gradation, grading, granular, gravel, greenhouse gas, horizontal shaft impact crusher, impact crusher, jaw crusher, lean concrete subbase (LCB), materials-related, natural, open-graded, permeable, proportioning, recycled concrete aggregate (RCA), recycling, sieve, stabilized, subbase, sulfate resistance, sustainable, sustainability, unstabilized, vertical shaft impact crusher, virgin aggregate, well-graded, workability, yield.

Abstract: This engineering bulletin provides background information on recycling concrete pavements into recycled concrete aggregate (RCA) for use in bases, subbases, new concrete mixtures, granular fill, etc. It details the economic and environmental (su stainable) reasons to recycle concrete pavements, the methods and steps of producing RCA, the properties and characteristics of RCA, the various uses of RCA, the properties of concrete containing RCA, and the performance of concrete pavements constructed using RCA. Recommendations and guidelines for using RCA in various applications also are provided.

Acronyms Commonly Used in this Bulletin:

AAR	alkali-aggregate reactivity
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ACR	alkali-carbonate reactivity
ASR	alkali-silica reactivity
ASTM	American Society for Testing and Materials
ATB	asphalt-treated subbase
AVA	air void analyzer
$Ca(OH)_2$	calcium hydroxide
CO_2	carbon dioxide
CRCP	continuously reinforced concrete pavement
CTB	cement-treated subbase
CTE	coefficient of thermal expansion and contraction
DOT	Department of Transportation
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GHG	greenhouse gas
JPCP	jointed plain concrete pavement
JRCP	jointed reinforced concrete pavement
LCB	lean concrete subbase
NaCl	sodium chloride (e.g., salt)
RCA	recycled concrete aggregate
w/cm	water-cementitious materials ratio

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Executive Summary

The cost of virgin aggregate (e.g., aggregate mined from natural sources, such as crushed stone, natural sand, crushed gravel, etc.) is increasing rapidly as available sources are depleted while policies and regulations restrict access to new sources. Concrete pavement recycling is a proven technology that offers an alternative aggregate resource that is both economical and sustainable.

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), a granular material that can be produced for any application for which virgin aggregate might be used. Concrete pavements are 100 percent recyclable (ACPA 2006).

Concrete recycling has been used extensively in Europe since the 1940's and in the U.S. since the 1970's (NHI 1998). Concrete recycling for paving applications is now performed in at least 41 states (FHWA 2004). Production of RCA in the U.S. currently averages about 100 million tons (91 million metric tons) per year (USGS 2000). The primary application of RCA has been subbase materials, but it also has been used in concrete and asphalt concrete paving layers, high-value rip-rap, general fill and embankment, and other applications.

One major incentive for concrete pavement recycling is economics. Aggregate costs (for fill, foundation and surface layers) constitute one of the greatest costs of highway construction, comprising between 20 and 30 percent of the cost of materials and supplies (Halm 1980). Concrete pavement recycling saves much of these costs. The cost of producing RCA can be considered to be limited to the costs of crushing the demolished concrete and screening and backhauling the RCA (along with quality control costs). The costs of concrete demolition, removal and hauling are required whether the pavement is recycled or simply discarded. RCA production costs may be offset by savings in hauling and disposal costs, especially if the RCA is produced on site. 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.

RCA particles tend to be highly angular and are comprised of reclaimed virgin aggregate, reclaimed mortar or both. Reclaimed mortar generally has higher absorption, lower strength and lower abrasion resistance than for most virgin aggregates. As a result, RCA generally has lower specific gravity and higher absorption than virgin aggregate. The properties of a specific recycled concrete aggregate depend upon many factors, including the properties of the original concrete and the processes used to produce the RCA, particularly the crushing processes. With proper care and process control, RCA can be produced to meet quality and grading requirements for almost any application for which virgin aggregate would be used. RCA should be considered to be 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.

When RCA is used in the production of 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. For example, when little reclaimed mortar is present in coarse RCA and virgin fine aggregate is used, the handling characteristics and engineering properties of the new concrete properties will be practically the same as if all virgin aggregate had been used; if the new mixture contains only coarse and fine RCA, these characteristics and properties will probably be quite different from those of traditional concrete mixtures when all other mixture design factors remain constant. Changes in mixture design and admixture usage can reduce (and sometimes eliminate) many differences in the properties of RCA concrete mixtures.

Fresh concrete mixtures containing RCA generally exhibit higher water demand and shrinkage, although these effects can be offset with good construction practices and mixture design modifications. When all other factors are held constant (i.e., no compensating mixture adjustments are made), hardened RCA concrete can be expected to have somewhat lower (but still acceptable) strength and elastic modulus values, significantly more permeability, drying shrinkage and creep potential, slightly lower specific gravity, somewhat higher coefficient of thermal expansion and contraction (CTE) and also may be more difficult to finish. Mixture design modifications can partially offset or eliminate many of these differences.

Recycled concrete aggregate has been used in the construction of hundreds of highway construction projects in the U.S. (and around the world) since the 1970's. These projects have included the use of RCA in pavement fill, foundation, subbase and surface courses (both asphalt and concrete). Projects have included relatively low-volume roads and some of the most heavily traveled roadway in the world (e.g., the Eden's Expressway in Chicago). They also have included the recycling of pavements that were severely damaged by D-cracking or alkali-silica reactivity (ASR) damage back into new concrete pavements.

Most of these projects have performed very well, frequently exceeding all expectations. Some projects, however, have failed prematurely in ways that were noteworthy. Some of these failures provided lessons in the design and construction of pavement details while others have led to 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.

This publication provides numerous recommendations concerning RCA production and use (including both foundation applications and use in new concrete mixtures), as well as guide specifications to assist users in developing successful RCA construction projects.

Executive Overview

For quick reference, key concepts for each chapter are listed as follows and indexed to the tabs on the page edges of this publication.

Chapter 1. Introduction – Page 1

Key Point		Page
●	The primary incentives for concrete pavement recycling are economic and environmental. Pavement recycling also may offer the opportunity to improve the potential performance of the pavement (through material modifications) while addressing other roadway deficiencies (e.g., geometrics, foundation corrections, etc.) during reconstruction.	1
●	The overall economic benefits of concrete recycling vary with many factors, including the availability and cost of virgin aggregate, processing and quality control costs for producing RCA of the required gradation and quality, hauling and tipping fees for disposing of old pavement, and project-specific environmental issues.	2
●	Concrete recycling is a smart and environmentally conscious choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy and reduces greenhouse gas emissions, and actually removes CO_2 from the air.	2
●	Reconstruction using RCA can provide additional performance benefits through improved foundation strength and stability and comparable or increased concrete strength.	4
●	Concrete recycling for paving applications is now performed in at least 41 states and has the support of the FHWA, which states that “reusing the material used to build the original highway system … makes sound economic, environmental, and engineering sense.” The Environmental Protection Agency (EPA) has identified “increasing the recycling and beneficial use of industrial materials” as one of the four national priorities of the Resource Conservation Challenge, an organized national effort to reduce greenhouse gas (GHG) emissions and to conserve natural resources; the use of RCA in new concrete mixtures certainly satisfies these requirements.	4

Chapter 2. Production of Recycled Concrete Aggregate (RCA) – Page 7

Key Point		Page
●	The major steps in concrete pavement recycling are: evaluation of the source concrete; preparation of the slab; 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.	7
●	The same basic equipment used to processes virgin aggregates also can be used to crush, size and stockpile RCA.	12
●	The runoff from RCA stockpiles is initially highly alkaline due to the leaching of calcium hydroxide from the freshly crushed material. Runoff alkalinity usually decreases rapidly within a few weeks as the exposed calcium hydroxide is depleted. In addition, runoff alkalinity is usually mitigated quickly through contact with and dilution by relatively low pH rainwater and other mechanisms, such as the reaction of dissolved calcium hydroxide with CO_2 from the atmosphere to form a stable limestone-like material. The bottom line is that there appear to be no negative environmental effects from using RCA that would significantly offset the positive environmental effect of reduced use of virgin aggregate and landfills.	14

Chapter 3. Properties and Characteristics of RCA – Page 17

Key Point		Page
●	RCA must generally meet the same requirements as virgin aggregate for the target application (e.g., concrete mixture, subbase layer, etc.). There are some clear differences in the physical, mechanical and chemical properties of typical virgin aggregate and RCA, but most of these differences, however, require little (if any) consideration or procedural adjustment for use in typical applications.	17
●	With appropriate adjustments, concrete crushing plants can be set up to produce almost any desired gradation, although there often is an excess of material passing the No. 4 (4.75 mm) sieve.	18
●	Absorption capacities of RCA are generally higher than those of conventional aggregates. The primary factor affecting RCA absorption is the amount of reclaimed mortar that is present because the reclaimed mortar is usually more porous and absorbent and has a greater surface area than most types of virgin aggregate.	18
●	L.A. abrasion mass loss values typically are higher for RCA than for the virgin aggregates contained in the RCA; they are, however, usually within specified limits.	19
●	D-cracked concrete pavements commonly have been recycled into unstabilized subbase layers and fill without any problems relating to the durability of the aggregate. Such pavements also have been successfully recycled into new concrete layers since at least the early 1980's.	19

Chapter 3. Properties and Characteristics of RCA – Page 17 (Continued)

	Key Point	Page
●	The potential for ASR in new concrete containing RCA is affected by the original alkali level of the old concrete, the remaining potential reactivity of the recycled aggregate, and the alkali content of new concrete. However, several tests exist to provide mitigation methods (e.g., substitution of Class F fly ash and/or slag cement, the use admixtures, such as lithium nitrate, etc.) to greatly reduce the potential of ASR expansion in new concrete.	20
●	High levels of NaCl have been found in RCA produced from sources with long-term exposure to this deicing chemical. No serious problems caused entirely by high chloride contents have been reported; however, some testing might be necessary when using RCA with high levels of NaCl in concrete mixtures for jointed reinforced concrete pavements (JRCP) or continuously reinforced concrete pavements (CRCP) to ensure that the NaCl levels are not high enough to be of concern.	20
●	Crushing concrete reveals previously unexposed surfaces that usually contain some calcium hydroxide and some previously-unhydrated or partially-hydrated cement grains. These materials can be dissolved and then recombined with atmospheric CO_2 to form calcium carbonate precipitate, which can fill pavement drain pipes and clog filter fabrics. Suggestions for avoiding this problem are presented in Chapter 7. Precipitate and crusher fines do not pose a problem for concrete mixture and undrained subbase layer applications.	21

Chapter 4. Uses of RCA – Page 23

	Key Point	Page
●	Unstabilized (granular) subbase applications are common for RCA produced from concrete pavements because of the potential for superior performance, economic savings, conservation of resources and environmental considerations.	23
●	RCA is an effective and economical material for dense-graded, unstabilized subbase applications. When properly graded, the angular nature of the product provides excellent stability. In addition, fine RCA often experiences a degree of secondary cementing, which further strengthens and stiffens the subbase layer.	23
●	RCA typically makes excellent free-draining subbase material when the production yields relatively angular, rough-textured particles that can be graded to applicable specification requirements. When these conditions are met, RCA can be placed to provide a subbase layer that is both permeable and is highly stable.	24
●	RCA has been used in concrete mixtures in the U.S. since the 1940's for roadway surfaces, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundations and even structural concrete.	25
●	Most states allow the use of recycled concrete for erosion control ("rip-rap") or slope stabilization.	26

Chapter 5. Properties of Concrete Containing RCA – Page 27

	Key Point	Page
●	When RCA is used in the production of new concrete mixtures, its ef fect on the properties of those mixtures can range from minimal to significant, depending upon the nature, composition and gradation of the RCA.	27
●	RCA particles tend to be angular and rough-textured, which can increase the harshness of fresh concrete mixtures. The irregular shape and texture of coarse RCA particles generally does not cause significant workability problems. The use of fine RCA, however, can greatly increase the harshness of the mixture. It is common to control workability by limiting the use of fine RCA in concrete mixtures to 30 percent or less replacement of natural sand.	28
●	The higher absorption capacities of RCA (especially fine RCA) can lead to a rapid loss of workability. Absorption problems have been addressed successfully by washing or wetting the aggregate and maintaining it in a moist (saturated, surface-dry) condition until batching.	28
●	Concrete containing coarse and/or fine RCA can be produced with adequate levels of compressive and flexural strength for paving and other applications, even when virgin aggregates are completely replaced by RCA products.	29
●	The CTE of RCA concrete is typically about 10 percent higher than for conventional concrete.	30
●	Studies have found 20 to 50 percent higher shrinkage in concrete containing coarse RCA and natural sand, and 70 to 100 higher shrinkage in concrete containing both coarse and fine RCA. Higher shrinkage can cause higher concrete pavement moisture warping stresses, which can usually be of fset by reducing the panel dimensions.	30
●	RCA concrete mixtures have been shown to have permeabilities up to five times higher than that of concrete made using conventional aggregate. This increased permeability can be offset by reducing the w/cm ratio by 0.05 to 0.10 and/or by the substitution of fly ash and/or slag cement for a portion of the cement.	31
●	RCA concrete can be highly durable, even when the RCA is produced from concrete with durability problems, 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.	31

Chapter 6. Performance of Concrete Pavements Constructed Using RCA – Page 33

Key Point		Page
●	A 1994 literature review identified nearly 100 RCA concrete paving projects in the U.S., including several where D-cracked or ASR-damaged pavements were recycled; many more projects have utilized RCA in pavement foundations, subbase layers and other applications. Most of these projects have performed well and are considered successes. Some projects, however, have not been successful and have offered lessons in the use of RCA in pavement construction.	33

Chapter 7. Recommendations for Using Recycled Concrete – Page 41

Key Point		Page
●	"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.	41
●	Moisture control of stockpiles is essential in ensuring the production of uniform RCA concrete.	42
●	The pavement design process should consider the possibility of significant stiffening of unstabilized RCA subbase materials caused by continued hydration of the cementitious materials (especially for dense-graded RCA base materials containing fine RCA particles).	43
●	Unbound RCA subbase layers that can pass water to pavement drainage systems or are designed to be drainable daylighted subbases should be free of fine materials to minimize the movement of dust and formation of calcium carbonate precipitate that can clog filter fabrics and reduce drain capacity. Fine unstabilized RCA may be suitable for placement in any layer below the pavement drainage system.	44
●	In general, RCA products intended for use in new concrete pavements should meet the same quality requirements as virgin aggregate.	45
●	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 content of fine RCA; reducing concrete permeability through lower water content; the use of admixtures such as lithium nitrate; and reducing slab exposure to moisture.	45
●	Recurrent D-cracking may be prevented by reducing coarse RCA top size to ¾ in. (19 mm) or less and by reducing slab exposure to moisture through the same techniques described above.	45

Chapter 7 continued on next page

Chapter 7. Recommendations for Using Recycled Concrete – Page 41 (Continued)

Key Point		Page
●	RCA intended for use in high-quality concrete should be free of potentially harmful components. More than 90 percent 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.	45
●	The basic proportioning of concrete containing RCA can be accomplished using the same procedures recommended for proportioning concrete containing only virgin aggregate.	45
●	The physical and mechanical properties of RCA concrete must be determined and considered in the development of RCA concrete pavement design details. For example, increased shrinkage and thermal response of concrete containing RCA can cause larger joint movements, requiring different sealant materials or reduced panel dimensions.	46

Chapter 1. Introduction

WHAT IS CONCRETE RECYCLING?

Concrete recycling is a relatively simple process. It involves breaking, removing and crushing hardened concrete from an acceptable source to produce RCA, a granular material that can be produced for use as a substitute for virgin aggregate in almost any application.

Old concrete pavements (including parking lots, sidewalks, curb and gutter, etc.) that are to be removed often are excellent sources of material for producing RCA because they are generally of good quality and are free of the contaminating materials that often must be removed from concrete building demolition debris. *Concrete pavements are 100 percent recyclable* (ACPA 2006).

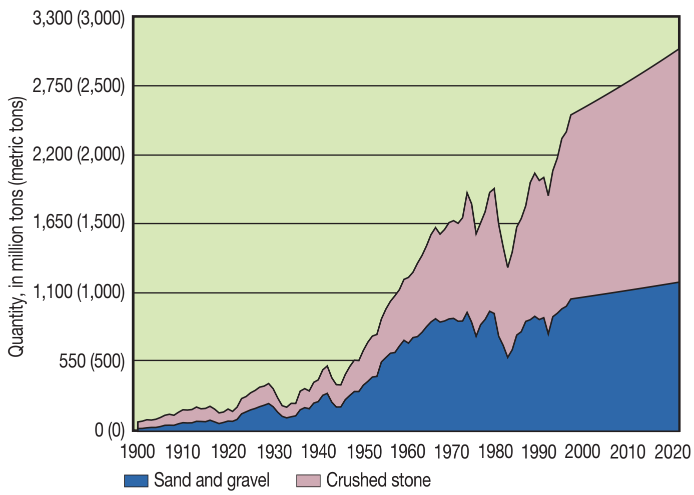

Figure 1. National aggregates production in the United States with projections to 2020 (USGS 1997).

WHY CONCRETE PAVEMENT RECYCLING?

Virgin aggregate production in the U.S. increased from 58 million tons (53 million metric tons) in 1900 (or 0.5 tons [450 kg]/person) to 2.3 billion tons (2.1 billion metric tons) (9.6 tons [8.7 metric tons]/person) in 1996, as shown in Figure 1 (USGS 1997). The demand for aggregate for the construction of pavements and buildings continues to increase rapidly.

Virgin aggregate resources are vast, but finite; many high-quality, conveniently located virgin aggregate resources are being depleted rapidly. In addition, environmental regulations, land use policies and urban/suburban construction and settlement are further limiting access to known aggregate resources. Virgin aggregate costs can be expected to rise with scarcity and increasing haul distances. Concrete pavement recycling is a proven technology that offers an economical and sustainable solution to these problems.

The primary incentives for concrete pavement recycling are economic and environmental. Pavement recycling also may offer the opportunity to improve the potential performance of the pavement (through material modifications) while addressing other roadway deficiencies (e.g., geometrics, foundation corrections, etc.) during reconstruction. These three categories of benefits (economics, environmental stewardship or sustainability, and improved or corrected pavement performance) are discussed below.

Economics of Concrete Pavement Recycling

Aggregate costs (for fill, base/subbase and surface layers) constitute one of the greatest costs of highway construction, comprising between 20 and 30 percent of the cost of materials and supplies, and 10 to 15 percent of total construction costs (excluding engineering and right-of-way acquisition) (Halm 1980).

Virgin aggregate costs are increasing rapidly in many areas as sources of high-quality virgin aggregate material are depleted and new sources cannot be extracted due to urban development, environmental concerns and governmental regulation (e.g., zoning). As available sources become increasingly scarce, haul distances increase, resulting in additional supply costs. In some urban areas, conventional aggregates must be hauled from sources that are up to 70 miles (113 km) from the project site, and haul distances greater than 200 miles (320 km) are not uncommon (ECCO 1999). These haul distances and associated costs can be expected to continue to increase as sources become more scarce.

The cost of producing RCA can be considered to be limited to the costs of crushing the demolished concrete and screening and backhauling the RCA (along with quality control (QC) costs). The costs of concrete demolition, removal and hauling are required whether the pavement is recycled or simply discarded. RCA production costs may be offset by savings in hauling and disposal costs, especially if the RCA is produced on site.

In a recent survey, prices for various RCA products ranged from less than $1 to more than $16 per ton ($1 to $18 per 1,000 kg) (USGS 2000). Some states have estimated savings of up to 60 percent from using recycled concrete aggregates in lieu of virgin aggregates (ECCO 1997a). When the RCA is used as aggregate for new concrete paving, this can mean a savings of about $4.00 per yd^2 ($4.80 per m^2).

More recently, it was reported that California's Department of Transportation (CalTrans) saved 5 million dollars by utilizing 800,000 tons of RCA (700,000 tons were produced from the existing roadway and 100,000 tons were imported from other sources) in the reconstruction and widening of a portion of I-5 near Anaheim (CMRA 2008).

It is clear that concrete pavement recycling offers several potential sources of cost savings. The overall economic benefits of concrete recycling vary with many factors, including the availability and cost of virgin aggregate, processing and quality control costs for producing RCA of the required gradation and quality, hauling and tipping fees for disposing of old pavement, and project-specific environmental issues.

Sustainability Issues

Every pavement construction or rehabilitation effort draws on a finite reserve of virgin aggregate resources. Concrete recycling is a smart and environmentally conscious choice that conserves aggregate and other resources, reduces unnecessary consumption of limited landfill space, saves energy and reduces greenhouse gas emissions, and actually removes CO_2 from the air.

The Environmental Protection Agency (EPA) has identified "increasing the recycling and beneficial use of industrial materials" as one of the four national priorities of the Resource Conservation Challenge, an organized national effort to reduce greenhouse gas (GHG) emissions and to conserve natural resources; the use of RCA in new concrete mixtures certainly satisfies these requirements (EPA 2009).

Conservation of Virgin Aggregate Resources

Replacing the slabs in one lane-mile (1.61 lane-km) of a 10-in. (250-mm) thick concrete pavement requires almost 2,000 yd^3 (1,500 m^3) of concrete, including about 3,000 tons (2,700 metric tons) of coarse and fine aggregate. In areas where acceptable aggregate supplies are limited, a single large highway project can rapidly deplete the locally available supply of virgin aggregate.

Because concrete is 100 percent recyclable, this same lane-mile of paving slabs can be recycled to *produce* about 4,000 tons (3,600 metric tons) of coarse and fine RCA – enough to supply the aggregate required to replace all of the slabs with additional material left for other applications. It also is worth noting that it can take significantly fewer tons of RCA to replace an equivalent volume of conventional aggregate in almost any application because RCA generally has a lower specific gravity than virgin aggregate.

Clearly, concrete recycling conserves valuable existing aggregate supplies and mitigates the need for new quarries.

Landfill Reduction

Placing demolished concrete slabs in landfills is becoming increasingly expensive as available landfill space becomes more scarce and more restricted (e.g., many urban landfill operators will not accept construction and demolition debris). Concrete pavement recycling eliminates the need to dispose of concrete in landfills, resulting in both cost savings and an extension of landfill usefulness for materials not as easily recycled as concrete.

Energy Savings

The production and use of virgin aggregate involves the consumption of a great deal of energy (as motor fuel and/or electrical power) at each step, including: the mining or extraction of the aggregate; the crushing, screening and washing; the stockpiling and/or transport to the job site; and the removal and disposal of the material (if it is not recycled) at the end of its period of use. Concrete recycling can greatly reduce the need for mining or extraction, and can reduce haul distances and fuel consumption associated with both supply and disposal.

An example of documented fuel savings is provided by Yrjanson (1989), who describes a 16-mile (26-km) concrete recycling project in Minnesota in 1981. A two-lane concrete pavement was recycled into coarse RCA for a new concrete pavement surface and fine RCA for a 1-in. (25-mm) lift on top of the subbase. The Minnesota Department of Transportation (DOT) estimated that recycling the concrete resulted in a 27 percent savings in the total cost of the project, including a savings of 151,000 gallons (572,000 liters) of fuel.

Reduced Emission of Greenhouse Gasses (GHGs) and Other Pollutants

Each step that consumes fuel or requires electrical power in the production and use of virgin aggregate described above also is responsible for the generation of GHGs and other pollutants. Water resources also are consumed and solid wastes produced either directly or indirectly in many production and transport activities. Concrete recycling helps to reduce the environmental impact of pavement reconstruction activities while helping to ensure the maintenance of our transportation infrastructure.

Carbon Sequestration Through RCA Carbonation

Research at the University of New Hampshire has shown that RCA has significant value as a sink for carbon dioxide (CO_2), a primary "greenhouse gas", through the mechanism of spontaneous carbonation, in which atmospheric CO_2 reacts with calcium hydroxide ($Ca(OH)_2$), a by-product of the cement hydration, in the concrete mortar to produce calcium carbonate (RMRC 2006). The potential for carbon dioxide sequestration is equal to all of the CO_2 that was originally evolved in from the raw materials (but not the fossil fuels) used in producing the included portland cement.

Rates of carbonation in RCA products increase with increasing humidity, increasing CO_2 concentration, increasing temperature and increasing surface area of the RCA. Figure 2 shows an example of laboratory test results documenting CO_2 removal over time

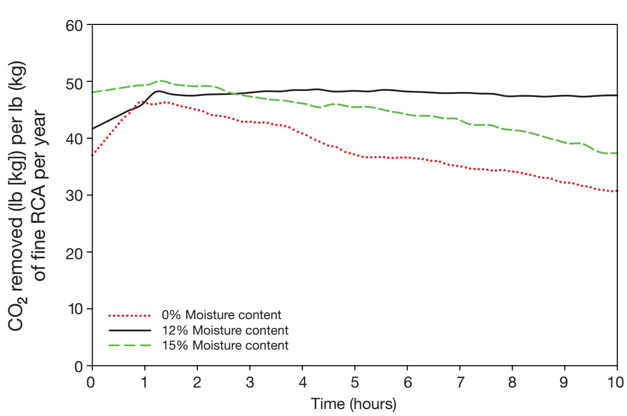

Figure 2. Illustration of carbon sequestration by fine RCA in laboratory column studies (after RMRC 2006).

for three levels of test moisture content. This study suggests that the use of RCA in unstabilized applications (e.g., unstabilized subbases, embankment stabilization, etc.) has the potential to "scrub" the local atmosphere of significant quantities of CO_2, further cementing the position of concrete as a "green" construction material.

Pavement Performance Improvements

Pavement reconstruction with either new or recycled aggregates offers the opportunity to correct pavement subgrade or subbase deficiencies to better ensure the performance of the new concrete pavement structure. Such corrections are not possible with typical rehabilitation and overlay options. Reconstruction also allows an opportunity for any existing concerns with pavement geometry, drainage and roadway safety to be addressed. Reconstruction using RCA can provide additional performance benefits through improved foundation strength and stability and increased concrete strength.

Foundation Stability

The angular, rough-textured nature of RCA results in excellent particle interlock, resulting in highly stable layers for pavement foundation, pipe bedding, and backfill applications. The use of fine RCA in pavement layers or soil stabilization applications offers the additional potential benefit of the development of additional strength and stiffness over time as the un- and partially-hydrated cement in the RCA continues to hydrate.

This secondary cementing effect can be significant, turning an "unbound" layer of dense-graded or fine RCA into a layer that behaves more like a cement-stabilized subbase. The benefits of this stiffening should be considered in predicting pavement performance, and pavement structural designs (e.g., joint spacing, slab thickness, etc.) should be engineered accordingly.

Concrete Strength

Several studies have shown that the strength and elastic modulus of concrete produced using coarse RCA may be lower than those of concrete containing all virgin aggregate if the RCA contains significant amounts of reclaimed mortar. However, research has shown that the replacement of up to 80 percent of the virgin fine aggregate with fine RCA can potentially increase the strength of the resulting concrete, with the peak strength increase occurring at a replacement rate of about 25 percent (Fergus 1981). Possible reasons for this are that the fine RCA is more coarse than natural sand, resulting in a better overall gradation to the aggregate blend, and that the supplemental cementing action also may contribute to the increased strength.

These effects are discussed further in Chapter 3 and Chapter 7, of this publication.

Recycled Concrete Pavements: A Proven Technology

Concrete recycling has been used extensively in Europe since the 1940's and in the U.S. since the 1970's (NHI 1998), with one of the first U.S. applications of RCA in pavement construction taking place in the 1940's on U.S. Route 66 (Epps et al 1980). Production of RCA in the U.S. currently averages about 100 million tons/year (91 million metric tons/year) (USGS 2000). The primary applications of RCA have been base and subbase materials, but it also has been used in concrete and asphalt paving layers, high-value rip-rap, general fill and embankment, and other applications.

Concrete recycling for paving applications is now performed in at least 41 states (Figure 3) and has the support of the Federal Highway Administration (FHWA), which states that "reusing the material used to build the original highway system …makes sound economic, environmental, and engineering sense." (FHWA 2007b, FHWA 2002). FHWA further states that "The engineering feasibility of using recycled materials has been demonstrated in research, field studies, experimental projects and long-term performance testing and analysis … When appropriately used, recycled materials can effectively and safely reduce cost, save time, offer equal or, in some cases, significant improvement to performance qualities, and provide long-term environmental benefits" (FHWA 2002).

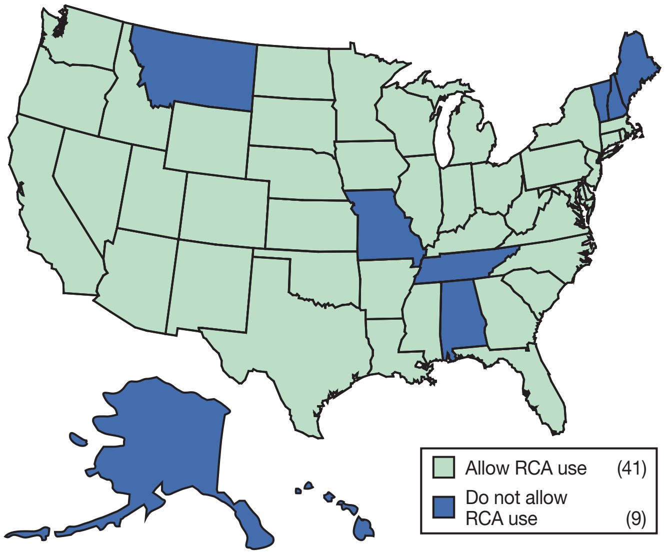

Figure 3. States that currently allow the use of recycled concrete aggregate (RCA) in pavement and other applications (FHWA 2004).

Chapter 2. Production of Recycled Concrete Aggregate (RCA)

RCA production processes should be selected and conducted to maximize the production of usable RCA in terms of both quality and quantity. Coarse RCA (material retained on the No. 4 [4.75mm] sieve) is typically more valuable and usable than fine RCA (material that passes the No. 4 [4.75mm] sieve), so efforts often are made to maximize the quantity of coarse RCA produced. RCA quality depends upon many factors, including the quality of the original concrete, the presence of contaminants, and the processes used in RCA production.

The major steps in concrete pavement recycling are: evaluation of the source concrete; preparation of the slab; 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 following sections discuss the impact of each of these steps on RCA quantity and quality.

EVALUATION OF SOURCE CONCRETE

The first step in producing RCA from a concrete pavement is to determine the quality and overall properties of the source concrete. Records of the original concrete components (aggregate sources and quality, cement type, admixtures, and reinforcing type (including fibers) and quantity), concrete strength and durability can be useful in determining the potential applications for the RCA produced. High-quality, durable concrete may be suitable for producing RCA for use in structural concrete or pavement surface layers. Lower quality materials may be best suited for subbases, fill or other applications.

PAVEMENT PREPARATION

If the RCA being produced is to be considered for use in a new concrete mixture, efforts must be made to minimize the potential for introducing contaminants throughout the production process. Contaminants are generally of much less concern for RCA intended for use in subbase aggregate and fill applications. Potential contaminants in concrete pavement recycling typically include joint sealants, asphalt concrete shoulders and patching materials, reinforcing steel and dowel bars, and soils and foundation materials (NHI 1998).

Joint sealant removal typically is accomplished using a cutting tooth sealant plow or other sealant removal tool mounted on an end loader or other piece of equipment. Some agencies elect to leave joint sealants in place prior to demolition, relying on other means of removal in the production process (especially if the RCA is intended for subbase or fill applications).

Concrete pavements with asphalt concrete patches and overlays can be processed to produce RCA for use in new concrete mixtures or other applications, but it generally is recommended that the two materials be recycled separately. Lab and field studies in the U.S. have concluded that when recycled asphalt pavement (RAP) is used as an aggregate in a concrete mixture, the asphalt cement inhibits air entrainment in the concrete mixture (Bergren and Britson 1977). However, it has been reported that Austria routinely recycles concrete with up to 30 percent coarse RAP into new concrete paving mixtures without any apparent detrimental effects (FHWA 2007a). Austrian specifications also allow up to 20 percent RAP particles in RCA used in the lower course of two-layer concrete pavement construction.

The most efficient way to remove large asphalt repairs and overlays from the concrete pavement often is through cold milling (Figure 4), although heavy pavement scrapers and bulldozers also have been used successfully (Figure 5). Front-end loaders or brooms may then be used to pick up or remove any remaining loose material.

Figure 4. Asphalt pavement surface removal using cold milling machine (Photo credit: National Highway Institute).

Figure 5. Asphalt pavement surface removal using heavy scraper and end loader (Photo credit: National Highway Institute).

Deteriorated asphalt shoulders should be removed before slab breaking operations on reconstruction projects (FHWA 1990a). This reduces lateral slab support and facilitates concrete pavement breaking and removal. Shoulders that are in good condition may remain in place for concrete inlay construction (ACPA 1993a).

PAVEMENT BREAKING AND REMOVAL

After the pavement slabs have been prepared for processing, the recycling process continues with on-site demolition. The main purpose of pavement breaking is to size the material for ease of handling and transport to the crushing plant. Breaking also should impart enough energy to maximize debonding of concrete to reinforcing steel (Yrjanson 1989, FHWA 1990a). The slabs are broken into pieces small enough (typically 18 to 24 in. [45 to 60 cm]) to be lifted and transported easily (the "pin and lift" technique, an alternative means to quickly remove full individual jointed plain concrete pavement (JPCP) slabs, may also be used but it typically requires some additional means to further break the individual slabs before they can be processed by the crushing equipment).

The most readily available equipment for this operation is the "impact breaker", which breaks the pavement by dropping or hurling a heavy mass onto the pavement (or, alternatively, onto an impact shoe sitting on the pavement surface). Examples include gravity drop hammers (Figure 6), hydraulic or pneumatic hammers (Figure 7), trailer-mounted diesel hammers (the most common option) (Figure 8), spring-arm whiphammers and drop balls (not recommended because they tend to produce a greater amount of excessively small fragments that are less easily salvaged). Production rates of 1,100 to 1,300 yd^2/hr (900 to 1,100 m^2/hr) for 8-in. (200-mm) thick concrete pavements have been achieved with diesel hammers (NHI 1998, Dykins and Epps 1987).

"Vibrating beam breakers" (also called "resonant breakers") use a large forged steel beam with a 12-in. (300-mm) square breaker plate attached at the end to break up the concrete pavement (Figure 9).

Figure 6. Examples of gravity drop hammer equipment for pavement breaking.

Figure 7. Multi-head hydraulic hammer pavement breaking equipment.

Figure 8. Trailer-mounted diesel hammer.

Figure 9. Vibrating beam pavement breaker.

The beam is excited to deliver a high-frequency, low-amplitude impact to the pavement surface, producing a smaller-sized slab fragments (generally less than 8 in. [200 mm] in diameter). This equipment is relatively quiet and does not disturb underground utilities, which makes it particularly well-suited for use in urban areas. Production rates of up to 800 yd^2/hr (670 m^2/hr) for 9-in. (225-mm) thick concrete pavements have been achieved (NHI 1998).

Several external factors affect the production rates of breaking equipment, including slab thickness, concrete strength, and amount and type of slab reinforcement. More impact energy is needed to break an existing concrete pavement as each of these factors increases. Increases in subbase support reduce impact energy requirements. Impact energy also must be controlled to minimize damage to the subbase and subgrade layers and to underlying pavement drainage facilities, utilities, and culverts. Impact energy can be varied by changing the drop height, the number of passes or the forward speed of the equipment.

Pavement breaking equipment and slab cracking patterns (Figure 10) should be selected after considering the intended crushing operation and desired product yield and gradation. For example, impact crushers typically can handle larger broken concrete pieces than compression (jaw or cone) crushers, allowing the use of a larger crack pattern and often resulting in higher breaking production rates. However, impact crushers generally yield slightly less coarse RCA and more fine RCA and minus No. 200 (75 µm) fines than do compression crushers. Maximizing coarse RCA yield may require the use of compression crushers and impact breaking equipment with an appropriate breaking pattern.

The first step in the removal process is to loosen the concrete pieces and separate any debonded reinforcing steel. Where steel mesh reinforcing or rebar are present and have not been broken or separated from the concrete by the breaking operation, a back hoe or bulldozer with a "rhino horn" attachment (a 30-in. [76-cm], curved and pointed steel pick, as shown in Figure 11) often serves as an excellent loosening tool. This tool can hook and pull the steel free from the concrete rubble. Some hand work (e.g., workers with torches or hydraulic shears) may still be required to cut the reinforcing steel and produce slab fragments with manageable sizes. Relatively small pieces of embedded steel will usually not cause problems in the crushing operations and will be removed after crushing. Dowel bars and tie bars generally also are removed during the crushing operation, but may become loose and fall out during demolition (NHI 1998).

Figure 10. Typical crack pattern for broken concrete pavement prior to removal.

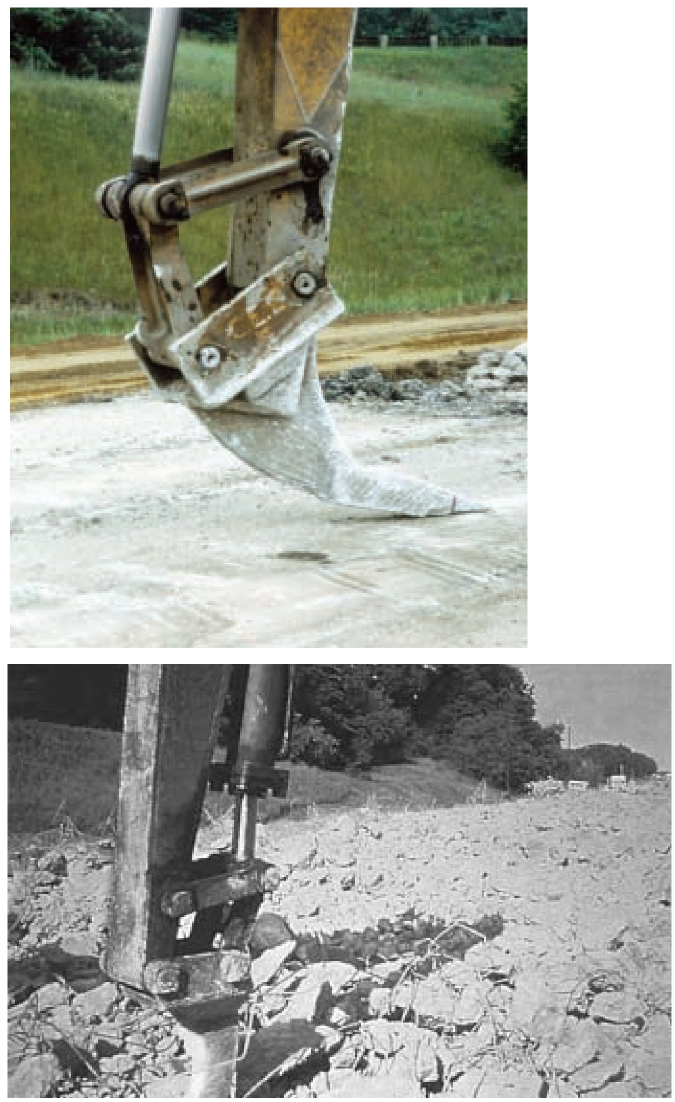

Figure 11. "Rhino horn" for use in loosening broken pavement fragments.

Front-end loaders and dump trucks can easily handle removal and transport of the broken pavement fragments to the crushing site (Figure 12). However, removal procedures vary with the intended use of the RCA.

Extra care must be taken to avoid contamination when the RCA is to be used in a new concrete mixture(s). If the concrete is situated directly on cohesive soil, this material can adhere to the broken concrete during wet weather. Soil and clay balls can be particularly troublesome, sometimes resulting in increased water demand, reduced concrete strength, and surface flaws. In such situations, it is sometimes necessary to limit removal operations to dry weather (Yrjanson 1989) or to use a 1-in. (25-mm) scalping screen ahead of the primary crusher.

Loader operators must avoid picking up subbase material with the broken concrete. The use of buckets and blades with digging teeth often helps in this regard, and small concrete fragments (diameter smaller than 6 in. [150 mm]) often are left behind in an effort to reduce the amount of dirt and other contaminants introduced to the recycling stream (NHI 1998). Also, it has been reported that rubber-tired loaders cause less subbase disturbance and pick up than do tracked loaders (ACPA 1993b).

Figure 12. Removal and transport of broken pavement fragments using end loader and dump truck.

Recommendations for maximum allowable limits on contaminants are presented in Chapter 3 of this publication.

Contaminants are usually of little or no concern in producing RCA intended for subbase and fill applications; thus, pavement removal operations can be conducted with less concern for contamination.

REMOVAL OF EMBEDDED STEEL

The removal of reinforcing steel, tie bars and dowels can occur during several phases of the recycling process, but typically is accomplished during the breaking and removal operation (particularly for continuous reinforcing steel) or following the primary and secondary crushing operations, where electromagnets often are used to pick steel from the conveyor belts (Figure 13). Manual labor may be used to supplement magnetic steel removal operations.

Figure 13. Removal of reinforcing steel on the job site or after crushing.

Salvaged steel generally becomes the property of the contractor, who can typically sell it as scrap metal. Wire mesh steel with large quantities of bonded concrete often is wasted.

CRUSHING AND SIZING

The same basic equipment used to processes virgin aggregates also can be used to crush, size and stockpile the RCA (ECCO 1999), although equipment modifications (e.g., the use of more wear-resistant components and the addition of electromagnets) permit more efficient processing of most salvaged concrete pavements.

Most concrete recycling plants have both primary and secondary crushers. The primary crusher typically reduces the material size down to about 3-4 in. (8-10 cm). The crushed material is then screened and material larger than ⅜ in. (9 mm) is fed into a secondary crusher, which breaks the material to the desired maximum coarse RCA size.

The three main types of crushers used in concrete recycling feature “jaw”, “cone” and “impact” designs, which differ in how they crush the concrete. Figure 14 illustrates the differences between these types of crushers.

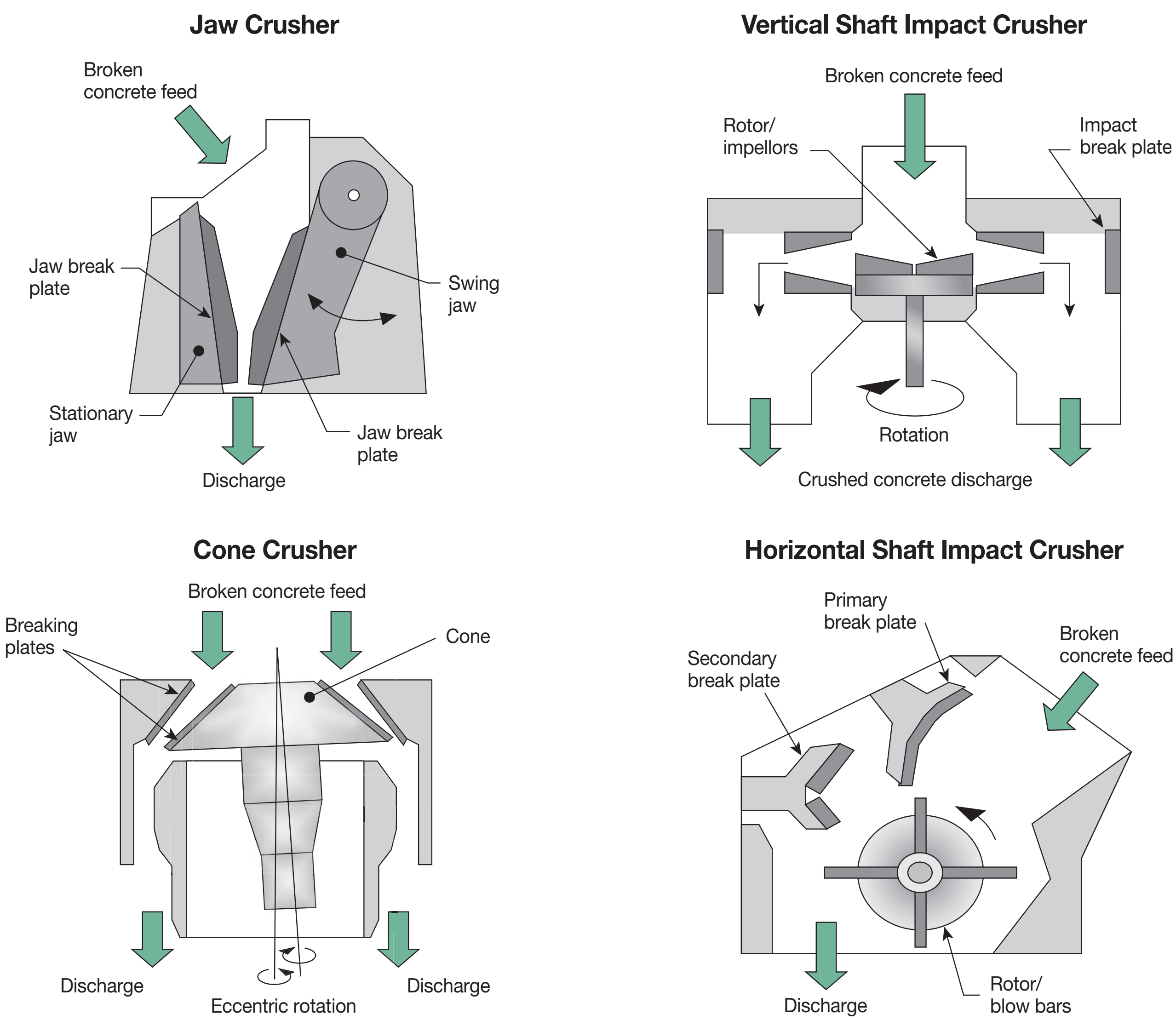

Figure 14. Schematic illustrations of various types of typical aggregate crushing equipment.

Jaw crushers use a large steel plate to compress concrete fragments against a stationary plate within the crusher housing. Aggregate top size is controlled by varying the amount of jaw closure. Jaw-type designs commonly are used in primary crusher applications because they can handle larger slab fragments than cone crushers.

Cone crushers use an eccentric rotating cone to trap and crush concrete fragments against the inner crusher housing walls. When the material becomes small enough, it escapes through the bottom of the crusher housing. Most cone crushers can handle slab fragments no larger than 8 in. (20 cm) in diameter. For this reason, they are used most often as the secondary crushing unit in concrete recycling operations.

Impact crushers use heavy steel "blow bars" mounted on a horizontal or vertical rotor to repeatedly impact concrete fragments and hurl them against steel anvils or "break plates" in the crusher housing. The rotor continues to hurl particles that are larger than the desired top size. Impact crushers tend to remove more mortar from crushed concrete particles, resulting in more fine RCA and minus No. 200 (75 µm) fines and lower coarse RCA yield. They must be fabricated to withstand the impact of any steel reinforcement that enters the crusher.

While most concrete crushing plants are designed for high-production use by large contractors, "mini concrete crushers" (capable of being towed behind a pick-up truck) also are available for small, local projects (Figure 15).

Concrete recycling conveyor systems are generally the same as for virgin aggregate crushing, except that the crushing of concrete fragments with embedded steel requires that the belt below the primary crusher be lowered to allow long pieces of steel to exit the crusher without jamming and ripping the belt.

The yield of coarse RCA from the recycling operation depends upon many factors, including the type, size, quality and quantity of virgin coarse aggregate used in the concrete, the quality and hardness of the con-

Figure 15. Mini concrete crushing plant.

crete mortar, the breaking and removal operations and the crushing processes used. Loss of material through removal operations can be as high as 10 percent (for recycling of jointed reinforced concrete pavement (JRCP) with field removal of the wire mesh) and may approach zero for jointed plain concrete pavements (JPCP). Crushing for larger top-size aggregate generally produces higher coarse RCA yields because less crushing is necessary. For example, 55 to 60 percent coarse RCA yield is common when crushing to ¾ in. (19 mm) top size, while 80 percent yield is not uncommon when crushing to 1.5 in. (28 mm) top size (NHI 1998).

BENEFICIATION

Beneficiation can be described as the treatment of any raw material to improve its physical or chemical properties prior to further processing or use. This can be a necessary step in some aggregate processing operations (including concrete crushing to produce RCA) to eliminate accidentally included organic material, excessive dust, and other contaminants that would cause problems in the intended application of the aggregate. Aggregate beneficiation takes advantage of the distinguishing properties of the materials to be separated (e.g., particle size, particle density, etc.) to concentrate the desirable components.

There are many established techniques for the removal of residual soil, loose cement mortar, undesirable minerals (e.g., chert) and other contaminants, including special crushing processes, washing, wet or dry screening, and hydraulic or heavy media separation (FHWA 2007b). Promising new technologies, such as air blowing and water floating techniques, also have been documented as being highly effective (Park and Sim 2006).

The degree of beneficiation required depends upon the condition and composition of the crushed concrete, as well as the intended use of the RCA. While often not required, washing has been shown to be beneficial in removing dust that might otherwise weaken the bond of coarse RCA particles with mortar in new concrete mixtures; such washing is comparable to the washing process that might be employed with dirty virgin aggregates. The removal of deleterious materials to levels that meet specified limits is essential for RCA intended for use in new concrete mixtures.

STOCKPILING

Coarse RCA can be stockpiled using the same techniques and equipment as are used with virgin coarse aggregate materials (Figure 16). Fine RCA stockpiles generally need to be protected from precipitation to reduce the potential for secondary cementing due to hydration of exposed and previously unhydrated (or partially hydrated) cement grains. As with virgin fine and coarse aggregates, more than two separate stockpiles may be necessary to allow the production of aggregate blends that meet project specifications.

Figure 16. RCA crusher, conveyor and stockpiling operation.

The runoff from RCA stockpiles is initially highly alkaline (e.g., one study found median pH values of 9.3 and 9.8 for fine and coarse RCA stockpiles, respectively, and this was found to not be significantly greater than the runoff from a bituminous milling stockpile, with a measured runoff pH of 8.1 [Sadecki et al 1996]) due to the leaching of calcium hydroxide from the freshly crushed material. In addition, studies have shown the presence of trace amounts of heavy metals and other naturally occurring contaminants in RCA stockpile runoff, although generally not to levels considered hazardous (Sadecki et al 1996). Runoff alkalinity usually decreases rapidly within a few weeks as the exposed calcium hydroxide is depleted through neutralization, dissolution and/or reaction with carbon dioxide in the air, etc.; similarly, the concentrations of other contaminants can be expected to decrease rapidly with time as well (Snyder 1995). In addition, runoff alkalinity is partially neutralized by rainwater pH (which is in the range of 5.2 to 5.4), dilution as rainwater concentrates, the effects of soil buffering and equilibration with atmospheric CO_2 during transport from the RCA source to local surface waters. The bottom line is that there appear to be no negative environmental effects from using RCA that would significantly offset the positive environmental effect of reduced use of virgin aggregate and landfills (Reiner 2008).

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. Such systems typically utilize primary and secondary crushers that have been specially adapted for in-place recycling and are mounted on crawler tracks. Figure 17 illustrates how the coarse RCA and fine RCA can be separated during recycling operations, making it easy to use only the coarse RCA in the subbase and/or shoulders.

Figure 17. In-place recycling of an existing concrete pavement with the coarse and fine RCA being separated as part of the process (Photo credit: Iowa DOT).

This in-place concrete pavement recycling technique was first used on I-80 near Des Moines, IA in 1994 and has been used on several projects since then. Production rates vary with the material being processed and the amount of reinforcing steel involved, but rates exceeding 2,000 lane-ft/day (610 lane-m/day) have been achieved (ECCO 1997).

In-place recycling saves the cost of fuel and labor involved in hauling raw and processed materials to and from the job site (in addition to the material and fuel savings associated with using recycled materials instead of mining virgin aggregates).

RECYCLING OF RETURNED 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. Research has shown that recycling of this material, as with recycling of any existing concrete material, presents significant sustainable benefits, including a reduction of landfill use and a reduction in virgin aggregates use (Obla 2009).

Chapter 3. Properties and Characteristics of RCA

RCA must generally meet the same requirements as virgin aggregate for the target application (e.g., concrete mixture, subbase layer, etc.). A summary and comparison of the typical properties of virgin and recycled concrete aggregates is presented in Table 1. There are some clear differences in the physical, mechanical and chemical properties of typical virgin aggregate and RCA, mainly because of the inclusion of reclaimed mortar in the RCA. Most of these differences, however, require little (if any) consideration or procedural adjustment for use in typical applications.

The following sections summarize the properties and characteristics of RCA that may affect the properties of concrete and foundation layers constructed using the material.

PHYSICAL PROPERTIES

Particle Composition, Shape and Texture

RCA particles are comprised of reclaimed virgin aggregate, reclaimed mortar or both. The relative proportions of these components varies with the original concrete mixture design, the properties of the virgin coarse aggregate particles (i.e., the angularity and surface texture, strength and elasticity), the bond between the virgin aggregate particles and the mortar, and the type and extent of crushing used in production.

Particle composition also varies with particle size. Larger particles tend to contain greater proportions of reclaimed virgin aggregate while particles passing the No. 4 (4.75 mm) sieve often are mainly crushed mortar (Fergus 1980).

Table 1. Comparisons of Typical Virgin Aggregate and RCA Properties (Snyder et al 1994)

Property	Virgin aggregate	RCA
Shape and Texture	Well-rounded, smooth (gravel) to angular and rough (crushed rock)	Angular with rough surface
Absorption Capacity	0.8 – 3.7 percent	3.7 – 8.7 percent
Specific Gravity	2.4 – 2.9	2.1 – 2.4
L.A. Abrasion Test Mass Loss	15 – 30 percent	20 – 45 percent
Sodium Sulfate Soundness Test Mass Loss	7 – 21 percent	18 – 59 percent
Magnesium Sulfate Soundness Mass Loss	4 – 7 percent	1 – 9 percent
Chloride Content	0 – 2 lb/yd^3 (0 - 1.2 kg/m^3)	1 – 12 lb/yd^3 (0.6 – 7.1 kg/m^3)

RCA particles tend to be highly angular and have rough surfaces (similar to crushed rock), although these characteristics vary with the nature of the included virgin aggregate and the type and extent of crushing used in production. Some crushing processes remove most of the mortar from smooth-surfaced virgin coarse aggregates, producing a coarse RCA that closely resembles the original virgin coarse aggregate in all respects.

Gradation

With appropriate adjustments, concrete crushing plants can be set up to produce almost any desired gradation, although there often is an excess of fine RCA produced.

Proper screen selection will enable a crushing plant to meet the gradation limits for concrete aggregates set forth in ASTM C33 (or AASHTO M43 gradations 57 and 67).

Table 2 shows a variety of RCA gradations that have been produced on various concrete pavement recycling projects.

Absorption Capacity

Absorption capacities of RCA are generally much higher than those of conventional aggregates (Table 1). The primary factor affecting RCA absorption is the amount of reclaimed mortar that is present because the reclaimed mortar is usually more porous and absorbent and has a greater surface area than most types of virgin aggregate. As RCA particle size decreases, mortar content and absorption tend to increase, as shown in Table 3 (Fergus 1980, Swedeen 1990, Yrjanson 1989).

*Table 2. Typical RCA Gradations from Crushing Operations (percent passing)**

Sieve size		Iowa**		Oklahoma***		Michigan****		Korea*****	
		Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
1½ in.	(38 mm)	100	—	—	—	100	—	—	—
1 in.	(25 mm)	72	—	100	—	98	—	100	—
0.8 in.	(20 mm)	—	—	—	—	—	—	96	—
¾ in.	(19 mm)	39	—	98.5	—	76	—	—	—
0.6 in.	(15 mm)	—	—	—	—	—	—	33	—
½ in.	(12.5 mm)	21	—	46.5	100	43	—	—	—
⅜ in.	(9.7 mm)	9.3	100	11.2	99.2	25	100	32	100
No. 4	(4.75 mm)	2.9	76	1.5	78.8	20	99	0	100
No. 8	(2.36 mm)	2	51	—	—	—	61	—	82
No. 10	(2.00 mm)	—	—	—	48.5	—	—	—	—
No. 16	(1.18 mm)	—	30	—	—	—	40	—	54
No. 30	(600 µm)	—	16	—	—	—	28	—	30
No. 40	(450 µm)	—	—	—	19.4	—	—	—	—
No. 50	(300 µm)	—	8	—	—	—	19	—	10
No. 80	(180 µm)	—	—	—	9.2	—	—	—	—
No. 100	(150 µm)	—	3.5	—	—	—	12	—	2
No. 200	(75 µm)	0.7	2	—	4.5	—	—	—	—

* Gradations shown are production examples and are not necessarily recommended.
** Produced 65% coarse RCA, 35% fine RCA - Yrjanson 1989
*** Produced 60% coarse RCA, 40% fine RCA - Yrjanson 1989
**** Jaw crusher used - Yrjanson 1989
***** Advanced recycling techniques applied - Park and Sim 2006

Table 3. Properties of One Coarse RCA (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

The section titled *Water Demand* in Chapter 5 of this publication describes techniques for addressing the effects of increased absorption capacity in concrete mixture design, including prewetting of RCA, limiting the inclusion of fine RCA, and the use of mineral and chemical admixtures.

Specific Gravity

Concrete mortar (comprising sand, cement, water and air) generally has a much lower specific gravity (2.1 to 2.4) than most virgin aggregate types (2.4 to 2.9). Therefore, RCA specific gravity mainly depends upon the relative proportions of reclaimed mortar and reclaimed virgin aggregate, and tends to decrease with particle size (generally increasing mortar content), as shown in Table 3.

MECHANICAL PROPERTIES

Los Angeles Abrasion Mass Loss

The Los Angeles (L.A.) abrasion test (ASTM C131 or AASHTO T96) measures the amount of particle degradation (in terms of percent mass loss) that takes place under standard aggressive handling conditions. L.A. abrasion mass loss values typically are higher for RCA than for the virgin aggregates contained in the RCA, as indicated in Table 1. This is usually attributed to the presence of the softer cement mortar and the presence of particles that were only partially fractured during the crushing process (Snyder and Vandenbossche 1993).

L.A. abrasion test values for RCA usually are within specified limits. For example, ASTM recommends a limit of 50 percent mass loss for aggregates intended for use in concrete, and 40 percent for crushed stones intended for use in roadbed construction. Most states specify the same L.A. abrasion test result limits for both virgin aggregates and RCA. Specifications may waive L.A. abrasion testing for either RCA or virgin aggregate if the material has a good performance record.

Freeze-Thaw Durability

Concrete pavements that have developed freeze-thaw durability cracking ("D-cracking") due to the use of frost-susceptible coarse aggregate in the concrete commonly have been recycled into unstabilized subbase layers and fill without any problems relating to the durability of the aggregate. Such pavements also have been successfully recycled into new concrete layers since at least the early 1980's.

When used as coarse aggregate in new concrete, the RCA has commonly been crushed to a ¾-in. (19-mm) top size. This approach has been successful in preventing recurrent D-cracking, but often has resulted in reduced aggregate interlock load transfer capacity on undoweled pavements. However, because most jointed concrete pavements (e.g., JPCP and JRCP) constructed today feature short panel lengths and dowel load transfer systems, aggregate interlock load transfer capacity is not of concern for these pavements.

Two projects containing RCA from D-cracked pavements are described in Chapter 6 of this publication.

CHEMICAL PROPERTIES

Alkali-Silica Reactivity (ASR)

The potential for ASR in new concrete containing RCA is affected by the original alkali level of the old concrete, the remaining potential reactivity of the recycled aggregate, and the alkali content of new concrete (Stark 1996). The use of low-lime Class F fly ash and slag cement has greatly reduced ASR expansion in new concrete. If fly ash and/or slag cement are being used to mitigate ASR in concrete utilizing RCA from an ASR-damaged concrete, the appropriate dosage levels should be determined by using ASTM C1567. Other mitigating techniques include limiting the content of RCA fines, reducing concrete permeability through a lower water content, using admixtures such as lithium nitrate, and reducing slab exposure to moisture. Chapter 6 of this publication describes a project in Wyoming that used fly ash and slag cement to reduce the potential for recurrent ASR in a concrete pavement constructed using RCA from an ASR-affected source.

Research and construction projects have demonstrated that, with appropriate selection of cementitious materials, RCA containing reactive (and even highly reactive) aggregate can be used safely.

Sulfate Soundness Mass Loss

Sulfate soundness tests are performed to provide an indication of aggregate resistance to weathering and other environmental effects. The two most widely used tests are the sodium sulfate soundness test and the magnesium sulfate soundness test, which are described in ASTM C88 and AASHTO T104.

RCA commonly fails the sodium sulfate soundness test while passing the magnesium sulfate soundness test with results that are better than those of the original aggregate (Snyder and Vandenbossche 1993). For example, sodium sulfate soundness mass losses typically range from 18 to 59 percent for RCA materials (Hansen 1992); ASTM recommends a limit of 12 percent. Hansen also reported magnesium sulfate test losses of 0.9 to 2.0 percent for coarse RCA while the virgin coarse aggregates used had a loss of 3.9 percent; ASTM recommends a limit of 18 percent. This contradiction between the two test methods suggests that either or both of these tests may be inadequate for predicting the durability of recycled aggregates. As a result, these tests often are waived for recycled concrete products.

Chloride Content

High chloride levels have been found in RCA produced from sources with long-term exposure to deicing chemicals. Significant amounts of chlorides often raise concerns about the potential for problems with concrete durability, set times (e.g., sodium chloride [NaCl] acts as a set accelerator) and corrosion of embedded steel. No serious problems caused entirely by high chloride contents have been reported; however, some testing might be necessary when using RCA with high chloride levels in JRCP or continuously reinforced concrete pavements (CRCP) to ensure that the chloride levels are not of concern.

Much of the chloride content in RCA has been found to be concentrated in fine particles produced from concrete at the pavement surface. For example, the total chloride content of RCA from I-84 near Waterbury, CT was found to be 12, 0.96 and 0.27 lb/yd^3 (7.1, 0.57 and 0.16 kg/m^3) at depths of 1.5, 4.0 and 6.5 in. (38, 102 and 165 mm) below the surface (Lane 1980). The RCA from this project was used to produce fresh paving concrete containing 1.93 lb/yd^3 (1.14 kg/m^3) total chloride. A typical NaCl limit for highly reinforced concrete (e.g., bridge decks) is approximately 4 lbs/yd^3 (2.4 kg/m^3) (Yrjanson 1989, Forster 1986). No critical level of chloride concentration has been clearly defined for pavements (Forster 1986).

It is best to check the chloride content of any recycled material that may contain excessive salt, and then estimate the corresponding chloride content of the resulting mixture (Forster 1986). If chloride levels are found (or believed) to be problematic, possible solutions include the use of epoxy-coated reinforcing steel and washing the fine RCA to reduce the amount of material passing the No. 200 (75 µm) sieve and the chloride content (Forster 1986, Van Matre and Schutzbach 1989).

Precipitate Potential

Crushing concrete reveals previously unexposed surfaces that usually contain some calcium hydroxide (a by-product of the cement hydration reaction) as well as some unhydrated or partially hydrated cement grains. Calcium hydroxide is highly soluble and is easily leached from the RCA particles in stockpiles and drainable subbase layers, resulting in highly alkaline runoff and effluent. The dissolved calcium hydroxide can combine with CO_2 (absorbed into the solution from the atmosphere) to form calcium carbonate, which precipitates out of solution to form a heavy, creamy substance that can fill pavement drain pipes and clog filter fabrics. Dust and other fine particles from the crushing, screening and handling operations also can settle on filter fabrics and in drain pipes, further exacerbating the problem (as described in the next section of this publication). Over time, these materials can clog drain pipes and blind filter fabrics.

Suggestions for avoiding this problem are presented in Chapter 7 of this publication and in ACPA's EB204P (ACPA 2007). These suggestions include using only coarse, washed RCA in drainable subbase layers, using daylighted subbase drainage designs, or modifying the filter fabric design to ensure that it does not completely surround the edge drain pipe trench.

Precipitate and crusher fines do not pose a problem for concrete mixture and undrained subbase layer applications where the presence of partially hydrated cement grains can actually aid in stabilizing and strengthening the layer.

CONCERNS WITH SURFACE DUST AND CONTAMINANTS

Small quantities of fine particles ("crusher dust") often remain on RCA particles after production. This dust *may* increase water demand and decrease aggregate-mortar bond quality in new concrete mixture applications and *may* migrate into drainage systems and filter fabric in drainable subbase layer applications. Aggregate washing, as is often performed in processing dirty virgin aggregates, is not universally required in either of these applications, but may be helpful or desirable in some cases.

Contaminants are usually a concern only for RCA that will be used in new concrete mixtures and not for unstabilized subbase and fill applications.

Contamination usually is not a problem for rural highway or airport recycling that use materials removed from the project site. Initial preparation (including removal of asphalt, if required) and careful removal by loader operators (to avoid inclusion of subbase and soil materials) usually provides adequate contaminant control. However, when RCA is manufactured from sources other than concrete pavements, as is common in urban recycling operations, it should be noted that contaminants such as plaster, soil, wood, gypsum, asphalt, plastic, vinyl and rubber can be present in sufficient quantities to warrant concern.

For new concrete mixture applications, RCA contaminants generally should be limited to the same values required for virgin coarse aggregate. Suggested limits are presented in Chapter 7 of this publication.

Chapter 4. Uses of RCA

RCA can be produced to be a substitute for almost any conventional virgin aggregate and, because of the chemical and residual cementitious properties of the reclaimed mortar, RCA also is useful in some additional applications. Some of the most common and interesting applications (and limitations) are described below.

UNSTABILIZED (GRANULAR) SUBBASE AND BACKFILL

Unstabilized (granular) subbase applications are common for RCA produced from concrete pavements because of the potential for superior performance, economic savings, conservation of resources and environmental considerations (see ACPA's EB204P (ACPA 2007) for additional details). Of the 41 states indicating their production of RCA in 2004, 38 stated that they use the material for aggregate subbase applications (FHWA 2004). In fact, some states believe that RCA outperforms virgin aggregate in unstabilized subbase applications (FHWA 2004).

An important benefit to using RCA as unstabilized subbase material is that the presence of contaminants (e.g., asphalt concrete, joint sealant materials, etc.) is of relatively little concern. For example, Minnesota allows up to 3 percent asphalt binder by weight of aggregate, and California has no limit on the relative proportions of RAP and RCA in their subbase materials. This provides maximum contractor flexibility in production and construction. Figure 18 shows the presence of both RAP and RCA in a Minnesota RCA stockpile (FHWA 2004).

Figure 18. Photo of RCA aggregate subbase stockpile (containing both concrete and asphalt material) in Minnesota (FHWA 2004).

Through process control and blending, contractors can produce RCA subbase material with almost any gradation.

Unstabilized Dense-graded Subbase

RCA is an effective and economical material for unstabilized dense-graded subbase applications. When properly graded, the angular nature of the product provides excellent stability. In addition, fine RCA often experiences a degree of secondary cementing, which further strengthens and stiffens the subbase layer.

RCA should not be used in unstabilized dense-graded subbase layers that will provide any signifi-

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cant flow or runoff to pavement edge drainage systems because the contribution of crusher dust and dissolved calcium hydroxide can form deposits in filter fabrics and pipe drains.

Additional recommendations concerning the use of RCA in unstabilized dense-graded subbases are presented in Chapter 7 of this publication.

Unstabilized Free-draining Subbase

RCA typically makes excellent unstabilized free-draining subbase material when the production yields relatively angular, rough-textured particles that can be graded to applicable specification requirements. When these conditions are met, RCA can be placed to provide a subbase layer that meets typical free-draining subbase permeability requirements and is highly stable.

The use of RCA in unstabilized free-draining subbase layers has been associated with the deposit of crushed concrete dust and leachate (calcium carbonate precipitate) in drainage pipes and on filter fabric. These products can clog the fabrics and pipes, reducing the capacity of the drainage system. The potential for these problems can be greatly reduced by washing the RCA (to remove crusher dust) and by eliminating fine RCA (passing the No. 4 [4.75 mm] sieve) from the subbase (Bruinsma 1995). Subbase layer stabilization with cement or asphalt also is effective in practically eliminating dust and leachate concerns.

Drainage systems also can be designed to allow residual crusher dust to settle in a granular filter layer while only partially wrapping the longitudinal drain trench with filter fabric, as shown in Figure 19. Note that the filter fabric (geotextile) does not completely surround the trench, which prevents the fabric from being clogged by leachates or other fine particles carried by water flowing through the subbase, and the drain is offset at least 3 ft (1 m) from the edge of paving whenever possible, which protects it from construction traffic.

Even still, such edge drainage systems have had a problematic history in the field, even when the subbase consisted of 100% virgin aggregates. Problems

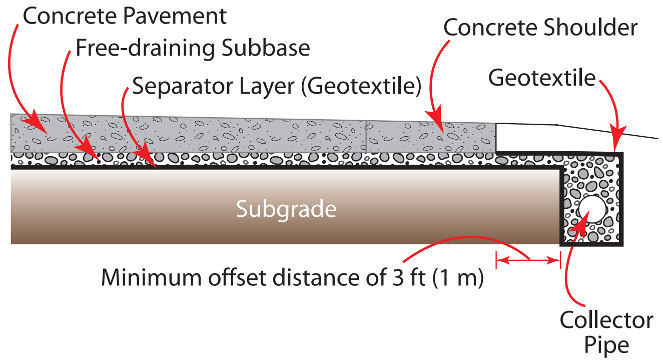

Figure 19. Typical drainage system detail for use of free-draining RCA subbase.

range from crushing of the drainage pipe during construction, yielding it ineffective, to clogging of the pipe due to a lack of maintenance, mouse nests, etc. (Baumgardner 2002). In fact, inadequate maintenance has been sited as an universal problem (FHWA 1990b), prompting FHWA to recommend that “if a state highway association [SHA] is unwilling to make the necessary maintenance commitment, subsurface drainage systems should not be provided” (Baumgardner 2002).

Though often disregarded in the past due to the mindset that they were less effective at removing water from the pavement, daylighted subbases have proven to be as effective as edge drainage structures (FHWA 2009). In a daylighted subbase, water and any free material that finds its way into the free-draining subbase will have many paths to follow that could potentially lead out of the pavement structure (Rodden and Voigt 2008). The magnitude of potential paths out of a daylighted subbase greatly reduces the probability of clogging of the subbase when using a RCA.

Additional recommendations concerning the use of RCA in unstabilized free-draining subbases are presented in Chapter 7 of this publication.

CEMENT-STABILIZED SUBBASE

Cement-stabilized subbase layers (e.g., cement-treated subbase (CTB) and lean concrete subbase (LCB)), also can be constructed using RCA. Coating or embedding the RCA in fresh cement paste or mortar prevents the migration of crusher fines and the dissolution and transport of significant amounts of calcium hydroxide, which can otherwise form calcium carbonate precipitate in drain pipes (for more on this topic, see the section titled *Precipitate Potential* in Chapter 3 of this publication).

The physical and mechanical properties of RCA (particularly the absorption characteristics) must be considered in the design and production of CTB and LCB, similar to their consideration in concrete production using RCA, as described below.

CONCRETE MIXTURES

RCA can be (and has been) incorporated as the primary or sole aggregate source in new concrete pavements. For example, RCA has been used in concrete mixtures in the U.S. since the 1940's for roadway surfaces, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundations and even structural concrete (NHI 1998, ECCO 1999). The design and performance of several RCA concrete pavements in the U.S. is discussed in Chapter 6 of this publication. The use of RCA also is common in the lower lift of two-lift concrete pavements in Europe (FHWA 2007a).

RCA also can be used in paving surfaces constructed using econocrete, which is a lower strength, more inexpensive concrete mixture that is identical in concept to LCB but is used in pavement surfacing.

The basic techniques for batching, mixing, delivery, placement and finishing need not be significantly different than those used for concrete mixtures containing virgin aggregate.

Two concerns when utilizing RCA in concrete mixtures are increased water demand and premature stiffening of the mixture caused by the presence of fine particles and the more absorptive nature of reclaimed mortar. Some agencies address these problems by limiting or eliminating the inclusion of fine RCA in concrete mixture applications. Presoaking RCA and maintaining it in a proper moisture state prior to use also can reduce these problems. These and other approaches are discussed in Chapter 5 and Chapter 7 of this publication.

Air entrainment can be difficult to achieve if certain contaminants are present in the RCA in sufficient quantities, and the measurement of air content in the fresh mixture can be complicated by the presence of entrained and entrapped air in the reclaimed concrete mortar (Wade et al 1997).

It also should be considered that the physical and mechanical properties of concrete products containing RCA may vary from those containing virgin aggregate. For example, the strength and modulus of elasticity of RCA concrete may be lower and the CTE higher than for concrete prepared using virgin aggregate when all other factors remain constant. Another example is that the potential for aggregate interlock load transfer often is reduced when using RCA coarse aggregate because the mortar comprising a portion of the particles is less resistant to abrasion effects than most virgin aggregates. Differences in strength and other physical properties often can be offset by modifying other aspects of the mixture design (e.g., reducing water-cementitous material ratio and/or including certain mineral admixtures) or the structure (e.g., increased concrete pavement thickness). Structural matters, such as load transfer, can usually be addressed with structural design modifications (e.g., required use of dowel bars at transverse joints) (Wade et al 1997).

There also have been concerns about recycling old concrete with freeze-thaw durability or ASR problems. However, modifications to traditional crushing and mixture design procedures have proven successful in preventing the reoccurrence of durability and reactivity problems in pavements containing RCA, as described in Chapter 6 of this publication.

Additional recommendations concerning the use of RCA in concrete mixtures are presented in Chapter 7 of this publication.

ASPHALT PAVEMENT AND ASPHALT-STABILIZED SUBBASE

RCA has been used successfully in new asphalt pavement and asphalt-stabilized subbase applications. Typical RCA particle angularity and rough texture provide excellent potential for stability and surface friction, and the use of asphalt to encapsulate RCA particles effectively eliminates the potential for clogging of drainage structures in subbase applications.

Unfortunately, the more absorptive nature of typical RCA particles significantly increases asphalt binder demand, which often increases costs prohibitively.

OTHER APPLICATIONS

Granular Fill

Crushed concrete is an economical and highly stable material that is well-suited for granular fill applications. This is a particularly good application for fine RCA products, which may be produced in quantities that are excessive for subbase, concrete mixture and other applications.

Erosion Control (Rip-rap)

Most states allow the use of recycled concrete for erosion control ("rip-rap") or slope stabilization (FHWA 2004). In this application, the concrete pavement is broken into pieces that are 6 in. (150 mm) or larger. Maximum size often is dictated by aesthetic consideration and original pavement thickness (to avoid using large flat pieces). Protruding steel usually is removed prior to use. An example RCA rip-rap installation is shown in Figure 20.

Innovative Applications

Numerous other applications for RCA products have been implemented, researched or suggested, including: soil stabilization, pipe bedding, landscape materials, railroad ballast, agricultural soil treatments (similar to soil modification using lime), treatment of acidic lake waters, trickling filters and effluent treatment, components of SO_2 scrubbers, ingredients in masonry block production, and formation of artificial reefs for establishing oyster beds. Additional details concerning these applications can be found in Vandenbossche and Snyder (1993), FHWA (2004) and CMRA (2008).

Figure 20. Photo of recycled concrete pavement used as "rip-rap" for erosion control (Photo credit: Blessing Construction, Kearney, NE).

Chapter 5. Properties of Concrete Containing RCA

When RCA is used in the production of 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. For example, when little reclaimed mortar is present in coarse RCA and virgin fine aggregate is used, the handling characteristics and engineering properties of the resulting concrete will be practically the same as if all virgin aggregate had been used; if the new mixture contains only coarse and fine RCA, these characteristics and properties probably will be quite different from those of traditional concrete mixtures when all other mixture design factors remain constant. Changes in mixture design and admixture usage can reduce (and sometimes eliminate) many differences in the properties of RCA concrete mixtures.

This chapter describes the impact of using RCA on the properties of fresh (plastic) and hardened concrete and describes measures that can be taken to mitigate any potentially negative effects.

PROPERTIES OF FRESH (PLASTIC) RCA CONCRETE

The use of RCA in concrete mixtures can alter the properties and behavior of the fresh concrete (also known as "plastic concrete"), mainly because of the more porous, rough-textured nature of the reclaimed mortar that comprises a portion of the RCA. The magnitude of the effects varies with the nature and quantity of reclaimed mortar that is present. A summary of the possible ranges of these effects on fresh concrete is presented in Table 4 and a brief discussion of each property effect is presented in the following sections. Appropriate techniques for successfully addressing any adverse effects also are discussed in this section and in Chapter 7 of this publication.

Workability, Finishability and Water Bleeding

Well-rounded, compact aggregate particles with smooth surface texture are most effective in pro-

Table 4. Effects of RCA on Fresh Concrete Properties and Behavior (after FHWA 2007b, ACI 2001)

Property	Range of expected changes from similar mixtures using virgin aggregates	
	Coarse RCA only	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

moting concrete workability. Many natural sands and gravels have these characteristics, but RCA particles tend to be angular and rough-textured, which can increase the harshness of fresh concrete mixtures. The irregular shape and texture of *coarse* RCA particles have generally not caused significant workability problems. The use of *fine* RCA however, can greatly increase the harshness of the mixture as the angular RCA particles replace the more spherical conventional sands that often act as tiny ball bearings, decreasing the workability of the mixture and making it more difficult to finish properly (Yrjanson 1989). Water bleeding from RCA concrete is generally slightly less than that from mixtures prepared using virgin aggregates (Mukai et al 1979, Narud 1983).

To produce the same workability as a conventional concrete mixture, about 5 percent more water is required for a mixture containing coarse RCA (Mukai et al 1979), and about 15 percent more water is needed for a mixture containing both coarse and fine RCA (Buck 1976). This additional water demand increases the water-cementitious materials (w/cm) ratio, resulting in corresponding decreases in strength.

For this reason, it is common to control workability by limiting the use of fine RCA in concrete mixtures to 30 percent or less replacement of natural sand. When greater amounts of fine RCA are used, chemical admixtures (such as water reducers and superplasticizers) and/or fly ash (which consists of very fine spherical particles) are useful in improving concrete workability. The Illinois DOT, for example, successfully used fly ash and small amounts of natural sand to utilize both coarse and fine RCA in the concrete mixture for a new concrete inlay (Van Matre and Schutzbach 1989).

Water Demand

The higher absorption capacities of RCA (especially fine RCA) can lead to a rapid loss of workability, which can severely limit the time available for placing and finishing the concrete. This may tempt contractors to add water at the jobsite, potentially resulting in concrete strength reductions and durability issues. Therefore, it is recommended that contractors not be allowed to add water in excess of the approved mixture design at the jobsite. Problems associated with the rapid loss of workability should be addressed by altering and controlling the moisture content of the RCA before mixing.

Absorption problems have been addressed successfully by washing or wetting the aggregate and maintaining it in a moist (e.g., saturated, surface-dry (SSD)) condition until batching. On very small projects it may be possible to modify mixing and batching procedures to avoid absorption problems (e.g., adjusting batch water for RCA absorption, then combining RCA and water and allowing 15 minutes of soak time before combining with other batch ingredients).

Air Content

Air contents of fresh concrete containing RCA often are up to 0.6 percent higher and are slightly more variable than the air contents of fresh concretes using conventional aggregates (Snyder and Vandenbossche 1993). This is generally assumed to be caused by the air that is entrained and entrapped in the reclaimed concrete mortar (Wade et al 1997). Because of this, it may be necessary to either increase total target air contents for RCA concrete mixtures or to use air measurement systems that measure only the air in the fresh paste (e.g., volumetric air content measurement (ASTM C173 / AASHTO T196) or the air void analyzer (AVA), as described in Fick 2008 and Taylor et al 2006). An alternate approach is to use an aggregate correction factor to correct for air voids in the reclaimed mortar, as has been done in Wisconsin (Yrjanson 1989).

The use of RCA in new concrete mixtures should have no impact on the effectiveness of air-entraining admixtures unless certain contaminants (e.g., asphalt or other petroleum-based materials) are present in sufficient quantities. For example, the recycling of asphalt and concrete together into a new concrete surface was considered the source of air entrainment problems on a project in Iowa (Bergren and Britson 1977).

PHYSICAL AND MECHANICAL PROPERTIES OF HARDENED RCA CONCRETE

The effects of RCA on the physical and mechanical properties of hardened concrete (e.g., strength, elastic modulus, etc.) have been the subject of many studies. The magnitudes of these effects can range from nonexistent to significant, depending upon the nature, composition and gradation of the RCA. A summary of the possible ranges of these effects on fresh concrete is presented in Table 5 and a brief discussion of each property effect is presented in the following sections.

Changes in mixture design (e.g., reduced w/cm ratio) and admixture usage (both chemical admixtures and the use of supplemental cementitious materials) can reduce (and sometimes eliminate) many of these effects; in other cases, it is simpler to consider the expected RCA concrete properties in the structural and geometric design of the pavement and develop the design accordingly. Appropriate approaches to mixture proportioning modifications and other structural or geometric adjustments are discussed in some portions of this section and in Chapter 7 of this publication.

Strength

Concrete containing coarse and/or fine RCA can be produced with adequate levels of compressive and flexural strength for paving and other applications, sometimes even with 100% replacement of virgin aggregate with RCA (Yrjanson 1989, ACI 2001). Lab and field tests also show adequate rates of strength development for concrete mixtures using RCA.

When all other mixture design and curing parameters are held constant, RCA concrete strength generally varies directly with the strength of the source concrete and varies inversely with the reclaimed mortar content (both coarse and fine RCA) and water-to-cement ratio for the new concrete mixture (Hansen and Narud 1983). Hansen (1986) found that strength reductions range from approximately 0 to 24 percent when only coarse RCA is used, and can reach about 40 percent when both coarse and fine RCA is used. The majority of the strength loss was attributed to particles passing the No. 10 (2 mm) sieve. Large strength reductions have not been observed on RCA paving projects in the U.S., as is documented in Chapter 6 of this publication. Figure 21 presents a summary of compressive strength test data showing the relatively minor strength reduction for concrete containing only coarse RCA.

Strength reductions in RCA have been attributed to the inherently weaker composition of the RCA (caused by the reclaimed mortar component) and the greater number of bonded interfaces in RCA concrete (i.e., more potential failure surfaces, including virgin aggregate-old mortar, virgin aggregate-new mortar, and old mortar-new mortar) (Snyder 1994).

Table 5. Effect of RCA on Physical and Mechanical Properties of Hardened Concrete (after FHWA 2007b, ACI 2001, Hansen 1986)

Property	Range of expected changes from similar mixtures using virgin aggregates	
	Coarse RCA only	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% more	70% to 100% more
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

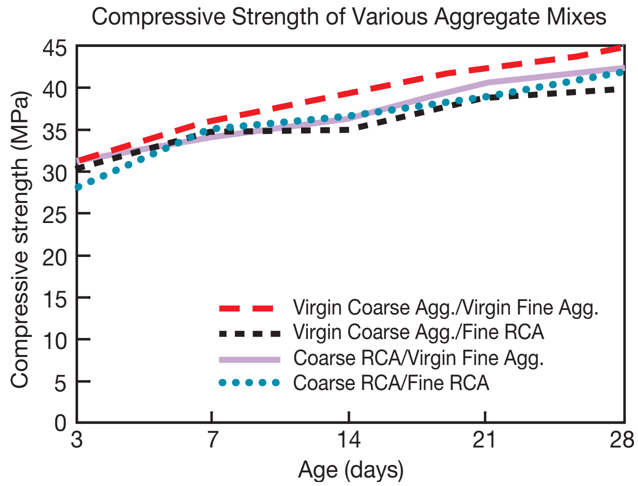

Figure 21. Compressive strengths of concretes containing different combinations of coarse and fine aggregates from virgin and recycled sources (Won 2007).

Blends of virgin and recycled fine aggregates (up to about 30 percent replacement) can be used in concrete mixtures to produce concrete with higher strength than can be obtained from using either virgin or recycled aggregates alone (Fergus 1981). This increase in strength has been attributed to improvements in the gradation of the blended fine aggregate, particularly over the No. 30 and No. 60 (600- and 300-µm) sieves, where RCA fines tend to be deficient (Fergus 1981).

Strength reductions from the use of RCA in concrete mixtures can be offset (or eliminated) by modifying the concrete mixture design to reduce the w/cm ratio (often in combination with the use of water-reducing admixtures) and/or the use of mineral admixtures such as fly ash or slag cement.

Modulus of Elasticity

The static modulus of elasticity of RCA concrete, like strength, is affected mainly by reclaimed mortar content and the w/cm ratio. When other mixture design parameters are held constant, the elastic modulus of concrete containing only coarse RCA is typically 10 to 33 percent lower than that of conventional concrete. When both coarse and fine RCA are used, the difference increases to 25 to 40 percent (ACI 2001). These reductions are attributed to the increased overall mortar content (new and reclaimed), which has a lower elastic modulus than most virgin aggregate.

Coefficient of Thermal Expansion and Contraction (CTE)

Tests of cores retrieved from several test sites around the U.S. suggest that the CTE of RCA concrete is typically about 10 percent higher than for conventional concrete (the observed range was approximately up to 30 percent higher) (Wade et al 1997). The CTE is primarily a function of virgin aggregate type and content.

Increased CTE values cause higher concrete pavement curling stresses when other factors remain constant. In jointed concrete pavements (e.g., JPCP and JRCP), these increases in curling stresses can usually be offset by reducing the panel dimensions.

Drying Shrinkage

Drying shrinkage is primarily a function of paste content and w/cm ratio and is restrained by virgin aggregate particles. Because concrete manufactured using RCA generally presents a higher paste content (considering both new and reclaimed paste), it is no surprise that studies have found 20 to 50 percent higher shrinkage in concrete containing coarse RCA and natural sand, and 70 to 100 higher shrinkage in concrete containing both coarse and fine RCA (ACI 2001 after BCSJ 1978).

Increased drying shrinkage values cause higher concrete pavement moisture warping stresses when other factors remain constant. In jointed concrete pavements (e.g., JPCP and JRCP), these increases in warping stresses can usually be offset by reducing the panel dimensions.

Creep

The creep of RCA concrete typically is 30 to 60 percent higher than that of comparable concrete produced using virgin aggregate. This is because creep is proportional to paste content, which can be up to 50 percent higher in RCA concrete (ACI 2001).

The increased potential for creep in RCA concrete is actually beneficial because it can reduce long-term curling and warping effects (caused by temperature and drying shrinkage gradients) through a relaxation effect, thereby reducing (after a time) slab stresses caused by these gradients.

Permeability

The rates of deterioration of many types of concrete distress (particularly materials-related distresses, such as freeze-thaw damage, D-cracking and ASR) are strongly affected by the ability of the hardened concrete to absorb water. The overall permeability and absorption characteristics of the concrete depend upon both the absorption capacity of the included aggregate and the permeability of the concrete matrix (which is strongly correlated with w/c).

A study by Rasheeduzzafar and Khan (1984) indicated that there is no significant difference in permeability of concrete produced using RCA (when compared to concrete produced using conventional aggregate) when the w/c of the new concrete is greater than or equal to the w/c of the concrete used to produce the RCA. However, when the w/c of the new concrete is less than that of the concrete used to produce the RCA, the water absorption (and, it is assumed, the permeability) of the RCA concrete may be up to three times greater than that of similar concrete made using virgin aggregate. This same study found that reducing the w/c of the RCA concrete by 0.05 to 0.10 was effective in compensating for the use of RCA in terms of concrete absorption and permeability.

Specific Gravity

The density of RCA concrete is typically 5 to 15 percent lower than that of concrete manufactured using virgin aggregate (Hansen 1986). This is because reclaimed mortar has a much lower specific gravity than most virgin aggregates and can easily comprise 50 percent of the RCA volume, which reduces the overall specific gravity of the concrete mixture. As a result, a given volume of RCA may have significantly less weight or mass than an equal volume of virgin aggregate. For this reason, RCA must be substituted for virgin aggregate on a volumetric (rather than weight) basis.

Durability

The effects of RCA on various aspects of concrete durability (e.g., freeze-thaw durability, ASR, etc.) also have been studied by many researchers. These studies suggest that RCA concrete can be highly durable, even when the RCA is produced from concrete with durability problems, 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.

A summary of the impact of using RCA in concrete mixtures on the durability of those mixtures is presented in Table 6 and a brief discussion of each property effect is presented in the following sections. Appropriate approaches to mixture proportioning modifications and other adjustments are discussed in some portions of this section and in Chapter 7 of this publication.

Freeze-Thaw Resistance

Most studies of RCA concrete freeze-thaw resistance show no significant difference in the durability of RCA concrete and conventional concrete when

Table 6. Effect of RCA on Concrete Durability (after FHWA 2007b)

Property	Range of expected changes from similar mixtures using virgin aggregates	
	Coarse RCA only	Coarse and Fine RCA
Freeze-thaw durability	Depends upon air void system	Depends upon air void system
Sulfate resistance	Depends upon mixture	Depends upon mixture
ASR	Less susceptible*	Less susceptible*
Carbonization	Up to 65% greater	Up to 65% greater
Corrosion rate	May be faster	May be faster

* For new concrete mixtures utilizing coarse or coarse and fine RCA to be less susceptible to ASR, the distress mechanism must be identified and proper mitigation techniques should be implemented during the mixture design procedure.

the concrete from which the RCA is manufactured is durable. Studies conducted in Japan using relatively low quality concrete indicated lower resistance for freezing and thawing if the RCA concrete included both coarse and fine RCA; when only coarse RCA was used, the RCA concrete durability was similar to that of the source concrete (ACI 2001 after BCSJ 1978).

There also have been successes in recycling concrete with known freeze-thaw durability deficiencies (e.g., D-cracking) into coarse RCA for new concrete mixtures. In such cases, the maximum particle size usually is limited to ¾ in. (19 mm) because it is the largest aggregate particles that expand the most and do the most damage during freeze-thaw cycles. Other steps commonly taken when recycling D-cracked concrete include the use of fly ash and a reduced w/cm ratio (to create a stronger, less permeable matrix that will pass less water to the aggregate) and the use of joint seals and pavement drainage systems (to prevent critical saturation of the aggregate particles). When these steps are taken, the RCA concrete generally has much better freeze-thaw durability than did the source concrete. Two of the case studies described in Chapter 6 of this publication involved recycling D-cracked pavement.

Alkali-Silica Reactivity (ASR)

ASR occurs when aggregates containing reactive silicates react with alkalis contained in the cement to form a highly expansive gel that surrounds and penetrates the aggregate particles. The disruptive expansive forces cause the aggregate particles and surrounding mortar to crack and deteriorate (Farny and Kerkhoff 2007).

RCA generally includes significant amounts of reclaimed mortar, which is not inherently reactive; therefore, the concentration of reactive silicates in RCA is generally reduced. In addition, significant quantities of reactive fine aggregate particles are contained in fine RCA, which can be processed into applications other than new concrete mixtures. As a result, new concrete mixtures containing properly processed RCA from an ASR-damaged concrete tend to be less susceptible to ASR than those containing conventional silicate aggregates.

Severely ASR-damaged concrete has been successfully recycled into new concrete with little evidence of recurrent ASR damage. This usually is accomplished by using a low-alkali cement (e.g., Type II or Type V), a class F fly ash (either as an addition or partial replacement of cement), slag cement and/or a low w/cm ratio (PCA 2007). If fly ash and/or slag cement are being used as a means to mitigate ASR in concrete utilizing RCA from an ASR-damaged concrete, the appropriate dosage levels should be determined by using ASTM C1567. Other mitigating techniques include limiting the content of RCA fines, using admixtures such as lithium nitrate, and reducing slab exposure to moisture.

For example, the Wyoming DOT successfully recycled several sections of ASR-damaged Interstate highway pavement into new concrete pavement in the 1980's; one of these projects is described as a case study in Chapter 6 of this publication. While microscopic examinations of cores retrieved from these pavements shows evidence of minor ASR activity, these pavements have been in service for more than 20 years and show little, if any, evidence of recurrent ASR damage.

Carbonation and Corrosion

Research indicates that rates of carbonation of concrete containing RCA derived from carbonated concrete is up to 65 percent higher than that of concrete containing only conventional aggregate. These rates (and depths of carbonation) are significantly decreased with decreases in the mixture w/cm ratio.

Increased surface carbonation can cause more rapid corrosion of embedded steel reinforcing, particularly in locations where chloride concentrations are high (caused by deicing chemicals or a marine environment). This accelerated corrosion can be offset by lowering the w/cm ratio of the RCA concrete (ACI 2001 after BCSJ 1978 and Rasheeduzzafar and Khan 1984). Additional depth of concrete cover over the reinforcing also will effectively reduce corrosion rates.

Chapter 6. Performance of Concrete Pavements Constructed Using RCA

Using existing concrete pavements as a source of aggregate for new pavement construction is not new. As mentioned, a portion of U.S. 66 was constructed using RCA concrete shortly after World War II, and many European countries utilized building rubble in new concrete pavement construction just after World War II (Yrjanson 1989).

After those early recycling efforts, little work was done in the U.S. in the area of concrete recycling until the mid-1970's, when interest and activity in concrete pavement recycling increased. By the early 1980's, many concrete pavements were being recycled into new concrete pavement systems. A 1994 literature review (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; many more projects have utilized RCA in pavement foundations, subbase layers and other applications. Most of these projects have performed well and are considered successes.

Some projects, however, have not been successful and have offered lessons in the use of RCA in pavement construction. For example, some early concrete recycling projects indicated the need to include at least some natural sand in RCA concrete mixtures to improve workability (Yrjanson 1989). There also have been cases where some JRCP constructed using RCA concrete quickly developed transverse cracks that deteriorated, indicating the need to adjust certain pavement design elements when using RCA concrete (mainly joint spacing, but also reinforcing steel content in JRCP) (Raja and Snyder 1991).

This section describes several RCA pavement construction projects and studies and discusses what was learned from them.

SELECT CASE STUDIES OF PAVEMENTS WITH RCA CONCRETE MIXTURES

In 1993, the FHWA sponsored a study (Wade et al 1997) that included a comprehensive evaluation of the properties and performances of 9 pavement projects that featured the use of RCA in new concrete paving. At the time of evaluation, these pavement sections ranged in age from 6 to 15 years and included a broad range of pavement designs, traffic loads, and environmental conditions. The study included pavements that had performed acceptably, as well as those that had not performed acceptably. Many of the selected sites included "control sections" (similar pavement sections constructed with conventional concrete rather than RCA concrete), while others featured alternate designs or other features. Data collected included field condition (distress) information, falling weight deflectometer test results, results of strength and mechanical property tests on cores, etc.

In 2006, the University of New Hampshire's Recycled Materials Resource Center (RMRC) conducted follow-up visits to all of the sites evaluated in the FHWA 1993 study (these sections were aged 18 to 27 years in 2006), and also evaluated additional RCA concrete pavement sites in Iowa and Illinois. This study included the collection of pavement condition (distress) data and tests of cores from the midpanel and joint areas (strength tests, joint face texture measurements, petrographic and microscopic examinations, etc.). The full details of this study are described by Sturtevant (2007).

Some of the key findings of these studies include the following (Wade et al 1997, Sturtevant 2007):

- The measurement of air content in fresh RCA concrete may be accurately obtained using volumetric techniques (e.g., the "Roll-O-Meter") rather than pressure techniques (e.g., the "Press-R-Meter") because of the air content and more porous nature of reclaimed mortar.
- Measures of the CTE were generally higher for RCA concrete than for conventional concrete when other mixture design parameters were held constant.
- Modulus of elasticity test values for the aged cores were generally 1 to 18 percent lower for RCA concrete than for conventional concrete. Most literature reports a greater difference (15 to 50 percent) for younger concrete specimens. The reduced differences were attributed to modified mixture designs for the RCA concrete in this study (e.g., lower w/cm ratio, etc.) and the benefits of extended curing.
- Tests of cores showed that the RCA concrete on these projects had compressive strengths similar to or higher than those of their companion control sections. This was, again, caused by a reduced w/cm ratio and other modifications to the RCA concrete mixture designs.
- Reducing coarse RCA top size may be effective in preventing the recurrence of D-cracking, but it also reduces the texture available for aggregate interlock load transfer at crack and joint faces. The use of dowel load transfer devices and properly designed longitudinal reinforcing (for CRCP and JRCP applications) often are essential to good performance.
- D-cracked or ASR-damaged pavement can be successfully recycled into coarse and fine RCA for use in new concrete pavement with appropriate adjustments to the concrete mixture design and structural design of the pavement (e.g., panel lengths, load transfer design, etc.).
- Recycled concrete aggregate should be considered an "engineered material" and concrete mixture designs and pavement structural designs should be adjusted according to the specific properties of the material being used to ensure good performance.

Specific details on two of the more interesting projects evaluated under these national studies (I-80 in Wyoming and U.S. 59 in Minnesota) are presented below.

I-80 near Pine Bluff, Wyoming – Recycling an ASR-Damaged Pavement

During the early 1980's, a section of I-80 west of Pine Bluffs, Wyoming was suffering from extensive alkali-aggregate damage (Figure 22), including extensive map cracking, potholes and joint spalling. Asphalt concrete had been used to repair some potholes and for placing localized overlays to improve ride quality, but these soon failed due to reflection cracking and delamination. Further restoration and overlay options were considered unfeasible because of the extent of the deterioration. Reconstruction with virgin aggregate also was ruled out because there was no suitable aggregate source near the site and

Figure 22. Photo of I-80 in Wyoming prior to recycling. Note ASR damage throughout (Photo credit: Wyoming DOT).

disposal and hauling costs would be high. Recycling the existing concrete pavement into a new concrete pavement surface was selected as the most feasible and economical rehabilitation alternative for this section.

In 1985, the original concrete pavement (an 8-in. [200-mm] thick JPCP) was removed, along with 2 in. (50 mm) of the underlying crushed stone subbase and the asphalt shoulders. The new pavement section consisted of a 10-in. (250-mm) JPCP on the remaining 4-in. (100-mm) crushed stone subbase. The transverse joints were skewed and placed at "random" intervals of 14, 16, 13, and 12 ft (4.3, 4.9, 4.0, and 3.7 m). No load transfer devices were installed at the transverse joints.

To ensure the feasibility of the RCA concrete mixture, several ASTM tests were conducted (i.e., C227, C289 and C441) to determine combinations of materials that would avoid recurrence of the ASR problems in the original pavement. These tests indicated that further problems with the reactive aggregate in the existing pavement could be controlled by: 1) using a low-alkali (less than 0.60 percent Na_2O) Type II cement, 2) blending the recycled concrete aggregate with a quality virgin aggregate, and 3) using a Class F fly ash meeting the requirements of Table 2A of ASTM C618 for reduction of expansion (Swedeen 1990).

The selected RCA concrete mixture design included a 60:40 ratio of coarse to fine aggregate, a 65:35 ratio of recycled to virgin coarse aggregates (1-in. [25-mm] top size), and a 22:78 ratio of recycled to virgin fine aggregates. Class F fly ash comprised approximately 30 percent of the volume of the cementitious material, and a w/cm ratio of 0.38 was used. An air-entraining admixture was used to produce average total air contents of 5.5 percent.
A control section was constructed in the eastbound lanes using all virgin aggregate, no fly ash, and a w/cm ratio of 0.44.

Construction was accomplished using typical construction equipment and procedures. Flexural beam test results averaged 700 psi (4.8 MPa) for the recycled concrete at 28 days. Cores obtained from the pavement in 1994 and 2006 indicated higher strength for the RCA concrete than for the control section, probably due to the use of fly ash and a much lower w/cm ratio in the recycled mixture (Wade et al 1995, Sturtevant 2007).

The control and RCA concrete sections were both opened to traffic in late 1985 and have sustained approximately the same traffic loadings and ESAL applications. The two-way ADT has increased from about 4,400 (35 percent trucks) in 1985 to more than 8,000 (45 percent trucks) in 2006. Although the area is relatively dry, modest levels of faulting began to develop at the joints (which were undoweled) under the heavy traffic loadings. After almost 20 years of service, the Wyoming DOT rehabilitated both the recycled and control sections in 2002 through dowel bar retrofit, diamond grinding and resealing the joints (Figure 23). Since that time, both sections have performed very well, providing excellent ride quality and developing very little distress.

Figure 23. Photos of Wyoming I-80 concrete recycling project near Pine Bluff in 2006 (Photo credit: University of New Hampshire Recycled Materials Research Center).

The success of this project led to the reconstruction of a total of 28 centerline miles of ASR-affected pavement on I-80 using RCA concrete between 1985 and 1991. Wyoming DOT pavement management data from 2006 indicated a Pavement Condition Index (PCI) of 99 to 100 (almost perfect) over the entire 28-mile length of concrete pavement (Sharpe 2006).

There is evidence of some ASR activity in cores recently obtained from the RCA concrete portion of the project (Sturtevant 2007) but progression is slow and only a few localized signs of ASR are visible on the pavement surface. The sections are expected to easily achieve their 30-year design lives (Sharpe 2006).

U.S. 59 near Worthington, Minnesota – Recycling a D-cracked Pavement

The Minnesota DOT selected a 16-mile (26-km) D-cracked segment of U.S. 59 near Worthington for their first concrete recycling project. This project, which was completed in 1980, was the first major concrete recycling project in the United States in which a D-cracked concrete pavement was used to furnish coarse RCA for new concrete pavement.

The original concrete surfacing was constructed in 1955 and consisted of a "thickened edge" concrete pavement (9 – 7 – 9 in. [230 – 180 – 230 mm]) placed over a minimum of 3 in. (75 mm) of unstabilized subbase, which was placed on a pre-existing asphalt surface. At the time of recycling, the existing concrete pavement was showing signs of extensive D-cracking. This concrete was recycled to provide coarse RCA for a new 8-in. (200-mm) JPCP. The fine RCA was placed in a construction platform layer 1 in. (25 mm) thick atop the remaining unstabilized subbase.

The mixture design featured 100 percent coarse RCA, 100 percent natural sand fine aggregate, replacement of 15 percent (by weight) of cement with 20 percent (by weight) of Class C fly ash, and a w/cm ratio of 0.44. The maximum particle size for the coarse RCA was limited to ¾ in. (19 mm) to reduce the potential for recurrent D-cracking in the new concrete pavement. The average slump and air content at the job site were 1.5 in. (38 mm) and 5.5 percent, respectively. Compressive strengths averaged 4,580 psi (31.6 MPa) after 60 days.

Paving was performed using a traditional slipform paving machine and standard paving techniques. The new transverse joints were skewed, undoweled, and spaced at 13-16-14-19-ft (4.0-4.9-4.3-5.8-m) intervals. Longitudinal edge drains also were provided throughout the project.

The pavement was opened to traffic in late 1980, at which time the two-way ADT was about 2,150 vehicles per day. By 2006, the ADT had increased to an average of about 3,225, including 230 heavy commercial vehicles per day.

Significant faulting developed quickly after construction. A 1994 survey reported average faulting of nearly ¼ in. (6.1 mm) in the outer wheelpaths and load transfer efficiencies averaging 32 percent (Wade et al 1997). The development of faulting was not surprising given the lack of dowels at the transverse joints. Many panels could be observed rocking under heavy traffic loads, and the longest panels had begun to develop transverse cracks. Low-severity joint spalling had developed at 70 percent of the transverse joints by 1994, probably due to joint sealant problems and excessive slab movements under heavy traffic loads (Wade et al 1997).

Cores obtained in 1994 (and at later times) were tested for strength, freeze-thaw durability, CTE and other properties. While most of the concrete properties were comparable to those of good conventional concrete, freeze-thaw testing (ASTM C666 or AASHTO T161 Procedure B, modified) indicated that the concrete was not durable. Microscopic examination of polished concrete specimens from the cores indicated a marginal air void system and some microcracking in the reclaimed mortar, but no evidence of recurrent D-cracking. Examination of failed freeze-thaw specimens showed deterioration initiating at large entrapped air voids.

The Minnesota DOT considered retrofitting dowels on this project to address faulting and slab movement problems as early as 1994, but was concerned that D-cracking or other freeze-thaw durability problems might redevelop at any time. They continued to monitor the pavement durability (and the development of additional faulting and slab cracking) and noted no additional freeze-thaw-related deterioration over the years. One possible explanation for the lack of freeze-thaw damage is that the field saturation conditions do not approach those of the ASTM test (caused by the presence of pavement drains and other factors).

In 2004, a major rehabilitation project was finally undertaken, with activities including replacement of some long panels that had cracked, retrofit dowels (outer wheelpaths only), diamond grinding (to remove the accumulated faulting) and joint sealing (Figure 24). Since that time, the pavement has provided a smooth, quiet ride. A 2006 condition survey indicated very little additional cracking or deterioration. This suggested that, after 26 years of service, this pavement still had a good deal of remaining service life and the concrete material itself was sound despite being constructed using RCA from a badly D-cracked pavement.

It appears that the RCA concrete generally has performed well on this project and that the primary performance-related problems have been related to deficiencies in the structural design. Had dowel bars been included in the 1980 pavement reconstruction, it seems likely that very little maintenance or rehabilitation would have been required, although the longest panels (19 ft [5.8 m]) may still have developed cracking because they were significantly longer than the suggested maximum joint spacing of 15 ft (4.6 m) for this pavement thickness/subbase combination.

There was no evidence of recurrent D-cracking on this project, indicating that at least some pavements with a history of durability problems can be successfully recycled into new concrete paving mixtures.

I-94 near Paw Paw, Michigan – Learning from Failure

During the mid-1980's, the Michigan DOT constructed several RCA concrete pavements on I-94 with a thickness of 9 in. (230 mm) and 41-ft [(2.5-m) steel mesh-reinforced panels. These pavements developed intermediate transverse cracks that rapidly faulted and spalled. It should be noted that intermediate cracking is expected to occur on JRCP, but the reinforcing steel is expected to hold the cracks tight so that aggregate interlock can be maintained, thereby preventing the cracks from deteriorating.

On these projects, the coarse RCA was crushed to a maximum size of ¾ in. (19 mm) to prevent the recurrence of D-cracking, which had been present in the original concrete. The small top size of the coarse RCA (which included reclaimed mortar) resulted in the formation of cracks that were very straight both across and through the slab (Darter 1988), offering very little texture for aggregate interlock load transfer

Figure 24. Trunk Highway 59 near Worthington, MN in 2006, after 15 years of service and 2004 rehab.

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(Snyder and Vandenbossche 1993). In addition, the reclaimed mortar is believed to have been less resistant to abrasion than virgin aggregate, resulting in rapid loss of aggregate interlock load transfer across the reinforced cracks (Yrjanson 1989). No significant problems were observed at the doweled joints.

The RCA was not solely responsible for the problems that these projects suffered, however. In the investigation of one of these projects, Darter (1988) noted a series of design and construction flaws that, in combination with the use of the RCA, resulted in the rapid deterioration of the pavements. These flaws included insufficient slab thickness, incompatible joint spacing between the reinforced mainline pavement and the nonreinforced concrete shoulder, and the absence of a separation layer beneath the permeable (open-graded) subbase, which allowed significant foundation settlement (Darter 1988). In addition, subsequent studies by Raja and Snyder (1991) indicated that the amount of longitudinal reinforcement (0.16 percent by area of concrete) was inadequate, particularly when considering the higher CTE of RCA concrete and the reduced potential for aggregate interlock at the transverse cracks.

These factors and the performance of these pavement sections illustrate the need for ensuring compatibility between the pavement structural design details and the concrete mixture components and proportions. Specific recommendations are provided in Chapter 7 of this publication.

I-10 near Houston, Texas – Using 100 Percent RCA in Concrete

In 1995, the Texas DOT began a project to replace a distressed portion of I-10 near Houston using RCA produced from the existing concrete pavement, which was a CRCP that had carried heavy traffic for almost 30 years (Won 2007). The concrete for the new CRCP was manufactured using 100 percent coarse and fine RCA.

The Texas DOT required that the RCA meet the same specification requirements as virgin aggregate intended for use in concrete paving mixtures. Tests of the RCA (which contained siliceous river gravel [SRG] from the original concrete) generally produced specific gravity, mortar content, absorption and L.A. abrasion values in the ranges described previously in this publication.

Several cores were retrieved from representative locations along the project and were used to determine the in-situ properties of the concrete (i.e., strength, elastic modulus, CTE, permeability, etc.). These tests indicated relatively low, but acceptable, strength and elastic modulus values for this 100 percent RCA concrete, as shown in Table 7.

Table 7 also shows unusually low CTE and permeability values for the RCA concrete – similar to or better than would be expected from conventional and high-performance concrete. Higher values were expected because of the high reclaimed mortar content of the RCA concrete. The low permeability may indicate an absence of microcracking due to the more elastic nature of the RCA concrete. Won (2007) offered no explanation for the low expansion and contraction CTE and permeability values, but did observe that they probably contributed to the excellent performance of the constructed pavement.

The contractor initially had some difficulty in producing RCA concrete with consistent workability.

Table 7. Selected Average in-situ RCA Concrete Properties for I-10 (after Won 2007)

Property	I-10 RCA concrete
28-Day compressive strength	4,615 psi (31.8 MPa)
28-Day elastic modulus	2.58×10^6 psi (17.8 MPa)
Coefficient of thermal expansion and contraction (CTE)	4.7 to 5.3 με/°F (8.5 to 9.5 με/°C)
Permeability (ASTM C1202/AASHTO T277)	466 coulombs (very low permeability)

These problems were found to be caused by inadequate moisture control of the recycled aggregate stockpiles. The situation was remedied with the installation of improved stockpile sprinkler systems.

There also were some problems with consistency of concrete strength as the averages of 10 flexural test results often failed to meet the specified minimum value. These failures were generally the result of one or two exceedingly low test results, probably due to mixture variability and/or specimen handling. At the time, the contractor was required to modify the mixture design to develop higher average strength. Since that time, the Texas DOT has recognized the sensitive nature (with regard to strength and workability) of concrete mixtures containing high contents of fine RCA. In 1999, the Texas DOT developed a special provision to limit the fine RCA content in concrete mixtures to 20 percent of all fine aggregate.

No significant adjustments in paving operations were required by the use of 100 percent coarse and fine RCA in the concrete (Won 2007).

After 12 years of service, the performance of the RCA CRCP (Figure 25) has been described as excellent, with narrow crack widths, few minor spalls, no punchouts and none of the meandering cracks and spalls that have typically been associated with the use of SRG in Texas CRCP (Won 2007). The transverse crack spacing distributions in this CRCP have been similar to those of CRCP containing virgin limestone aggregate (Won 2007). The relatively low elastic modulus of the RCA concrete and the good bond between the old and new mortar are considered key factors in the excellent performance of this pavement to date.

PERFORMANCE OF CONCRETE PAVEMENT STRUCTURES WITH RCA IN SUBBASE LAYERS AND FILL APPLICATIONS

RCA is widely used in concrete pavement subbase layers and fill applications with great success. There appear to be no documented pavement performance problems that are related to structural deficiencies in any properly designed and constructed foundation placement using RCA. There have been concerns with the impact and efficacy of concrete recycling in urban areas, as well as some problems with the use of RCA materials in drainable foundation layers. The following section address these aspects of using RCA in pavement foundation layers.

Figure 25. Photo of I-10 RCA CRCP near Houston, Texas.

Urban Recycling: Eden's Expressway, Chicago, Illinois

Recycled concrete was used in the 1978 reconstruction of the Eden's Expressway (I-94 through the northern suburbs of Chicago). This very high-profile project was notable for several reasons (Dierkes 1981, Krueger 1981):

- It was the first major urban freeway in the U.S. to be completely reconstructed.
- It was the largest highway project on which concrete recycling had been used.
- It was the largest single highway contract ever awarded in the U.S. at that time, with a total project cost of $113.5 million (1978 dollars).
- It was the first major recycling effort in the U.S. involving a mesh-reinforced concrete pavement.

At that time, the Illinois DOT did not allow the use of RCA in new concrete surface layers, but did permit its use in subbase layers and fill applications, which was an option on this project. Although there was an adequate supply of good quality aggregate in the Chicago area, the 18-mile (29-km) haul distance from the stockpile to the job site would have required a 3-hour round trip during daytime traffic conditions, so the recycling option was exercised (NHI 1998).

The crushing plant was set up in an interchange cloverleaf area (Figure 26). This area was heavily populated, so noise was a serious concern. Crushing operations were suspended from midnight until 6 a.m. every day, and some modifications to typical operational procedures were instituted (e.g., truck drivers were not allowed to bang their tailgates to help discharge materials from the truck beds).

About 350,000 tons (318,000 metric tons) of the old pavement was crushed at this site. About 85 percent of the RCA produced was used in fill areas, while the remaining 15 percent was used as a 3-in. (75-mm) unstabilized subbase over the chemically modified / stabilized subgrade. An asphalt-treated subbase and 10-in. (250-mm) CRCP were placed over the RCA subbase (NHI 1998).

This pavement has provided excellent service for nearly 30 years under extremely heavy traffic (up to 170,000 vehicles per day in 2007). This 1978 recycling project demonstrated the feasibility (and economy) of completely recycling and reconstructing a high-volume urban concrete expressway. Just one measure of the savings realized was the estimated 200,000 gallons (757,000 liters) of fuel that would have been consumed in disposing of demolished concrete and hauling virgin aggregate (NHI 1998).

Figure 26. Concrete recycling operation set up inside of cloverleaf interchange.

Chapter 7. Recommendations for Using Recycled Concrete

RCA PRODUCTION

Guidelines for the production of RCA are available in *Appendix A. Guidelines for Removing and Crushing Existing Concrete Pavement* near the end of this publication.

Source Materials

Determine the quality and properties of any candidate source materials. If the pavement to be recycled is still in place, a materials engineer should visit the site to observe the type and extent of any distresses present, and to retrieve samples for visual inspection and laboratory evaluation (FHWA 2007b). With proper care in demolition and processing, existing concrete pavement usually can be recycled to produce aggregate for new paving applications; building demolition materials may contain considerable amounts of contaminants and should be evaluated carefully prior to selection for use in new paving applications.

Production Processes

Jaw crushers are most useful for the first stage of crushing operations because they usually can handle remaining embedded steel (if any is present). Secondary crushers should be selected with consideration of the type of product desired. Jaw crushers tend to produce fewer fines than impact or cone crushers, resulting in higher yields of coarse RCA, which often is more useful than fine RCA, particularly in new concrete mixtures. Table 8 presents a typical gradation for concrete crushed using a jaw crusher set to an opening of 1 in. (25 mm). Impact and cone crushers often are more effective in removing most of the reclaimed mortar, producing coarse RCA that looks and behaves similarly to the original virgin aggregate in the source concrete. Impact crushers also can supply particle size distributions that are well-suited for constructing unbound foundation layers (ACI 2001).

"Closed system" aggregate processing plants are preferred because they allow greater control over

Table 8. Typical Grading of RCA Produced using a Jaw Crusher set to an Opening of 1 in. (25 mm) (after ACI 2001)

Sieve opening	Percent finer (mass)
>1.5 in. (38 mm)	97
1.5 in. (38 mm)	68
1.0 in. (25 mm)	53
¾ in. (19 mm)	34
1/2 in. (13 mm)	26
⅜ in. (9.5 mm)	13
No. 4 (4.75 mm)	0

the aggregate particle size distribution and provide a more uniform finished material (ACI 2001, Hansen 1986).

Fine impurities (e.g., dirt from pavement foundations or plaster and gypsum from building demolition) usually can be reduced to tolerable levels by screening. Wet screening is useful in eliminating lightweight contaminants.

Stockpiling

Coarse RCA can be stockpiled using the same techniques and equipment as traditional coarse aggregate materials. Fine RCA stockpiles generally need to be protected from precipitation to reduce the potential for secondary cementing due to hydration of exposed and previously unhydrated (or partially hydrated) cement grains. As with virgin fine and coarse aggregates, more than two separate stockpiles may be necessary to allow the production of aggregate blends that meet project specifications.

Moisture control of stockpiles is essential in ensuring the production of uniform RCA concrete. Coarse RCA stockpile sprinkler systems may be useful in controlling absorption of mixture water and the resulting rapid loss of workability.

USE IN PAVEMENT SUBBASE LAYERS

The following sections provide recommendations and rationale concerning various aspects of using RCA in pavement subbase layers. A detailed specification concerning the use of RCA for unstabilized subbases can be found in AASHTO M319 and general guidelines are available in *Appendix B. Guidelines for Using RCA in Unstabilized (Granular) Subbases* near the end of this publication.

Quality Requirements

The final report for NCHRP Project 4-31 (Saeed 2008) identifies several properties of recycled aggregate subbase materials that influence the performance of the overlying pavement. These properties include aggregate toughness, frost susceptibility, shear strength and stiffness. The following tests are recommended for evaluating these properties: Micro-Deval (AASHTO T327), Tube Suction*, Static Triaxial (AASHTO T234) and Repeated Load Tests*, and Resilient Modulus* (* indicates test procedure described in Saeed et al 2001).

Saeed and Hammons (2008) also have provided a matrix (Table 9) that summarizes recommendations

Table 9. Recommended RCA Subbase Quality Tests and Values for Various Applications (after Saeed and Hammons 2008)

<table>
<tr><th colspan="2" rowspan="3">Tests and Test Parameters</th><th>Traffic</th><th colspan="2">High</th><th colspan="2">Med.</th><th colspan="2">High</th><th colspan="2">Low</th><th>Med.</th><th colspan="2">Low</th></tr>
<tr><th>Moisture</th><th>High</th><th>Low</th><th>High</th><th>Low</th><th>High</th><th colspan="2">Low</th><th colspan="3">High</th><th>Low</th></tr>
<tr><th>Climate</th><th colspan="4">Freeze</th><th colspan="2">Nonfreeze</th><th>Freeze</th><th colspan="4">Nonfreeze</th></tr>
<tr><td colspan="3">Micro-Deval Test (percent loss)</td><td colspan="3">< 5 percent</td><td colspan="4">< 15 percent</td><td colspan="3">< 30 percent</td><td>< 45 percent</td></tr>
<tr><td colspan="3">Tube Suction Test (dielectric constant)</td><td colspan="3">≤ 7</td><td colspan="4">≤ 10</td><td colspan="3">≤ 15</td><td>≤ 20</td></tr>
<tr><td rowspan="2">Static Triaxial Test (Max. Deviator Stress)</td><td colspan="2">OMC, σ_c = 5 psi (35 kPA)</td><td colspan="3">> 100 psi (0.7 MPa)</td><td colspan="4">> 60 psi (0.4 MPa)</td><td colspan="3">> 25 psi (170 kPa)</td><td>Not required</td></tr>
<tr><td colspan="2">Sat., σ_c = 15 psi (103 kPA)</td><td colspan="3">≥ 180 psi (1.2 MPa)</td><td colspan="4">≥ 135 psi (0.9 MPa)</td><td colspan="3">≥ 60 psi (410 kPa)</td><td>Not required</td></tr>
<tr><td rowspan="2">Repeated Load Test (Failure Deviator Stress)</td><td colspan="2">OMC, σ_c = 15 psi (103 kPA)</td><td colspan="3">≥ 180 psi (1.2 MPa)</td><td colspan="4">≥ 160 psi (1.1 MPa)</td><td colspan="3">≥ 90 psi (620 kPa)</td><td>Not required</td></tr>
<tr><td colspan="2">Sat., σ_c = 15 psi (103 kPA)</td><td colspan="3">≥ 180 psi (1.2 MPa)</td><td colspan="4">≥ 160 psi (1.1 MPa)</td><td colspan="3">≥ 60 psi (410 kPa)</td><td>Not required</td></tr>
<tr><td colspan="3">Stiffness Test (Resilient Modulus)</td><td colspan="3">≥ 60 ksi (0.4 MPa)</td><td colspan="4">≥ 40 ksi (275 kPa)</td><td colspan="3">≥ 25 ksi (170 MPa)</td><td>Not required</td></tr>
</table>

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

for critical test values for each of these tests to ensure good RCA subbase performance in specific traffic, moisture and temperature conditions.

Gradation

It is common to produce two sizes of RCA for pavement subbase applications. While almost any sizes can be produced, two of the most common and useful sizes are 1.5 to 3 in. (38 to 76 mm) and 1.5 in. (38 mm) maximum size. Regardless of the size(s) produced, the grading bands should be adjusted to provide suitable gradations for the intended application (e.g., free-draining vs. dense-graded) and to minimize production of materials that cannot be used.

Guidance on specific gradations to achieve unstabilized subbase materials that provide good stability with varying degrees of permeability (free drainage capacity) can be found in ACPA's EB204P (ACPA 2007).

Structural Design Considerations

The pavement design process should consider the possibility of significant stiffening of unstabilized RCA subbase materials caused by continued hydration of the cementitious materials (especially for dense-graded RCA base materials containing fine RCA particles). After time, such unstabilized subbases can behave as stabilized subbases, resulting in excellent strength and erosion resistance, but also in higher curling and warping stresses in overlying concrete slabs. See ACPA's EB204P (ACPA 2007) for more on this topic and means to mitigate potential problems.

Preventing Clogging of Edge Drainage Structures

The formation of calcium carbonate precipitate in edge drainage structures and on associated filter fabrics as a result of using RCA in drainable foundations (Figure 27) has long been a concern. The mechanism of precipitate formation is presented completely by Bruinsma et al (1997), who describe the dissolution of calcium hydroxide (a by-product of cement hydration) into water from freshly exposed crushed concrete surfaces and the subsequent precipitation of calcium carbonate as the dissolved calcium hydroxide reacts with atmospheric CO_2. The availability of calcium hydroxide increases with increasing surface area of crushed concrete (i.e., with increasing content of fine RCA) and decreases over time as the available calcium hydroxide is depleted.

Figure 27. Photo of extreme (atypical) case of calcium carbonate precipitate in a drainage outlet (Photo credit: Richard Proszek, City of Seattle Materials Laboratory).

Bruinsma (1995) and Tamarisa (1993) also determined that as much as 50 percent of the material deposited in drainage structures and on associated filter fabrics may be dust and insoluble residue produced by the crushing operation. Bruinsma (1995) found that washing the product prior to use minimized the presence of this material.

There have been many lab and field studies to characterize and identify solutions to this potential problem. Some of the most important of these studies were summarized by Snyder (1995) and Snyder and Bruinsma (1996). The following conclusions, drawn from these reports, are useful in preventing problems with pavement drainage systems when using RCA subbase materials:

- All recycled concrete aggregates, regardless of gradation, may produce various amounts of precipitate, with the precipitate potential being directly related to the amount of freshly exposed cement paste surface (i.e., increased quantities of cement paste fines).

- Selective grading (i.e., elimination of fine RCA particles) and blending with virgin aggregate will reduce, but not completely eliminate, precipitate potential.
- Washing the RCA prior to placement in the subbase minimizes the contribution of "crusher dust" to drainage system problems, but does not significantly reduce precipitate potential.
- Accumulations of precipitate and insoluble residue can significantly reduce the permittivity of filter fabrics. However, there are fabrics with initial permittivities high enough to withstand typical accumulations of precipitate and insoluble residue and still have sufficient remaining permittivity to function adequately.
- Accumulations of precipitate and residue in drainage pipes can be significant and can reduce discharge capacity, but are rarely (if ever) observed to significantly impede drainage flow.

The following recommendations are presented for the use of RCA in drainable, unstabilized subbase layers:

- Unbound RCA subbase layers that can pass water to pavement edge drainage systems or are designed to be drainable daylighted subbases should be free of fine materials to minimize the movement of dust and formation of calcium carbonate precipitate that can clog filter fabrics and reduce drain capacity. Unstabilized fine RCA may be suitable for placement in any layer below the pavement drainage system.
- Washing the RCA prior to placement, while not absolutely necessary, is effective in reducing precipitate and dust deposits in drainage structures.
- For filter fabrics used in conjunction with drainable RCA subbase layers, consider using materials with initial permittivity values that are at least double the minimum required so that adequate flow will be maintained even if some clogging takes place (Snyder 1995).
- When filter fabrics are used in conjunction with pipe drain trenches, leave the top of the trench unwrapped (Figure 19) to reduce deposits of residue on the fabric.
- Consider using daylighted subbase designs that provide broad paths for drainage (rather than concentrating all residue in outlet structures), as described in ACPA's EB204P (ACPA 2007).

RCA intended for use in cement-stabilized subbase layers require none of the special treatment or handling described above for unstabilized RCA subbases. The considerations described below for RCA in concrete mixtures are generally applicable.

Environmental Considerations

The effluent from RCA foundation layers is initially highly alkaline (an effect that diminishes with time in service), but is generally not considered to be an environmental hazard because it is effectively diluted at a very short distance from the drain outlet with much greater quantities of surface runoff (Sadecki et al 1996, Reiner 2008). It is not uncommon, however, to see very small regions of vegetation kill in the immediate area of the drain outlet. The gradation and washing recommendations provided above to prevent precipitate formation also are generally effective in reducing initial pH levels in RCA subbase drainage effluent (Snyder and Bruinsma 1996).

Construction Considerations

RCA subbases can be placed using standard equipment and techniques. Efforts should be made to avoid excessive handling and movement of the RCA during placement and compaction because these activities can produce additional fine material through abrasion.

USE OF RCA IN CONCRETE MIXTURES FOR CONCRETE PAVEMENT STRUCTURES

The following sections provide recommendations and rationale concerning various aspects of using RCA in new concrete paving mixtures. A detailed specification concerning the use of RCA in hydraulic cement concrete can be found in AASHTO MP16 and general guidelines are available in *Appendix C. Guidelines for Using RCA in Concrete Paving Mixtures* near the end of this publication.

Quality Requirements and Properties

In general, RCA products intended for use in new concrete pavements should meet the same quality requirements as virgin aggregate (FHWA 2007b). Exceptions are the magnesium and sodium sulfate soundness tests, which are sometimes waived for RCA because they may be unreliable in predicting RCA durability.

Materials-Related Distress

If any materials-related distresses (e.g., D-cracking or alkali-aggregate reactivity [AAR]) were observed in the source concrete, evaluations and tests should be conducted to ensure that mitigation measures will be effective in preventing recurrence of these distresses.

Techniques that may be effective in preventing recurrent AAR (including ASR) include: the use of lithium-based admixtures; the use of Class F fly ash and/or slag cement in place of a portion of the cement; limiting the content of fine RCA; reducing concrete permeability through lower water content (reduced water-cementitious materials ratio); and reducing slab exposure to moisture through improved pavement drainage, joint sealing, increasing the distance to water sources, and other techniques.

Recurrent D-cracking may be prevented by reducing the coarse RCA top size to ¾ in. (19 mm) or less and by reducing slab exposure to moisture through the same techniques described above.

Contaminants

RCA intended for use in high-quality concrete should be free of potentially harmful components. More than 90 percent of the material should be cement paste and aggregate (FHWA 2007b). Typical suggested limits for various contaminants include: asphalt – 1 percent by volume; gypsum – 0.5 percent by weight; organic substances – 0.15 percent by weight; soil – in accordance with ASTM C33; and glass – not allowed because it can cause ASR problems, along with popouts and cracking.

If the RCA is suspected to contain excessive amounts of salt, the chloride content of the RCA should be measured and used to determine the chloride content of the corresponding mixture. High levels may cause problems with concrete durability, set times and corrosion of embedded steel. These problems should be addressed by ensuring that any steel reinforcing is epoxy-coated and/or by washing (or removing) the fine RCA to reduce the amount of material passing the No. 200 (75 µm) sieve, which tends to have the highest chloride content. FHWA (2007b) recommends not using RCA derived from concrete containing more than 0.06 lb of chloride ion per cubic yard (0.04 kg of chloride ion per cubic meter) in JRCP or CRCP. Dowel bars and reinforcing steel in such installations should, as a minimum, be epoxy-coated, with consideration given to using more corrosion-resistant materials, such as stainless steel (solid, sleeved or clad) products, zinc-sleeved or clad steel products or other suitable materials.

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 (NHI 1998).

Gradation

Coarse RCA should be graded as required for concrete durability and workability requirements, and to meet the appropriate grading requirements. The coarse, angular nature of fine RCA can reduce concrete workability and make finishing more difficult. To avoid these problems, limit fine RCA content to no more than 30 percent replacement. Higher replacement rates can be used, but added water and cement may be required to achieve good workability, as described in the recommendations for mixture proportioning below.

Mixture Proportioning

The basic proportioning of concrete containing RCA can be accomplished using the same procedures recommended for proportioning concrete containing only virgin aggregate. The following mixture proportioning recommendations and guidelines are generally adopted from ACI 555R-01 (ACI 2001), except as noted:

- RCA specific gravity, unit weight and absorption must be determined before determining mixture proportions. In particular, the lower specific gravity of RCA should be considered in determining aggregate batch weights on the basis of absolute volumes of components.
- When developing a target average strength for the mixture based on the minimum required strength, use a higher standard deviation of strength (e.g., 700 psi [4.8 MPa]) if the RCA quality is variable. When the RCA quality is - uniform, use the same standard deviation of strength as for virgin aggregate (e.g., 500 psi [3.2 MPa]).
- Selection of the w/cm ratio is the most critical part of controlling the strength of the RCA concrete. If a valid relationship between the w/cm ratio and the RCA concrete strength is not available during the preliminary mixture design phase, designers can use (for mixtures containing coarse RCA and virgin fine aggregate) the same relationship used for conventional concrete mixtures. If trial mixtures show a lower strength than was assumed, reduce the w/cm ratio accordingly.
- To obtain the same slump as a conventional concrete mixture, the free water content of a mixture containing coarse RCA and natural sand should be increased about 5 percent. If the mixture will contain both coarse and fine RCA, up to 15 percent additional water may be required to maintain workability. These increases in water content can be reduced or eliminated through the use of chemical and/or mineral admixtures (e.g., fly ash, water reducers, superplasticizers, etc.).
- The ratio of coarse aggregate to fine aggregate should be approximately the same as for conventional concrete made using virgin aggregates.
- Reclaimed mortar included in RCA often contains both entrapped and entrained air, but neither are effective in protecting the new concrete paste from freeze-thaw damage. Volumetric air meters may more accurately indicate the effective air content of fresh concrete than pressure-based air meters, which may reflect the air in the reclaimed mortar (Wade et al 1997). Freeze-thaw testing (ASTM C666/AASHTO T161) is the best way to qualify concrete mixtures containing RCA for use in areas where freeze-thaw damage is a possibility (FHWA 2007b).
- Some states have found it difficult to entrain air in concrete containing both coarse and fine RCA (FHWA 2007b). The presence of contaminants may impact required chemical admixture dosages.
- Trial mixtures are essential. As a minimum, laboratory trials should be conducted to ensure that the properties of the RCA mixture meet job requirements. Field trials should be conducted when feasible.

Table 10 presents example RCA concrete mixture designs from several recent highway paving projects.

Pavement Design

The physical and mechanical properties of RCA concrete must be determined and considered in the development of RCA concrete pavement design details. For example, increased shrinkage and thermal response of concrete containing RCA can cause larger joint movements, requiring different sealant materials or reduced panel dimensions. They also may increase slab curling and warping deformation. Strength and elastic modulus reductions can impact stress distributions and fatigue damage and may cause increases in required pavement thickness. RCA also tends to have lower potential for aggregate interlock load transfer, especially when the maximum particle size is reduced to address freeze-thaw durability concerns.

Table 11 summarizes some of the most common pavement design modifications that should be considered when using RCA concrete in new pavement construction.

*Table 10. Example RCA Concrete Mixture Proportions**

Components	Minnesota DOT lb/yd³	(kg/m³)	Wisconsin DOT lb/yd³	(kg/m³)	Grand Forks, ND Int'l Airport lb/yd³	(kg/m³)	Wyoming DOT lb/yd³	(kg/m³)
Cement (Type I)	472	(280)	480	(285)	400	(237)	488	(290)
Fly ash (Type C)	83	(49)	110	(65)	130	(77)	133	(79)
Water	255	(151)	265	(157)	230	(136)	258	(153)
Coarse RCA	1,630	(967)	1,815	(1077)	1,650	(979)	1,349	(800)
Virgin coarse aggregate							601	(357)
Fine RCA							253	(150)
Virgin fine aggregate	1,200	(712)	1,315	(780)	1,260	(748)	882	(523)
Admixtures:								
Air entrainer	yes		yes		yes		yes	
Water Reducer	no		no		yes		yes	

*Proportions shown are representative examples and are not necessarily recommended.

Table 11. RCA Concrete Pavement Structural Design Guidelines and Recommendations

Concrete pavement design element	Design recommendations
Pavement type	Use JPCP with panel length of 15 ft (4.6 m) or less to minimize potential for mid-panel cracking. JRCP and CRCP may be considered if aggregate interlock is enhanced with larger aggregate top size and/or blending virgin and recycled coarse aggregate. Additional reinforcement may be desirable to ensure that cracks are held tight.
Slab thickness	Generally the same as for conventional concrete pavement design provided that the RCA concrete mixture design provides adequate strength. For two-course construction using RCA concrete, the overall slab thickness might need to be greater than what is required for a conventional concrete pavement design, depending on the materials and mixture proportions used in each lift.
Joint spacing	Panel length should be selected to minimize the incidence of midpanel cracks in JPCP or to keep crack width to a minimum in JRCP.
Load transfer	The criteria for using dowels in RCA concrete pavements should be identical to those used for pavements constructed using virgin aggregate. Reinforcing steel recommendations for crack load transfer are presented below.
Joint sealant reservoir design	Dimensions must consider both the selected sealant material and expected joint movements caused by temperature and shrinkage effects, which may be higher for RCA concrete.
Subbase type	Subbase material should be selected in consideration of the structural requirements of the pavement type selected (as for conventional concrete pavement designs). Free-draining subbase layers should be considered for RCA concrete pavements produced from D-cracked or ASR-damaged concrete.
Reinforcement	Higher amounts of longitudinal steel reinforcing may be required in JRCP and CRCP to hold cracks tight so that aggregate interlock load transfer can be maintained.
Shoulder type	Same as for conventional concrete pavement.

Pavement Construction

Preparing the Foundation and Subbase

Proper preparation of the pavement foundation layers is just as important for RCA concrete pavements as for conventional pavement construction. Weak support areas should be located and corrected prior to pavement construction. Subbase layers should be properly placed and consolidated or compacted, as appropriate.

Concrete Production and Testing

The high absorption capacity of RCA can cause problems with mixture uniformity and premature stiffening. It is strongly recommended that contractors use a stockpile sprinkling system to keep coarse RCA stockpiles uniformly moist during concrete production.

Air content tests should be performed using volumetric devices (e.g., the Roll-O-Meter) to develop more accurate estimates of total useful air content in the fresh concrete.

Paving Operations

Properly developed and manufactured RCA concrete mixtures can be placed using standard concrete paving, finishing and curing equipment and techniques. No special training or other requirements are necessary. As larger percentages of fine RCA are used, finishing may become more difficult.

Ride Quality

Projects constructed using RCA concrete should be held to the same standards of ride quality and smoothness as those built using conventional paving concrete.

Two-Course Pavement Construction

Two-course (or two-lift) construction using RCA concrete usually involves the wet-on-wet placement of a lower layer comprising concrete containing RCA and a relatively thin (1.5 to 3 in. [4 to 8 cm]) layer of high-quality concrete wearing surface that is manufactured using highly durable virgin aggregate (Figures 28 and 29).

Two-course construction is popular in Europe, where the lower concrete layer can contain RCA containing significant amounts of recycled asphalt material from sources such as adjacent asphalt shoulders, an ATB, etc. (FHWA 2007a). The first two-course concrete pavement in the U.S. was constructed in 1909. Although the typical two-course concrete pavement constructed in the U.S. included the characteristic high-quality concrete wearing surface, virgin aggregate, and not RCA, typically was used in the bottom lift. Because of this, many pavement engineers in the U.S. have felt that the benefit of building an improved top lift was not justified by the increased cost of two-course construction (Cable et al 2004).

Now that many high-quality, conveniently located virgin aggregate resources are being depleted rapidly, because advances in RCA processing technologies can now produce RCA aggregates that perform comparably to virgin aggregates in new concrete mixtures, and because the use of RCA in the bottom lift of a two-course concrete pavement has been proven a viable option in Europe (FHWA 2007a), RCA is now being considered as a sustainable and less costly bottom lift for two-course concrete pavement applications in the U.S.

Figure 28. Two-course concrete pavement construction; this photo was taken after the first lift was spread and consolidated and the second lift was spread, but before the second lift was slipformed, showing the second slipform paving machine and top lift (Photo credit: Missouri/Kansas Chapter, ACPA).

Figure 29. Two lift construction of a portion of I-70 in Salina, KS in 2008; note that in the paving train there are two combin ations of placers and slipform pavers, one for each lift, followed by texturing and curing machines (Photo credit: Missouri/Kansas Chapter, ACPA).

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Appendix A.

GUIDELINES FOR REMOVING AND CRUSHING EXISTING CONCRETE PAVEMENT

(Note: These guidelines were derived mainly from the 1993 version of ACPA's TB014P, "Recycling Concrete Pavements," from AASHTO M319, "Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course," and from AASHTO MP16, "Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete." Users are referred to these documents, as well as existing State and Local construction specifications, for additional details concerning the production of reclaimed concrete aggregate products.)

SCOPE

These guidelines are intended to provide users with a framework for use in developing a suitable specification for removing and crushing existing concrete pavement to produce reclaimed concrete aggregates (RCA) suitable for use in typical nonstructural highway construction applications (e.g., concrete pavements, subbases, sidewalks, median barriers, curbing, etc.).

State and local regulations, laws and specifications may be applicable to specific projects and may supersede these guidelines; users of these guidelines are cautioned to contact appropriate state and local authorities to identify any additional or superseding requirements/specifications.

DESCRIPTION

These guidelines are for breaking, removing, crushing, screening, and stockpiling existing concrete pavement. All concrete pavement designated on the plans for removal and salvage may be handled and processed as described herein.

REMOVAL

Where asphalt resurfacing or patching material is present, remove the asphalt before removing the concrete pavement unless otherwise directed on the project plans and specifications or by the engineer. Remove all joint sealing materials before removing the concrete pavement. Asphalt and sealing materials removed from the project usually becomes the property of the contractor, who will dispose of them in an environmentally acceptable manner.

Fracture the existing concrete pavement in place using pavement breaking equipment with the capacity to break the pavement into appropriately sized pieces for removal from the site (the maximum fractured slab size for processing in the crushing operation might also be considered at this point). Breaking and removal equipment or methods that damage culverts under the roadbed are not be permitted.

Remove and transport the broken material to the pavement fragment stockpile site. Remove concrete using equipment and methods that avoid the inclusion of subgrade and subbase materials.

Remove all reinforcing steel (including dowels and tie bars) from the salvaged pavement either prior to or during the crushing operation. All reinforcing steel removed from the pavement usually becomes the property of the contractor, who will dispose of it in an environmentally acceptable manner.

PROCESSING SALVAGED CONCRETE

Crush and size the salvaged concrete to meet the specified requirements for the intended use of the recycled material. Adjust the crushing operations to maximize the production (yield) of recycled materials that meet the quality and grading requirements for the intended use of the material. Any surplus salvaged concrete or unusable crushed material usually becomes the property of the contractor, who will dispose of it in an environmentally acceptable manner.

Remove any remaining reinforcing steel, dowel bars, dowel bar assemblies, joint filler, bituminous materials (in excess of allowable limits) and other foreign material from the crushed concrete and dispose of such materials in an environmentally acceptable manner.

QUALITY CONTROL (QC)

Develop and implement a quality control (QC) plan for aggregate production. The QC plan should describe the production procedures, test methods and frequency of testing to ensure consistent production of RCA meeting the requirements of the intended application. The QC plan also should describe methods to be used to ensure that reclaimed concrete source materials are not contaminated with unacceptable amounts of deleterious materials. Establish methods and criteria for examining RCA prior to its use.

Stockpile RCA products to assist in qualitative and quantitative identification of the presence of deleterious materials. (Stockpiling can also be used as a means to qualitatively assess the uniformity of the material.) Stockpiles may represent all or part of the material to be used on a specific project. Thus, construct stockpiles in a manner that will minimize segregation and permit visual examination and representative sampling of the material.

Test RCA intended for use in concrete mixtures should be tested according to AASHTO T85 ("Specific Gravity and Absorption of Coarse Aggregate") to determine the specific gravity and absorption of the material. For specific gravity, the total variability of tests (from minimum value to maximum value) should not exceed 0.100. For absorption, the total variability of tests (from minimum value to maximum value) should not exceed 0.8 percent. Stockpile RCA having specific gravity and absorption variability values that fall outside of these limits separately where they might be used included in a project with less stringent specific gravity and absorption values.

Note 1 – *Coarse RCA may contain varying amounts of reclaimed concrete mortar, which generally has a lower specific gravity and is more absorptive than virgin aggregate. Therefore, RCA can be highly absorptive and can exhibit low specific gravity values, and the absorption and specific gravity values can be highly variable, especially between RCA obtained from different sources or produced at different facilities. The use of aggregates with variable specific gravity and absorption characteristics in concrete mixtures can adversely affect the weighing and batching processes in concrete production and can result in concrete workability and finishing problems and variability. Control of stockpile moisture conditions will help alleviate absorption problems.*

MEASUREMENT AND PAYMENT

Payment for removal and crushing of existing concrete pavement typically is based on the square yards (square meters) of concrete pavement removed (i.e., $/yd^2 [$/m^2]). Payment for this item typically constitutes full payment for breaking, removing, hauling, crushing, screening, and stockpiling the old concrete, and for removing and disposing of waste steel, foreign material and incidentals necessary to completing the work.

Appendix B.

GUIDELINES FOR USING RCA IN UNSTABILIZED (GRANULAR) SUBBASES

(Note: These guidelines were derived mainly from the 1993 version of ACPA's TB014P, "Recycling Concrete Pavements," and from AASHTO M319, "Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course." Users are referred to these documents, as well as existing State and Local construction specifications, for additional details concerning the production of RCA products.)

SCOPE

These guidelines are intended to provide users with a framework for use in developing a suitable specification for using aggregate materials derived from recycled concrete aggregate (RCA) in constructing unstabilized subbases for typical road or highway construction applications.

Note 1 – *When properly processed, hauled, spread and compacted on a prepared subgrade to appropriate density standards, RCA used alone or blended with natural or crushed aggregate can be expected to provide adequate stability and load support for use as road or highway subbase courses.*

State and local regulations, laws and specifications may be applicable to specific projects and may supersede these guidelines; users of these guidelines are cautioned to contact appropriate state and local authorities to identify any additional or superseding requirements/specifications.

These guidelines are not intended for use in the construction of unstabilized base/subbase courses in locations where concrete or asphalt surfacing will not be placed over the subbase.

Note 2 – *The engineer is cautioned to provide appropriate construction specifications to ensure compaction is achieved to such an extent that further densification of the compacted subbase material due to traffic loadings will be insignificant.*

USE OF RCA IN UNSTABILIZED (GRANULAR) SUBBASES

RCA may be used without restriction in unstabilized (granular) subbases where drainage layers or perforated drainage pipes will not be installed, provided that the crushed concrete material meets all other requirements of this specification.

Approval should be granted by the engineer before using RCA in proximity to perforated drains for all uses not specifically addressed in the contract. The engineer may approve the following uses of RCA as a granular material in embankment or backfill where perforated pipe is installed, or is to be installed, or where water moving through these materials may enter the perforated pipe:

- All RCA material will be placed below the invert elevation of any perforated subsurface drainage pipe.
- All RCA material products used are larger than (will not pass) the No. 4 (4.75 mm) sieve.

Note 3 – *The engineer should be aware of the highly alkaline nature of RCA, the relatively high degree of solubility of the hydroxide-bearing components of the material, and the potential increase in pH that could occur in waters percolating through an RCA subbase. Depending on the sensitivity of local soils, surface waters and groundwater to the presence of alkaline material, the engineer should set appropriate limits on the proximity of placement of RCA relative to groundwater and surface waters. Unstabilized RCA materials should not be used in the vicinity of metal culverts that are sensitive to highly alkaline environments.*

Note 4 – *The engineer is cautioned to minimize (or prevent, when possible) the use of unstabilized RCA in locations where waters that pass through the aggregate would also flow through or over geotextile drainage layers, geotextile-wrapped pipe drains, drain field or pavement drainage piping, or any other pavement drainage system. Soluble minerals and dust can be transported hydraulically from the RCA material and be precipitated out or deposited in the drainage structures, thereby reducing the permeability and/or capacity of the drainage system. Further discussion on this topic can be found elsewhere in this publication, in AASHTO M319 and in numerous research reports.*

Note 5 – *The engineer should be aware that RCA subbase layers can gain strength and lose permeability over time due to recementing of mortar portion of the RCA. The structural design and geometry of the overlying pavement surfacing should be developed with consideration of this possibility.*

ORDERING INFORMATION

The following information typically is included in the purchase order or contract documents:

- grading to be furnished,
- soundness testing requirements,
- exceptions or additions to this specification, and
- additional testing requirements (if any).

GRADING

RCA or blends of RCA with other approved virgin aggregate materials should comply with the gradation requirements of AASHTO M147, ASTM D2940, or the requirements of the specifying agency.

Note 6 – *There is usually no reason that the gradation requirements for RCA to differ significantly from those for virgin aggregate materials used for the same application.*

Note 7 – *Depending upon the source of the concrete and the processes used in removing, crushing and processing the material, it may be necessary to produce RCA material of at least two separate sizes that can be blended together (and/or with virgin aggregate) to meet the gradation requirements.*

PHYSICAL PROPERTIES

RCA consists of crushed concrete material and virgin aggregate particles derived from the crushing of concrete pavement fragments.

Typical maximum Los Angeles abrasion loss values for the coarse RCA are 50%, measured in accordance with AASHTO T96 ("Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine").

Note 8 – *AASHTO T327 ("Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus") may be required in lieu of AASHTO T96 if the specifying agency has experience with the procedure and has established appropriate testing limits.*

RCA soundness testing may be required at the discretion of the engineer.

Note 9 – *RCA can be susceptible to sulfate attack when tested for soundness using sodium sulfate or magnesium sulfate solutions, leading to unreasonably high loss values. Sulfate soundness test methods (AASHTO T104) may be applied if local experience has found these methods to produce satisfactory results with RCA. Alternative test* *approaches include AASHTO T103, New York State DOT Test Method NY 703-08, Ontario Ministry of Transportation Test method LS-614, and the "No-Test" Alternative (acceptance or rejection based on other quality measures).*

DELETERIOUS SUBSTANCES

RCA containing more than five percent bituminous concrete materials by mass may be validated for acceptance using one or more of the following criteria:

- validation by use of California Bearing Ratio (AASHTO T193) testing
- validation by use of Resilient Modulus (AASHTO T307) testing
- validation by field application

Details concerning these three validation approaches are presented in Appendix D of AASHTO M319 ("Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Construction").

RCA material intended for use in unstabilized subbase layers should be free of all materials that are considered to be solid waste or hazardous materials, as defined by the State or local highway agency.

QUALITY CONTROL (QC)

If RCA or combinations of RCA and other approved virgin aggregate materials are to be used in a subbase, approval should be granted by the engineer. The proposed percentages of combined materials should be established as part of the request. At the engineer's discretion, revised density acceptance testing may be required when percentages or sources of materials change.

Note 10 – *Revised density acceptance testing is recommended when percentages or sources of materials change because RCA will have a different specific gravity and absorption characteristics than virgin aggregate and may vary significantly between sources.*

The quality control (QC) plan for the RCA should detail the production procedures, test methods and frequency of testing to ensure consistent production of RCA meeting the requirements of the intended application. The QC plan will also describe methods to be used to ensure that RCA materials are not contaminated with unacceptable amounts of deleterious materials. Methods and criteria for examining RCA materials prior to use should be established.

Note 11 – *Density control is typically accomplished using the "Proctor test" to compare in-place density values with the maximum dry density. Procedural methods (e.g., specifying a designated number of compaction passes based on the experience of the specifying agency) have also been used successfully in the placement of RCA materials in subbase applications. Density control problems may result, however, when RCA from different sources is used on a single job, or when the RCA is blended with other virgin aggregates. Alternate compaction control methods for such situations are described in Appendix A of AASHTO M319. Revised density acceptance testing is recommended when percentages or sources of materials change because RCA will have a different specific gravity and absorption characteristics than virgin aggregate and may vary significantly between sources.*

Note 12 – *Stockpiling may be required to assist in qualitatively identifying the presence of deleterious materials and assessing the uniformity of the material. When this approach is used, the stockpile may represent all or part of the material to be used on a project, and should be constructed in a manner that will minimize segregation and permit visual examination and representative sampling of the material.*

If RCA is blended with other approved aggregates, blending should be accomplished using a method that ensures uniform blending and prevents segregation.

Appendix C.

GUIDELINES FOR USING RCA IN CONCRETE PAVING MIXTURES

(Note: These guidelines were derived mainly from the 1993 version of ACPA's TB014P, "Recycling Concrete Pavements," and from AASHTO MP16, "Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete." Users are referred to these documents, as well as existing State and Local construction specifications, for additional details concerning the production of RCA products.)

SCOPE

These guidelines are intended to provide users with a framework for use in developing a suitable specification for using recycled concrete aggregate (RCA) in typical concrete paving mixtures.

Note 1 – *Concrete pavement structures of acceptable strength and durability can be produced using RCA materials that is properly processed and manufactured to meet the typical aggregate requirements when those materials are incorporated in a concrete mixture that is proportioned and mixed in accordance with appropriate requirements and procedures, and is placed, consolidated and cured properly. However, using RCA in new concrete mixtures requires the use of suitable quality control (QC) and quality assurance (QA) procedures to ensure that deleterious materials that might be present in the RCA will not adversely impact the quality of the concrete pavement structure.*

State and local regulations, laws and specifications may be applicable to specific projects and may supersede this guide specification. Users of this guide specification are cautioned to contact appropriate state and local authorities to identify any additional or superseding requirements/specifications.

ORDERING INFORMATION

The following information typically is included in the purchase order or contract documents:

- grading to be furnished,
- soundness testing requirements,
- designated aggregate class,
- whether any restrictions on reactive materials applies,
- exceptions or additions to this specification, and
- additional testing requirements (if any).

GRADING

RCA or RCA/virgin aggregate blends should conform to the aggregate gradation requirements prescribed for the specific intended concrete application.

Note 2 – *There is usually no reason that the gradation requirements for RCA to differ significantly from those for virgin aggregate materials used for the same application.*

Note 3 – *Depending upon the source of the concrete and the processes used in removing, crushing and processing the material, it may be necessary to produce RCA material of at least two separate sizes that can be blended together (and/or with virgin aggregate) to meet the gradation requirements.*

PHYSICAL PROPERTIES

RCA consists of crushed concrete material and virgin aggregate particles derived from the crushing of concrete pavement fragments.

Typical maximum Los Angeles abrasion loss values for the coarse RCA are 50%, measured in accordance with AASHTO T96 ("Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine").

Note 4 – *AASHTO T327 ("Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus") may be required in lieu of AASHTO T96 if the specifying agency has experience with the procedure and has established appropriate testing limits.*

RCA used in concrete that will be subject to in-service wetting, extended exposure to humid atmosphere, or contact with moist ground should not contain any materials that are reactive with alkali components in the cement in an amount sufficient to cause excessive expansion of mortar or concrete unless materials that will prevent harmful alkali-aggregate reactions (e.g., Class F fly ash, slag cement, etc.) will be added in appropriate quantities. If necessary, test RCA for Alkali-aggregate reactivity (AAR) in accordance with AASHTO T303 ("Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars due to Alkali-Silica Reaction") and/or ASTM C1567 ("Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)") when alkali-silica reaction (ASR) is suspected, and in accordance with ASTM C586 ("Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)") when alkali-carbonate reaction (ACR) is suspected.

Note 5 – *If the source and history of the RCA are known and no reactive failures were present in the source concrete, testing for reactive expansion may not be necessary. However, unless a precise history is known, the source concrete may have not been exposed to all elements required to cause reactive expansion and the RCA may be unknowingly reactive.*

RCA used in concrete that will be subjected to freeze-thaw action should not contain aggregate components that will result in D-cracking of the concrete. When potential D-cracking is suspected, test RCA in accordance with AASHTO T161 ("Resistance of Concrete to Rapid Freezing and Thawing") or equivalent local methods. Acceptance criteria for AASHTO T161 and equivalent methods should be based on local criteria that have been developed to address the issue of D-cracking.

RCA should meet the flat and elongated particle requirements of the specifying agency if the agency has such requirements.

Test RCA intended for use in concrete mixtures should be tested according to AASHTO T85 ("Specific Gravity and Absorption of Coarse Aggregate") to determine the specific gravity and absorption of the material. For specific gravity, the total variability of tests (from minimum value to maximum value) should not exceed 0.100. For absorption, the total variability of tests (from minimum value to maximum value) should not exceed 0.8 percent. Stockpile RCA having specific gravity and absorption variability values that fall outside of these limits separately where they might be used included in a project with less stringent specific gravity and absorption values.

Note 6 – *Coarse RCA may contain varying amounts of reclaimed concrete mortar, which generally has a lower specific gravity and is more absorptive than virgin aggregate. Therefore, RCA can be highly absorptive and can exhibit low specific gravity values, and the absorption and specific gravity values can be highly variable, especially between RCA obtained from different sources or produced at different facilities. The use of aggregates with variable specific gravity and absorption characteristics in concrete mixtures can adversely affect the weighing and batching processes in concrete production and can result in concrete workability and finishing problems and variability. Control of stockpile moisture conditions will help alleviate absorption problems.*

DELETERIOUS SUBSTANCES

RCA should not contain clay lumps and friable particles, chert, and coal and lignite or other deleterious substances that exceed the maximum allowable amounts listed in Table 12.

Note 7 – *The presence of deleterious materials in aggregates used in the production of concrete mixtures can adversely affect concrete setting time and/or strength, and can also induce expansive reactions that could result in premature deterioration of the concrete structure. As a result, strict quality control (QC) and quality assurance (QA) procedures are required to ensure that RCA material used as coarse aggregate in the production of concrete mixtures will not adversely affect the quality of the concrete product.*

QUALITY CONTROL (QC)

If RCA or combinations of RCA and other approved virgin aggregate materials are to be used in a new concrete mixture, approval from the engineer might be necessary. The proposed percentages of combined materials should be established as part of the request. At the engineer's discretion, revised concrete mixture designs may be required when percentages or sources of materials change.

Note 8 – *A revised concrete mixture design is recommended when percentages or sources of RCA materials change. It is likely that the RCA will have different specific gravity and absorption characteristics than the virgin aggregate.*

Develop and implement a quality control (QC) plan for aggregate production. The QC plan should describe the production procedures, test methods and frequency of testing to ensure consistent production of RCA meeting the requirements of the intended

Table 12. Typical Limits for Deleterious Substances and Physical Property Requirements of RCA for Use in New Concrete Mixtures (after AASHTO MP16)

Class designation[b]	Clay lumps and friable particles	Chert (sp gr SSD < 2.40)[c]	Sum of clay lumps, friable particles and chert (sp gr SSD < 2.40)[c]	Other deleterious substances[d]	Coal and lignite
	Maximum allowable, percent[a]				
A	2.0	3.0	2.3	0.3	0.2
B	3.0	5.0	5.0	0.3	0.2
C	3.0	8.0	8.0	0.3	0.2

[a] The engineer may supplement the requirements of this table by placing limits on the amount of deleterious substances or physical properties in accordance with local experience and practice.

[b] RCA conforming to the requirements for the various classes designated in this table should generally be suitable for the following uses:

Typical suggested uses	Weathering exposure	Class of aggregate
Concrete pavements, cement-treated subbases, sidewalks, median barriers, curbing and other non-structural applications	Severe	A
	Moderate	B
	Negligible	C

[c] These limitations in this table apply only to RCA in which chert appears as an impurity. They are not applicable to gravels that are predominantly chert. Limitations on the soundness of such aggregate should be based on service records in the environment in which the material is used.

[d] Other deleterious substances include adherent fines, vegetable matter, plastics, plaster, paper, gypsum board, metals, fabrics, wood, brick, tile, glass, and asphalt (bituminous) materials. The percentages of these materials should be determined in accordance with ASTM C295 or other equivalent methods approved by the specifying agency.

application. The QC plan also should describe methods to be used to ensure that RCA source materials are not contaminated with unacceptable amounts of deleterious materials. Methods and criteria for examining RCA should be established prior to its use.

Stockpile RCA products to assist in qualitative and quantitative identification of the presence of deleterious materials. (Stockpiling can also be used as a means to qualitatively assess the uniformity of the material.) Stockpiles may represent all or part of the material to be used on a specific project. Thus, construct stockpiles in a manner that will minimize segregation and permit visual examination and representative sampling of the material.

If RCA is blended with other approved aggregates, blending should be accomplished using a method that ensures blending and prevents segregation.

RCA should be brought to and maintained at a moisture condition that approaches a saturated surface-dry (SSD) condition prior to batching. This may be accomplished by using a water sprinkling system or another approved method. Appropriate batch water adjustments should be made if the RCA is not precisely in a SSD condition at the time of batching.

Appendix D.

AASHTO STANDARDS

All American Association of State Highway and Transportation Officials (AASHTO) documents references in the text of this publications are listed as follows and can be obtained at https://bookstore.transportation.org/; please consult the AASHTO website to ensure that you have obtained the most recent version of any AASHTO standard before using it.

M6 Standard Specification for Fine Aggregate for Hydraulic Cement Concrete

M43 Standard Specification for Sizes of Aggregate for Road and Bridge Construction

M80 Standard Specification for Coarse Aggregate for Hydraulic Cement Concrete

M92 Standard Specification for Wire-Cloth Sieves for Testing Purposes

M146 Standard Specification for Terms Relating to Subgrade, Soil-Aggregate, and Fill Materials

M147 Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses

M319 Standard Specification for Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course

MP16 Standard Specification for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete

T2 Standard Method of Test for Sampling of Aggregates

T11 Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing

T19 Standard Method of Test for Bulk Density ("Unit Weight") and Voids in Aggregate

T27 Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates

T85 Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate

T87 Standard Method of Test for Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test

T88 Standard Method of Test for Particle Size Analysis of Soils

T89 Standard Method of Test for Determining the Liquid Limit of Soils

T90 Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils

T96 Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

T99 Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop

T103 Standard Method of Test for Soundness of Aggregates by Freezing and Thawing

T104 Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate

T112 Standard Method of Test for Clay Lumps and Friable Particles in Aggregate

T113 Standard Method of Test for Lightweight Pieces in Aggregate

T161 Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing

T176 Standard Method of Test for Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test

T180 Standard Method of Test for Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop

T193 Standard Method of Test for The California Bearing Ratio

T196 Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method

T234 Standard Method of Test for Strength Parameter of Soils by Triaxial Compression

T260 Standard Method of Test for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials

T277 Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

T299 Standard Method of Test for Rapid Identification of Alkali-Silica Reaction Product in Concrete

T303 Standard Method of Test for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars due to Alkali-Silica Reaction

T307 Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials

T327 Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus

Appendix E.

ASTM STANDARDS

All American Association of State Highway and Transportation Officials (AASHTO) documents references inAll American Society for Testing and Materials (ASTM) documents references in the text of this publication are listed as follows and can be obtained at www.astm.org; please consult the ASTM website to ensure that you have obtained the most recent version of any ASTM standard procedure before using it.

C33 Standard Specification for Concrete Aggregates

C88 Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate

C125 Standard Terminology Relating to Concrete and Concrete Aggregates

C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

C173 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method

C227 Standard Test method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)

C289 Standard Test method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)

C295 Standard Guide for Petrographic Examination of Aggregates for Concrete

C342 Standard Test Method for Potential Volume Change of Cement-Aggregate Combinations (Withdrawn 2001)

C441 Standard Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction

C586 Standard Test Method for Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregates (Rock Cylinder Method)

C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

C666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

C856 Standard Practice for Petrographic Examination of Hardened Concrete

C1202 Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration

C1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

D2940 Standard Specification for Graded Aggregate Material for Bases or Subbases for Highways or Airports

D5101 Standard Test Method for Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio

D6928 Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus

Glossary

This Glossary is not intended to cover all terms used in the vernacular of recycling concrete pavements and several other extensive sources of terms are readily available, such as ACI Committee 116 and AASHTO/ASTM standards.

A

AAR – See *Alkali-Aggregate Reactivity*.

Absolute Volume – The displacement volume of an ingredient of concrete or mortar; in the case of solids, the volume of the particles themselves, including their permeable or impermeable voids but excluding space between particles; in the case of fluids, the volume which they occupy.

Absorbed Moisture – The moisture held in a material and having physical properties not substantially different from those of ordinary water at the same temperature and pressure.

Absorption – The amount of water absorbed under specific conditions, usually expressed as a percentage of the dry weight of the material; the process by which the water is absorbed.

Accelerator – An admixture which, when added to concrete, mortar, or grout, increases the rate of hydration of hydraulic cement, shortens the time of set, or increases the rate of hardening or strength development.

Admixture – A material other than water, aggregates, and cementitious material (including cement, slag cement, fly ash, and silica fume) that is used as an ingredient of concrete and is added to the bath before and during the mixing operation.

Aggregate – Granular material, such as sand, gravel, crushed stone, recycled concrete, or iron blast furnace slag.

Aggregate, Angular – See *Angular Aggregate*.

Aggregate Blending – The process of intermixing two or more aggregates to produce a different set of properties, generally, but not exclusively, to improve grading or include a RCA.

Aggregate, Coarse – See *Coarse Aggregate*.

Aggregate, Crusher-Run – See *Crusher-Run Aggregate*.

Aggregate, Dense-Graded – See *Dense-Graded Aggregate*.

Aggregate, Fine – See *Fine Aggregate*.

Aggregate, Gap-Graded – See *Gap-Graded Aggregate*.

Aggregate Gradation – See *Grading*.

Aggregate Interlock – The projection of aggregate particles or portion of aggregate particles from one side of a joint or crack in concrete into recesses in the other side of the joint or crack so as to affect load transfer in compression and shear and maintain mutual alignment.

Aggregate, Maximum Size – See *Nominal Maximum Size*.

Aggregate, Natural – See *Natural Aggregate*.

Aggregate, Open-Graded – See *Open-Graded Aggregate*.

Aggregate, Virgin – See *Virgin Aggregate*.

Aggregate, Well-Graded – See *Well-Graded Aggregate.*

Air Content – The amount of air in mortar or concrete, exclusive of pore space in the aggregate particles, usually expressed as a percentage of total volume of mortar or concrete.

Air-Entraining – The capabilities of a material or process to develop a system of minute bubbles of air in cement paste, mortar, or concrete during mixing.

Air-Entraining Agent – An addition for hydraulic cement or an admixture for concrete or mortar which causes air, usually in small quantity, to be incorporated in the form of minute bubbles in the concrete or mortar during mixing, usually to increase its workability and frost resistance.

Air-Meter – A device for measuring the air content of concrete and mortar.

Alkali-Aggregate Reactivity (AAR) – A chemical reaction in mortar or concrete between alkalis (sodium and potassium) released from portland cement or from other sources, and certain compounds present in the aggregates; under certain conditions, harmful expansion of the concrete or mortar may be produced.

Alkali-Carbonate Reactivity – The reaction between the alkalies (sodium and potassium) in portland cement binder and certain carbonate rocks, particularly calcite dolomite and dolomitic limestones, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Alkali-Silica Reactivity (ASR) – The reaction between the alkalies (sodium and potassium) in portland cement binder and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Angular Aggregate – Aggregate particles that possess well-defined edges formed at the intersection of roughly planar faces.

Asphalt-Treated Subbase (ATB) – A stabilized subbase that is bound by asphalt binder.

ASR – See *Alkali-Silica Reactivity*.

ATB – See *Asphalt-Treated Subbase.*

B

Base – A layer within an asphalt pavement structure; usually a granular or stabilized material, either previously placed and hardened or freshly placed, on which the pavement surface is placed in a later operation.

Beneficiation – The treatment of any raw material to improve its physical or chemical properties prior to further processing or use.

Bulk Density – The mass of a material (including solid particles and any contained water) per unit volume, including voids.

Bulk Specific Gravity – See *Specific Gravity*.

C

Calcium Hydroxide – A by-product of the cement hydration reaction that is highly soluble and is easily leached from RCA particles in stockpiles and drainable subbase layers.

Carbonation – Reaction between carbon dioxide and the products of portland cement hydration to produce calcium carbonate.

Cement – A hydraulic cement consisting essentially of an intimate and uniform blend of portland cement or slag cement and fine pozzolan produced by intergrinding portland-cement clinker and pozzolan within specified limits.

Cement-Treated Subbase (CTB) – A stabilized subbase that is bound by portland cement with a general dosage of about 4 or 5 percent cement by weight. CTB are best controlled using compaction and/or density requirements, but typical target strengths for a CTB layer are between 300 and 800 psi (2.1 and 5.5 MPa) compression at 7 days.

Cement-Stabilized Subbase – A class of stabilized subbases that includes cement-treated subbases (CTB) and lean concrete.

Cementitious – Having cementing properties.

Cementitious Materials – Substances that alone have hydraulic cementing properties (set and harden in the presence of water); includes slag cement, natural cement, hydraulic hydrated lime, and combinations of these and other materials.

Chloride Content – Level of sodium chloride (NaCl) in the to-be-recycled concrete pavement due to exposure to deicing chemicals.

Coarse Aggregate – Aggregate predominately retained on the No. 4 (4.75 mm) sieve; may be either virgin or recycled materials.

Coefficient of Thermal Expansion and Contraction (CTE) – Change in linear dimension per unit length or change in volume per unit volume per degree of temperature change.

Combined Aggregate Grading – Particle size distribution of a mixture of fine and coarse aggregate.

Cone Crusher – A crusher that uses an eccentric rotating cone to trap and crush concrete fragments against the inner crusher housing walls; commonly used in secondary crusher applications because they can handle slab fragments no larger than 8 in. (20 cm) in diameter.

Contaminant – In the context of recycled concrete, refers to materials such as joint sealants, asphalt concrete shoulders, patching materials, etc. that might be included in the final RCA product.

Continuously Reinforced Concrete Pavement (CRCP) - A pavement with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints.

CRCP – See *Continuously Reinforced Concrete Pavement*.

Crushed Gravel – The product resulting from the artificial crushing of gravel with a specified minimum percentage of fragments having one or more faces resulting from fracture; a type of virgin aggregate.

Crushed Stone – The product resulting from the artificial crushing of rocks, boulders, or large cobblestones, substantially all faces of which possess well-defined edges and have resulted from the crushing operation; a type of virgin aggregate.

Crusher, Cone – See *Cone Crusher*.

Crusher, Impact – See *Impact Crusher*.

Crusher, Jaw – See *Jaw Crusher*.

Crusher-Run Aggregate – Aggregate that has been broken in a mechanical crusher and has not been subjected to any subsequent screening process; a type of virgin aggregate.

CTB – See *Cement-Treated Subbase*.

CTE – See *Coefficient of Thermal Expansion and Contraction.*

Curing – The maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop.

Curling – Deformation of concrete pavement slabs due to thermal gradients.

D

D-cracking – (also known as Durability Cracking) – Cracking of the concrete that results from freeze-thaw deterioration of the coarse aggregate within the concrete.

Daylighted Subbase – (also known as Daylighting) – An edge drainage system in which a subbase is extended through the edge of the pavement system to a point where it is capable of freely carrying water to side ditches, hence being daylighted.

Daylighting – See *Daylighted Subbase*.

Dense-Graded Aggregate – Aggregates graded to produce low void content and maximum weight when compacted.

Dense-Graded Subbase – A subbase (typically unstabilized) that is composed of dense-graded aggregate.

Density – Mass per unit volume; by common usage in relation to concrete, weight per unit volume, also referred to as unit weight.

Dowel – 1) A load transfer device, commonly a plain round steel bar, which extends into two adjoining portions of a concrete construction, as at a joint in a pavement slab, so as to transfer shear loads; 2) a deformed reinforcing bar intended to transmit tension, compression, or shear through a construction joint.

Drainable Subbase – See *Permeable Subbase*.

Drainage – The interception and removal of water from, on, or under an area or roadway; the process of removing surplus ground or surface water artificially; a general term for gravity flow of liquids in conduits.

Drying Shrinkage – Contraction caused by drying.

Durability Cracking – See *D-cracking.*

E

Econocrete – Although sometimes known as lean concrete subbase, this material is a lower strength, more inexpensive concrete mixture that is identical in concept to lean concrete subbase material but used as a paving surface.

Edge Drainage System – A system designed to carry water that has infiltrated the pavement surface to a side ditch. The two most common types of edge drainage systems are collector pipes with redundant outlets and daylighted subbases.

F

Fine Aggregate – Aggregate passing the 3/8-in. (9.5 mm) sieve and almost entirely passing the No. 4 (4.75-mm) sieve and predominantly retained on the No. 200 (75 mm) sieve; may be either virgin or recycled materials.

Fly Ash – The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the fire box through the boiler by flu gasses; Used as mineral admixture in concrete mixtures.

Free-draining Subbase – A subbase with a target permeability between 50 and 150 ft/day (15 and 46 m/day) in laboratory tests; the maximum permeability for a free-draining subbase is approximately 350 ft/day (107 m/day) in laboratory tests and any materials that provide higher permeability rates should be considered permeable subbases.

Freeze-Thaw Durability – The ability of the concrete material to resist repeated freezing and thawing cycled.

Fresh Concrete – (also known as Plastic Concrete) – A condition of freshly mixed concrete such that it is readily remoldable and workable, cohesive, and has an ample content of cement and fines, but is not over-wet.

G

Gap-Graded Aggregate – Aggregate so graded that certain intermediate sizes are substantially absent.

Geosynthetics – Thin pliable sheets of textile material of varying permeability. The varieties of geosynthetics include geotextiles, geogrids, geonets, geocells and geomembranes. The usefulness and effectiveness of geosynthetics directly depends on the type of geosynthetic, the intended function (filtration, separation and/or reinforcement), in-situ soil conditions and installation techniques.

Geotextile – See *Geosynthetics*.

GHG – See *Greenhouse Gas*.

Gradation – See *Grading*.

Grading – The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings).

Granular Subbase – See *Unstabilized Subbase*.

Gravel – Granular material predominantly retained on the No. 4 (4.75 mm) sieve and resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate; a type of virgin aggregate.

Greenhouse Gas (GHG) – Any of the atmospheric gasses that contribute to the greenhouse effect.

H

Harsh Mixture – A concrete mixture that lacks desired workability and consistency due to a deficiency of mortar.

Harshness – Deficient workability and cohesiveness caused by insufficient sand or cement, or by improperly graded aggregate.

High Range Water-Reducing Admixture – See *Water-Reducing Admixture*.

Horizontal Shaft Impact Crusher – See *Impact Crusher*.

Hydration – The chemical reaction between cement and water which causes concrete to harden.

I

Impact Crusher – A crusher that uses heavy steel "blow bars" mounted on a horizontal or vertical rotor to repeatedly impact concrete fragments and hurl them against steel anvils or "break plates" in the crusher housing; commonly used as in secondary crusher applications and the crushing processes yields more fine aggregate and less coarse aggregate.

J

Jaw Crusher – A crusher that uses a large steel plate to compress concrete fragments against a stationary plate within the crusher housing; commonly used in primary crusher applications because they can handle larger slab fragments.

Jointed Plain Concrete Pavement (JPCP) – Pavement containing enough joints to control all natural cracks expected in the concrete; steel tie bars are generally used at longitudinal joints to prevent joint opening, and dowel bars may be used to enhance load transfer at transverse contraction joints depending upon the expected traffic.

Jointed Reinforced Concrete Pavement (JRCP) – Pavement containing some joints and embedded steel mesh reinforcement (sometimes called distributed steel) to control expected cracks; steel mesh is discontinued at transverse joint locations.

JPCP – See *Jointed Plain Concrete Pavement*.

JRCP – See *Jointed Reinforced Concrete Pavement.*

K

L

Lean Concrete Subbase – A subbase that is bound by portland cement and with higher cement and water contents than cement-treated subbases, but they less cement than conventional concrete and an average 7-day compressive strength between 750 and 1,200 psi (5.2 and 8.3 MPa). The aggregates used in lean concrete subbases do not necessarily meet conventional quality standards for aggregates used in pavements.

Load Transfer Device – See *Dowel*.

Load Transfer Efficiency (LTE) – The ability of a joint or crack to transfer a portion of a load applied on side of the joint or crack to the other side of the joint or crack.

Los Angeles Abrasion Mass Loss (L.A. Abrasion Test) – Measures the amount of particle degradation (in terms of mass loss) that takes place under standard aggressive handling conditions.

LTE – See *Load Transfer Efficiency.*

M

Materials-Related Distress – Distresses (e.g., D-cracking, ASR, etc.) that are related to the materials that make up a concrete pavement structure.

Maximum Size of Aggregate – See *Nominal Maximum Size.*

Mix – See *Mixture*.

Mixture – The assembled, blended, commingled ingredients of mortar, concrete, or the like, or the proportions for their assembly.

Mixture Design – See *Proportioning*.

Moisture Content of Aggregate – The ratio, expressed as a percentage, of the weight of water in a given granular mass to the dry weight of the mass.

Mortar – Concrete with essentially no aggregate larger than about 3⁄16 in. (4.8 mm).

N

Natural Aggregate – Aggregate resulting from the natural disintegration and abrasion of rock; a type of virgin aggregate.

Natural Sand – Sand resulting from natural disintegration and abrasion of rock; a type of virgin aggregate.

Nominal Maximum Size – In specifications for and descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass; sometimes referred to as maximum size (of aggregate).

O

Open-Graded Aggregate – Aggregate so graded that most intermediate and fine sizes are substantially absent; typically used in a permeable subbase as a means to promote drainage.

Open-Graded Subbase – See *Permeable Subbase*.

P

Particle-Size Distribution – The division of particles of a graded material among various sizes; for concrete materials, usually expressed in terms of cumulative percentages larger or smaller than each of a series of diameters or the percentages within certain ranges of diameter, as determined by sieving.

Paste – Constituent of concrete consisting of cement and water.

Pavement Structure – The combination of asphalt/concrete surface course(s) and base/subbase course(s) placed on a prepared subgrade to support the traffic load.

Percent Fines – Amount, expressed as a percentage, of material in aggregate finer than a given sieve, usually the No. 200 (75 μm) sieve; also, the amount of fine aggregate in a concrete mixture expressed as a percent by absolute volume of the total amount of aggregate.

Permeability – A soil's ability to transmit water through its voids. The permeability of any material is heavily dependent on the connectivity of its pore network; the more connected and the larger the pore network is, the greater the permeability.

Permeable Subbase – Unstabilized layer consisting of crushed aggregates with a reduced amount of fines to promote drainage and increase the permeability of the subbase above 350 ft/day (107 m/day) in laboratory tests, although typical levels range from 500 to 20,000 ft/day (152 to 6,100 m/day) in laboratory tests. Despite their intuitive advantage to quickly be able to remove excess water, permeable subbases are no longer considered a cost effective design element for concrete pavements due to their very problematic history.

Plain Concrete – Concrete without reinforcement.

Plastic Concrete – See *Fresh Concrete*.

Proportioning – Selection of proportions of ingredients for mortar or concrete to make the most economical use of available materials to produce mortar or concrete of the required properties.

Process Control – See *Quality Control*.

Q

QA – See *Quality Assurance*.

QC – See *Quality Control*.

Quality Assurance (QA) – All those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service.

Quality Control (QC) – (also known as Process Control) – Actions and considerations taken by a producer and/or contractor to assess, document, and adjust production and construction processes so as to control the level of quality being produced in the end product. QC is not the same as quality assurance (QA); in fact, QC is a component of QA.

R

Reactive-Aggregate – Aggregate containing certain silica or carbonate compounds that are capable of reacting with alkalis in portland cement, in some cases producing damaging expansion of concrete.

Recementing – See *Secondary Cementing*.

Reclaimed Asphalt Pavement (RAP) – Previously existing asphalt pavement that has been processed for reuse, typically as aggregate in a subbase layer.

Recycled Concrete – Previously existing, hardened concrete that has been crushed and sorted for reuse, such as aggregate in a subbase layer or a new concrete pavement. Recycled concrete can come from any number of sources, not just concrete pavements, and sorting processes can be adjusted to remove contaminants such as reinforcing steel.

Recycled Concrete Aggregate (RCA) – A granular material that can be produced by recycling existing concrete for use as a substitute for natural (virgin) aggregate in almost any application.

Recycling – The act of processing existing pavement material into usable material for a layer within a new pavement structure.

Reinforced Concrete – Concrete containing adequate reinforcement (prestressed or not prestressed) and designed on the assumption that the two materials act together in resisting forces; see *Continuously Reinforced Concrete Pavement* and *Jointed Reinforced Concrete Pavement.*

Reinforcement – Bars, wires, strands, and other slender members embedded in concrete in such a manner that the reinforcement and the concrete act together in resisting forces.

Retardation – Reduction in the rate of hardening or strength development of fresh concrete, mortar, or grout; i.e., an increase in the time required to reach initial and final set.

Retarder – An admixture that delays the setting of cement and hence of mixtures such as mortar or concrete containing cement.

Rubblizing – A destructive procedure to break existing concrete pavement in place to fragments that range in size from 4 to 8 in. (100 to 200 mm).

S

Sand – The fine granular material (usually less than 3⁄16 in. (4.75 mm) in diameter) resulting from the natural disintegration of rock, or from the crushing of friable sandstone; a type of virgin aggregate.

Saturated Surface-Dry (SSD) – Condition of an aggregate particle or other porous solid when the permeable voids are filled with water but there is no water on the exposed surface.

Saturated Surface-Dry (SSD) Particle Density – The mass of the saturated-surface-dry aggregate divided by its displaced volume in water or in concrete. (Also called Bulk Specific Gravity).

Saturation – 1) In general, the condition of the coexistence in stable equilibrium of either a vapor and a liquid or a vapor and solid phase of the same substance at the same temperature. 2) As applied to aggregate or concrete, the condition such that no more liquid can be held or placed within it.

SCM – See *Supplementary Cementitious Material*.

Secondary Cementing – Also known as Recementing. The result of hydration of exposed and previously unhydrated or partially-hydrated cement grains of the mortar portion of RCA when the RCA is used in a new unstabilized mixture; can be significant enough to effectively cause an unstabilized layer of dense-graded RCA (often found in foundations, pipe beds, backfill applications, etc.) to behave like a cement-treated material.

Set-Accelerating Admixture – See *Accelerator*.

Set-Retarding Admixture – See *Retarder*.

Sieve – A metallic plate or sheet, a woven-wire cloth, or other similar device, with regularly spaced apertures of uniform size, mounted in a suitable frame or holder for use in separating granular material according to size.

Sieve Analysis – The classification of particles, particularly of aggregates, according to sizes as determined with a series of sieves of different openings.

Slag Cement – The non-metallic by-product, consisting essentially of silicates and aluminosilicates of lime and other bases, which is produced in a molten condition simultaneously with iron in a blast furnace.

Slump – A measure of consistency of freshly mixed concrete, equal to the subsidence measured to the nearest ¼-inch (6-mm) of the molded specimen immediately after removal of the slump cone.

Specific Gravity – The ratio of the weight in air of a given volume of material at a stated temperature to the weight in air of an equal volume of distilled water at the same temperature.

Stabilized Subbase – A subbase layer that is bound by either portland cement or asphalt binders. Stabilized subbases fall into three general categories: cement-treated, lean concrete and asphalt-treated. The primary benefit of stabilized bases is that they provide relatively strong, uniform support and are resistant to erosion (pumping).

Subbase – The layer(s) of select or engineered material of planned thickness placed between the subgrade and a concrete pavement that serve one or more functions such as preventing pumping, distributing loads, providing drainage, minimizing frost action, or facilitating pavement construction.

Subbase, Asphalt-Treated – See *Asphalt-Treated Subbase.*

Subbase, Cement-Stabilized – See *Cement-Stabilized Subbase.*

Subbase, Cement-Treated – See *Cement-Treated Subbase.*

Subbase, Daylighted – See *Daylighted Subbase*.

Subbase, Dense-Graded – See *Dense-Graded Subbase.*

Subbase, Free-Draining – See *Free-Draining Subbase.*

Subbase, Lean Concrete – See *Lean Concrete Subbase.*

Subbase, Permeable – See *Permeable Subbase*.

Subbase, Stabilized – See *Stabilized Subbase*.

Subbase, Unstabilized – See *Unstabilized Subbase.*

Subgrade – The natural ground, graded and compacted, on which a pavement structure is built. Also called grade.

Sulfate Attack – Chemical or physical reaction between certain constituents in cement and sulfates in the soil or groundwater; sufficient attack may disrupt concrete that is susceptible to it.

Sulfate Resistance – The ability of aggregate, cement paste, or mixtures thereof to withstand chemical attack by sulfate ion in solution.

Sulfate Soundess Mass Loss – Provides an indication of aggregate resistance to weathering and other environmental effects.

Superplasticizer – See *Water-Reducing Admixture*.

Supplemental Cementing – The result of hydration of exposed and previously unhydrated or partially-hydrated cement grains of the mortar portion of RCA when the RCA is used in a new cement-based mixture (e.g., concrete paving mixture, cement-treated subbase mixture, lean concrete mixture, etc.); can, especially with the inclusion of fine RCA, potentially cause new concrete mixtures to have higher strengths than comparable mixtures made with 100% virgin aggregates.

Supplementary Cementitious Material (SCM) – Mineral admixtures consisting of powdered or pulverized materials which are added to concrete before or during mixing to improve or change some of the fresh (plastic) or hardened properties of Portland cement concrete. Materials are generally natural or by-products of other manufacturing processes.

T

Thermal Expansion – Expansion caused by increase in temperature.

Thermal Movement – Change of dimension of concrete or masonry resulting from change of temperatures. See also Contraction and Expansion.

U

Unit Water Content – The quantity of water per unit volume of freshly mixed concrete, often expressed as pounds or gallons per cubic yard. It is the quantity of water on which the water-cement ratio is based and does not include water absorbed by the aggregate.

Unit Weight – See *Bulk Density and Specific Gravity.*

Unreinforced Concrete – See *Plain Concrete*.

Unstabilized Subbase – A subbase layer composed of crushed stone, bank run sand-gravels, sands, soil-stabilized gravels, bottom ash, crushed or granulated slag, recycled concrete aggregate, or local materials such as crushed wine waste and sand-shell mixtures and not including any stabilizing agent (i.e., cement or asphalt binders). These are the most common type of subbase for applications such as streets, roadways and highways. The principal criterion for creating a good unstabilized subbase is to limit the amount of fines passing the No. 200 sieve (75 µm) to 15%; if there are too many fines, the unstabilized subbase may hold water more readily and will be prone to erosion, pumping and frost action.

Untreated Subbase – See *Unstabilized Subbase*.

V

Vertical Shaft Impact Crusher – See *Impact Crusher*.

Virgin Aggregate – Aggregate that is mined from natural sources; includes materials such as sand (either natural or crushed), gravel (either natural or crushed), crushed stone, etc.

Virgin Material – Material that has not been previously used or consumed, or subjected to processing other than for its production.

Volume Batching – The measuring of the constituent materials for mortar or concrete by volume.

W

w/c – See *Water-Cement Ratio*.

w/cm – See *Water-Cementitious Materials Ratio*.

Warping – Deformation of concrete pavement slabs due to hygrothermal (relative humidity/drying shrinkage) gradients.

Water-Cement Ratio – The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of portland cement in a concrete or mortar mixture; preferably stated as a decimal by weight.

Water-Cementitious Materials Ratio – The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of portland cement and other cementitious material (fly ash, pozzolan, etc.) in a concrete or mortar mixture; preferably stated as a decimal by weight.

Water-Reducing Admixture – A material that either increases slump of freshly mixed mortar or concrete without increasing water content or maintains a workability with a reduced amount of water, the effect being due to factors other than air entrainment; also known as water reducer.

Water-Reducing Admixture (High Range) – A water-reducing admixture capable of producing large water reduction or great flowability without causing undue set retardation or entrainment of air in mortar or concrete.

Weight Batching – Measuring the constituent materials for mortar or concrete by weight.

Well-Graded Aggregate – Aggregate having a particle size distribution that will produce maximum density; i.e., minimum void space.

Workability – That property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished.

X

Y

Yield – The volume of fresh concrete produced from a known quantity of ingredients; the total weight of ingredients divided by the unit weight of the freshly mixed concrete.

Z

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