An **IPRF** Research Report

Innovative Pavement Research Foundation

Airport Concrete Pavement Technology Program

Report IPRF-01-G-002-03-5

Evaluation, Design and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base

Programs Management Office
5420 Old Orchard Road
Skokie, IL 60077

July, 2006

An *IPRF* Research Report

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Evaluation, Design and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base

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EXECUTIVE SUMMARY

INTRODUCTION

There are sufficient published data available to demonstrate that recycled concrete aggregate (RCA) is a viable alternative to virgin aggregate for unbound base course construction. This research effort evaluated RCA on engineering, economic, and environmental criteria and developed a set of minimum material standards and specifications by evaluating the performance of existing RCA unbound base courses.

Products of this research effort include this report and a recommended specification for Federal Aviation Administration (FAA) Item X-XXX, "Recycled Concrete Aggregate Base Course."

SUMMARY OF FINDINGS

LITERATURE REVIEW

Approximately 68 percent of RCA is used in unbound base course. It compares well with virgin aggregate in the following ways:

- Lower specific gravity
- Rougher surface texture
- Greater water absorption
- Higher optimum moisture content (OMC)
- Higher sulfate soundless loss
- Slightly less abrasion resistance
- Higher California bearing ratio or limerock bearing ratio (CBR/LBR)
- Higher shear strength
- Higher rutting resistance (lower permanent strains)
- Higher resilient modulus, M_R (stiffness)

CONTACTS WITH INDUSTRY REPRESENTATIVES

Industry representatives were contacted to gather information on policies, practices, experiences, and perspectives on using RCA as unbound base material. The results of industry contacts indicated:

- There are no restrictions on the use of RCA as aggregate in base/subbase layers; 100 percent RCA is commonly used in base/subbase layers.

- Economic savings are the most often cited reason for using RCA; however, the choice of whether to use RCA is usually left to the contractor.

- RCA generally is considered a better material than virgin aggregate; however, RCA is treated equal to virgin aggregate for practical purposes because data quantifying the improvement are not available.

- Environmental tests of virgin aggregate or RCA are not required when the intended use is as unbound base/subbase layers.

- There are no constructability issues related to the use of RCA; some respondents preferred RCA because of ease of compaction.

- Overall, the performance of RCA as aggregate for unbound base/subbase layers is excellent.

ENVIRONMENT ASSESSMENT

Adverse environmental effects are generally not associated with RCA; thus, environmental tests are not required. Published literature indicates that the potential of environmental hazard is insignificant. There is no serious concern about an environmental hazard from recycling portland cement concrete (PCC) from airfield and highway pavement.

ECONOMIC ASSESSMENT

Economic factors are important when crushed PCC recycling is considered. In the absence of a robust experience base to conduct a life cycle cost analysis (LCCA), a procedure based on quantifying initial material and construction costs was developed. Sample worksheets were developed to help designers evaluate costs and make an informed decision.

TECHNICAL ASSESSMENT

Site Visits

Eight projects were identified and visited:

- Shaw Air Force Base (AFB)
- North Auxiliary Field at Charleston AFB
- Holloman AFB
- Mountain Home AFB
- Grand Forks AFB
- Atlanta-Hartsfield Jackson International Airport
- Offutt AFB
- US 167, Dubach, Louisiana

The purpose of these site visits was to learn how RCA was performing in the field and to identify and address considerations unique to its use. Some of the construction-related considerations identified from the site visits include the following:

- Higher water demand
- Segregation potential
- Grading control
- Plant operations
- Density control

These should be considered carefully during construction operations.

Laboratory Investigation

Alkali silica reactivity (ASR)-distressed RCA has been used successfully at Atlanta-Hartsfield Jackson International Airport, Offutt AFB, Mountain Home AFB, and Pease Air Force Base (now Pease Intl. Trade Airport). Field performance information suggests that ASR-distressed PCC can be recycled as base course aggregate. The design engineer should evaluate the use of ASR-distressed RCA carefully with respect to the intended use. Laboratory tests were conducted on ASR-distressed RCA (from Pease International Trade Port) and RCA from PCC with D-cracking (from Grand Forks AFB). These tests verified some of the information available in the literature, such as:

- RCA has a higher OMC and lower maximum dry density (MDD) relative to typical virgin aggregate.

- Static Triaxial Shear Test results indicated that even distressed RCA is comparable to an average virgin aggregate material.

- RCA permanent deformation characteristics are comparable to virgin aggregate material. Distressed RCA compared well with a typical virgin aggregate at a failure permanent deformation strain of 10 percent.

PROPOSED FAA ITEM X-XXX "CRUSHED CONCRETE AGGREGATE BASE COURSE"

Specifications for FAA Item X-XXX, "Recycled Concrete Aggregate Base Course," are proposed; RCA is treated as virgin aggregate material. The soundness test should be waived because of the incompatibility between PCC and the chemical reactants used in the test protocol.

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1 INTRODUCTION

1.1 BACKGROUND

The United States Geological Survey (USGS) estimates that about 330 million tons (300 metric tons) of crushed stones were used in road base/subbase construction in 1996. The USGS further stated that development of aggregate resources is "being constrained by urbanization, zoning regulations, increased costs, and environmental concerns." A small increase in the amount of recycled concrete aggregate (RCA) to replace the virgin aggregate in pavement construction will have large economic and environmental benefits while extending the supply of traditional construction materials. The benefit of recycling road construction materials can exceed $41 per ton (1 ton = 0.91 metric tonne); this estimate does not include processing and transportation costs, but includes the avoided cost of virgin aggregate (Wilburn, 1998; Kelly, 1998).

RCA can be used as aggregate in pavement construction if it has suitable engineering, environmental, and economic properties. Significant societal benefits of using recycled materials in pavement construction include conservation of natural resources and extending the life of available landfill space. The American Concrete Pavement Association (ACPA) estimates that approximately 200 miles (322 km) of concrete pavement are being recycled each year. One mile of average thickness concrete pavement yields about 6,000 tons (5,440 metric tons) of crushed concrete. This translates to about 1.2 million tons (1.1 million metric tons) of RCA being used. Overall, about 50 million tons (45.36 million metric tons) of RCA are recycled annually from airports, city and county roads and streets, and State and interstate highways (Saeed, 2004).

Most of the research relative to recycling has been conducted by the Federal Highway Administration (FHWA), the recycled materials research centers, the Transportation Research Board (TRB), the National Cooperative Highway Research Program (NCHRP), State departments of transportation (DOTs), Army Corps of Engineers, and industry associations. The primary support for recycling has been from the FHWA, which began its recycling program in the 1970s. Since then, the FHWA has conducted numerous feasibility studies and demonstration projects. In 1997, FHWA published *User Guidelines for Waste and Byproduct Materials* (Chesner, 1998). More recently, two NCHRP projects were completed: NCHRP Project 4-21 developed appropriate uses for waste materials in transportation, and NCHRP Project 25-9 evaluated the environmental impact of (highway) construction and repair materials on surface and groundwater.

However, most of the research does not address potential issues regarding the use of RCA from deteriorated portland cement concrete (PCC) pavements (due to alkali-silica reactivity [ASR], sulfate attack) or further deterioration of RCA when used as base and subbase material due to ASR or sulfate attack.

1.2 PROJECT OBJECTIVE

The terms *base* and *subbase* are often used interchangeably in concrete pavement literature to mean the layer immediately below the PCC layer. IPRF Project 02-01, "Design Guide for Stabilized and Drainable Bases," suggests that the layer immediately below the PCC slab be referred to as the base layer, and the layer or layers between the base and above the subgrade be referred to as subbase. To be consistent, this research effort follows the same approach. It should be noted that RCA could be used for base and subbase applications.

The final research product is a set of evaluation, design, and construction guidelines, developed with industry input, to define the minimum standards pertaining to material and engineering properties for using RCA as unbound base. These criteria will allow designers to use RCA bases and provide the basis for assuring owners that pavements constructed with RCA base will perform successfully. Economic benefits will ensue as the cost savings associated with re-use of RCA drive down the costs of pavement construction. Also, societal benefits will accrue, because RCA can replace a portion of the virgin aggregates and in the long run will reduce the demand for virgin aggregates and the environmental impacts associated with aggregate mining and production.

1.3 RESEARCH APPROACH

This report includes a summary for the following activities:

- Conduct a literature search to identify and include any existing research without duplicating it.

- Identify current RCA production and usage methodologies.

- Compile, review, and compare specifications from selected case studies sites.

- Perform performance-related physical and mechanical properties tests on RCA.

- Establish minimum material standards and construction guidelines for RCA as an unbound base.

- Prepare guidelines for evaluation, design, and construction of RCA base layers.

The basis for the materials standards and construction guidance was data collected from:

- Comprehensive literature review
- Telephone interviews with industry representatives
- Extensive case studies of up to eight selected sites
- Limited laboratory testing

The type of data and information sought from each information source are shown in Table 1.1.

Table 1.1. Overview of data types and sources.

Type of Data	**Data Source**			
	Literature Review	**Telephone Interview**	**Case Studies**	**Laboratory Tests**
Material specifications	✓	✓	✓	
Material test data	✓	✓	✓	✓
Construction records		✓	✓	
Pavement performance indicators	✓	✓	✓	

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2 INFORMATION GATHERING

2.1 INTRODUCTION

The information included here is a summary of two subtasks: a literature search and review, and interviews with industry representatives. The goal was to collect and review all available domestic and foreign literature on the project subject matter. Many sources were queried to identify and obtain information pertinent to the use of RCA as base course material. Appendix A provides details of the literature review.

2.1.1 IMPETUS TO USE RCA

RCA is the aggregate produced from the demolition of existing PCC pavements and consists of high-quality aggregate particles. Initially, the momentum to use RCA was because of environmental concerns about waste disposal in landfills, preservation of natural resources, environmental preservation, and sustainable development. It also has economic advantages and engineering material properties similar to virgin aggregates. Research indicates that RCA will generally have better engineering properties than virgin aggregates (Chesner et al., 1998).

2.1.2 PRODUCTION, USE, AND ECONOMICS

RCA is used predominantly in pavement construction as virgin aggregate replacement for granular, cement-treated, or econocrete subbase layers and, to a lesser extent, in hot mix asphalt (HMA) and PCC surface layers. Wilburn (1998) estimates that approximately 68 percent of RCA is used as subbase course, as shown in Figure 2.1. Saeed et al. (1995, 1996, and 1997) investigated the use of RCA in granular bases and developed a specification based on laboratory tests.

PCC slabs are usually broken into smaller pieces upon removal and hauled to a central processing facility to produce RCA. The next step removes reinforcing steel and dowel bars by magnetic separation. The broken PCC is then crushed and screened to produce the specified gradation using conventional equipment (Chesner et al., 1998). In addition to aggregates, processed RCA has hardened cement paste that holds smaller aggregate particles together. The amount of cement paste attached to aggregate in RCA depends on the process used to produce RCA and the properties of the original concrete (Chini and Kuo, 1998). Each aggregate size is usually stored separately; the screening process limits the amount of aggregate fines (passing in the No. 200 [75 μm] sieve) to 5 percent or less.

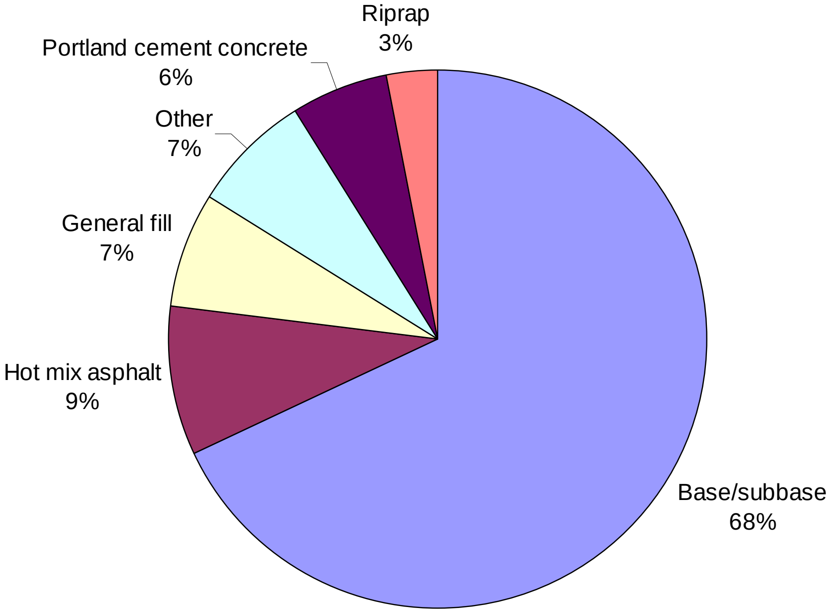


Figure 2.1. Uses of RCA (adapted from Wilburn, 1998).

The RCA production process affects the particle size and shape properties. Using a jaw crusher as the primary crusher and a rotating crusher as the secondary crusher produces the best particle grading and shape (Chini and Kuo, 1998). Typical gradations of RCA are shown in Table 2.1.

Table 2.1. Range of RCA particle size distribution after processing.

Sieve Size	**Range of Particle Size Distribution (Percent Finer)**		
	New Jersey DOT	Florida DOT	Texas DOT
1.5 in (37.5 mm)	92	100	100
1.0 in (25 mm)	86	97.6	98
3/4 in (19 mm)	80	-- [a]	77
1/2 in (12.5 mm)	64	46.4	70
3/8 in (9.5 mm)	56	-- [a]	58
1/4 in (6.3 mm)	-- [a]	4.8	-- [a]
No. 4 (4.75 mm)	42	-- [a]	45
No. 8 (2.36 mm)	34	4.2	35
No. 10 (2.00 mm)	32	-- [a]	-- [a]
No.16 (1.18 mm)	28	-- [a]	25
No. 30 (0.60 mm)	22	-- [a]	17
No. 50 (0.30 mm)	14	-- [a]	5
No. 100 (0.15 mm)	10	-- [a]	1
No. 200 (0.075 mm)	8	-- [a]	0

Laboratory tests performed on different sources of PCC show consistent results (Chini and Kuo, 1998). When RCA is used as aggregate in unbound base, there is little or no RCA particle breakdown during material handling and construction. Typical physical properties of processed RCA are given in Table 2.2 (ACPA, 1993).

Table 2.2. Typical physical and mechanical properties of RCA.

Property Type	Property	Typical Value
Physical	Specific Gravity	Coarse (plus No. 4 sieve): 2.2 to 2.5 Fine (minus No. 4 sieve): 2.0 to 2.3
	Absorption (%)	Coarse (plus No. 4 sieve): 2 to 6 Fine (minus No. 4 sieve): 4 to 8
Mechanical	LA Abrasion Loss (%)	Coarse (plus No. 4 sieve): 20 - 45
	Magnesium Sulfate Soundness loss (%)	Coarse (plus No. 4 sieve): 4 or less Fine (minus No. 4 sieve): less than 9
	California Bearing Ratio (%)	94 to 184

Aggregates account for 10 to 14 percent of the total construction cost, excluding right-of-way and engineering costs (Halm, 1980). Recycling pavement is especially economical where the hauling distance for virgin aggregate exceeds 50 miles (80.5 km). Crushing costs are generally the only cost associated with recycling concrete pavements, because the costs of hauling aggregate and disposing of the old pavement are eliminated and the costs of breaking, removing, separating steel, and transporting are considered incidental (Mack, 1993).

2.1.3 ENGINEERING PROPERTIES

Important characteristics of aggregate particles include shape, grading, and LA abrasion. Base permeability, density, and moisture content are essential characteristics of the aggregate matrix for different types of bases. The shape and grading of aggregates affect the shear strength of granular base, which is an important performance-related property. The LA abrasion and soundness test are related to the potential degrading of aggregate, though these are not applicable to RCA and RCA typically has a higher Los Angeles (LA) abrasion loss than virgin aggregate. Note that density and moisture content are crucial properties to determine the compaction effort.

Appendix A discusses in detail RCA material properties.

2.1.3.1 Physical Properties

The grading of RCA is similar to the grading of crushed stone aggregate. RCA fines are non-plastic and hardened cement paste attached to the aggregate results in the following changes in the general aggregate characteristics relative to virgin aggregate:

- Lower specific gravity

- More surface texture
- Greater water absorption
- Higher optimum moisture content (OMC)
- Higher sulfate soundless loss
- Less abrasion resistance

2.1.3.2 Mechanical Properties

Mechanical properties of RCA and virgin aggregate should be compared only under similar testing conditions, which are valid for RCA use, and only when samples were prepared using comparable techniques. Under these conditions, RCA has the following advantages over conventional aggregates:

- Higher California bearing ratio or limerock bearing ratio (CBR/LBR)
- Higher shear strength
- Higher rutting resistance (lower permanent strains)
- Higher resilient modulus, M_R (stiffness)

Appendix A discusses in detail these comparisons. There generally is no breakdown of RCA particles during handling and construction activities. However, tests with the Corps of Engineers gyratory test machine (GTM) have indicated potential for breakdown under repeated loading.

One study observed that there is an increase in stiffness with time due to hydration properties (ARM, 2000). Research conducted by Poole et al. (2004) demonstrated that the residual potential for cement hydration was too small to be of practical use (especially, for conventional PCC) and RCA is more likely to be carbonated to the point that hydration potential would not exist. Evaluation of RCA use in pavement base courses by Pomeroy (1981), Hansen (1992), and Kibert (1994) indicated that RCA materials often tend to form crusts that could give a false impression of stiffening. If these crusts form, they have the potential to inhibit drainage through poorly designed filter fabric drainage systems.

2.1.4 ENVIRONMENTAL GUIDELINES

A number of studies have been conducted to investigate the environmental concerns arising from the use of RCA as unbound base material. The effluent has a relatively high pH value at the source; the relative high pH mitigates rapidly away from the source. No heavy metals are released under alkaline conditions; however, trace amounts of heavy metals, well below Environmental Protection Agency (EPA) guidelines, sometimes are released under acidic conditions (Kuo, 2002) which generally do not exist in field conditions. The EPA raises no objections to using recycled concrete on the site from which it is obtained.

2.1.5 CURRENT RCA BASE/BASE SPECIFICATIONS

Chini et al. (1998) specified the natural aggregate gradation for RCA and recommended a maximum LA abrasion loss of 40 percent for RCA to be used as base course. In addition, they recommended a maximum plasticity index of 6 percent, limited the amount of flat or elongated particles to 8 percent, and required an LBR of at least 100 percent. These requirements match virgin aggregate specifications. The sodium sulfate soundness test for RCA was waived. Mack et al. (1993) also recommended waiving the sulfate soundness test for RCA. U.S. Army and Air Force (1988) recommended RCA meet all the same requirements and use the same testing procedures as natural aggregates, which for all practical purposes eliminates its use.

The Unified Facility Guide Specification (UFGS) UFGS-02709, "Portland Cement-Stabilized Base or Subbase Course," accounts for the use of RCA for cement-stabilized and lean concrete base or subbase courses has been prepared by the U.S. Army Corps of Engineers (UFGS, 2004a). Other UFGS specifications, prepared by the Naval Facilities Engineering Command (NAVFAC), are also available for stabilized base, including the UFGS-02712 (UFGS, 2004b) for lean concrete base and the UFGS-02713 (UFGS, 2004c) for cement-stabilized base. The UFGS also has specifications for granular base, but they are specified for use under flexible pavement only. The specification prepared by the U.S. Army Corps of Engineers is the UFGS-02704 (UFGS, 2004d), whereas the NAVFAC prepared the UFGS-02722 (UFGS, 2004e).

Research conducted by the Florida DOT and the University of Central Florida to develop guidelines and specifications account for recycled material (Kuo et al. 2001; 2002). Some of the laboratory tests recommended to be performed on RCA included grading, LBR, LA abrasion, soundness by sodium sulfate, sand equivalent, optimum moisture content, maximum dry unit weight, permeability, impurities, and M_R. Florida DOT also recommended that RCA should similar compressive and shear strength to virgin aggregate, in addition to meeting grading requirements. The specification proposed by Kuo et al. (2002) is shown in Table 2.3, along with average results from laboratory tests and the current Florida DOT specification for conventional aggregate.

The FAA construction requirements for airfield pavements follow Advisory Circular (AC) 150/5370-10B, "Standards for Specifying Construction of Airports" (FAA, 2005-a). The use of RCA as a base material is not addressed in this standard. A summary of the current specification requirements for P-208 (aggregate) and P-209 (crushed aggregate) base courses is shown in Table 2.4. This table illustrates the acceptance and control procedures for granular bases. The control procedures are separated depending on the time relative to layer placement (before, during and after). The specified tests to be conducted prior (and sometime during) placement are shown in Table 2.5. Chesner et al. (1998) provided the list of standard test methods to evaluate traditional granular materials for pavement layers, as shown in Table 2.6.

Table 2.3. Comparison of base specifications by Kuo et al. (2002).

Type of Test	Average Test Results	Proposed Specification For RCA	FDOT Specification for Base	Specification
Sieve Analysis	Average Grading	Average Grading	Average Grading	FM 1-T027
2 in (50.8 mm)	100	100	100	
1.5 in (37.5 mm)	99.5	98 – 100	95 – 100	
3/4 in (19 mm)	83.2	65 – 100	65 – 90	
3/8 in (9.5 mm)	61.2	40 – 83	45 – 75	
No. 4 (4.75 mm)	44.8	27 – 63	35 – 65	
No. 10 (2.00 mm)	34.4	20 – 49	25 – 45	
No. 50 (0.30 mm)	15.7	8 – 24	5 – 25	
No. 200 (0.075 mm)	3.8	2 – 6	0 – 10	
LBR Test	181.71	Min. 120	100	FM - 515
LA Abrasion Loss	44%	< 48%	< 45	FM 1-T096
Sodium Sulfate Test	52%	< 50%	15%	15%
Sand Equivalent	70.50%	> 70%	≥ 28%	AASHTO T - 104
Heavy Metals	0 – 12 ppm	5 ppm	5 ppm	EPA - 96
Asbestos	Free of Asbestos	Free of Asbestos	Section 112 EPA	EPA - 89
Optimum Moisture Content	11.2% – 12.1%	10% – 12%	Not Specified	FM 5 - 521
Maximum Dry Unit Weight	113.8 – 114.8 lb/ft^3 (1 lb/ft^3 = 16 kg/m^3)	108 lb/ft^3 – 120 lb/ft^3	98% of Max. Dry Density	FM 5 - 521
Permeability	0.72 (ft/day)	0.10 to 1.40 (ft/day)	Not Specified	FM 5 - 513
Impurities	1.99% by weight	< 2.0% by weight	Substantially free of impurities	FM 1 T - 194
Structural Coefficient	0.34	0.30	0.15	–
Thickness Requirement	4 in. (102 mm)	Min. 8.0 in (203 mm)	Min. 8.0 in (203 mm)	–

Table 2.4. Summary of the FAA specification for P-208 and P-209.

Acceptance/control	Properties	Specified value
Control prior to placement	See Table 2.12	-
Control during placement	Moisture	Within ± 1.5% omc
Acceptance	Density*	100% of the maximum laboratory density ASTM D 1556 or D 2167
Control after placement	Thickness**	At most 0.5 in. (13 mm) less than design thickness
	Smoothness	3/8 inches max tested using a 16-ft straightedge

* Density is accepted on a lot basis, which consists of 2400 yd^2 (2007 m^2)max and each lot has 2 equal sublots. One test should be performed for each sublot.

** For P-208, one thickness test (depth or core) should be performed every at least 300 yd^2 (251 m^2). For P-209, four thickness determinations should be performed per lot, as defined under density acceptance.

Table 2.5. FAA specification control prior to granular layer placement.

Layer	Test	Specified value	ASTM testing
P-208	Los Angeles (LA) wear at 500 revolutions	Uncrushed (45% max) and crushed (55% max)	C 131
	Fractured faces (FF) of material retained on No.4 sieve	60% min of 2 FF and 75% min of 1 FF (draft spec)	-
	Grading		C 117 and C 136
P-209	Los Angeles (LA)	45% max	C 131
	Fractured faces (FF) of coarse material retained on No.4 sieve	90% min of 2 FF and 100% min of 1 FF (by weight)	-
	Grading		C 117 and C 136
	Flat or elongated particles: + No.4 sieve	15% max by weight	D 693
	Sodium sulfate soundness loss	12% max after 5 cycles	C 88
	LL and PI of minus No.40 material	LL: 25 max and PI: 4 max	D 4318
	Sand equivalent value for fine aggregate	35 min	D 2419
	Percent passing (PP) No.200 sieve	60% max of PP the No.30 sieve	-

Table 2.6. Granular aggregates test procedures (Chesner et al., 1998).

Property	Test Method	Reference
General Specifications	Graded Aggregate Material for Bases or Subbases for Highways or Airports	ASTM D2940
Sieve Analysis	Sizes of Aggregate for Road and Bridge Construction	ASTM D448 / AASHTO M43
	Sieve Analysis of Fine and Coarse Aggregate	ASTM C136 / AASHTO T27
Particle Shape	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Voids Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)	AASHTO TP33
	Index of Aggregate Particle Shape and Texture	ASTM D3398
Base Stability	California Bearing Ratio	ASTM D1883 / AASHTO T193
	Moisture-Density Relations of Soils Using a 5.5 lb (2.5 kg) Rammer and a 12-in. (305 mm) Drop	ASTM D698 / AASHTO T99
	Moisture- Density Relations of Soils Using a 10-lb (4.54 kg) Rammer and an 18-in. (457 mm) Drop	AASHTO T180
Permeability	Permeability of Granular Soils (Constant Head)	ASTM D2434 / AASHTO T215
Plasticity	Determining the Plastic Limit and Plasticity Index of Soils	ASTM D4318 /AASHTO T90
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM D2419 / AASHTO T176
Abrasion Resistance	Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131 / AASHTO T96
Resilient Modulus	Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46	AASHTO T274

2.2 RESULTS OF INTERVIEWS WITH INDUSTRY REPRESENTATIVES

Information from industry representatives regarding their policies, practices, experiences (including past studies), and perspectives on RCA as a base material was obtained to seek insight and information. Identification of candidate projects used the following data sources:

- Design and construction records of individual team members
- FAA regional offices
- U.S. Army Corps of Engineers (Center of Expertise and District offices)
- Airport consulting firms
- Air Force Civil Engineering Support Agency (AFCESA) and Air Force Major Command offices

Interviews by phone to a number of individuals representing airports of interest (where RCA has been used as base) and FAA and DOD representatives were asked for:

- Policy on RCA use as base
- Pavement design
- Material specifications
- Construction and constructability issues
- Performance observations

The information from 5 DOD respondents, 8 contractors, 1 airport, and 12 DOTs is summarized below.

2.2.1 POLICY ON RCA USE AS BASE

There are no restrictions on the use of RCA as aggregate unbound base. All respondents allow and/or use up to 100 percent RCA as base. However, a few respondents indicated that the amount of RCA used is based on the grading. Economic savings were the most often cited reason for using RCA. When economics was cited, the choice of whether to use RCA was left to the contractor. The second most often cited reason was the lack of quality virgin aggregate in certain areas, and the availability of PCC from an existing highway or airport pavement.

2.2.2 PAVEMENT DESIGN

For pavement design purposes, RCA is generally considered to be equivalent to virgin aggregate material. In most cases, RCA is treated as virgin aggregate for structural design purposes with 100 percent replacement of virgin aggregate with RCA during construction; however, RCA has to meet the same specifications requirements (laboratory tests) as virgin aggregate.

Rigid pavement modulus of reaction (k) values are measured in the field (seldom done recently) or assigned based on thickness of base and subgrade k. Requirements for rigid pavement base are grading and Atterberg limits. If RCA meets subgrade k and Atterberg limits requirements, which it usually does, then it is simply plugged into the system as another aggregate source.

2.2.3 MATERIAL SPECIFICATIONS

None of the respondents indicated that their agencies required environmental testing of virgin aggregate or RCA when the intended use was as aggregate in unbound base. In most cases, current virgin aggregate specifications are modified to allow the use of RCA.

2.2.4 CONSTRUCTION AND CONSTRUCTABILITY

Crushing and screening is the most often used processing operation for production of RCA. AFCESA indicated a preference for pulverizing/rubblizing in lieu of crack and seat when an HMA overlay was being considered. Grading and maximum particle size are mostly used as criteria for accepting and control of RCA base. Only two respondents required unit weight tests to be conducted. In addition, density tests are typically used for quality control during construction.

None of the respondents indicated any constructability issues related to the use of RCA as compared to virgin aggregates. Three contractors indicated a preference for using RCA over virgin aggregate due to ease of compaction. More importantly, material degradation was not a problem when vibratory rollers are used for compaction.

2.2.5 PERFORMANCE OBSERVATIONS

All but two respondents indicated that they have observed excellent performance from RCA base. AFCESA indicated satisfactory performance. The performance of RCA as aggregate for unbound base is excellent.

2.3 SUMMARY OF GATHERED INFORMATION

RCA has a proven history of use as base, subbase, fill, and drainage layers within the airfield pavement structure. Construction and performance has been excellent. The only document failure occurred in a RCA base at Holloman AFB in New Mexico, which heaved and expanded due to sulfate attack (Rollings, 1993, 2003).

RCA can be crushed and processed to almost any desired grading and generally has properties similar to conventional aggregate. When properly processed and placed, current experience and research indicates RCA can have engineering strength and stiffness properties at least equal to conventional aggregates of similar characteristics (grading, moisture content, percent compaction, etc.).

RCA tends to have lower specific gravity, higher absorption, and higher LA abrasion loss than conventional aggregates. These tests are often used to infer or rate conventional aggregate durability for freezing and thawing and for breakdown during construction. However, these tests are widely recognized to have at best a weak correlation with field durability of conventional aggregates. Field performance of RCA has generally been excellent under conditions of freezing and thawing and during field handling and placement. Consequently, the weak correlation of these test results to RCA field performance reflects the limitations of the test procedures themselves and not the actual field durability.

Chemical durability of RCA is a concern. Even sulfate-resistant PCC that have been recycled into base and fill has proven vulnerable to sulfate attack. Until more is understood or effective countermeasures are found, RCA should not be used where exposure to sulfates is likely. The problem of ASR in PCC that is recycled is less difficult to assess. Several possible adverse reactions can occur because of ASR in RCA (as detailed in appendix A). However, current information does not clearly identify whether these concerns are valid. This is an important topic that needs additional research.

3 ENVIRONMENTAL AND ECONOMIC ASSESSMENTS

3.1 INTRODUCTION

Reclaimed materials must be assessed for value based on technical, environmental, societal, and economic considerations (Saeed et al. 2004; 1997; 1996; 1995). The technical, economic, and environmental aspects of recycling are quantifiable, and Saeed (1996) proposed an objective methodology for societal assessment.

3.2 ENVIRONMENTAL ASSESSMENT

3.2.1 GENERAL

RCA is being used successfully as base course without evidence of environmental problems. Several contractors and agencies indicated that environmental tests of the recycled material sources are not required provided the origin and use locations are the same; that is, PCC used to produce RCA is obtained from the same location where RCA will be used. The basis for this practice is that PCC is not considered hazardous (because of the slow rate that some chemical constituents could be leached from the material). RCA, even though it has increased surface area, when interacted with groundwater and/or infiltration the rate of release of chemical constituents remains extremely slow.

3.2.2 CHEMICAL COMPOSITION OF CONCRETE COMPONENTS

With the exception of chemical admixtures, process admixtures, and polymers, the components of concrete are naturally occurring geological materials.

3.2.2.1 Portland Cement Concrete

The principal component of portland cement is quarried limestone, or some other high-calcium material such as marl, coral, or silica. Some calcium sulfate (natural gypsum or natural anhydrite) is added in very small quantities to adjust the time of set.

Basic chemical reactions involved in the synthesis of the major portland cement compounds are summarized below:

$$\left.\begin{array}{l}\text{Limestone} \rightarrow CaO + CO_2 \\ \\ \\ \text{Clay} \rightarrow SiO_2 + Al_2O_3 + Fe_2O_3 + H_2O\end{array}\right\} \rightarrow \left\{\begin{array}{l} 3CaO.SiO_2 \\ 2CaO.SiO_2 \\ 3CaO.Al_2O_3 \\ 4CaO.Al_2O_3.Fe2O_3\end{array}\right.$$

Organic surfactants are used as grinding aids during the clinker grinding process and pumping aids to assist in moving cement in a stream of air. Ethanolamine compounds, ethylene glycol compounds, glycerol, coal, and sulfate lye are commonly used materials

(Moothedath, 1992). Typical doses are less than 0.1 percent, by mass of portland cement (approximately 0.015 percent by mass of concrete). None of these are sources of hazardous material and are most likely chemically bound within the calcium-silicate-hydrate (C-S-H).

3.2.2.2 Supplemental Cementing Materials

Since 1980, Supplemental Cementing Materials (SCM), such as pozzolan and/or ground granulated blast furnace slag, have been used as partial replacement for the cementitious fraction in some concrete mixtures. These materials are derived from the waste stream of other industrial processes. Coal fly ash has been the primary SCM used. Ground granulated blast furnace slag has become a major SCM in recent years.

3.2.2.3 Aggregates

Being processed rock from surface or near surface deposits, virgin aggregates are not considered to be an environmental hazardand have not been the subject of study. Processing typically causes no change in chemical composition.

3.2.2.4 Chemical Admixtures

Chemical admixtures comprise a wide variety of organic compounds. Materials likely to be used in paving concrete include water reducers, high-range water reducers, and air entraining admixtures.

Water reducing admixtures typically are based on lignosulfonate compounds, and typically also contain some amount of sugar. These are byproducts from processing of wood pulp into paper. Lignosulfonates are relatively complex molecules based around benzene-ring types of structures. Significant amounts of material typically do not leach from PCC (Rixom, 1999).

High range water reducers are based principally on five molecular configurations: sulfonated naphthalene formaldehydes, sulfonated melamine formaldehydes, polycarboxylate esters, carboxylic-acrylic esters, and cross-linked acrylic polymers. Typical maximum dosages are 1 to 3 percent by mass of cement (15–45 ppm by mass of concrete). With leaching rates that are apparently very low, environmental aspects about melamine and naphthalene based compounds are not a concern (Rixom, 1999).

Air entraining admixtures are represented by five types of compounds: neutralized wood resins, fatty acid salts, alkyl-aryl sulfonates, alkyl sulfates, and phenol ethoxylates. No information was found indicating any potential for long-term environmental hazard.

3.2.2.5 Polymers in Concrete

Polymers in concrete derive from at least three sources: curing compounds, polymers incorporated as part of repair materials, and paint. Curing compounds are applied during construction and usually wear off after a relatively short period of time; therefore, it is not expected that significant quantities would be found in concrete being recycled.

Polymers used in repair materials are typically latexes or multipart epoxies. The literature indicated no concern for long-term environmental effects. These tend to be highly resistant to environmental breakdown, so that any release rate of chemicals that would plausibly interact in the environment seems unlikely. Airfield pavement PCC does not contain sufficient quantities of lead based paint for it to be an environmental concern.

3.2.2.6 Mixing Water

Mixing water used to make concrete commonly is taken from sources low in dissolved solids and not usually thought of as a source of potential hazard to the environment. The practice of using recycled water from washing operations at concrete production facilities can cause the amount of dissolved material to increase significantly over conventional water sources but this is not an environmental problem.

3.2.3 CHEMISTRY OF CONCRETE

Ultimately the chemistry of the concrete paste matrix, the way it changes with time, and the degree to which critical chemical species are extracted from it by natural processes are the important features of the environmental impact of use of RCA in pavement construction.

3.2.3.1 Fresh Concrete and Time-Dependent Changes in Chemistry

When portland cement hydrates, it generates calcium hydroxide as one of the reaction products. The reactions for the two major components involved are summarized as follows:

$$2(3CaO.SiO_2) + 7\ H_2O \longrightarrow 3Cao.2SiO_2.4H_2O + 3Ca(OH)_2$$
$$2(2CaO.SiO_2) + 5\ H_2O \longrightarrow 3Cao.2SiO_2.4H_2O + Ca(OH)_2$$

The calcium hydroxide generates a pore solution pH of 12.5. Depending on the concentration of some of the less prevalent chemical components in the cement, primarily the sodium and potassium, the pore solution pH can reach as high as about 14. This is a relatively extreme pH by normal health and environmental standards, but the buffering capacity is very low so it is not an issue. Some environmental statements identify this as potential for the concrete developing a high pH. However, concrete is not considered hazardous because of its alkaline components.

3.2.3.2 Specific Issues Related to Recycled Concrete

For most concretes, the density, and hence the permeability, is low enough that the leaching rates are very low, even under relatively aggressive leaching conditions. Most concrete structures have ratios of surface area to volume of concrete that are very low; thus, most of the material in concrete is not readily exposed to leaching behavior when exposed to rain or natural waters.

For RCA used as material in bases and fill, the ratio of surface area to volume is increased, however since the pore system is so small increasing the surface area does not make a significant difference on leaching when RCA is exposed to a natural field environment. When stockpiles of recycled materials are exposed to the environment for long periods of time, the surface of the particles carbonates and it becomes more stable. There will be effluent that has a 12+ pH which will have an impact on vegetation for a short distance from the pile. Overall, this has no significant environmental impact.

RCA base course materials are not built to have contact with groundwater. In rare cases, exposure to groundwater could occur but it would be a temporary condition. And, base course materials are not exposed to rainwater unless very small amounts infiltrate through joints and cracks.

3.2.4 SUMMARY OF ENVIRONMENTAL ASPECT OF RCA

A wide variety of work is reported in literature in which the potential for the release of the toxic substances known to be present in PCC was evaluated. Pertinent literature falls into three major categories: summary reports, leaching studies, and field studies. Even though many of these studies are described as evaluations of PCC, the methods used are designed for evaluation of RCA, involving crushing and low-pH leaching. Therefore, it can be reasonably concluded that the results of these studies would represent the performance of RCA as well as intact concretes; however it is essential to recognize RCA used as base will never be subject to low pH as present in landfills.

In general, the conclusions are that leaching of crushed PCC, even under acidic conditions, does not result in the release of significant amounts of the toxic materials known to be present in PCC.

3.2.5 ENVIRONMENTAL ADVANTAGES TO USING RCA

Motivations to recycle concrete were initially based on economic considerations (Forster, 1986). These principally involved costs associated with extracting virgin materials as opposed to onsite recycling, and hauling and disposal costs if the concrete is disposed in a landfill. Environmental benefits have apparently always been recognized, but seem to be emphasized more in recentpublications on recycling. Examples include a Portland Cement Association bulletin on Recycled Aggregates (www.cement.org/tech/cct_aggregates_recycled.asp) and FHWA Focus for April 2005 (www.tfhrc.gov/focus/apr05/03.htm).

Landfilling demolished concrete pavement is expensive and could be a concentrated source of leachate due to the acidic environment (if combined with normal waste). One of the major findings of many of the leaching studies reviewed is the occasionally high value of a particular compound found in leachate from concrete was considered to be insignificant in practice because of the effects of slow leaching rates, environmental dilution, and interaction with soil that occurs when the material is spread out in a paving applications. Landfilled material could result in a more highly concentrated distribution of the material that could overwhelm the effects of soil interaction or relatively slow release.

The other relatively obvious environmental effect is that use of recycled concrete materials results in less pressure on virgin sources of materials, less demand for energy required to extract, process, and haul them, and reduction in the associated effects of quarrying (e.g., dust, environmental damage).

A current sequestering research project at the University of New Hampshire's Recycled Materials Research Center's Web site is investigating the balance between carbon dioxide generated during cement manufacture and atmospheric carbon dioxide consumed during the carbonation reactions in concrete during its life cycle. Carbonation reactions are normally a very slow process, but the crushing associated with recycling operations and especially use as a base (high humidity) greatly accelerates the carbonation reactions, partially offsetting the original 1 ton of CO_2 release per ton of Portland cement manufactured (www.rmrc.unh.edu/Research/Rprojects/ Project12/project12.asp).

3.2.6 CONCLUSIONS REGARDING ENVIRONMENTAL ASSESSMENT

As a general conclusion, the bulk of published information on RCA indicates that using RCA as unbound base material is safe and the potential for environmental hazards is very low or nonexistent. Leaching rates under realistic environmental base conditions are nonexistent to very low at best due to several properties of concrete: low diffusion rates of most substances in PCC, chemical immobilization by interaction with hydrated cement paste, and the relative durability of PCC forms (even relatively small pieces of RCA, as represented in the TCLP test) to chemical degradation at all but very low sustained pH's, which are never found in paving base applications. Effects of dilution, environmental degradation of toxic organic compounds, and adsorption onto soil particles appears to be a major buffering mechanism.

Although the high pH of concrete pore fluids is probably the most commented-on feature of concrete in the context of environmental hazards, little work was found addressing high pH pore fluids. High pH rarely develops outside of the relatively minute amount of liquid water found in the paste pores. Calcium hydroxide, which is the ultimate cause of the high pH can be leached slowly from RCA if it is in the presence of water but, when exposed to air in a wet condition, it instantly converts to a lower pH form (calcium carbonate). So, basic chemistry predicts that any pH problems that could occur would be local and very temporary in exposure and only if water moves through the base.

The foremost conclusion is that the current literature indicates no concern for environmental hazard from recycling RCA made from sound uncontaminated concrete.

3.3 ECONOMIC ASSESSMENT

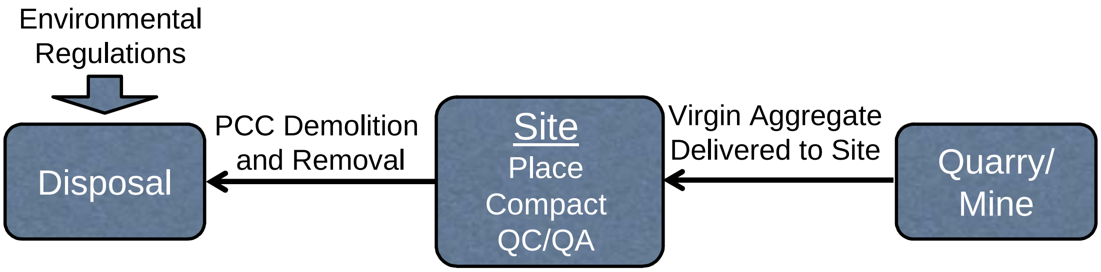
Economic factors are an important consideration in selecting RCA as a base material. While a life cycle cost analysis (LCCA) would be preferable, the experience data base required to defend such a computation is not currently available. Therefore, the procedure described below is based upon quantifying initial materials and construction costs.

Evaluating the economic viability of RCA involves calculating the tangible costs of recycling the PCC pavement as aggregate and comparing costs with the tangible costs of using virgin aggregate materials. One of the major expenses of using virgin aggregate is the disposal of existing PCC pavement as waste in compliance with Federal, State, and local environmental regulations.

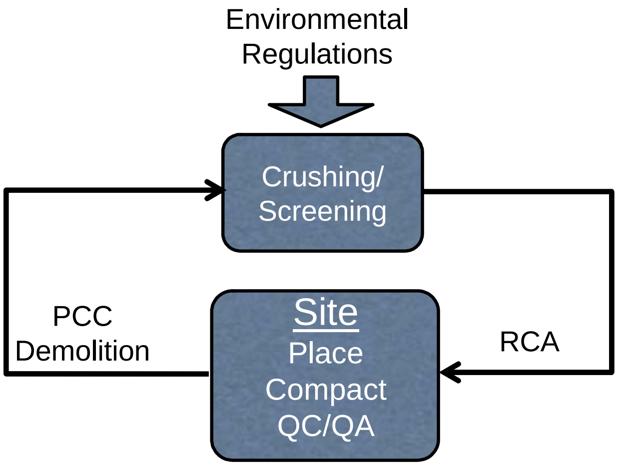
The economic assessment procedure presented in this section is limited to factors that can be determined rationally and defended as having a direct impact at the project level. The societal benefits of using recycled materials are significant on a global, national, and perhaps regional level. However, societal benefits are subjective; thus, they can be difficult to quantify and defend for a project-level economic assessment and are more appropriately addressed at the policy level.

Figure 3.1 presents a graphical presentation of the major components of cost for construction with virgin aggregates and construction with RCA. In the case of virgin aggregates, the following costs must be quantified in the economic analysis:

- Cost of virgin aggregate meeting the project specifications delivered to site
- Cost to demolish and remove the existing PCC
- Cost of disposal of existing PCC in accordance with environmental regulations
- Cost of placement of virgin aggregate (may or may not be the same as RCA)
- Cost of compaction (may or may not be the same as RCA)
- Cost of quality control/quality assurance (may or may not be the same as RCA)



a) Construction with virgin aggregate



b) Construction with RCA

Figure 3.1. Economic factors to be considered in economic analysis.

In the case of RCA, the following costs must be quantified in the economic analysis:

- Cost of removal of existing PCC
- Cost for land for crusher
- Cost of crushing/screening/stockpiling
- Cost to meeting environmental regulations at crusher/stockpile site
- Cost of hauling to/from crushing/stockpiling site
- Cost of placement of RCA
- Cost of compaction of RCA
- Cost of quality control/quality assurance of RCA

The objective of the economic analysis is to make a direct comparison of all tangible costs related to the alternatives of RCA versus virgin aggregate. Figure 3.2 and Figure 3.3 present sample worksheets to help the designer to evaluate these costs. They lead the user to evaluate the initial costs of using virgin aggregates (Figure 3.2) and recycled concrete aggregates (Figure 3.3). The worksheets shown in the figures are intended to be only guides and may be modified for the specifics of a job's location, plans, specifications, or site-related factors. The user must exercise care to ensure that the units used in the analysis are consistent.

Economic Analysis Worksheet: Virgin Aggregate

Project Scope

	Item		Units Symbolic[1]	Actual[2]
(A)	Plan area of subbase required:		L^2	
(B)	Thickness of subbase required:		L	
(C)	Total volume of virgin aggregates (A) X (B):		L^3	
(D)	Compacted unit weight:		F/L^3	
(E)	Total mass of aggregate required (C) x (D):		M	
(F)	Plan area of existing PCC to be removed:		L^2	
(G)	Thickness of existing PCC to be removed:		L	
(H)	Total Volume of PCC to be removed (F) X (G):		L^3	

Cost of Virgin Aggregate:

(I)	Unit cost of virgin aggregate delivered to site:		$/M	
(J)	**Total cost of virgin aggregate materials (E) X (I):**		**$**	

Cost of Existing PCC Disposal

(K)	Unit cost of demolition of PCC:		$\$/L^2$	
(L)	Total cost of PCC demolition (F) x (K):		$	
(M)	Unit cost of transporting to disposal site:		$\$/L^3$	
(N)	Total transportation cost (H) x (M):		$	
(O)	Unit cost of PCC disposal:		$\$/L^3$	
(P)	Total cost of PCC disposal (H) x (O):		$	
(Q)	**Total cost of PCC demolition, transportation, and disposal (L) + (N) + (P):**		**$**	

Construction Costs

(R)	Unit placement cost:		$/M	
(S)	Total placement costs (E) X (R):		$	
(T)	Unit compaction cost:		$/M	
(U)	Total compaction costs (E) X (T):		$	
(V)	Unit QC/QA costs:		$/M	
(W)	Total QC/QA costs (E) x (V):		$	
(X)	**Total construction costs (S) + (U) + (W):**		**$**	

Other Costs

(Y)	**Other costs not considered above:**		**$**	

Total Costs

(Z)	**Sum of all costs (J) + (Q) + (X) +(Y):**		**$**	

NOTES:

1. The symbolic unit notation indicates the units expected, i.e., L refers to length, F refers to force, M refers to mass, and $ refers to cost.
2. Use a consistent set of units throughout the computations in this worksheet.

Figure 3.2. Sample economic analysis worksheet for virgin aggregates.

Economic Analysis Worksheet: Recycled Concrete Aggregate

Project Scope

	Item		Units	
			Symbolic[1]	Actual[2]
(A)	Plan area of subbase required:	____________	L^2	____________
(B)	Thickness of subbase required:	____________	L	____________
(C)	Total volume of aggregates required (A) X (B):	____________	L^3	____________
(D)	Compacted unit weight:	____________	F/L^3	____________
(F)	Total mass of recycled concrete aggregate required (C) x (D) :	____________	L^3	____________
(G)	Plan area of Existing PCC to be removed:	____________	L^2	____________
(H)	Thickness of existing PCC to be removed:	____________	L	____________
(I)	Total volume of PCC to be removed (G) X (H):	____________	L^3	____________

Cost of Manufacturing RCA

(J)	Unit cost of demolition of PCC:	____________	$\$/L^2$	____________
(K)	Total cost of PCC demolition (G) x (J):	____________	$	
(L)	Unit cost crushing/screening/stockpiling RCA:	____________	$\$/L^3$	____________
(M)	Total Cost of crushing/screening/stockpiling RCA (F) x (L):	____________	$	
(N)	Land costs for crushing/screening/stockpiling RCA:	____________	$	
(O)	Costs for environmental compliance at crusher site:	____________	$	
(P)	**Total cost of manufacturing RCA (K) + (M) + (N) + (O):**	____________	**$**	

Construction Costs

(Q)	Unit placement cost:	____________	$/M	____________
(R)	Total placement costs (F) X (Q):	____________	$	
(S)	Unit compaction cost:	____________	$/M	____________
(T)	Total compaction costs (F) X (S):	____________	$	____________
(U)	Unit QC/QA costs:	____________	$/M	____________
(V)	Total QC/QA costs (F) x (U):	____________	$	
(W)	**Total construction costs (R) + (T) + (V):**	____________	**$**	

Other Costs

(X)	**Other costs not considered above:**	____________	**$**	

Total Costs

(Y)	**Sum of all costs (P) + (W) + (X) +(Y):**	____________	**$**	

NOTES:

1. The symbolic unit notation indicates the units expected, i.e., L refers to length, F refers to force, M refers to mass, and $ refers to cost.
2. Use a consistent set of units throughout the computations in this worksheet.

Figure 3.3. Sample economic analysis worksheet for recycled concrete aggregates.

4 TECHNICAL ASSESSMENT

4.1 CASE STUDIES

Candidate sites for comprehensive case studies were identified; these are listed in Table 4.1. The selected sites include airports under the jurisdiction of FAA and DOD. Highway sites, selected with the help of State DOTs and the FHWA, were used to supplement information for cases in which an airport site meeting the requirements was not available.

Two sites were identified that used RCA manufactured from PCC that had undergone ASR. Some sites are located in ASR prone areas; however ASR was not identified but RCA manufactured from ASR distressed PCC could have been used. Currently, existing PCC with D-cracking from Runway 17-35 at Grand Forks Air Force Base (AFB) is being used as RCA during runway reconstruction.

Table 4.1. Candidate sites for comprehensive case studies.

Recycling Method	Site Conditions			
	Benign	Sulfate Attack	ASR	D-Cracking
Dense Graded	• Shaw AFB • North Auxiliary Field at Charleston AFB	• Holloman AFB	• Mountain Home AFB • Atlanta-Hartsfield Jackson International	• Grand Forks AFB
Open Graded	• Offutt AFB • US 167, Dubach, LA			

4.1.1 SHAW AFB

4.1.1.1 Location and Climate

Shaw AFB is centrally located in Sumter County, South Carolina. The climate is relatively mild with long humid summers and mild winters.

4.1.1.2 RCA Use Summary

Shaw AFB has a long history of using RCA. The first project was constructed in 1987-88 on the main runway. PCC slabs from the old runway construction were crushed to produce RCA. The original runway was constructed in 1941 (initial 5,000 ft [1,524 m] on south end) and extended in 1952 (4,000 ft [1,219 m]). The airfield layout at Shaw AFB is shown in Figure 4.1. The following airfield pavements were constructed using RCA as base.

- Runway 04L-22R
- Aprons 1 and 3

- Taxiways A, C, D, E, F, G

On Runway 04L-22R, the existing PCC thickness varied from 6 to 12 inches (152 to 305 mm); the thicker PCC section occurred in the first 2,000 ft (610 m) on both ends of the runway. The PCC had a maximum aggregate size of 1.50 inches (38 mm), and the coarse aggregate consisted of a blend of crushed granite and rounded river gravel. The PCC was in good condition.

For the runway replacement, the project engineers recommended that the existing PCC should be considered for recycling as an alternative to virgin aggregate material. The use of RCA did not affect the pavement structural design, because RCA was considered structurally equal or better than virgin aggregate. The selected pavement design was 11.5 inches (292 mm) of PCC over 6.0 inches (152 mm) of crushed aggregate (RCA) base course (LPA 1984).

Using RCA saved on the disposal costs of PCC. A crushing plant was set up near the base entrance, thus saving RCA transportation costs.

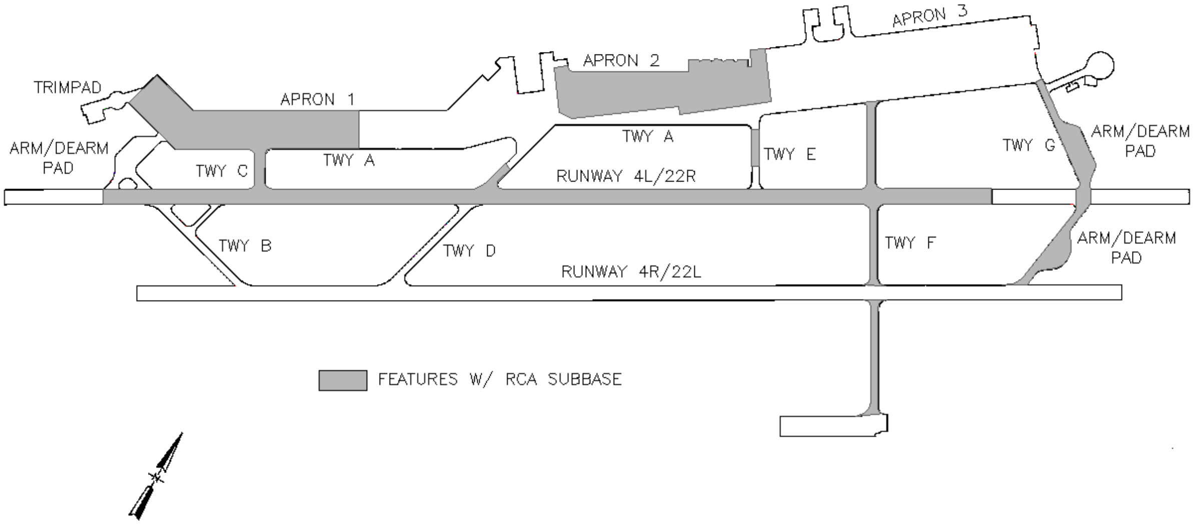


Figure 4.1. Shaw AFB airfield layout.

4.1.1.3 Construction Using RCA

RCA was treated as virgin aggregate. The finished subgrade surface was graded to within a tolerance of 0.1 ft (30 mm) and to drain water away from the pavement (see Figure 4.2). RCA was placed on prepared subgrade in windrows (Figure 4.3), spread using a motor grader (Figure 4.4) and compacted using rubber tire roller (Figure 4.5).

Tests used to evaluate RCA during construction are shown in Table 4.2.

Table 4.2. Aggregate tests used at Shaw AFB.

Test Designation	Test Title
MIL-STD 621A	Test Method for Pavement Subgrade, Subbase, and Base Course Materials
ASTM C 117	Materials Finer than No. 200 Sieve in Mineral Aggregate by Washing
ASTM C 131	Resistance to Degradation of Small Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
ASTM D 1556	Density of Soils in Place by the Sand-Cone Method
ASTM D 1557	Moisture-density Relations of Soils and Soil Aggregates Mixtures Using 10 Pound Rammer and 18 inch Drop
ASTM D 4318	Liquid Limit, Plastic Limit and Plasticity Index of Soils

The grading specifications were met by controlling the crushing plant operations. The RCA had to comply with all the virgin aggregate specifications, including LA Abrasion Test loss limit of 40 percent. The RCA had an average LA Abrasion Test loss of about 36 percent. The RCA exceeded the 30 CBR bearing capacity requirement.

Figure 4.2. Typical subgrade preparation at Shaw AFB (Runway 4l-22R).

Figure 4.3. RCA was placed in windrows on prepared subgrade.

Figure 4.4. RCA was spread out to grade using a motor grader before compaction.

Figure 4.5. RCA base grading (motor grader) and compaction (rubber tire roller).

Field personnel reported that RCA base was easier to compact than virgin aggregate material used on other projects. Water requirements were similar and the material did not breakdown during compaction. Construction traffic was allowed on the finished RCA base layer without any detrimental affects.

Environmental testing was not a concern during construction using RCA. No dust problems were noted during construction operations. The material was placed at the same location from where it was removed and not transported to a landfill or other location for disposal.

4.1.1.4 RCA Performance

Pavements with RCA base material continue to perform well at Shaw AFB. No distresses have been reported in any pavement section, including some that were constructed 25 years ago.

AFCESA's 2004 airfield pavement evaluation determined that the surface condition of 93 percent was very good to excellent. Dynamic cone penetrometer (DCP) tests conducted during this evaluation also indicated that the base material (with the exception of Apron 1) was of high quality; DCP test results were as follows (AFCESA 2004):

- Apron 1: 12 CBR
- Apron 2: 50 CBR (top 3 inches[76 mm]), 36 CBR (bottom 6 inches [152 mm])

- Runway 4L-22R, west end: 39 CBR
- Runway 4l-22R, middle: 26 CBR
- Runway 4L-22R, east end: 31 (top 5 inches [127 mm]), 40 CBR (bottom 12 inches [305 mm])

Typically, at least 30 CBR is required for base material.

Economic savings has prompted RCA use at Shaw AFB; however, the final decision is left to the contractor. Reconstruction of Runway 4L-22R using RCA as unbound base was the largest job. Successful experience with RCA has resulted in the fact that any future construction projects at Shaw AFB will use RCA due to economic savings, landfill problems, superior material (relative to virgin aggregate), and stable construction platform.

The contractor preferred using RCA as compared to virgin aggregate for base construction. The lack of an adequate quantity of RCA was cited as a problem; as such, approximately 1,000 ft (305 m) of Runway 4L-22R could not be constructed using RCA, and virgin aggregate had to be used.

4.1.2 NORTH AUXILIARY FIELD, CHARLESTON AFB

4.1.2.1 Location and Climate

North Auxiliary Field (NAF) is located approximately 60 miles (97 km) northwest of Charleston AFB near the town of North, in the Atlantic coastal plain of South Carolina. There are two runways, seven taxiways, and a parking ramp at NAF. The layout of NAF is shown in Figure 4.6; at the time of site visit, the north end of Taxiway No. 2 was being reconstructed with an RCA base.

Due to its coastal location, NAF has warm, humid summers and mild winters. The weather at NAF is temperate, benefiting from South Atlantic sea breezes and the Gulf Stream. Summers are generally hot and humid, and winters are mild with some snow (Parsons, 2003).

4.1.2.2 RCA Use Summary

Experience by NAVFAC in the use of RCA and the contractor’s previous experience promoted the use of RCA base for reconstruction of Taxiway 2. The existing 7-inch-thick (178-mm-) PCC, placed circa World War II, was rough and inadequate for aircraft traffic.

4.1.2.3 Construction Using RCA

A crushing plant (Figure 4.7) was set up on site to produce RCA for reconstruction of Taxiway No. 2. The approximate location of the plant is shown in Figure 4.6. The material specification called for LA Abrasion loss of less than 40 percent and a bearing capacity of at least 30 percent (4-day soaked CBR test), among other requirements. The RCA produced at the site exceeded the specification requirements.

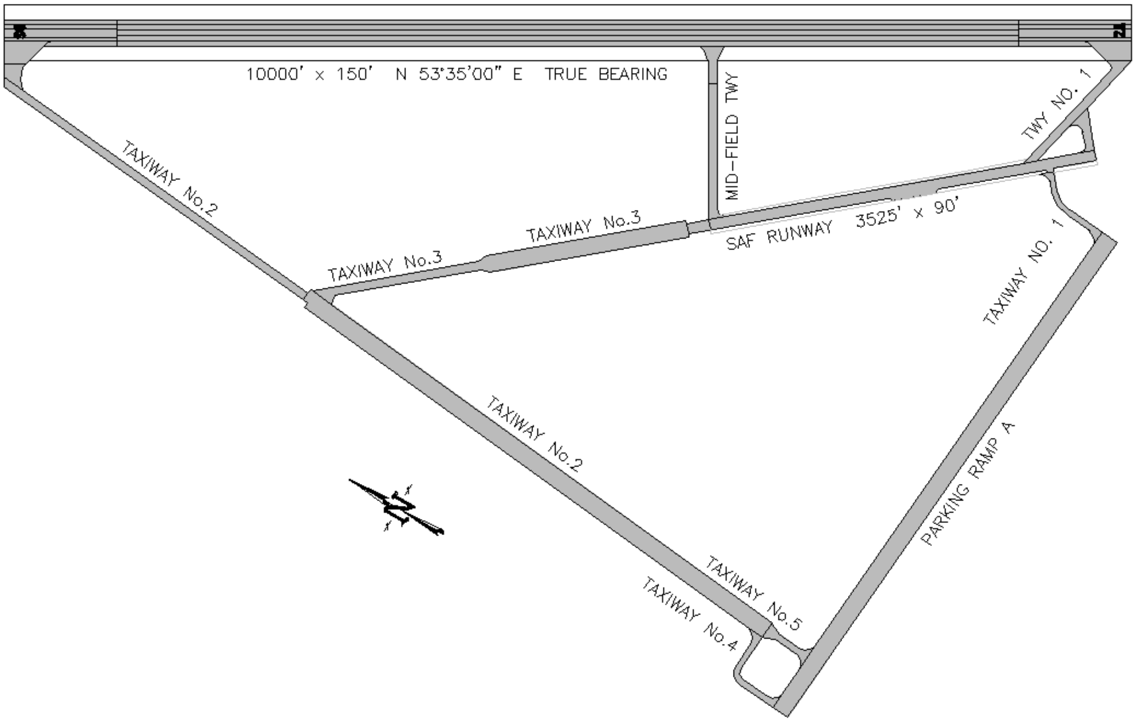


Figure 4.6. Layout of North Auxiliary Field at Charleston AFB.

Figure 4.7. Crusher was set up on job site at North Auxiliary Field to produce RCA.

The RCA was spread using motor graders and compacted using vibratory rollers. The base layer was compacted to 100 percent of maximum laboratory density measured using ASTM D 1557 (Laboratory Compaction Characteristics of Soil Using Modified Effort). The RCA grading was tested several times before and after compaction, and no significant changes were noticed; the RCA material met the grading requirements before and after compaction by vibratory roller. The RCA base surface was finished using blading and rolling until the surface was free from waves and irregularities. Figure 4.8 shows the RCA before compaction; the finished RCA base surface is shown in Figure 4.9.

The contractor requested and obtained approval to allow construction traffic on the finished RCA. Dump trucks carried RCA over the finished RCA without detrimental affects.

Density requirements were easily attained, and no excessive watering of the RCA was required. The contractor did notice that the nuclear density gage had to be calibrated for RCA material; minor differences between field densities were absorbed when using the sand-cone method and nuclear density gage.

Figure 4.8. RCA material before compaction at North Auxiliary Field.

Figure 4.9. Finished RCA base surface at North Auxiliary Field Taxiway No. 2.

Figure 4.10. Construction of RCA base utilized standard construction equipment.

4.1.2.4 RCA Performance

RCA was used successfully at Charleston AFB and NAF. The option to use it at NAF was provided by NAVFAC, but the final decision to use RCA material was left to the contractor. The contractor selected RCA over virgin aggregate for the following reasons:

- RCA was easier to handle during construction and compaction.
- RCA provided a stable working platform, allowing work to continue even when wet.
- RCA provided economic savings.
- RCA conserved landfill space and eliminated excessive tipping fees to dispose of PCC.

The contactor indicated a quantity of 7,000 tons (6,350 metric ton) of PCC was used as the cut-off for a decision between using and not using RCA. This contractor considers that plant mobilization and set up costs exceed transportation costs associated with virgin aggregate for jobs smaller than 7,000 tons (6,350 metric ton).

4.1.3 US 167 DUBACH, LOUISIANA

4.1.3.1 Location and Climate

Dubach is located 12 miles (19 km) north of Ruston, Louisiana, on US 167. The weather in Dubach is temperate, with mild winters and hot summers.

4.1.3.2 RCA Use Summary

Louisiana State Route 67/US 167 was widened and rehabilitated; the project includes both rigid and flexible pavements. The contractor was given the choice of using RCA or virgin aggregate for base course, and the RCA option was selected. The thickness of RCA base in rigid sections was 8 inches (203 mm), and in flexible sections it was 12 inches (305 mm). All pavement sections were built over 6-inch (152–mm) cement stabilized subgrade.

A crushing plant was set on site to produce RCA; the PCC slabs originated from several Louisiana Department of Transportation and Development (LaDOTD) rehabilitation projects near Ruston, Louisiana.

4.1.3.3 Construction Using RCA

RCA base was constructed using standard construction equipment. Water was added to the RCA at a central plant and dump trucks hauled and dumped the material in windrows (see Figure 4.11). RCA base material was spread to grade using a bulldozer, as shown in Figure 4.12, rather than with a motor grader. The construction contractor had more experience using a bulldozer, and in his opinion, the bulldozer was more efficient than using a motor grader.

Figure 4.11. Construction equipment used for RCA base construction on US 167.

Figure 4.12. A bulldozer was used to spread RCA base material to grade.

The vibratory roller shown in Figure 4.13 was used for compaction of RCA base; the roller followed closely behind the spreading equipment to minimize moisture loss. The vibratory roller was not considered to be detrimental to RCA, and did not break down RCA particles. The contractor established and followed a rolling pattern during compaction. Layer density was checked with a nuclear density gage after three passes of the vibratory roller; two more passes were applied if the density requirements were not met.

Moisture content of the RCA material was considered critical in achieving proper compaction. Rolling the layer as soon as the bulldozer had spread the RCA base material to grade ensured proper moisture for compaction. Figure 4.13 shows that the vibratory roller right behind the bulldozer; RCA base compaction was started as soon as the proper grade had been achieved. Figure 4.14 shows an example of typical RCA base surface after compaction at the optimum moisture content. To avoid RCA particle breakdown, the contractor further recommended that compacting dry RCA material should be avoided. An example of dry RCA material is shown in Figure 4.15. The contractor further suggested compaction should be stopped as soon as dust starts coming up. Further compaction should only be carried out after wetting and allowing the water to soak in the placed material. Figure 4.16 shows an example of compacted and loose RCA surface condition at the proper moisture content. Construction traffic (Figure 4.17) was allowed on the finished RCA base as soon as compaction had been achieved. The specified field was at least 95 percent of maximum density determined using DOTD TR 418.

If a layer was placed too thick, the procedure was to scarify the layer, flood the layer with water, and make a few passes with the sheep foot roller. Compaction was then achieved with a vibratory roller when the water content had stabilized.

Figure 4.13. RCA being compacted using a vibratory roller at US 167.

Figure 4.14. Typical RCA base surface after compacting at the proper moisture content.

Figure 4.15. Typical RCA surface condition when further rolling should be avoided.

Figure 4.16. RCA base surface condition during proper spreading and compacting.

Figure 4.17. Construction traffic was allowed on compacted RCA base.

LaDOTD allows 100 percent RCA or blends with an approved virgin aggregate for base course. RCA had to meet all virgin aggregate tests, as indicated below, but the grading requirements (as shown in Table 4.3) and field density controlled construction quality.

- Deleterious Materials (DOTD TR 119)
- Foreign Matter in Shell (DOTD TR 109)
- Unit Weight (AASHTO T 19)
- Specific Gravity & Absorption of Fine/Coarse Aggregate (AASHTO T 84/85)
- Polish Value (AASHTO T 278)
- Amount of Material Finer than the No. 200 Sieve (75 µm) (DOTD TR 112)
- Sieve Analysis (Gradation) (DOTD TR 113)
- Liquid Limit and Plasticity Index (DOTD TR 428)

Table 4.3. Grading requirements for LaDOTD Class II RCA base.

U.S. Sieve	Metric Sieve	Percent Passing
1 1/2 inch	37.5 mm	100
1 inch	25.0 mm	90-100
3/4 inch	19.0 mm	70-100
No. 4	4.75 mm	35-65
No. 40	425 µm	12-32
No. 200	75 µm	5-12

4.1.3.4 RCA Performance

The contractor used RCA successfully at other projects. The main incentive to use RCA was a lack of quality virgin aggregate, which consequently costs more due to transportation costs. In addition, local contractors prefer RCA because it is perceived to be easier to work with and provides a stable work platform even during periods of excessive rainfall.

4.1.4 GRAND FORKS AFB

4.1.4.1 Location and Climate

Grand Forks AFB is located in the heart of the Red River Valley located on the North Dakota-Minnesota border at the junction of the Red Lake River and the Red River of the North. The terrain is flat with an average elevation of 911 ft.

Spring and summer temperatures at the base are mild; the greatest amount of annual rainfall also occurs during spring and summer. Fall and winter gradually shift from mild summer temperatures to more severe weather (Parsons 2003).

4.1.4.2 RCA Use Summary

The layout of Grand Forks AFB pavements is shown in Figure 4.18.

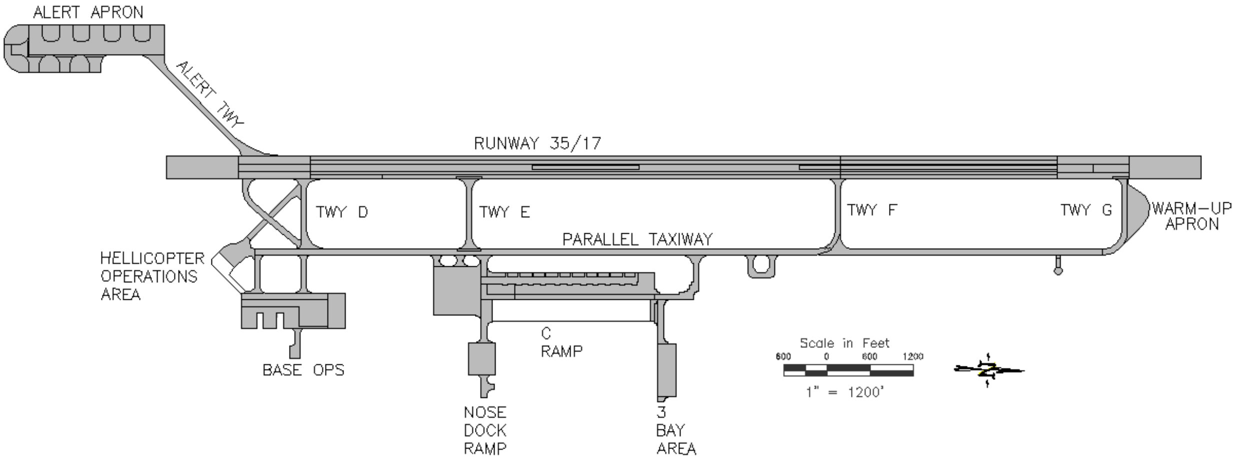


Figure 4.18. Layout of airfield pavements at Grand Forks AFB.

Grand Forks AFB Runway 17-35 (12,350 ft [3,764 m]) was reconstructed; the project included milling, rubblizing, and removal of the existing runway pavement surface. Upon completion, the new runway had a 1,080- by 150-ft (329- by 46-m) PCC pavement section on the south end, a 10,270- by 150-ft (3,130- by 46-m) HMA pavement in the interior, and a 1,000- by 150-ft (305- by 46-m) PCC pavement section on the north end.

The 1000-ft (305-m) PCC ends (D-cracked) of the original runway were rubblized and then crushed to produce RCA; an onsite plant was used, and the produced RCA was stockpiled at that location. The existing PCC was cracked using a guillotine (Figure 4.19), and then a ramhoe (Figure 4.20) was used to further reduce the size of cracked PCC slabs. The broken PCC pieces were then loaded into dump trucks and transported to the onsite crushing plant to produce RCA. The stockpiled RCA material is in Figure 4.21.

The crushing plant consisted of a jaw crusher with a stack of sieves. RCA grading was routinely checked to ensure compliance with grading requirements. Material not meeting requirements was run through a cone crusher.

Figure 4.19. A guillotine was used to crack existing PCC at Runway 17-35.

Figure 4.20. A ramhoe was used to further reduce the size of cracked PCC.

Figure 4.21. Crushed PCC material was stockpiled on site.

4.1.4.3 Construction Using RCA

The contractor opted to use available RCA for the construction of the runway overruns and the Runway 17-35 until most of the RCA material was expended. The RCA material was treated as virgin aggregate for testing purposes and was required to exceed all specification requirements except the LA Abrasion test and magnesium sulfate soundness test.

For the purposes of this construction project, graded coarse aggregate was defined as consisting of clean, sound, durable particles of crushed stone, crushed slag, crushed gravel, crushed recycled concrete (from this project only), angular sand, or other approved material. Following typical practice, the No. 4 sieve (4.75 mm) differentiated between coarse and fine aggregate.

RCA was exempted from LA Abrasion and sulfate soundness tests. The amount of flat and elongated particles were specified not to exceed 20 percent for the fraction retained on the 1/2 inch sieve nor 20 percent for the fraction passing the 1/2 inch (13 mm) sieve. The required aggregate gradings are listed in Table 4.4.

Table 4.4. Aggregate grading for Runway 17-35 reconstruction.

Sieve Designation	Percentage by Weight Passing Square-Mesh Sieve		
	No. 1	No. 2	No. 3
2 inch (50.8 mm)	100	---	---
1-1/2 inch (37.5 mm)	70-100	100	
1 inch (25.0 mm)	45-80	60-100	100
1/2 inch (13.0 mm)	30-60	30-65	40-70
No. 4 (4.75 mm)	20-50	20-50	20-50
No. 10 (2.0 mm)	15-40	15-40	15-40
No. 40 (425 µm)	5-25	5-25	5-25
No. 200 (75 µm)	0-5	0-5	0-5

RCA material was placed on prepared subgrade using conventional construction equipment. The subgrade was finished using a motor grader and compacted using static rollers (Figure 4.22). The plant-mixed RCA was brought in side-dump trucks to the finished subgrade (Figure 4.23) and dumped in front of a mechanical spreader. The RCA base was compacted using a static roller; however, the material had problems meeting compaction requirements. . This was traced to segregation of the placed material as shown in Figure 4.24. The segregation problem was traced to improper stockpiling of the crushed material.

Figure 4.22. Subgrade preparation for Runway 17-35 at Grand Forks AFB.

Figure 4.23. Plant mixed RCA base material was side dumped on finished subgrade.

Figure 4.24. View of finished RCA base showing material segregation.

4.1.4.4 RCA Performance

RCA was used successfully at Grand Forks AFB. The main reasons for its use included:

- Economics
- Abundance of PCC material

Terms of the construction contract required disposal of demolished PCC in landfills if not used during construction. This prompted the use of RCA produced from existing PCC with D-cracking; however, no significant problems were noticed during construction.

Crushing of the existing PCC to produce RCA was an issue. The crushing operation removed cement paste from the aggregate in the PCC mix and did not crush the PCC as a whole composite. The coarser of the specified gradings, grading No. 1 in Table 4.4, could not be met; grading No. 3 was allowed. Also, RCA could not meet the specification for number of faces.

4.1.5 MOUNTAIN HOME AFB

4.1.5.1 Location and Climate

Mountain Home AFB (MHAFB) is located in a rural area on the Snake River Plateau and is surrounded by the desert plains between two large mountain ranges, the Danskin and Owhyee Mountains. The plateau, approximately 3,000 ft (914 m) above sea level, has some effect on the climate; Pacific and Arctic air masses effect weather at MHAFB. Although nearby mountains experience harsh seasonal weather variations, the climate at MHAFB is mild (Saeed, 2003).

4.1.5.2 RCA Use Summary

The layout of Mountain Home AFB is shown in Figure 4.25

Runway 12-30 and the transient ramp were reconstructed in 2002. The transient ramp (1,200 x 500 ft [366 x 152 m]) and touch down areas of Runway 12-30 (1,000 x 200 ft [305 x 61 m] on both ends) used RCA as base material. Figure 4.25 indicates the location of the transient ramp.

4.1.5.3 Construction Using RCA

PCC from touchdown areas on Runway 12-30 and the mobility apron was used as a source for RCA. An onsite crushing plant (jaw crusher) produced RCA consisting of minus 2-inch (51-mm) material. The crushed material was stockpiled onsite, as shown in Figure 4.26. Figure 4.27 shows the relative fractions of the crushed material.

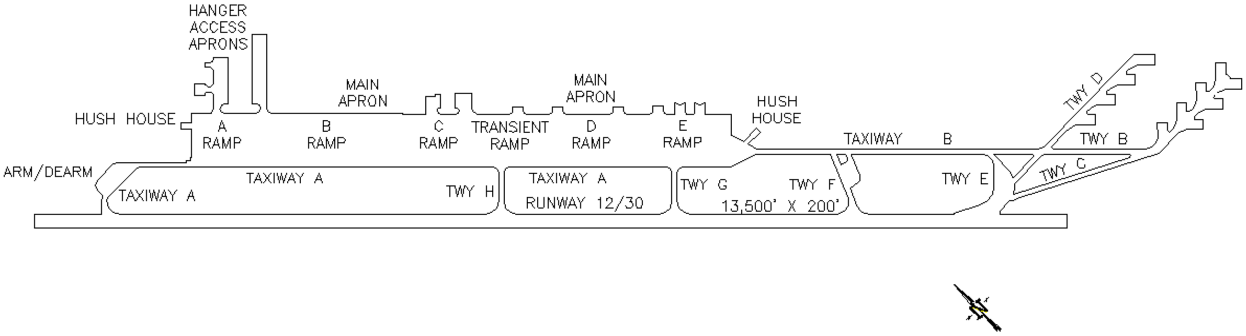


Figure 4.25. Pavement layout at Mountain Home AFB.

Figure 4.26. RCA stockpiles at Mountain Home AFB.

ASR was expected in the Mountain Home concrete, because aggregates from the Snake River Valley are known to be reactive. Figure 4.28 shows a photograph of the condition of the parent PCC from Mountain Home. Dark circles can be seen around the larger aggregate particles, suggesting that ASR was active in the parent PCC.

Figure 4.27. PCC at Mountain Home AFB was crushed to minus 2-inch size.

Figure 4.28. Condition of aggregate in parent PCC at Mountain Home AFB.

The project specification required aggregate base course to be clean, sound, durable particles of 1) crushed stone, 2) crushed slag, 3) crushed gravel, 4) crushed recycled concrete, or 5) other approved material. The crushed recycled concrete consisted of previously hardened PCC or other containing pozzolanic binder material and had to meet all the virgin aggregate requirements (shown in Table 4.5).

Conventional construction equipment was used. RCA was treated as a virgin aggregate material for design purposes.

There was a concern about RCA base material might undergo degradation during placing and compaction but this did not occur. A pad foot roller was used for the initial compaction followed by a vibratory steel drum roller. Sieve analysis conducted on RCA before and after placement/compaction confirmed that the material was within specifications. RCA did have a higher optimum water content compared to virgin aggregate and RCA required additional water trucks during construction.

Table 4.5. Aggregate base course specifications.

Test Method	**Test Title**	**Specified Criteria**
ASTM C 131	Resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine	≤ 50 percent loss
ASTM D 4971	Flat and elongated particles	≤ 30 percent
ASTM D 4318	Plastic and liquid limits (material passing No. 40 sieve)	Non-plastic or LL < 25 and PL ≤ 5
ASTM D 5821	Fractured particles	≥ 50 percent
ASTM C 117	Particle with diameter less than 0.0008 inch (0.02 mm)	≤ 3 percent
ASTM C 136	Grading requirements (% weight passing square mesh sieve)	1-inch sieve: 100 ½-inch sieve : 40 –70 No. 4 sieve: 20 – 50 No. 10 sieve: 15 – 40 No. 40 sieve: 5 – 25 No. 200 sieve: 0 -8

Environmental tests were not required and not conducted. Some segregation of the stockpiles was noted during crushing. Figure 4.29 shows segregated RCA stockpiles at Mountain Home AFB.

4.1.5.4 RCA Performance

The use of RCA base was an alternative, and selection of this option was left to the contractor. The contractor chose this option because there was:

- Reduction in construction costs
- Material and transportation cost savings
- No PCC disposal costs

This project was considered so successful that the Air Force reconstructed the ladder taxiways in 2004 using RCA. The contractor for Runway 12-30 and the mobility apron constructed Taxiway H using the same specifications.

A pile of stockpiled RCA remains from this project, and the base is using it for base on roads and parking lots. There appears to be segregation in the RCA stockpile. Possible carbonation action was also noted, with some portions of the stockpile standing vertically, as shown in Figure 4.29. There are plans to crush PCC from demolished structures on the base and use RCA for road/parking lot base material.

The project engineer cited several lessons learned during construction:

- Good crusher control – Crusher control to obtain the specified grading is important for RCA construction projects. Recycled concrete aggregate shape depends on the strength of the recycled concrete, crushing plant type, and plant operation speed. A number of trial batches may have to be produced before crushed recycled concrete aggregate meeting the shape and grading requirements can be produced.

- Proper stockpiling technique – Improper stockpiling will cause segregation problems. Using conveyors to stockpile material was found to mitigate this problem at Mountain Home AFB.

- High optimum moisture content – RCA has a high water demand, and this should be considered during construction planning. One option is to pre-process wet of optimum before placing. RCA may be difficult to compact if the water content is incorrect.

- Proper RCA placement – Windrowing and use of motor graders to spread RCA can lead to segregation and “bony pockets.” RCA base can be placed with an asphalt paver or box spreader to minimize segregation.

- Density control – Improper density impacts the performance of the base. Frequency of in-place density tests should be increased to one per 1,000 sq. yd (836 sq. m) per lift to verify that the required density is being obtained.

- Calibration of nuclear gage – The nuclear gauge allows the user to input offsets to gauge readings to correct for non-standard conditions.

Figure 4.29. Segregation of stockpiled RCA at Mountain Home AFB.

4.1.6 OFFUTT AFB

4.1.6.1 Location and Climate

Offutt AFB is located south of Omaha, Nebraska, adjacent to the Missouri River flood plain. The general climate of eastern Nebraska includes four seasons. The summers are generally hot and humid, and the winters can be severe (May, 2002; AFCESA, 1999).

4.1.6.2 RCA Use Summary

Figure 4.30 shows the layout of airfield pavements at Offutt AFB. In 1994, portions of Runway 12-30 were reconstructed. RCA was used for base material and a rapid drainage layer. Areas where RCA was used are highlighted.

4.1.6.3 Construction Using RCA

The project involved removing and replacing the keel section of Runway 12-30 at the western section (about 4,300 ft (1,311 m)) long, and the eastern section about1,200 ft (366 m) long.

The keel section of the runway was excavated to a depth of 4 ft (1.2 m); the side slopes were 10:1 to facilitate water drainage towards the longitudinal axis of the keel sections. Figure 4.31 shows a bulldozer preparing the subgrade to required grade.

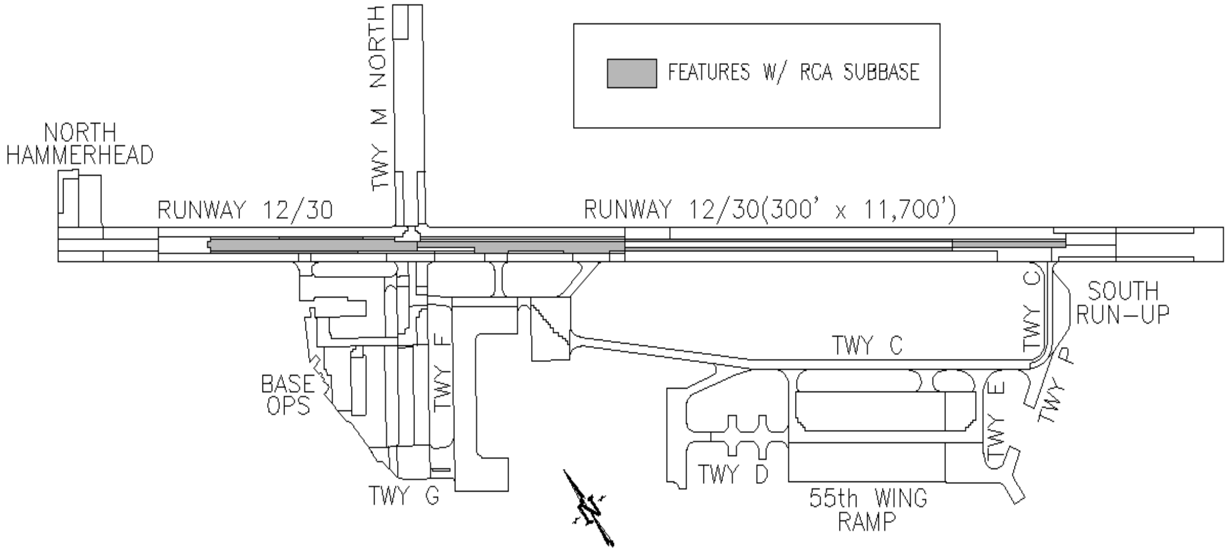


Figure 4.30. Layout of airfield pavements at Offutt AFB.

Figure 4.31. The keel section was excavated to a depth of 10 ft (10:1 side slopes).

After completion of the subgrade, an 8-inch-diameter (203-mm) perforated pipe was installed along the longitudinal axis of the keel section. The subgrade was lined with geotextile and covered with 4 inches (102 mm) of RCA base material. The RCA rapid draining material was then installed to grade to form the underlying material for the new PCC slabs. Figure 4.32 shows a close-up of the RCA rapid draining material; the compacted RCA rapid draining material is shown in Figure 4.33. A schematic of the typical keel pavement section is shown in Figure 4.34.

RCA material was treated as virgin aggregate and had to exceed the virgin aggregate specifications used for the project. The grading specification used for rapid draining material and base did not distinguish between RCA and virgin aggregate.

A test section was constructed to identify the appropriate method for mixing, placing, and compacting. The contractor used a front-end loader for loading and mixing the RCA rapid draining material. Belly dump trucks were used to haul RCA to the job sites where the material was placed in windrows. A motor grader was then used to spread the material to a uniform thickness of 8 inches (203 mm). Vibratory and static rollers were tried, and both were found to be satisfactory. However, in some places the vibratory roller increased the material passing the No. 16 sieve (1.12 mm) to be out specification; thus, five passes of the static roller were recommended for compaction. Similarly the Los Angeles Abrasion test loss was slightly more than the specified limit of 40 percent. The allowable material loss was raised to 45 percent; RCA material loss averaged about 42 to 44 percent for this test.

Figure 4.32. View of the RCA rapid draining material.

Figure 4.33. View of the compacted RCA rapid draining material.

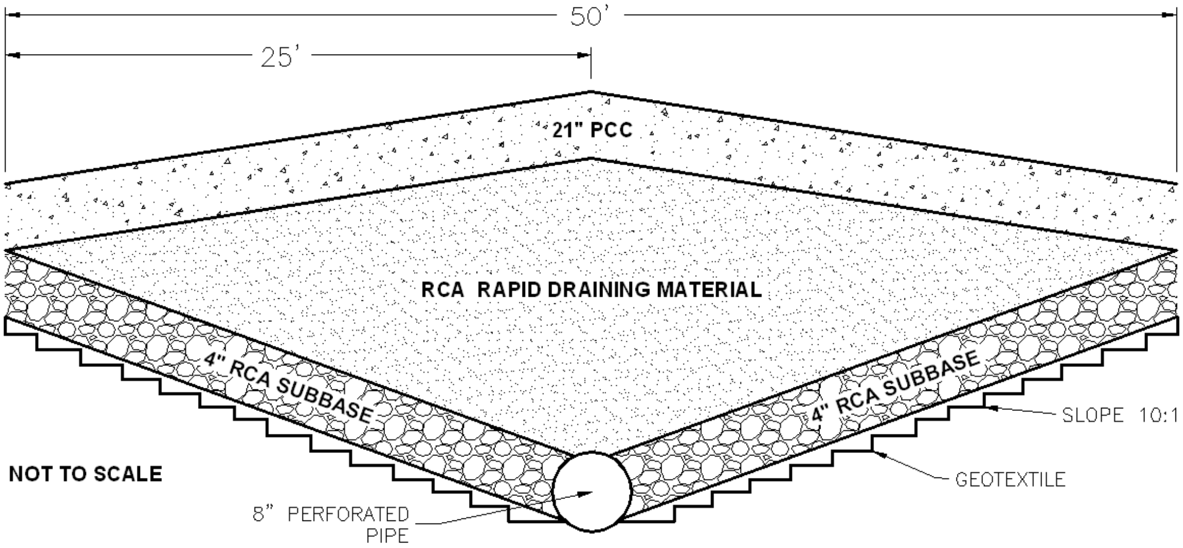


Figure 4.34. Pavement detail of the typical keel section containing RCA.

4.1.6.4 RCA Performance

Using RCA was considered an opportunity to reduce construction costs. The onsite delivered cost for RCA was \$5.00/ton compared to \$12/ton for virgin aggregate material (1 ton = 0.9 metric ton). Using RCA was included as an option for the contractor to consider, and the choice was left to the contractor.

RCA exceeded the virgin aggregate material requirements. However, the allowable LA Abrasion test loss had to be increased to 45 percent, and the limit for material finer than the No. 16 sieve (1.12 mm) had to be increased. These changes were not considered to have a significant impact of the long-term performance of the RCA base or rapid draining material.

4.1.7 HOLLOMAN AFB

4.1.7.1 Location and Climate

Holloman AFB, New Mexico, is located on a high desert plateau between the Sacramento and San Andreas mountain ranges. Its location provides for hot and dry summers and little annual precipitation.

4.1.7.2 RCA Use Summary

Figure 4.35 shows the layout of airfield pavements at Holloman AFB.

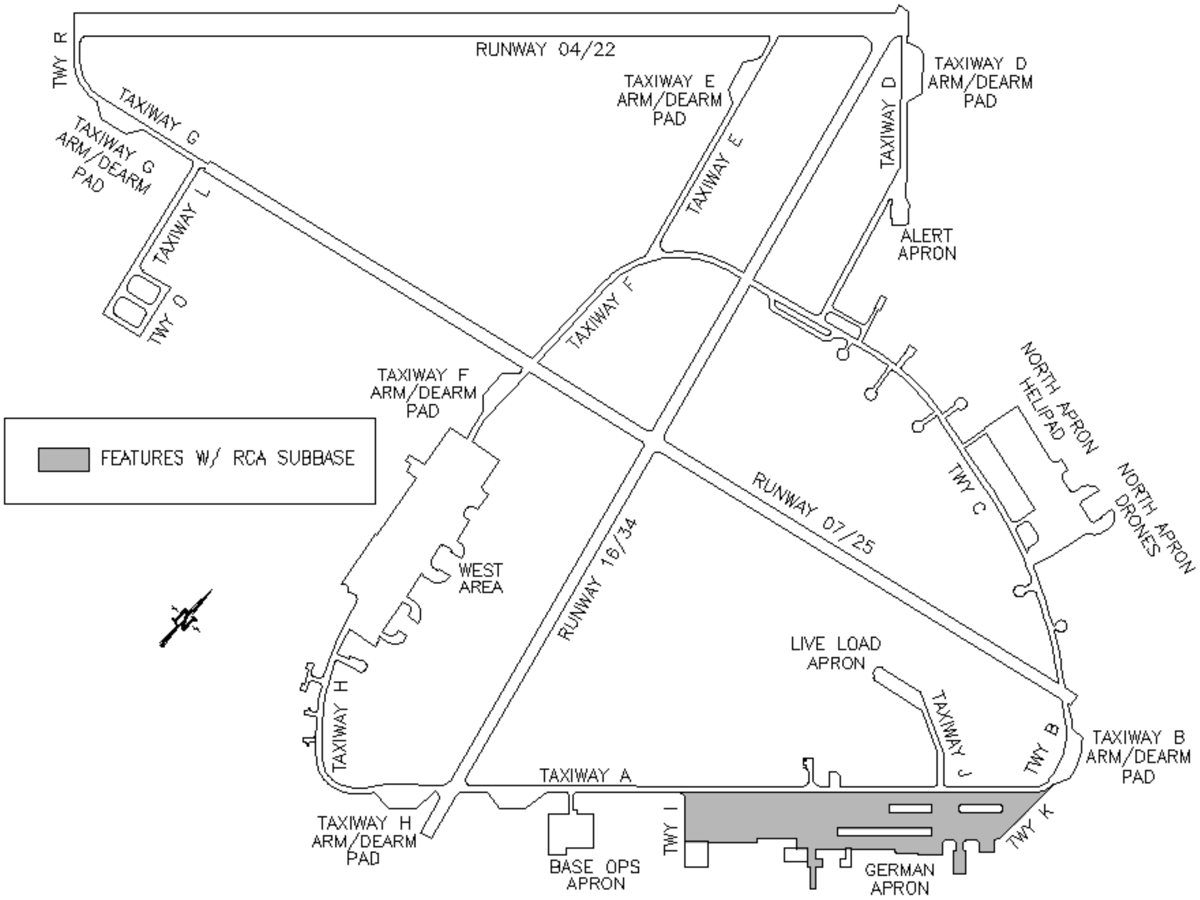


Figure 4.35. Layout of airfield pavements at Holloman AFB, New Mexico.

The soils in the area are typically loose fine silty sands and sandy silts, and the water table is often high; sulfate exposure in local soils is very high. Difficult site conditions at Holloman AFB demand that all construction be placed on a minimum 2-ft-thick (610 mm) non-expansive fill, and Type V sulfate-resistant cement is used in all concrete in contact with or near the ground (Rollings 2002).

In 1995, the German Air Force apron was built. The project consisted of a PCC parking ramp, access taxiway, an aircraft shelter, a large maintenance hangar, and associated asphalt roads and parking lot, concrete sidewalks, and landscaped areas. Because of the grades and detailing, the fill requirements varied from 2 to 5 ft (0.6 to 1.5 m). The contractor proposed and the government accepted RCA as fill; RCA was produced from PCC being removed predominately from an airfield apron undergoing repairs, spanning from 1957 to 1990. The existing PCC had minor distresses and construction defects but exhibited no durability problems. Tests conducted on the removed PCC showed it to be sulfate resistant, and no sulfate attack prior to its removal was indicated. Existing PCC was crushed to the grading required for a military pavement base course and compacted to 100 percent modified density. RCA was used as fill and base course throughout the GAF1 project (Rollings, 2002; Rollings, 1999).

Appendix A provides additional information.

4.1.7.3 RCA Use Failure

RCA is a not a traditional base in the sense that aggregate particles are held together with cement paste to form an individual piece; nevertheless, RCA is composed of individual discrete bound particles. Shortly after construction, heaving began, appearing initially in a few areas, then spreading in an erratic pattern, and becoming progressively worse and more widespread with time. The magnitude and severity of heaving varied; heaving initiated as minor elevation changes between areas with and without RCA became progressively more widespread and severe with time. Rollings et al. (2002) reported that upheaval was occurring in a variety of structures founded on the recycled concrete fill (rigid pavements, flexible pavements, foundation slabs, and sidewalks).

Rollings et al. (2002; 1999) studied the causes of pavement heaving due to RCA. Samples removed from RCA base found abundant ettringite and thaumasite. Sulfate attack was determined to be occurring and causing pavement heaving. No evidence was found that the heaving came from expansive soils (which can mimic many of the observed symptoms) or alkali-silica reaction (which is common on the base). Clearly, sulfate attack on this supposedly sulfate-resistant concrete occurred. Their investigation suggested three possible reasons that sulfate attack occurred in RCA produced from sulfate-resistant PCC:

- Severe Exposure Conditions: Fill and base course were more conducive to sulfate attack than intact PCC on the surface. RCA base is more permeable than intact PCC, and water and sulfates have more ready access to the limited alumina available in Type V cement. As fill, the fluctuating water table, vapor transmission under a covered surface, and retarded evaporation all will bring water and sulfates needed for the reaction into RCA. The sulfate exposure level is very severe. In cases where heaving was not apparent, cores taken from the RCA base were intact, as though the RCA had re-hydrated itself (gypsum was determined to be the cementing agent). No heaving was apparent, though ettringite and thaumasite were found in these cores. Cores from heaved areas crumbled when extracted from the core barrel, and PCC fragments were often soft, moist, and could be broken or deformed with finger pressure. Examination of RCA from stockpiles failed to find gypsum, ettringite, or thaumasite. Consequently, this gypsum must have been deposited during or after placement or both.

- Soil Contamination: If RCA was contaminated with soil, clay particles in the soil could potentially provide chemically active alumina to participate in the ettringite formation. Since neither lime- nor cement-stabilization was used, the pH would not be so high and the alumina not so soluble. Discussions with inspection and contractor personnel found there had been some initial problems with soil contamination that the contractor had taken steps to control, because it was causing problems with keeping the fines within specification limits. No evidence was found suggesting any particular problem with soil contamination.

- Thaumasite: This mineral was found consistently with the ettringite; however, thaumasite is not the major cause of heaving. Rollings et al. (2002) state that in this case, if conditions 1 or 2 were sufficient to develop initial ettringite from limited available alumina, conditions for thaumasite formation are good: wet environment under the covered surfaces, ample sulfate, and cool conditions underground favoring its formation for much of the year. Thaumasite reacts with the silicate phase and not the aluminate phase of the matrix; hence, sulfate-resistant cements with their lowered alumina content offer no protection. In these reactions, thaumasite destroys the cement paste. The soft easily broken recycled-concrete particles are consistent with thaumasite formation.

4.1.8 HARTSFIELD-JACKSON ATLANTA INTERNATIONAL AIRPORT

4.1.8.1 Location and Climate

The Hartsfield-Jackson Atlanta International Airport (ATL) is located near Atlanta, Georgia. The airfield pavements at ATL are shown in Figure 4.36.

The weather in ATL is typical of southern States. Summer months are also characterized by evening thunderstorms and occasional snowfall during winter months.

4.1.8.2 RCA Use Summary

The typical pavement section at ATL is 16-inch-thick (406-mm) PCC over 6-inch (152-mm) cement treated base over 6-inch (152-mm) cement stabilized subgrade over compacted natural subgrade. This typical section is followed for all pavements at the airfield. RCA typically is used as a fill and base material at ATL.

The RCA fill at ATL follows the Georgia DOT graded aggregate base specification. Taxiway M on the 27R end of the runway have RCA stabilized with 5 percent cement. RCA has also been used as cement treated base (5 percent cement) under flexible pavement at the Southeast Navigation, Lighting, and Visual Aid Road (NLVR).

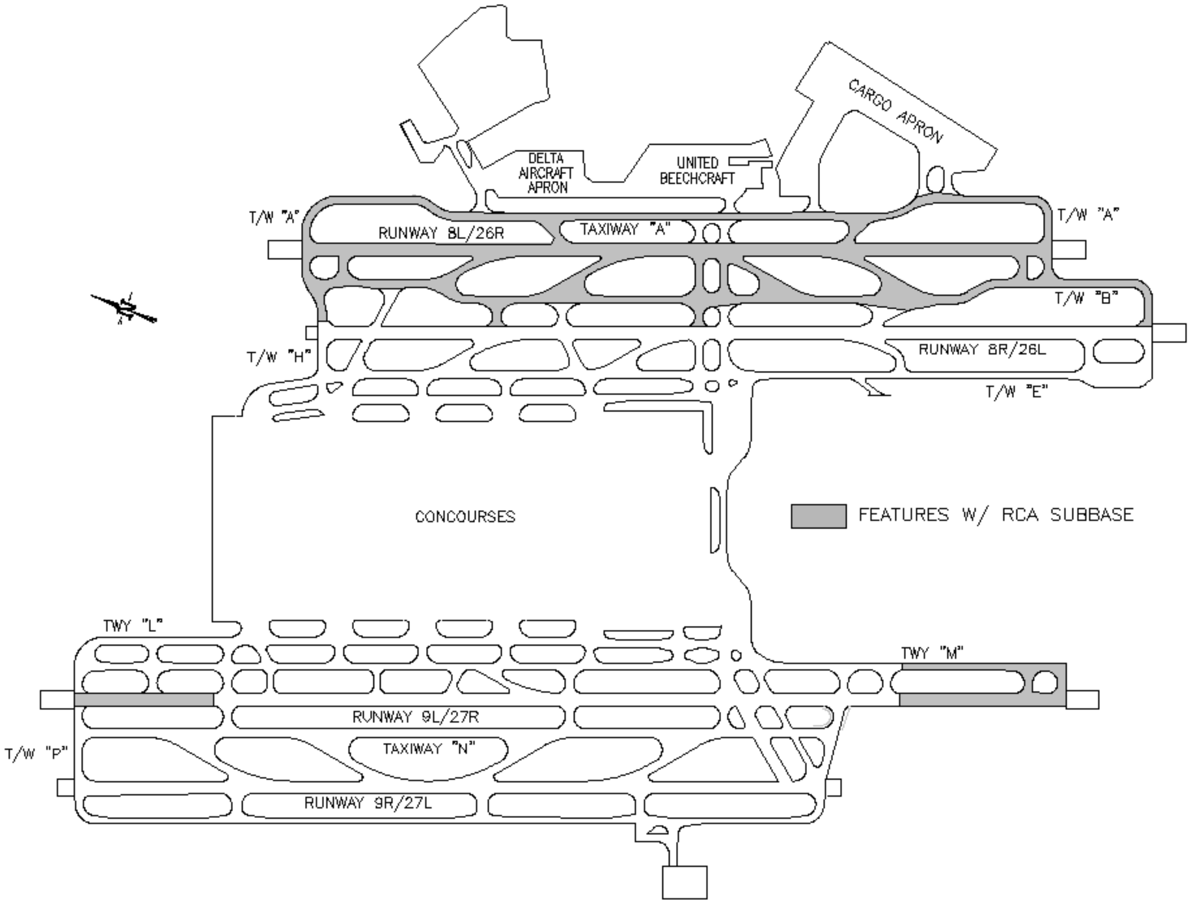


Figure 4.36. Airfield pavement layout at Hartsfield-Jackson Atlanta airport.

4.1.8.3 Construction Using RCA

RCA has to exceed all virgin aggregate specifications when used at ATL. RCA material is specified in accordance with Georgia DOT standard specifications for Sections 800 (Coarse Aggregate) and 815 (Graded Aggregate). Accordingly, RCA is classified as Group II Class B aggregate material. The grading requirements are shown in Table 4.6. The specified allowable LA Abrasion test material loss is 51 to 65 percent. RCA is also specified to have a sand equivalent of at least 28; sand equivalent values as low as 20 are acceptable as long as they could be attributed to rock flour and the percent passing the No. 10 (2-mm) sieve does not exceed 40.

RCA was produced onsite using PCC from airport pavements constructed in the early 1980's. Some areas had ASR; ATL is known to be in an ASR prone area. All slabs were crushed to produce RCA. Some of the remaining slabs are stacked up at the crushing plant site for future use (see Figure 4.37).

Conventional construction equipment was used. There was a concern that RCA might degrade during compaction, but no evidence of degradation was found.

Table 4.6. Grading requirements for RCA at ATL (Georgia DOT Group II Class B).

U.S. Sieve	Metric Sieve	Percent Passing
2 inch	50.8 mm	100
1 1/2 inch	37.5 mm	97 - 100
3/4 inch	19.0 mm	60 – 90
No. 10	2.0 mm	25 – 45
No. 60	250 µm	5 - 30
No. 200	75 µm	4 - 11

Figure 4.37. PCC slabs are stacked at ATL for future use as RCA.

4.1.8.4 RCA Performance

ATL uses RCA extensively as general fill and base material and RCA has performed adequately. It is used at ATL for economic savings (landfill costs); the most successful use of this material has been as fill material meeting the graded aggregate base requirements.

4.1.9 SUMMARY OF SITE VISITS

RCA is used successfully at commercial and DOD airports, as well as highway projects as base and compacted fill material. In most cases, RCA exceeded the virgin aggregate requirements. The most often cited reason to use RCA was economic savings, which result from savings in transportation, landfill tipping fees, or unit costs of virgin aggregate. Ease of use (placing, compaction) was confirmed by several contractors.

4.1.9.1 Pavement Materials

Typically, RCA is allowed as an alternative in material specifications, and the decision is typically left to the contractor's discretion. RCA has been produced successfully to the open graded and dense graded aggregate material requirements.

4.1.9.2 Pavement Construction

Construction using RCA is the same as construction using virgin aggregate materials. Contractors that have had experience with RCA construction generally prefer RCA to virgin aggregate for the following reasons:

- Easier compaction
- Perceived better than virgin aggregate
- Easier to handle during construction
- Stable working platform allowing work to continue even when wet

Special construction equipment is not required. The contractors used different means to spread RCA. Some contractors preferred spreaders to spread plant-mixed RCA base material to control segregation, while others felt that a motor grader or a bulldozer did an adequate job of spreading RCA dumped in windrows. The method used was usually based on the contractor's experience.

Despite the general perception that RCA has a tendency to degrade during transportation and compaction, there is no supporting evidence. Contractors with RCA construction experience have used a variety of means to transport, spread, and compact RCA. The material has been plant mixed as well as brought to the job site and watered in place. Regular as well as belly dump trucks have been used to transport RCA without any degradation. The material has been spread using box spreaders as well as bulldozers and motor graders without any observed degradation.

Static and vibratory rollers have been used successfully to compact RCA with no degradation. The contractors noted that RCA has a relatively high water demand, and RCA should not be compacted to a moisture level below optimum.

4.1.9.3 Environmental Test Data

Environmental tests on RCA generally are not required, and typically none are conducted. Contractors and owners did not feel the need to conduct environmental tests, as RCA in base course applications is usually covered up with either PCC or HMA.

4.1.9.4 Typical Problems and Solutions

Experience is the key to using RCA as base course aggregate, and some potential problems can be avoided with careful planning. Some of these include:

- High water demand: RCA typically compacts at a higher water contact relative to virgin aggregate material. This should be considered during project planning, as this potentially has impact on work progress.

- Segregation: RCA segregation problems can be traced to poor stockpiling when RCA is produced or when it is spread into lifts before compaction. Conveyor belts should be used to create RCA stockpiles, and stockpile height should be controlled to avoid RCA segregation. Using a mechanical spreader to spread plant-mixed RCA helps to control the in-field segregation.

- Grading control: RCA grading before and after compaction should be specified to alleviate concerns that RCA tends to degrade during construction.

- Plant operations: Proper crushing plant operation is the key to producing quality RCA that meets all the specification requirements. Plant crushing speed may need to be adjusted to ensure that PCC is crushed and the operation merely does not separate the original aggregate from the cement mortar. The front loader driver should be advised not to drive on the stock piles and should avoid “undercutting” of stockpiles to ensure that contamination of RCA base with inferior underlying soils does not occur. Conveyor belts should be used, and proper stockpile height should be maintained to safeguard against stockpile segregation.

- Density control: RCA could be especially difficult to compact if the water content is incorrect because improper density impacts the performance of the base. The frequency of in-place density tests should be increased to at least every 1,000 sq. yd (836 sq. m) per lift. Nuclear density gages should be recalibrated in the field for RCA, or else misleading densities could be reported.

4.1.9.5 Construction/Material Specifications

RCA construction and material specification are similar to those for virgin aggregate. Typically, virgin aggregate specifications are used. The LA Abrasion test requirements are relaxed to a material loss of around 45 percent. The soundness test usually is not carried out. All other requirements remain the same.

4.2 RESULTS OF LIMITED LABORATORY INVESTIGATION

The literature search reported several instances where RCA has been tested for conformance with general virgin aggregate material requirements. Questions still remain about the adequacy of RCA produced from distressed PCC, especially PCC that has had ASR or D-cracking. Limited laboratory testing was conducted as part of this research effort to gain insight into this aspect.

4.2.1 SELECTED LABORATORY TESTS

The conducted tests included:

ASTM C 136	Sieve Analysis of Fine and Coarse Aggregate
ASTM D 1557	Modified Moisture/Density Test, Procedure C
ASTM D 4767	Static Triaxial Shear Test
NCHRP RPT 453	Repeated Load Triaxial Test
AASHTO T309	Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials

4.2.1.1 Aggregate Grading

Aggregate mass grading is an important indicator of aggregate performance. Most agencies consider aggregate grading for aggregate selection. Aggregate grading is used to indicate permeability, frost susceptibility, and shear strength (Saeed, 2001). The grading of each RCA material was determined in accordance with ASTM C 136.

4.2.1.2 Moisture/Density Relationship

Laboratory compaction is important to determine the anticipated density achievable in the field and for fabrication of laboratory specimens for other tests. Laboratory compaction was conducted in accordance with ASTM D 1557. Compaction of aggregate materials generally results in increasing density, shear strength, and stiffness and decreasing permeability with increasing moisture content to a point of maximum density beyond which the trends reverse. The point of maximum density is a function of compactive effort (Saeed, 2001).

4.2.1.3 Static Shear Triaxial Test

Shear strength is the single most important property that governs unbound pavement layer performance. The static shear triaxial test is well accepted in geotechnical applications and is conducted at confining stresses of 5, 10, and 15 psi (34, 69, and 103 kPa). The static shear test is conducted in accordance with ASTM D 4767.

4.2.1.4 Repeated Load Triaxial Shear Tests

The repeated load triaxial shear test provides a relative measure of an aggregate's ability to resist permanent deformation. The test procedure considers repeated loads at a rate of loading similar to actual highway traffic loading but also convenient for laboratory application. Saeed et al. (2001) provide test procedure details.

The test was conducted at only one confining pressure (15 psi [103 kPa]) and carried to failure (defined as reaching the machine limit or a permanent deformation of 10 percent). The results of the repeated load testing are presented as plots of permanent deformation versus time, permanent deformation versus principal stress ratio, and permanent deformation occurring within a load level versus the load cycles.

4.2.1.5 Resilient Modulus (Stiffness)

Triaxial testing can be developed to obtain a stiffness value without adding significant complexities to the test method. Since the study was not aimed at determining design parameters, conducting a full resilient modulus test to determine the stiffness as a function of the state-of-stress was unnecessary.

Because resilient modulus values can be determined from the repeated load triaxial test, a stiffness test was not needed. In the triaxial testing, the resilient modulus is determined at the end of each load increment and is presented as a function of the principal stress ratio.

4.2.2 LABORATORY TEST MATERIALS

Two RCA materials were selected for laboratory investigation:

- RCA from Pease International Trade Port, New Hampshire (formerly Pease AFB)
- Grand Forks AFB, North Dakota

RCA from former Pease AFB is characterized as having ASR distress, and RCA from Grand Forks AFB is distressed with D-cracking. RCA material was re-blended to typical open graded drainage layer (OGDL) and dense graded base layer (DGBL) gradings as shown in Figure 4.40. These gradings were used for all subsequent tests.

Figure 4.38. RCA materials as-received from Pease International Trade Port, NH.

Figure 4.39. RCA material as-received from Grand Forks AFB, ND.

4.2.3 LABORATORY TEST RESULTS

Laboratory test were conducted on RCA materials to test the hypothesis that the engineering properties of RCA are equal to those of a typical virgin aggregate. The virgin aggregate materials chosen for comparison were tested as part of NCHRP Project 4-23 and reported by Saeed et al. (1991):

- Material A (90 percent crushed dolomitic limestone and up to 10 percent fines)
- Material B (100 percent uncrushed natural gravel)

Virgin aggregate materials A and B establish the typical upper and lower ends of virgin aggregate shear strengths, respectively.

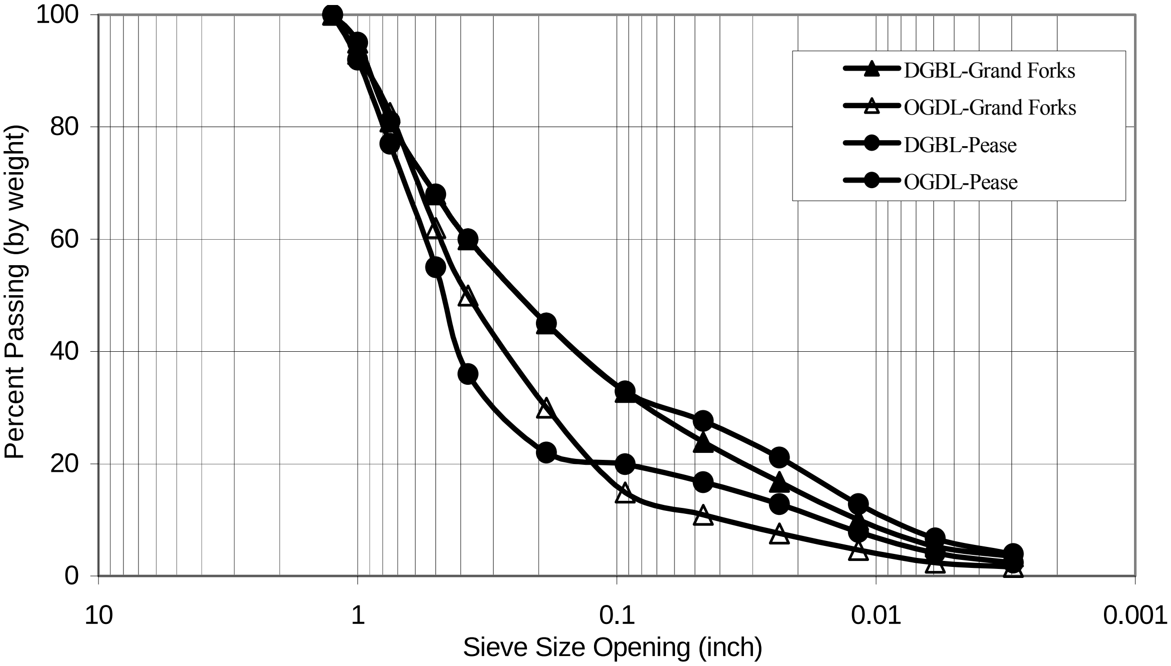


Figure 4.40. Typical test gradings for RCA used in laboratory investigation.

4.2.3.1 Moisture/Density Relationship

A moisture/density relationship needs to be developed for determining the field densities that could be achieved and to prepare laboratory specimens. Compaction generally increases density, shear strength, and stiffness, and decreases permeability. Test results are shown in Table 4.7. The results indicate that RCA OMC is about 4 percent higher and maximum dry density (MDD) is about 20 pcf (320 kg/m^3) lower than typical virgin aggregate.

Table 4.7. Optimum moisture density for RCA and virgin aggregate materials.

Sample	OMC[1], percent	MDD[2], pcf
Grand Forks – DGBL	11.7	123.3
Grand Forks – OGDL	12.0	124.5
Pease – DGBL	9.8	127.0
Pease – OGDL	8.9	128.3
Virgin A	6.3	142.0
Virgin B	Free draining material	Free draining material

[1] Optimum moisture content
[2] Maximum dry density (1 pound/ft^3 = 16 kg/m^3)

4.2.3.2 Static Triaxial Shear Test

Static triaxial shear tests were conducted at confining stresses of 5, 10, and 15 psi (34, 69, and 103 kPa) to determine the shear strengths. Test samples were prepared at 95 percent or greater MDD and at OMC. Table 4.8 shows the failure deviator stress.

Table 4.9 shows the cohesion (c) and angle of internal friction (ϕ) values. Figure 4.41 shows the effect of confining stresses on the deviator stresses for RCA and virgin aggregate. Note that the high and low shear strength virgin aggregate materials bracket RCA failure deviator stresses. In addition, RCA failure deviator distresses are grouped together. Results of static shear triaxial confirm the expected order of RCA and virgin aggregate.

Table 4.8. Failure deviator stress for RCA and virgin aggregate materials.

Samples	Confining Pressure, psi (kPa)		
	5 (34)	10 (69)	15 (103)
	Failure Deviator Stress, psi (kPa)		
Grand Forks – DGBL	47.2 (325.4)	82.6 (569.5)	129.2 (890.8)
Grand Forks – OGDL	46.5 (320.6)	76.4 (526.8)	120.8 (832.9)
Pease – DGBL	49.3 (339.9)	82.6 (569.5)	147.2 (1,014.9)
Pease – OGDL	56.3 (388.2)	79.2 (546.1)	122.2 (842.5)
Virgin A	76.7 (528.8)	111.3 (767.4)	155.5 (1,072.1)
Virgin B	24.0 (165.5)	46.8 (322.7)	69.8 (481.3)

Table 4.9. Values for cohesion (c) and angle of internal friction (ϕ).

Sample	Cohesion (c), psi (kPa)	Angle of internal friction (ϕ^o)
Grand Forks – DGBL	4.93 (34.0)	51.0
Grand Forks – OGDL	5.00 (34.5)	49.5
Pease – DGBL	4.86 (33.5)	53.0
Pease – OGDL	5.56 (38.3)	49.0
Virgin A	5.9 (40.7)	53.0
Virgin B	Non cohesive material	Non cohesive material

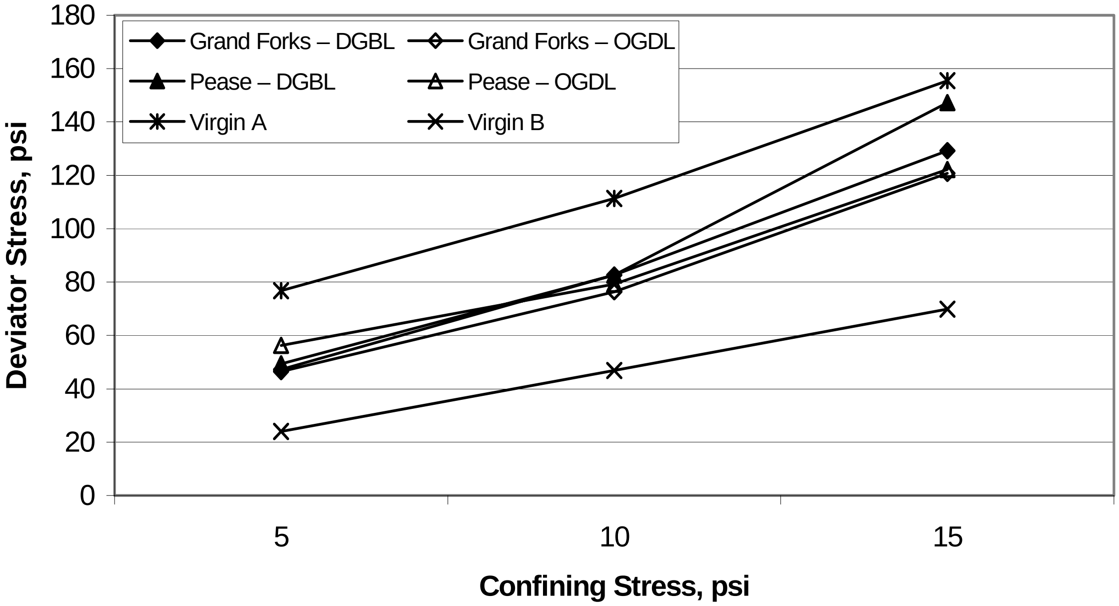


Figure 4.41. Comparison of static triaxial test results for RCA and virgin aggregate.

4.2.3.3 Repeated Load Triaxial Tests

Repeated load triaxial shear tests were conducted to obtain a relative measure of an aggregate's ability to resist permanent deformation. Because no standard test procedure was available, one developed and reported by Saeed et al. (2001) was used. The repeated load tests were conducted at a confining pressure of 15 psi (103 kPa), and 1,000 applications were applied at each load increment. A haversine load pulse of 0.1-sec load duration was used to apply load to the test specimen. The load levels were applied until the samples failed; the sample was considered failed when the permanent deformation reached 10 percent.

Figure 4.42 shows the results of Grand Forks AFB RCA (both OGDL and DGBL). Similar curves are shown for Pease International Trade Port RCA in Figure 4.43. For comparison, the curves of high shear strength virgin aggregate reported by Saeed et al. (2001) are shown in Figure 4.44. The "start" (solid plot line) and "end" (dashed plot line) curves represent the permanent strain at the beginning (average of repetitions 96 to 100) and at the end (average of repetitions from 996 to 1000) of a repeated stress loading, respectively.

Both Pease and Grand Forks RCA are comparable to virgin aggregate when compared in terms of repeated triaxial shear strength. In terms of static triaxial strength, there appears to be some difference between RCA produced from distressed PCC, but results of repeated triaxial shear strength do not indicate such a difference. Comparison of deviator stress at 10 percent strain shows that Pease RCA performed slightly better than Grand Forks AFB RCA, with DGBL gradings performing slightly better than OGDL grading. Pease RCA in DGBL grading could not be failed, as it did not reach 10 percent strain at the end of 10,000 cycles. Table 4.10 shows deviator stress at 10 percent strains for RCA and Virgin A materials.

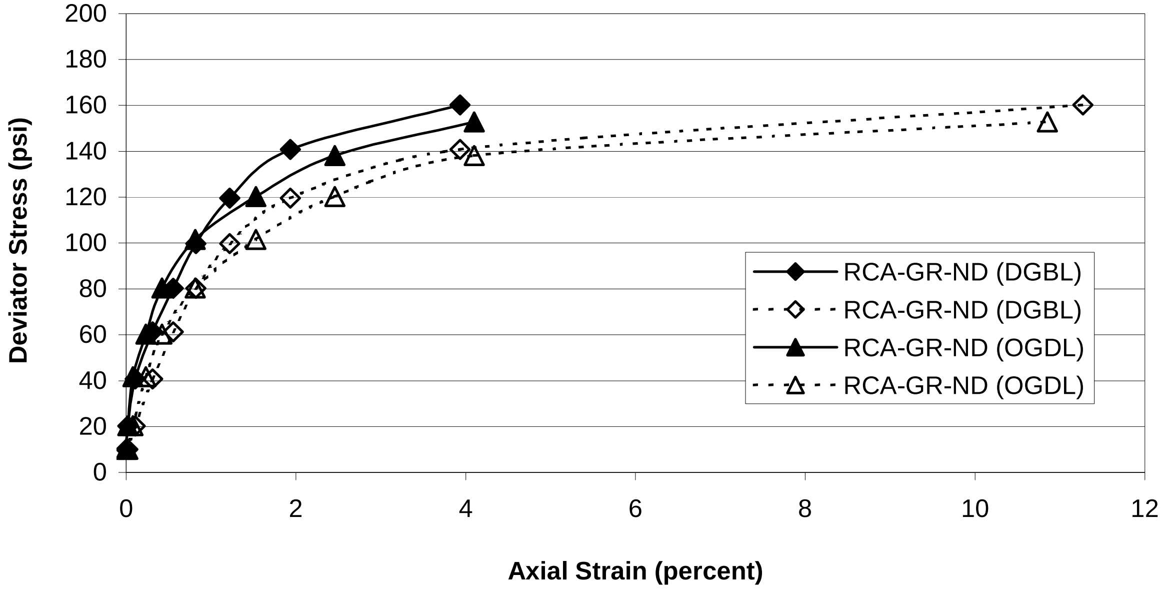


Figure 4.42. Repeated load triaxial test results for Grand Forks AFB RCA.

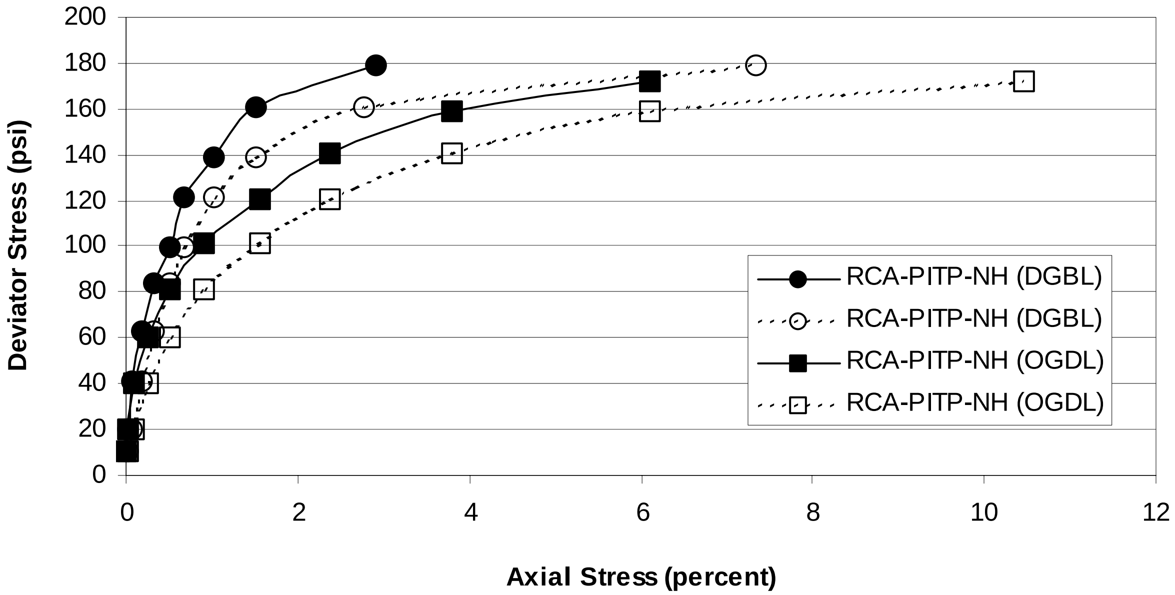


Figure 4.43. Repeated load triaxial test results for Pease Int. Trade Port RCA.

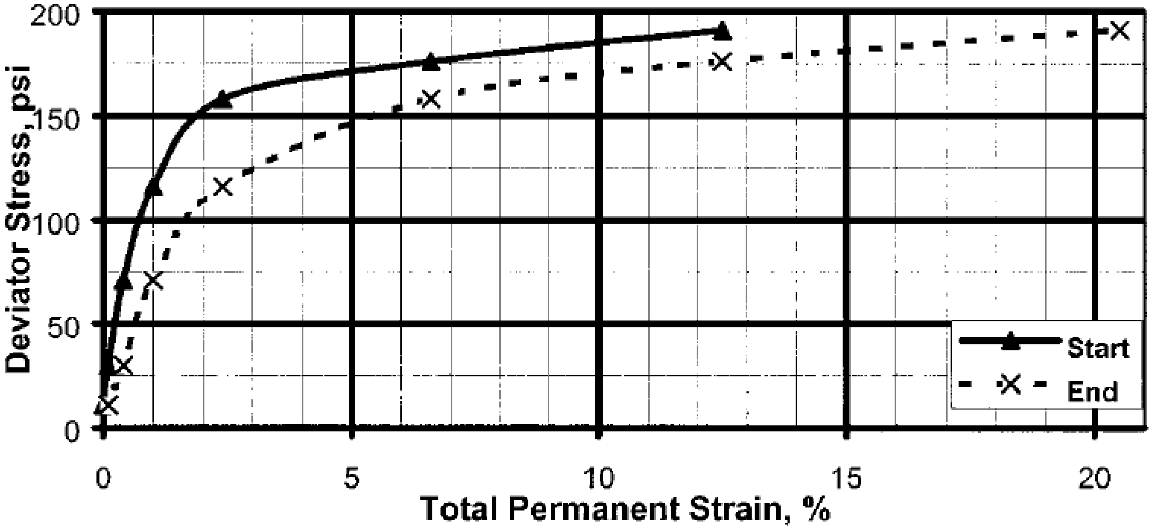


Figure 4.44. Repeated load triaxial results for Virgin A material (Saeed, 2001).

Table 4.10. Deviator stress at 10 percent strain for RCA and Virgin A materials.

Sample	**Deviator Stress at 10 percent Strain, psi (kPa)**	
	DGBL	OGDL
Grand Forks AFB RCA	155 (1,068.7)	150 (1,034.2)
Pease Int. Trade Port RCA	Material did not fail [1]	170 (1,172.1)
Virgin A	175 (1,206.6)	

[1] Material had 7.34 percent strain at 10,000 repetitions; test was stopped.

Figure 4.45 shows the number of load cycles to failure. Grand Forks RCA reached failure strain earlier than Pease RCA; these results are summarized below. Also, Pease DGBL material did not fail, and testing was stopped after 10,000 load repetitions.

- Pease RCA – OGDL: 10 percent permanent strain reached at cycle #726 of loading sequence #10
- Pease RCA – DGBL: 7.34 percent permanent strain reached at cycle #1000 of loading sequence #10
- GF AFB RCA – OGDL: 10 percent permanent strain reached at cycle #727 of loading sequence #9
- GF AFB RCA – DGBL: 10 percent permanent strain reached at cycle #830 of loading sequence #9

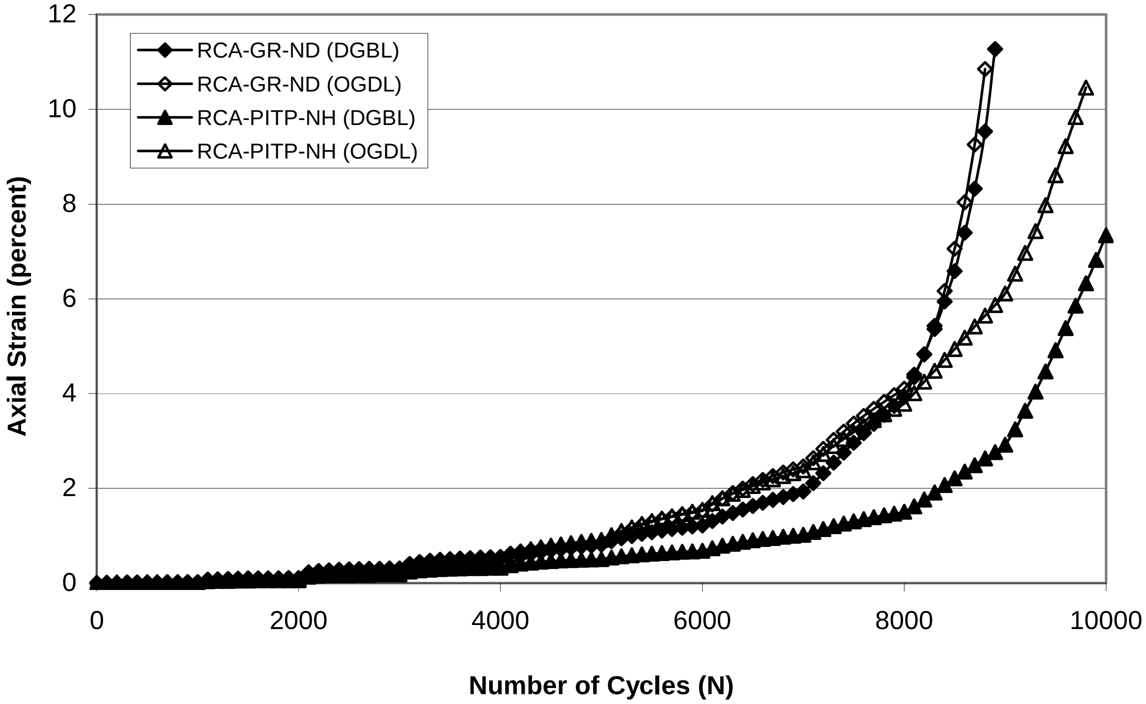


Figure 4.45. Axial strain versus number of cycles for RCA materials.

4.2.4 SUMMARY OF LABORATORY INVESTIGATION

Information gathered during this effort pointed to the fact that RCA is comparable to virgin aggregate material for base course application. However, questions remained about the adequacy of distress RCA (produced from ASR and durability distressed PCC) for use as base course material. As such, RCA produced from ASR-distressed and D-cracked PCC was tested. The results of laboratory testing (supplemented with experience from similar research efforts and other project tasks) of distressed RCA indicated the following:

- Sieve Analysis – RCA could be produced and blended to provide the desired open and dense gradings.
- Moisture-Density Relationship – Generally, RCA has a higher OMC and lower MDD than typical virgin aggregate.
- Static Triaxial Shear Test –distressed RCA is comparable to a typical average virgin aggregate material.
- Repeated Load Triaxial Shear Test – RCA permanent deformation characteristics are comparable to virgin aggregate material. RCA compared well with a typical virgin aggregate at a failure permanent deformation strain of 10 percent.

Results of the tests conducted as part of this research effort indicated that distressed RCA (and RCA, for that matter) is comparable to virgin aggregate material for use as base course aggregate.

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5 ALKALI SILICA REACTIVITY

5.1 INTRODUCTION

Alkali silica reaction (ASR) is a deleterious chemical reaction in PCC between the hydroxyl (OH^-) ion associated with alkalis (sodium [Na^+] and potassium [K^+]) from cement paste or other sources and certain reactive forms of silica that may be present in coarse or fine aggregates (FAA 2004-b and 2005-b). The chemical reaction between alkalis and silica produces a gel that expands in the presence of sufficient moisture. The expansive gel can produce cracks in both the cement paste and aggregate particles. Reactive aggregates, ample concentrations of alkalis, and availability of sufficient water are essential ingredients for ASR. Additional information on ASR identification is provided in FAA Advisory Circular AC 150/5380-8 (FAA, 2004-b).

5.2 USE OF RCA FROM ASR-DISTRESSED PCC

Active alkali silica reaction (ASR) in pavements being demolished for producing RCA is expected to continue when RCA is used as unbound base layer aggregate. However, a continuation of the ASR reaction in RCA should not be a significant source of damage in unbound base course applications because the porosity in the structure of unbound base should be able to allow expansion of the reaction product without deleterious stress within the structure. This expectation is supported by the absence of known cases of pavement failures due to residual ASR in unbound base. However, given the current level of concern about ASR in pavements and the absence of quantitative knowledge, it is prudent to make some assessment on the use of RCA from ASR-distressed PCC in unbound base courses according to the criticality of the construction.

5.3 EVALUATING RCA FROM ASR-DISTRESSED PCC

The pavement designer should exercise due care in evaluating site conditions, severity of ASR, and other factors to ensure the proper use of ASR distressed PCC. Figure 5.1 provides a flow chart to determine the severity of the ASR. Once the ASR severity is determined to be either mild or aggressive, Table 5.1 can be used to determine the acceptable uses of RCA from ASR-distressed PCC. RCA manufactured from PCC with mild severity ASR can be used in most airfield pavement applications. However, in case of RCA manufactured from PCC with aggressive ASR, the engineer is cautioned to conduct detailed benefit/risk analysis. There are on-going research activities intended to develop techniques to ascertain when reactively levels are no longer sufficient to support on-going ASR reactions. The engineer should use the latest research results to develop an understanding of benefits of using RCA from ASR-distressed PCC and risks thereof.

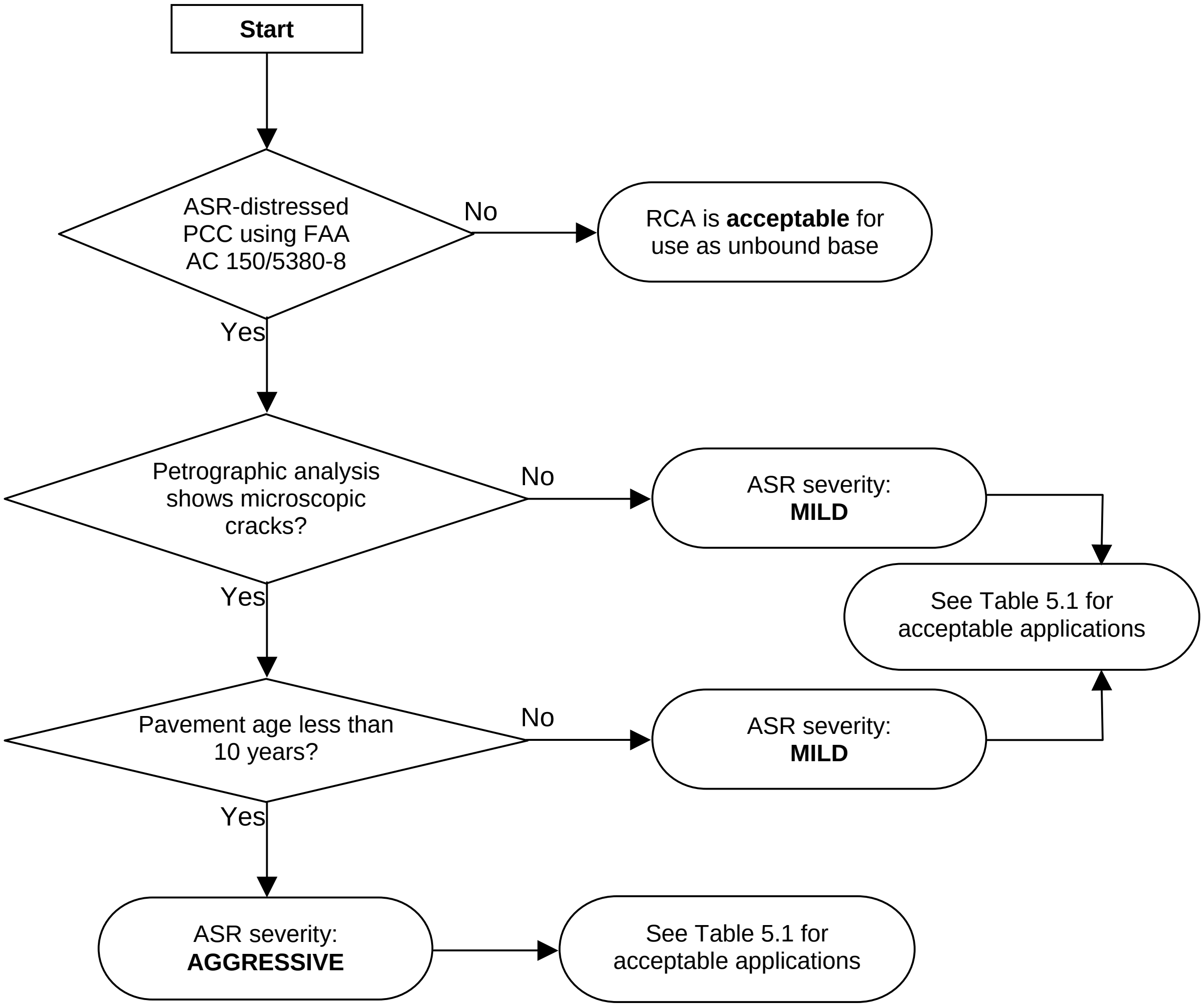

Figure 5.1. Flow chart to determine severity of ASR.

Table 5.1. Application and risk matrix for ASR-distressed PCC RCA.

Construction Application	ASR Severity: Aggressive			ASR Severity: Mild		
	Pavement Type[1]			Pavement Type[1]		
	Primary	Secondary	Tertiary	Primary	Secondary	Tertiary
Deep fill	●	●	●	●	●	●
Subbase	--[2]	●	●	●	●	●
Base	--[2]	--[2]	●	●	●	●
Drainage layer	--[2]	--[2]	●	●	●	●

Notes: [1] Primary, essential pavements (runway, parallel taxiway, main apron); secondary, occasional use pavements - engines running (ladder taxiways, hold apron); tertiary, other airfield pavements
[2] Detailed benefit/risk analyses must be conducted

6 MATERIAL STANDARDS AND CONSTRUCTION GUIDELINES

6.1 INTRODUCTION

A construction and material specification must include a set of essential information, and most include the following items:

- Description of product
- Materials
- Equipment
- Construction method
- Material acceptance
- Product acceptance
- Method of measurement
- Basis of payment
- Testing requirements

6.2 MINIMUM MATERIAL STANDARDS

Material requirements for crushed aggregate base course are more stringent than those of an aggregate base course. A base course constructed with crushed material will usually have higher strength and stability. To achieve this objective, published literature, limited laboratory tests, and specifications from current projects were studied to develop minimum material standards pertaining to RCA. These minimum material standards will allow the designers to use RCA with confidence.

RCA is treated as virgin aggregate material and has to meet all virgin aggregate material requirements. Some of the requirements are relaxed where these are not applicable for obvious reasons.

6.2.1 AGGREGATE

RCA is to be derived from concrete pavement. RCA should consist of clean, sound, and durable crushed particles and be free of silt, clay, organic matter, HMA, steel reinforcement, or other objectionable material. An incidental amount of recycled asphalt concrete pavement could be present in the RCA and to control the amount asphalt concrete overlays should be removed from the surface prior to pavement removal and crushing. Also, full-slab asphalt concrete panels (used as a replacement for a removed PCC slab) should be removed. A reasonable number of small asphalt concrete patches (less than a full slab panel) may be incorporated with the RCA.

6.2.2 AGGREGATE GRADING

Aggregate mass grading is determined in accordance with ASTM C 136. The specified aggregate grading refers to grading of the stockpiled material. Typical RCA aggregate gradings are shown in **Table 4.4**; the maximum aggregate size should be limited to 2 inches.

6.2.3 PERCENT ABRASION LOSS

The Los Angeles Abrasion test has long been used as an index for aggregate toughness. The test, as described in AASHTO T96 or ASTM C 131, is included in aggregate material specifications. The LA Abrasion test loss is generally limited to 40 percent. However, this limit can be increased to 45 percent for RCA. This practice is allowed at RCA construction sites with no discernable impact on performance.

6.2.4 FLAT AND ELONGATED PARTICLES

The shape of the aggregate particle has long been used to judge the potential of an aggregate to resist permanent deformation. Flat and elongated particles can break during mixing, hauling, and placing, and especially under compaction, and ultimately change aggregate grading; flat and elongated particles can also influence ease of compaction. An excess of such particles can be detrimental to good performance.

The shape of the aggregate particles in terms of the percentage of flat or elongated particles is determined in accordance with test procedure ASTM D 4791. A flat particle is defined as one having a ratio of width to thickness greater than 3, and an elongated particle is defined as one having a length to width ratio greater than 3. The amount of flat and elongated particles is limited to 30 percent. Some of the more restrictive specifications have limited the amount of flat and elongated particles to 20 percent on material retained and passing the 1/2-inch (13 mm) sieve.

6.2.5 PERCENT OF FRACTURED PARTICLES

Fractured particles consist of crushed RCA particles containing fine and coarse aggregates within the concrete matrix and are not limited to single aggregate particles without attached matrix. A higher percentage of fractured particles contribute to an increase in shear strength. The percentage of fractured particles is determined in accordance with ASTM D 5821. A fractured particle is defined as having two or more fractured faces with the area of each face being at least 75 percent of the smallest midsectional area of the piece. For contiguous fractures, the angle between the fractures planes should at least be 30 degrees to be considered as two fractured faces. The fractured particles should at least be 50 percent of the by weight of the material retained on each specified sieve; specifications requiring 90 percent fractured particles by weight have also been used.

6.2.6 SOUNDNESS TEST

Aggregate durability or resistance to weathering is determined using the magnesium or sodium sulfate soundness test conducted in accordance with AASHTO T 104 or ASTM C 88. This test simulates the weathering action using crystallization of soluble salts in aggregate pores; test results are represented as percent loss. Typically, material loss is specified to be less than 15 percent (weighted average after five cycles). This requirement is usually waived for RCA materials because this test is chemically unsuited. The sulfate component of sodium or magnesium sulfate salts reacts with the concrete mortar, leading to erroneous results.

6.2.7 LIQUID AND PLASTICITY LIMITS

The liquid and plasticity limits of the aggregate fraction finer than the 0.425-mm (No. 40) sieve are determined in accordance with AASHTO T89 and T90, respectively. Atterberg Limits are indexes defined as the moisture contents at which the fine content (passing No. 200 [75 µm] sieve) changes from one state into another (i.e., from solid to semi-solid as moisture increases beyond the plastic limit). The Atterberg Limits are specified for the completed course; the portion passing the No. 40 (425 µm) sieve is specified to be nonplastic or have a liquid limit of less than 25 and plasticity of less than 5.

6.3 CONSTRUCTION GUIDELINES

Conventional construction equipment is used to construct unbound pavement layers incorporating RCA, and RCA material is treated no differently than virgin aggregate for construction purposes. Construction guidelines typically include information on the following:

- Aggregate stockpiling
- Preparation of existing pavement layer
- Installation
    - Mixing
    - Placing
    - Compaction
    - Finishing
- Maintenance

6.4 PROPOSED SPECIFICATIONS FOR ITEM X-XXX, RECYCLED CONCRETE AGGREGATE BASE COURSE

Proposed specifications for Item X-XXX, “Recycled Concrete Aggregate Base Course,” are included as appendix B.

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7 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

RCA can be used as unbound base material if produced from uncontaminated PCC. RCA should not be used where there is a potential for sulfate exposure from subgrade soils, ground water, or other external sources.

RCA is not a hazard to the environment. Localized environmental effects from raised pH in leachate are insignificant. Discharge of heavy metals or organics from common sources of RCA, if any, is insignificant.

Hydration has not been shown as a chemical phenomenon in RCA. The perception that unbound RCA base can gain strength through hydration is not supported.

An economic analysis can be conducted by considering initial material and construction costs for both RCA and virgin aggregate. RCA typically is a better economic option, especially when transportation costs of virgin aggregate and disposal costs of PCC are considered.

Guide specifications for Item P-XXX, “Crushed Concrete Aggregate Base Course,” are included as appendix B. All the virgin aggregate tests and their limits are applicable to RCA except the sulfate soundness test. The sulfate soundness test is waived for RCA due to the incompatibility of PCC components with the chemical reactants used in the test. With due consideration and evaluation of site conditions, RCA from ASR-distressed PCC can be used.

7.2 RECOMMENDATIONS

The FAA should adopt the proposed guide specifications for Item P-XXX, “Crushed Concrete Aggregate Base Course.” The adoption of this guide specification will facilitate the use of RCA in pavement construction providing serviceable pavements while accruing economic and environmental benefits.

The use of RCA from ASR distressed PCC should be based on an evaluation of the site conditions, severity of ASR, and other factors. A decision methodology for using RCA from ASR-distressed PCC as an unbound base is given in Chapter 5 of this report. RCA manufactured from PCC with mild severity ASR can be used as an unbound base in most airfield pavement applications. However, in case of RCA manufactured from PCC with aggressive severity ASR, the engineer is cautioned to conduct detailed benefit/risk analysis.

7.3 RECOMMENDED FUTURE RESEARCH

Published literature provided information on a number of issues but had limited information on others. Appendix C discusses additional research that would aid and expand the use of RCA in airport pavement structures.

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APPENDIX A

Results of Literature Search and Review

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A.1 LITERATURE SEARCH AND REVIEW

The goal of this subtask is to collect and review all available domestic and foreign literature on the project subject matter. Many different sources were queried to identify and obtain information pertinent to the development of the Guide and other key documents. Among the sources investigated via the Internet and through the University of Illinois library information service and U.S. Army Corps of Engineers Waterways Experiment Station were the following:

- Transportation Research Information Service (TRIS)
- National Technical Information Service (NTIS)
- National Transportation Library (NTL)
- Transportation Research Board (TRB)
- Innovative Pavement Research Foundation (IPRF)
- Federal Aviation Administration (FAA)
    - Center of Excellence for Airport Technology
    - National Airport Pavement Test Facility (NAPTF)
    - Regional and District offices
- Air Force Civil Engineering Support Agency (AFCESA)
- Airport Consultants Council (ACC)
- American Association of Airport Executives (AAAE).
- National Association of State Aviation Officials (NASAO)
- American Society of Civil Engineers (ASCE)
- U.S. Army Corps of Engineers
    - Waterways Experiment Station (WES)
    - Cold Regions Research and Engineering Laboratory (CRREL)
    - Center of Expertise in Transportation, Omaha District
- State Transportation Libraries
- Advanced Transportation Research and Engineering Laboratory (ATREL)
- American Association of State Highway and Transportation Officials (AASHTO)
- Federal Highway Administration (FHWA)
- American Concrete Pavement Association (ACPA)
- Portland Cement Association (PCA)

All of the documents collected have been reviewed for pertinence to the study and are summarized here. Additional documents will be added to the literature summary as they become available.

A.2 BACKGROUND

RCA is the coarse and/or fine aggregate originated from the demolition of mostly existing PCC pavements and consists of high-quality, well-graded aggregate particles. Initially, the impetus to use RCA was because of environmental concerns about waste disposal in landfills, preservation of natural resources, environmental preservation, and sustainable development. It also has economic advantages and engineering material properties similar to virgin aggregates. Reid (2000) indicated that alternative (or recycled) materials perform as well as natural ones. In fact, some recent researchers have indicated that RCA generally have better engineering properties than virgin aggregates (Chesner et al., 1998). In addition to environmental concerns, economic advantages and similar engineering properties, there is a political aspect that requires consideration of recycling materials for transportation application. Holtz and Eighmy (2000) listed some important developments and events related to pavement recycling, as follows:

- Some States, such as Pennsylvania, passed legislation that promotes recycling
- Interest of several State DOTs and environment protection agencies (EPAs)
- Environmental Council of States (ECOS) involvement in agreements to permit beneficial use determinations (BUDs) between States on the use of recycled materials in highway construction
- The FHWA participation on national and international events promoting the use of recycled materials on numerous research projects
- The creation of the Recycled Materials Resource Center (RMRC) at the University of New Hampshire (UNH) in 1998 through the U.S. Congress Transportation Equity Act for the 21st Century (TEA-21)

In 1996, the production of virgin aggregate in the U.S. was 2.2 billion tons (2.24 billion metric tons), and 40 percent of this amount was used in for highway system (Chini et al., 1998). Wilburn and Goonan (1998) reported that RCA consumption increased 170 percent between 1994 and 1996, but in 1995 less than 0.4 percent of the total aggregates were recycled. This USGS report indicated that the use and extraction of natural aggregate were “increasingly being constrained by urbanization, zoning regulations, increased costs, and environmental concerns.” At the time of this survey, about 50 percent of all concrete debris or 7.25 million tons ended up in landfills. In contrast, a small country like Denmark recycled 81 percent of the total produced 1.2 million tons (2.6 billion pounds) of crushed concrete (Holtz and Eighmy, 2000). This was attributed to a high population density and low natural aggregate availability.

A.3 RCA USE, PRODUCTION AND ECONOMICS

A.3.1 APPLICATION OF RCA

RCA is used predominantly in pavement construction as virgin aggregate replacement for granular, cement-treated, or econocrete subbase layers, and, to a lesser extent, in hot mix asphalt (HMA) and PCC surface layers. PCC recycling should be considered in the following instances (Halm, 1980):

- Unavailability of good local aggregates

- Cost of virgin aggregate
- Removing and disposal cost of the old pavement is relatively more expensive than recycling

Saeed et al. (1995, 1996, and 1997) investigated the use of RCA in granular bases and developed a specification based on laboratory tests. Schroeder (1994) reported that RCA was already accepted for highway construction as base course and embankment. Wilburn (1998) estimated that approximately 68 percent of produced RCA is used as subbase course with minor amounts used in HMA and as fill material, as shown in Figure A.1.

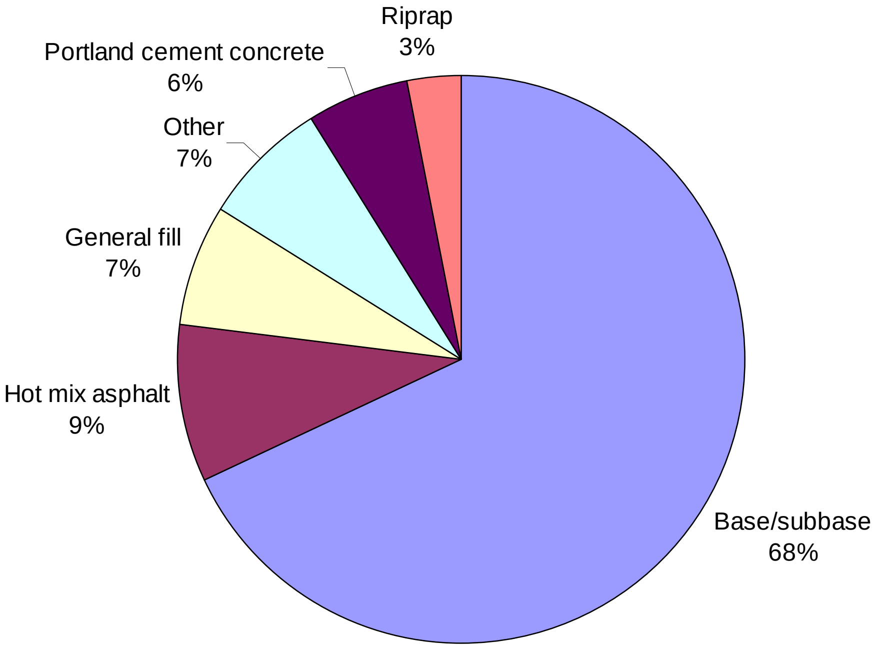


Figure A.1. Uses of RCA (Wilburn, 1998).

A.3.2 RCA PRODUCTION

Demolished concrete from existing PCC slabs is usually hauled to a central processing facility, where metal (reinforcing steel and dowel bars) is removed by magnetic separation. The demolished concrete is then crushed and screened to produce the specified grading using conventional equipment (Chesner et al., 1998). In addition to aggregates, processed RCA has hardened cement paste which holds the aggregate particles together. The amount of cement paste attached to aggregate in RCA depends on the process used to produce RCA and the properties of the original concrete. The cement paste causes RCA to weigh less, increases water absorption, and lowers abrasion resistance compared to conventional aggregate (Chini and Kuo, 1998).

According to the U.S. Army and Air Force (1988), the equipment used to break up the existing concrete included pile-driving hammers, various concrete pavement breakers, and rhino-horn-tooth-ripper-equipped hydraulic excavators. They divide the crushing process into the following activities: crushing and screening, stockpiling, aggregate preparation, and reinforcing steel removal. They further recommend that each size of aggregate be stored separately and that processing equipment be able to control the amount of fines to less than 5 percent of the fine aggregate passing the No. 200 (75 µm) sieve.

The production process affects the particle size and shape properties. Chini and Kuo (1998) recommended using a combination of two crushers (jaw crusher as the primary and a rotating crusher as the secondary) during the crushing process to produce the best particle grading and shape. Compared to typical virgin aggregate, processed RCA particles are highly angular in shape and have a rougher surface texture, lower specific gravity, and higher water absorption. In addition, processed RCA is more permeable than most natural sands, crushed limestone and gravel. Typical RCA gradings after processing are shown in Table A.1.

Table A.1. Range of RCA particle size distribution after processing.

Sieve Size	**Range of Particle Size Distribution (Percent Finer)**		
	New Jersey DOT	Florida DOT	Texas DOT
1.5 in (37.5 mm)	92	100	100
1.0 in (25 mm)	86	97.6	98
3/4 in (19 mm)	80	-- [a]	77
1/2 in (12.5 mm)	64	46.4	70
3/8 in (9.5 mm)	56	-- [a]	58
1/4 in (6.3 mm)	-- [a]	4.8	-- [a]
No. 4 (4.75 mm)	42	-- [a]	45
No. 8 (2.36 mm)	34	4.2	35
No. 10 (2.00 mm)	32	-- [a]	-- [a]
No.16 (1.18 mm)	28	-- [a]	25
No. 30 (0.60 mm)	22	-- [a]	17
No. 50 (0.30 mm)	14	-- [a]	5
No. 100 (0.15 mm)	10	-- [a]	1
No. 200 (0.075 mm)	8	-- [a]	0

[a] Data not provided

Laboratory tests performed on different sources of PCC show consistent results (Chini and Kuo, 1998). When RCA is used as aggregate in unbound base, there is little or no RCA particle breakdown during material handling and construction. Typically, RCA has a higher Los Angeles (LA) abrasion loss, a lower dry density, and a higher optimum moisture content than virgin aggregate materials. However, these values still are within the acceptable range for use as unbound base aggregate. Typical physical properties of processed RCA are given in Table A.2 (ACPA, 1993).

Table A.2. Typical physical and mechanical properties of RCA.

Property Type	Property	Typical Value
Physical	Specific Gravity	Coarse (plus No. 4 sieve): 2.2 to 2.5 Fine (minus No. 4 sieve): 2.0 to 2.3
	Absorption (%)	Coarse (plus No. 4 sieve): 2 to 6 Fine (minus No. 4 sieve): 4 to 8
Mechanical	LA Abrasion Loss (%)	Coarse ((plus No. 4 sieve): 20 - 45
	Magnesium Sulfate Soundness loss (%)	Coarse (plus No. 4 sieve): 4 or less Fine (minus No. 4 sieve): less than 9
	California Bearing Ratio (%)	94 to 184

A.3.3 RCA COST

Aggregates constitute one of the most costly components among all construction costs: between 21 and 30 percent of the cost of materials and supplies and in the range of 10 to 14 percent of the total construction cost, excluding right-of-way and engineering costs (Halm, 1980). Recycling pavement is especially economical where the hauling distance for virgin aggregate exceeds 50 miles. Research conducted by the Massachusetts Institute of Technology (MIT) concluded that recycling of aggregates was a feasible alternative, especially in metropolitan areas with scarce virgin aggregate.

The cost of crushing is the only cost associated with recycling concrete pavements, because the cost of hauling aggregate and disposing of the old pavement are eliminated and the cost of breaking, removing, separating steel, and transporting are considered incidental (Mack, 1993). Horvath (2003) reported that the average tipping fee charged to dump material in landfills in the U.S. is $37/ton, which results in a marginal benefit of more than $41/ton for avoiding dumping and cost of virgin material. This estimate does not even include processing and transportations costs. Based on a survey in Florida, Chini and Monteiro (1999) found that 6 out of 10 concrete plants that recycled concrete reported that RCA is cheaper than natural aggregate, whereas only 2 responded that it was more expensive. In the previous year, Chini et al. (1998) had indicated that RCA was less expensive or competitive with natural aggregate in Florida, except in the southern part of the State, where major natural aggregate sources are abundant.

A.4 RCA PHYSICAL AND MECHANICAL PROPERTIES

Important characteristics of aggregate particles include shape, grading, and LA abrasion. Base permeability, density, and moisture content are essential characteristics of the aggregate matrix for different types of bases. The shape and grading of aggregates affect the shear strength of granular base, which is an important performance-related property. The LA abrasion and soundness test are related to the potential degrading of aggregate. It is essential to characterize permeability for drainage design, whereas density and moisture content are crucial properties to determine the compaction effort. These and other material properties are presented in this section for both recycled and conventional aggregate for comparison purposes.

The shape of RCAs is highly angular (Chesner et al., 1998). In addition, it was reported that RCA tends to be more permeable than natural sand, crushed limestone, and gravel (Hanks and Magni, 1989).

Table 2.1 shows typical RCA gradings after processing. The New Jersey grading was based on the work by Bennert et al. (2000), whereas the gradings from Texas and Florida were based on the research performed by Rathe et al. (2002) and Kuo et al. (2001), respectively. It is observed that the RCA gradings from New Jersey and Texas are similar, while the Florida grading is comprised of only coarse aggregate.

Chini and Monteiro (1999) evaluated the use of RCA (PCC from Interstate 10 near Pensacola, Florida) for use as base material. The following tests were performed: grading, limerock bearing ratio (LBR), soundness loss, LA abrasion, permeability, plasticity, and compaction. They found that RCA has grading characteristics and aggregate shape similar to conventional aggregate and experiences a comparable amount of particle reduction during the crushing process. It was deficient, however, in the amount of material finer than the 3/8-in sieve, indicating the need for changing the crushing plant. The LBR of RCA was very high (above 200 percent), which is superior to conventional aggregate. In contrast, the soundness loss by sodium sulfate test was 34 percent after 5 cycles, which is outside the acceptable limit of 15 percent established by the Florida DOT for graded aggregate base. RCAs were characterized as non-plastic, satisfying the typical maximum plasticity index of 6 percent. A modified proctor compaction test indicated the tested RCA had a maximum dry density of 119.7 lb/ft^3 and optimum moisture content of 12.2 percent. Finally, RCA was found to produce 5 percent of flat and elongated particles, which is within the acceptable limit of 8 percent for typical aggregates.

Chini et al. (1998) reported consistency between laboratory tests performed on different sources of concrete. During the construction of unbound RCA base, the particle breakdown is minimal. Compared to virgin aggregate materials, RCAs usually have higher LA abrasion loss, lower dry density, and higher optimum moisture content. However, these values are usually within the acceptable range for use in pavement layers. Chini and Monteiro (1999) also reached a similar conclusion in terms of abrasion loss for use in base course. Chini and Monteiro (1999) also reported that RCA has higher permeability than natural aggregate due to the greater amount of void space in its mortar, which is also the reason for higher absorption and lower density.

Cho and Yeo (2003), while evaluating RCA for lean concrete base in Korea, determined that RCAs have lower specific gravity and high water absorption characteristics than natural aggregate. Park (2003) found the following range for some physical properties of the RCA in South Korea: optimum moisture content between 9 and 12.8 percent, maximum density between 113 and 138 lb/ft^3, particle index between 14 and 18, and uncompacted voids between 42 and 50 percent.

Petrarca and Galdiero (1984) compiled RCA physical test data during a 5-year period. This database included the results of 112 LA abrasion and 107 soundness tests. The mean values of these test results were 36.5 percent and 3.75 percent, respectively, with a coefficient of variation (CV) of 10 and 35 percent. California Bearing Ratio (CBR) and maximum dry density were also analyzed (but in two periods) because of the addition of a third crusher that increased CBR and dry density. From the first to the second period, the mean CBR increased from 143.8 (133 tests) to 168.7 (24 tests), and the standard deviation decreased from 28.7 to 27.2. The mean maximum dry density increased from 128.5 lb/ft^3 (119 tests) to 130 lb/ft^3 (24 tests), but the standard deviation decreased from 2.6 to 1.6 lb/ft^3. The authors concluded that RCA bases satisfy the requirements for a good long-term base performance.

Mack et al. (1993) reported that typical values of sulfate soundness tests are 3 or less, which is far below than maximum allowed by the American Society for Testing and Materials (ASTM). They also reported that residual chloride does not seem to be a concern for road applications, since it usually varies from 0.07 to 0.09 percent. It was also reported that typical LA abrasion loss values for RCA are in the range from 20 to 45 percent.

Chini et al. (1998) concluded that plants in Florida are capable of producing RCA grading that complies with the requirements for natural aggregate. They also concluded that Florida's RCA complies with stability, particle size distribution and shape, permeability, plastic index, LBR, LA abrasion, and compaction requirements for aggregate base course. They further recommended not to test RCA soundness by means of sulfate test, because it is chemically unsuited. This research also showed that the maximum dry density varied from 104 to 118 lb/ft^3, the optimum moisture content was in the range of 10 to 20 percent, and LBR varied from 139 to 242 percent.

Rathje et al. (2001) characterized RCA samples taken throughout Texas using Atterberg limits, specific gravity, pH, and resistivity. The average liquid limit (LL) was 21 with a standard deviation of 4; the plastic limit could not be calculated, since RCA are non-plastic materials. The average specific gravity was 2.62 with a standard deviation of 0.04. The pH was calculated using ASTM 4972-95a (Standard Test Method for pH of Soils) and was about 12.4 with a standard deviation varying from 0.10 to 0.79 depending on the location. The average resistivity was 299 ohms-in with a standard deviation between 20 and 197 ohms-in. when determined using the California DOT Test 643 procedure. Rathje et al. (2002) further concluded that material breakdown does not seem to be a major concern for RCA, since the amount of fines produced during compaction was not significant. Figure A.2 shows that the dry density increases as water content increases from 0 to 12 percent and then remains almost constant for water contents greater than 12 percent. This could be attributed to the fact that water starts draining from the bottom of the compaction mold. The RCA compaction curve does not exhibit the distinct peak that is typical for soils as it does with any non-cohesive soil. In addition, the results of triaxial compression test indicated that RCA has excellent strength with effective friction angles of about 55°.

PCC strength has little or no effect on the particle breakdown of RCA under compaction (Chini et al., 1998). Furthermore, RCA has lower density, higher optimum content, and higher LA abrasion loss than natural aggregate, but these values are acceptable for aggregate bases. Rathje et al. (2002) compared nuclear gage density and moisture with other techniques. They concluded that the moist densities measured with the nuclear gauge were 10 to 20 percent greater than those measured with the rubber balloon method and that water content was about 20 percent higher than that measured with oven drying. As a result, they recommended the nuclear gage be calibrated on site.

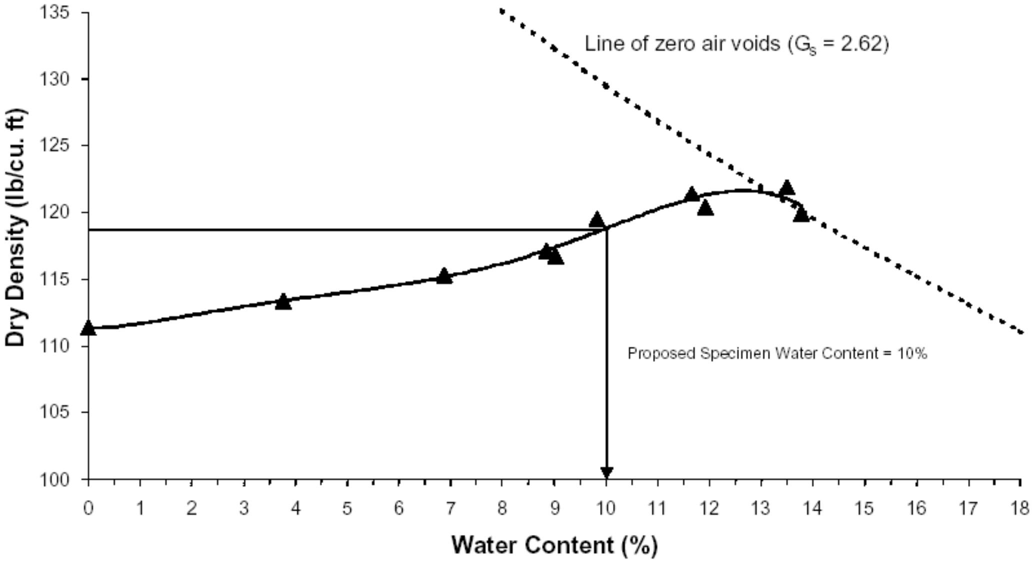


Figure A.2. Compaction curve for RCA using Tex-113-E test method.

LBR tests were conducted on RCA samples from seven Florida DOT districts every month for 1 year to evaluate the variability in RCA strength characteristics (Kuo et al., 2001). The LBR test (FDOT, 2000) evaluates an aggregate's overall bearing and shearing strength relative to limerock, which has a standard strength of 800 psi (5.5 MPa). The LBR test sample is prepared by compacting the base material in a 6-inch (15.2-cm) diameter and 6-inch (15.2-cm) high mold using a 10-lb (0.0445-KN) piston hammer dropped from a height of 18 inches (45.7 cm) (FDOT, 2002). Load readings are recorded for each 0.01-inch (0.25-mm) penetration of a 1.95-inch (49.5-mm) piston, and the load versus penetration results are plotted. The load at 0.1-inch penetration as a percentage of the standard LBR strength is termed as the LBR strength of the material. Almost all RCA samples met the Florida DOT specifications for LBR of 100 percent or more. A comparison of average LBR with Florida DOT LBR specification is shown in Figure A.3.

Barksdale et al. (1992), while studying 8 unbound base materials (5 virgin aggregate, 3 RCA), determined that degrading of the base materials due to compaction and repeated loading to 70,000 repetitions. Degrading was evaluated by comparing the before and after grain size distribution as shown in Table A.3. RCA exhibited the most degrading although the level of degrading was not considered serious.

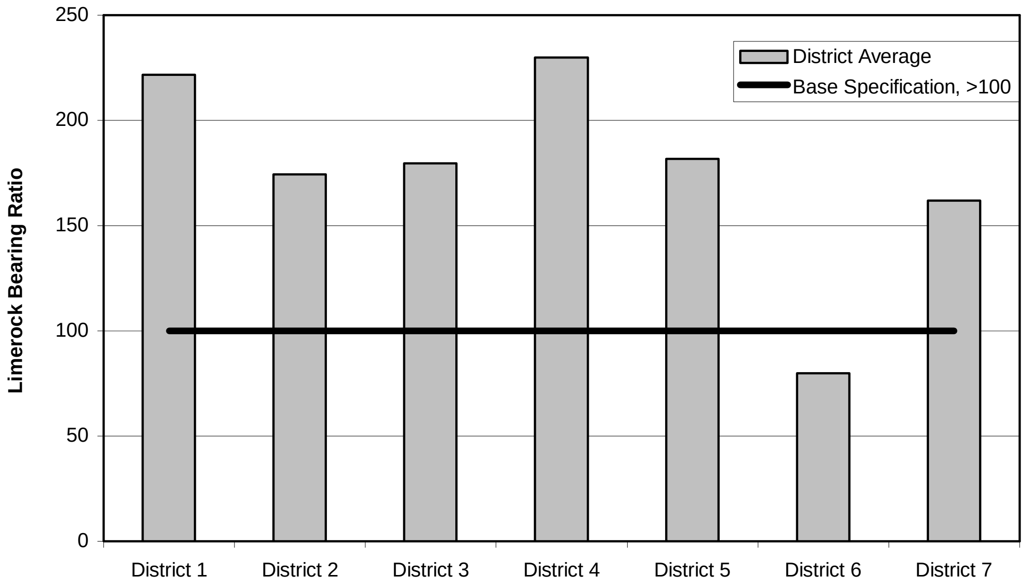


Figure A.3. Average LBR for all districts in the Florida DOT study.

Table A.3. Properties of tested aggregate bases.

Material	Percent Passing[1]							LA[2] %	Abs.[3] %	DD[4] pcf	OMC[4] %
	1	3/4	3/8	#4	#10	#40	#200				
Dolomite	100.0	97.0	70.0	45.0	33.0	19.0	8.5	41.6	3.19	139	7.0
	100.0	97.9	71.9	47.3	34.2	21.2	8.7				
Dolomite (OG[3])	100.0	98.3	50.7	27.7	18.5	6.8	0.9	37.2	2.6	131	6.0
	100.0	98.7	54.6	30.3	19.8	7.2	1.1				
Dolomite (2”)	89.0	72.0	46.0	29.0	20.0	14.0	7.0	39.7	2.8	144	6.5
	90.6	76.0	48.9	31.4	21.7	15.3	7.6				
Granite	*3/4*	*1/2*	*3/8*	*#4*	*#8*	*#50*	*#200*	34.6	1.72	140	5.5
	100.0	94.6	73.8	38.0	27.3	14.6	6.8				
	100.0	95.9	75.7	42.7	30.1	16.2	8.2				
RCA II	100.0	97.0	70.0	45.0	33.0	19.0	8.5	38.3	4.94	128	8.5
	100.0	97.1	73.6	46.5	34.6	21.2	9.1				
RCA I	100.0	97.0	70.0	45.0	33.0	19.0	8.5	37.1	5.56	123	8.0
	100.0	97.0	74.0	49.4	36.8	22.7	9.2				
RAC & Dolomite	100.0	97.0	70.0	45.0	33.0	19.0	8.5	37.2	5.9	135	8.0
	100.0	98.1	72.1	47.9	34.4	21.7	9.3				
Sand &Gravel	100.0	97.0	70.0	45.0	33.0	19.0	8.5	22.9	1.32	145	4.5
	100.0	97.1	71.0	47.0	34.0	21.0	8.6				

[1] First grading is before compaction and testing; the second one is after testing.
[2] Los Angeles test abrasion loss (ASTM C-131).
[3] Absorption as determined by the AASHTO T-85 specific gravity test
[4] Density and optimum moisture content as determined by the AASHTO T-180 test.

A.5 RCA PERFORMANCE RELATED PROPERTIES

Bennert et al. (2000) analyzed the performance of 100 percent and 25, 50, and 75 percent blends of RCA in terms of resilient modulus (M_R) and permanent deformation under cyclic triaxial tests. Results of static triaxial tests, shown in Figure A.4, indicated that dense-graded aggregate base (DGAB) has significantly more shear strength than 100 percent RCA material. The 100 percent RCA and its blends were stiffer than the DGAB material, and RCA samples did not show any large permanent strains indicating future rutting potential. Figure A.5 shows that the stiffness of RCA increased with an increase in the amount of RCA in the mix. An example of stiffness tests conducted at VTI in Sweden, shown in Figure A.6, shows the same trend.

Barksdale et al. (1992) investigated eight unstabilized aggregate bases, among which three were made using RCA. Contrary to work by Bennert et al. (2000), they found that stiffness characteristic in terms of M_R is not always related to rutting behavior in terms of permanent deformation since the RCA bases presented the lowest M_R but had a better permanent strain performance (more resistant to rutting) than crushed base and similar performance to the dolomite aggregate base (see Table A.4). It was also concluded that base with RCA becomes stiffer with time, and this was attributed to increase in fines due to degrading effects or rehydration.

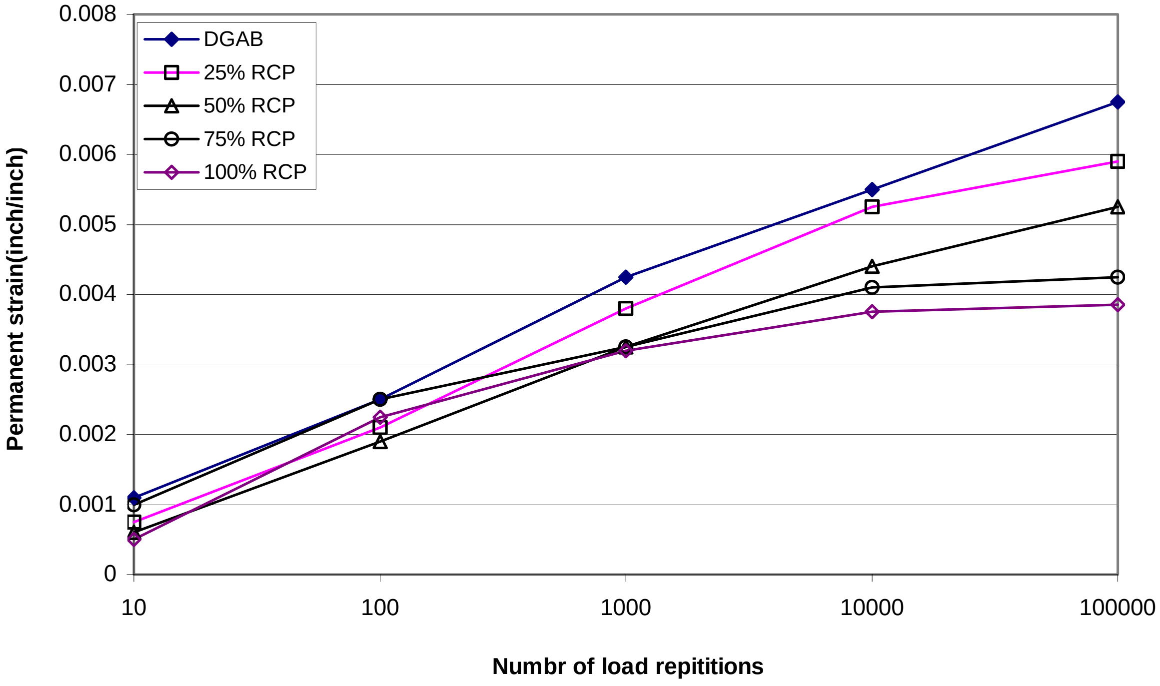


Figure A.4. Result of permanent strain tests on RCA.

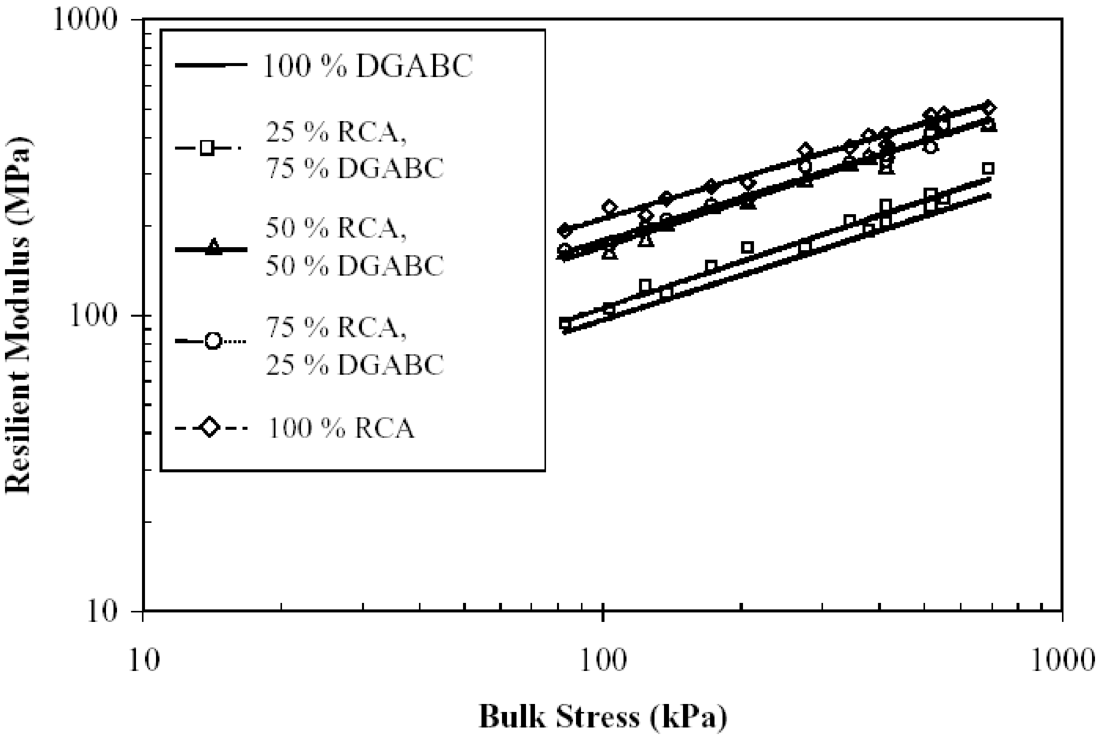


Figure A.5. Resilient modulus increased with percent of RCA in the blend.

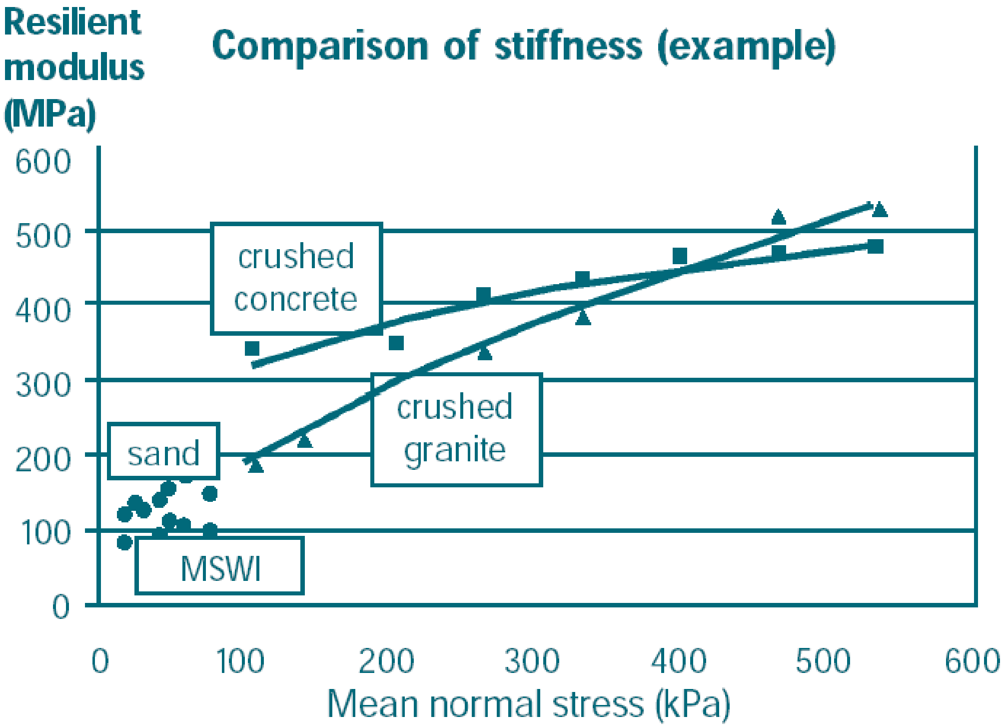


Figure A.6. Triaxial testing data from Sweden.

Table A.4. Summary of M_R and rutting index test on base course materials.

Material	Resilient Modulus (psi) at 50 psi bulk stress						Rut Index [2]		
	100 % T-180 [1]		95% T-180 [1]		100% T-180 Soaked				
	N=1200	N=8600	N=1200	N=8600	N=1200	N=8600			
Dolomite	23.0	26.0	21.0	24.0	18.0	18.0	29.0	48.6	32.0
Dolomite (OG[3])	28.8	28.8	24.0	28.8	24.0	24.0	29.0	48.6	32.0
Dolomite (2”)	26.0	28.0	20.0	24.0	24.0	28.0	38.5	56.0	42.0
Granite	22.0	23.0	17.0	20.8	19.5	21.0	41.0	62.0	54.0
RCA II	19.2	22.4	15.5	16.8	13.4	14.4	51.0	86.0	81.0
RCA I	18.5	21.6	13.5	15.0	13.0	13.6	55.0	95.0	80.0
RAC & Dolomite	21.0	24.0	19.2	19.0	17.2	20.0	58.6	100.0	82.0
Sand &Gravel	21.0	24.0	17.2	18.5	13.5	15.0	62.0	102	91

[1] Samples tested at optimum water content.
[2] Rut index estimated as permanent strain after 70,000 repetitions.
[3] Open graded

Petrarca and Galdiero (1984) analyzed RCA physical test data compiled during a period of 5 years and in-situ deflection data from tests performed on RCA base course and conventional bases. The analysis of these data indicated that pavements with RCA bases have similar or higher strength than pavements with conventional granular bases in addition to providing economical pavements.

Chini et al. (2001) studied the performance of RCA unbounded bases (and concrete slabs) under accelerated traffic. Nine pavement test sections were constructed and subjected to accelerated loading at the University of Central Florida's Circular Accelerated Test Track. Flexible pavement sections 1, 3, and 4, and rigid pavement section 9 were constructed with RCA base course. The performance analysis carried out during this study showed that the performance of RCA is at least equal to that of virgin aggregates.

Arm (2000) studied the self-cementing properties of RCA in unbound pavement layers using triaxial and field tests. The 2-year study included repeated load triaxial tests on manufactured samples after different storage times and FWD tests on test sections; the results showed a clear increase in M_R (Figure A.7) and backcalculated layer modulus (Figure A.8). The rate of increase is initially high and then levels off with time.

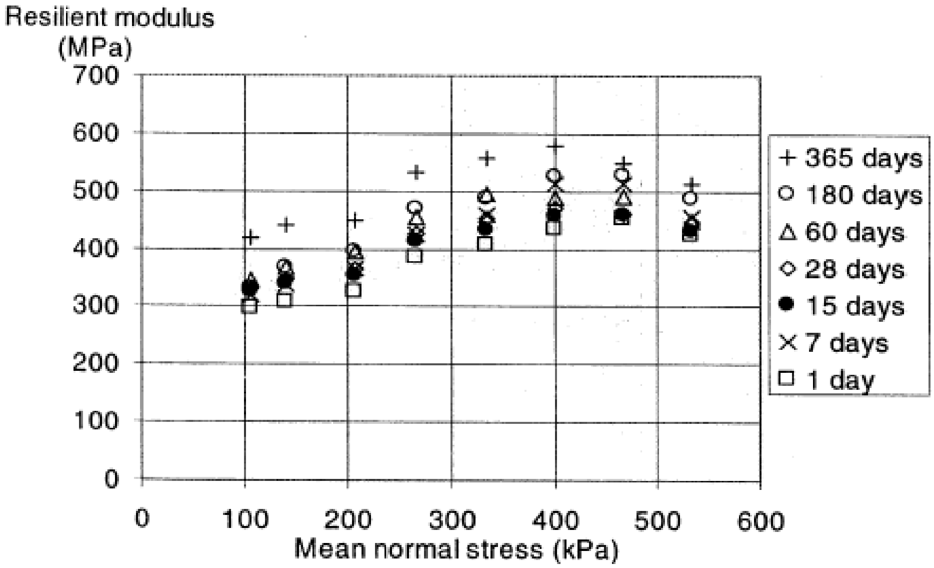


Figure A.7. Growth in resilient modulus of crushed concrete with age.

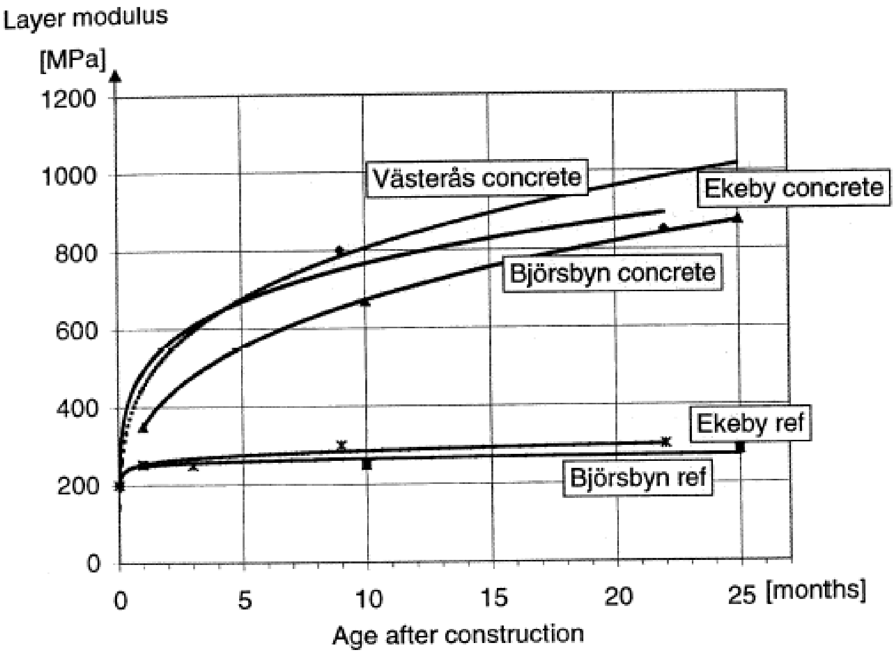
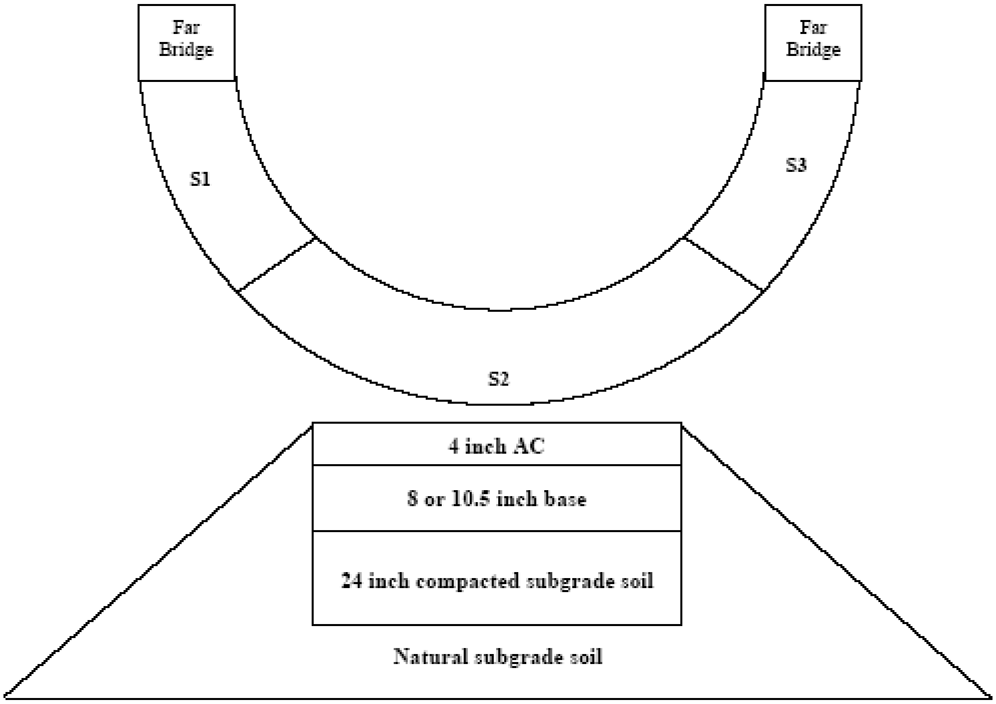


Figure A.8. Increase in backcalculated modulus with time for unbound RCA layer.

A.6 FIELD PERFORMANCE OF RCA AS BASE

Information on pavements with RCA subbase courses is limited; most of the available information performance-related was for recycled concrete pavement or recycled stabilized base. Since the comparison between performance of pavements with and without RCA allows evaluating, at least roughly, the effect of RCA on pavement performance, these analyses are presented in this section.

Kuo et al. (2001, 2002) analyzed the performance of three asphalt pavement test sections at the University of Central Florida Circular Accelerated Test Track (UCF-CATT). The objective of this experiment was to evaluate the performance of bases with and without RCA. Two of these sections had RCA unbounded bases of different thickness (8 and 10.5 in), whereas the other section had a 10.5-in-thick virgin limerock base, as shown in Figure A.9. Kuo et al observed that one crack developed on the limerock section, but the RCA test sections did not present any cracks. As a result, Kuo et al concluded that RCA aggregate bases performed better than conventional aggregate base. Figure A.10 presents average deflections measured during Falling Weight Deflectometer (FWD) tests at the UCF-CATT.



Section	Base Course	Thickness (inch)
S1	RCA	8.0
S2	RCA	10.5
S3	Limerock	10.5
All sections	Compacted Subgrade Soil	24

Figure A.9. Test section layout and cross-section details at the UCF-CATT.

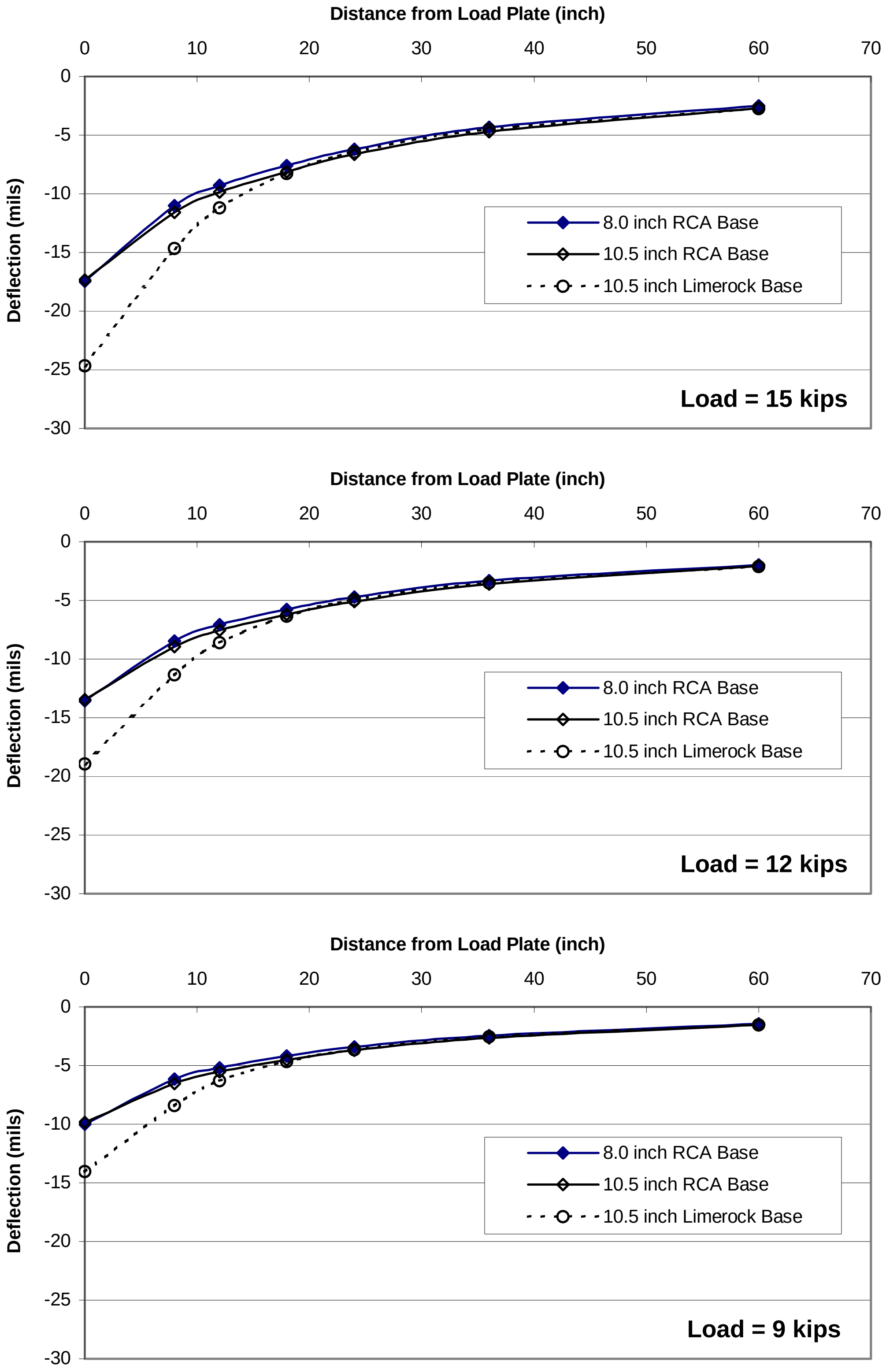


Figure A.10. Average deflections of pavement sections at UCF-CATT.

Cross et al. (1996) reported the experience of the Kansas Department of Transportation (KDOT) on Demonstration Project 47, "Recycling Portland Cement Concrete Pavement." Four test sections were constructed consisting of two control sections, one section of recycled cement-treated base (CTB), and one section using RCA on the concrete and CTB. The performance of these test sections was monitored over a 10-year period for faulting, roughness, load transfer, and friction. Pavement performance data from the same area and similar traffic and age were obtained from KDOT's pavement condition survey database and compared to the recycled section. Cross et al. concluded that the use of RCA or virgin aggregates on CTB resulted in similar pavement performance. The section with recycled base and surface presented similar joint distresses but slightly worse performance in terms of smoothness than pavements without RCA.

A.7 RECYCLING EXPERIENCE

This section describes national and international research on recycling of concrete pavements. The major studies performed in the U.S. are described in this section, along with some international research. The objective of this section was to identify and summarize the major and the most innovative studies performed worldwide. The major conclusions of some studies are also presented.

A.7.1 DOMESTIC RESEARCH

FHWA (2004) is currently conducting a research on the best domestic recycling practices in the U.S. One of the project objectives is to document the state-of-the-art of the use of RCA and share this information with the State transportation agencies (STAs). Five States (Minnesota, Michigan, Texas, Utah, and Virginia) were selected, and their experience with RCA was reviewed. FHWA is currently documenting each State's experience with the implementation of their RCA program, in addition to their specifications and construction practices.

NCHRP has sponsored several research projects on RCA in pavements, most recently NCHRP 25-09, "Environmental Impact of Construction and Repair Materials on Surface and Ground Waters" (Nelson et al., 2001), NCHRP 4-21, "Appropriate Use of Waste and Recycled Materials in the Transportation Industry" (Chesner et al., 1998), and NCHRP 4-31, "Tests of Recycled Aggregates for Use in Unbound Pavement Layers" (Saeed and Hall, 2004). Simon et al. (2000) discussed the completed or on-going recycling research sponsored by FHWA and NCHRP.

Many DOTs are interested in the use of recycled materials. In addition to the States selected by FHWA (2004) for the recycling program review, other States are actively engaged in promoting recycling, including Florida and Texas. Chini and Monteiro (1999) presented the results of a survey sent to concrete plants in Florida. Out of 200 companies contacted at that time, only 18 recycled PCC. According to Saeed et al. (1995) and Davio (2000), the Texas Department of Transportation (TxDOT) started a program in 1994 to provide incentive for the recycling of road construction material.

Davio (2000) described the most important learning experience of TxDOT in the following seven steps:

1. Designate a point-of-contact
2. Asses the situation
3. Identify competitive recycled materials
4. Formulate a plan
5. Develop a tracking system
6. Create a level playing field
7. Communicate

In September 1999, a U.S. delegation traveled to Europe to learn about their policies, programs, and technique. Holtz and Eighmy (2000) provided some information about this tour, and Schimmoller et al. (2000) published a final report documenting this unique experience in detail. The U.S. delegation had representative from the FHWA, EPA, State DOTs, the American Public Works Association (APWA), the National Asphalt Pavement Association (NAPA), and academia. Five European countries were visited: Sweden, Denmark, Germany, the Netherlands, and France. This tour focused on general highway material recycling, and specific information on the use of RCA for base was not provided.

The RMRC promotes the use of recycled material for highway construction in the U.S. In 2000, two years after it was established, the Center had already funded 10 research projects (Magee, 2000). Currently, the RMRC has completed 7 research projects and has 18 projects underway. A list of all the projects, as well as brief descriptions, can be found at http://www.rmrc.unh.edu/. Two of the current projects at the RMRC are Project 13/14, “Development and Preparation of Specifications for Recycled Materials in Transportation Applications,” and Project 6, “Evaluation of Tests for Recycled Material Aggregates for Use in Unbound Applications.”

Yrjanson (1981) described a concrete recycling project at the Jacksonville International Airport in Florida. The existing 11-in concrete slabs were crushed at a crushing plant after breaking up with drop hammers. The RCA was produced to a top size of 2 inches, separated on the 3/8-inch sieve and stockpiled for use in a subbase (filter) course and econocrete under the new concrete pavement. The RCA produced a lean concrete with a 28-day compressive strength of 1,000 psi, which was within the acceptable limits. As virgin aggregate had to be hauled from a distance of 350 miles, the savings for using the RCA is apparent. Yrjanson (1989) briefly described other airport recycling projects in the U.S. Most of these projects used RCA for cement-treated base, with exception of the Technical Center Airport of the FAA, which used RCA in a granular base. No performance data were provided for any of these projects.

Griffiths and Krstulovich (2002) described the IDOT experience on using recycling materials for highway construction. All recycled material used and not used in highway construction are listed. The annual amount of recycled materials in Illinois is about 1.5 million tons. RCA is among the recycled materials used in the state; the Materials

Integrated System for Test Information and Communication (MISTIC) reported that 321,300 tons of RCA was used in 2001. The IDOT allows the use of RCA in aggregate layers, stabilized base and subbase layers, and granular embankment, as long as they meet the applicable specifications. RCA has also been used in membrane waterproofing and in drainage layers used to protect against erosion.

A.7.2 INTERNATIONAL RESEARCH

Molenaar and Van Niekerk (2002) reported that, since the late 1970s, it is a common practice in the Netherlands to reuse RCA as road base materials. After more than two decades, however, very little information was available on the effects of grading and composition. As a result, they conducted a large research program at the Delft University of Technology to study some factor that affect the behavior of unbound base made from RCA and crushed masonry. The effect of the following influence factors on the mechanical behavior of RCA was investigated:

- Grading
- Composition
- Particle shape
- Degree of compaction
- Curing time

This study was based on numerous triaxial tests. Gradings with a higher percent of fines had a higher cohesion, but the degree of compaction (DOC) had the highest effect on cohesion. The angle of internal friction of tested material was around 40^o, as shown in Figure A.11. DOC also had the highest effect on M_R, whereas grading had the smallest effect. Another conclusion of this study was that DOC, composition, and grading affect resistance to permanent deformation, in that order. The main conclusion of this study was that, among the factors analyzed, DOC had the greatest effect on the mechanical characteristics of unbonded base. This result was important from a practical standpoint because the DOC is much easier to control than factors such as grading and composition. The authors concluded that RCA can be used to construct good-quality road bases.

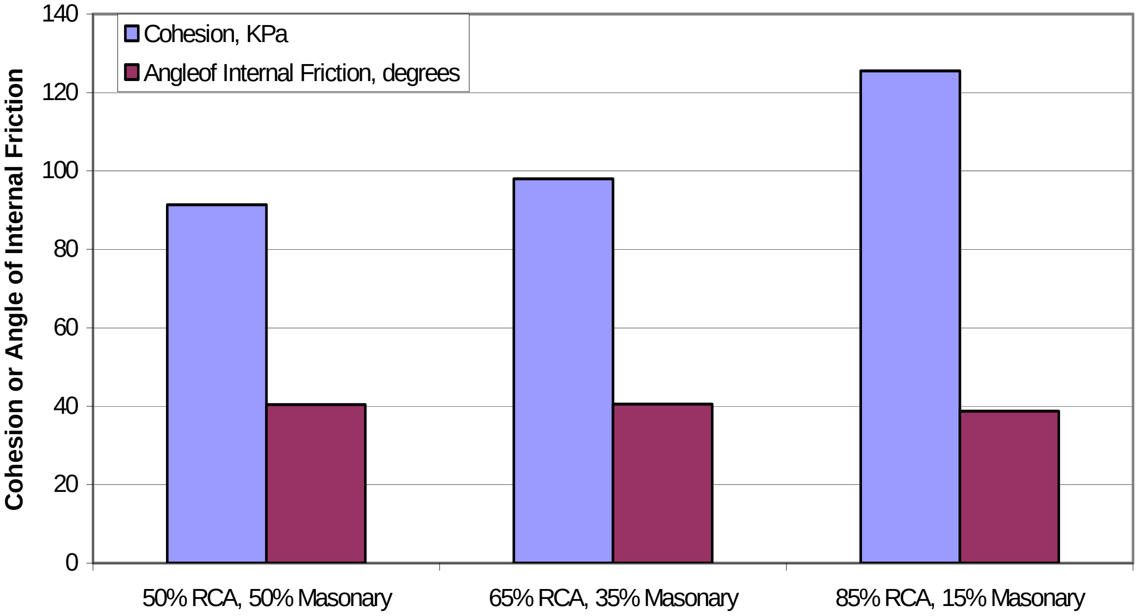


Figure A.11. Change in cohesion and angle of internal friction with composition.

Reid (2000) provided a summary of the European research project ALT-MAT (ALTernative MATerials in road construction), which involved nine organizations from seven countries (United Kingdom, Austria, Denmark, Finland, France, Sweden, and Switzerland). The main objective of this project was to develop test methods to evaluate the use of alternative or recycled materials for base and surfacing of highway pavements. A second objective was to test mechanical and environmental performance of these materials. A number of materials including crushed concrete were investigated. The mechanical tests included the LA and Micro-Deval abrasion tests, and the gyratory compaction and vibratory table tests.

The results of the LA abrasion test, shown in Figure A.12, indicated a linear response for natural aggregates, regardless of their mechanical resistance. Crushed concrete, on the other hand, had a greater material loss at the beginning of the test compared to the end of the test. Results of Micro-Deval tests, shown in Figure A.13, indicated similar trends.

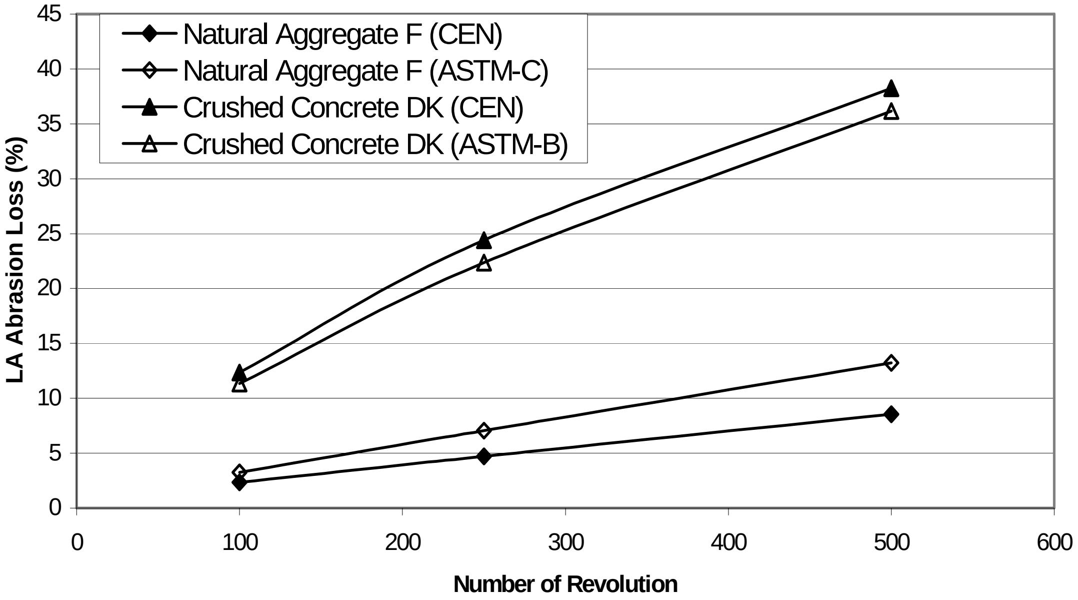


Figure A.12. Comparison of LA abrasion test results for RCA and natural aggregate.

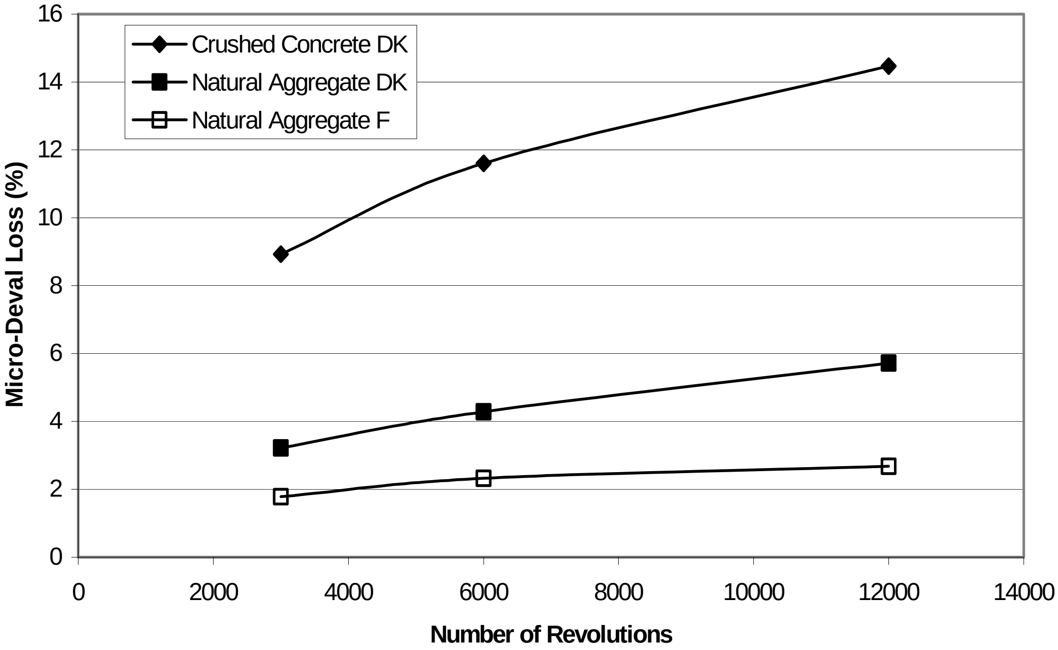


Figure A.13. Comparison of Micro-Deval test results for RCA and natural aggregate.

This project demonstrated that alternative materials can provide performance on par with natural materials. This research also developed a hydrogeological model for assessment of the environmental impact of the use of alternative material on ground water. This model confirmed that such alternative materials do not cause pollution of groundwater. Reid et al. (2001) published the final report summarizing all the research effort and accomplishments.

The University of Nottingham coordinated a project entitled COURAGE (COnstruction with Unbound Road Aggregates in Europe), which was funded by the European Commission. One of the objectives of this project was to analyze the fundamental characteristics and mechanical behavior of unbound granular materials through laboratory and field tests (European Commission, 1999). In addition to crushed natural aggregates, one recycled aggregate was a mix of recycled crushed concrete mixed with asphalt (RCC&A). The results of this research indicated that the optimum moisture content for RCC&A decreased with an increase in the fines content, which is opposite to the behavior of the virgin aggregate (limestone); this comparison is shown in Figure A.14 and Figure A.15.

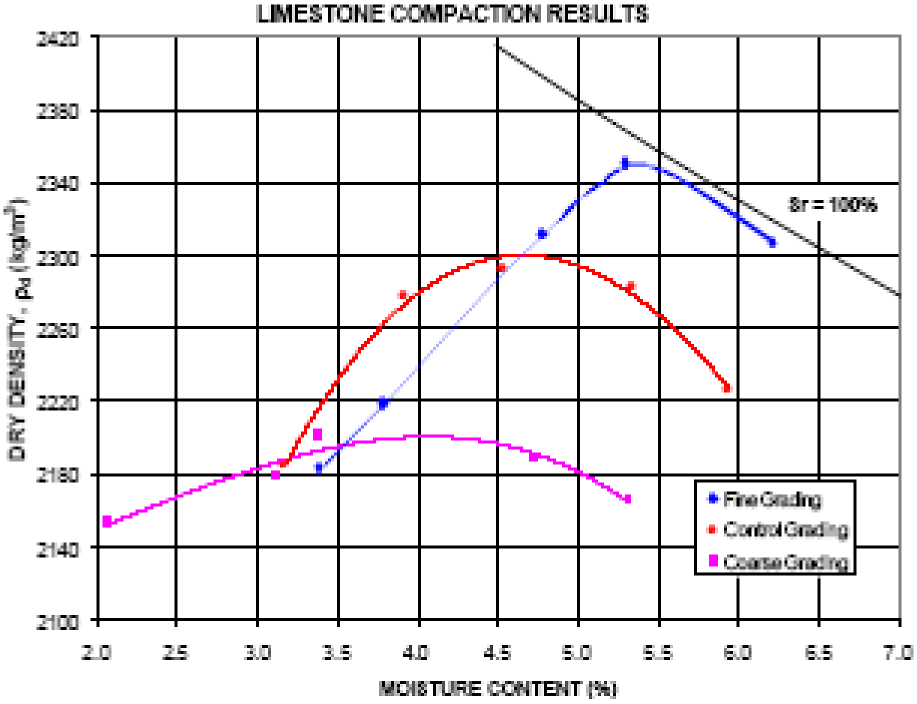


Figure A.14. Compaction curves for limestone material.

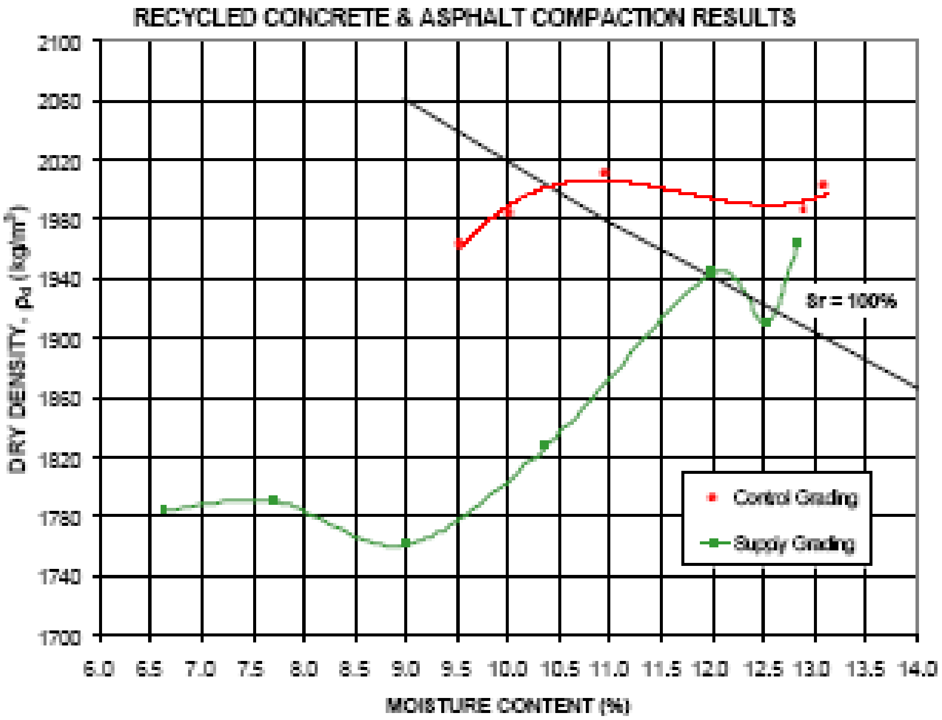


Figure A.15. Compaction curves for RCA.

Nataatmadja et al. (2001) reported an experiment performed in Australia in which the performance of four RCAs was analyzed based on triaxial tests under repeated loading. The original concrete had compressive strength varying from 690 to 75015 MPa (2,175 to 10,880 psi). The following commercial aggregate and RCA (referred to by the PCC strength) were tested:

- AF – commercial aggregate mix of RCA and brick (15 MPa)
- 18.5 MPa RCA
- 49.0 MPa RCA
- 75.0 MPa RCA

Figure A.16 shows the particle size distribution of the tested materials (compacted to Talbot's n of 0.5 for a dense mixture); basic properties of the RCA aggregates are shown in Table A.5.

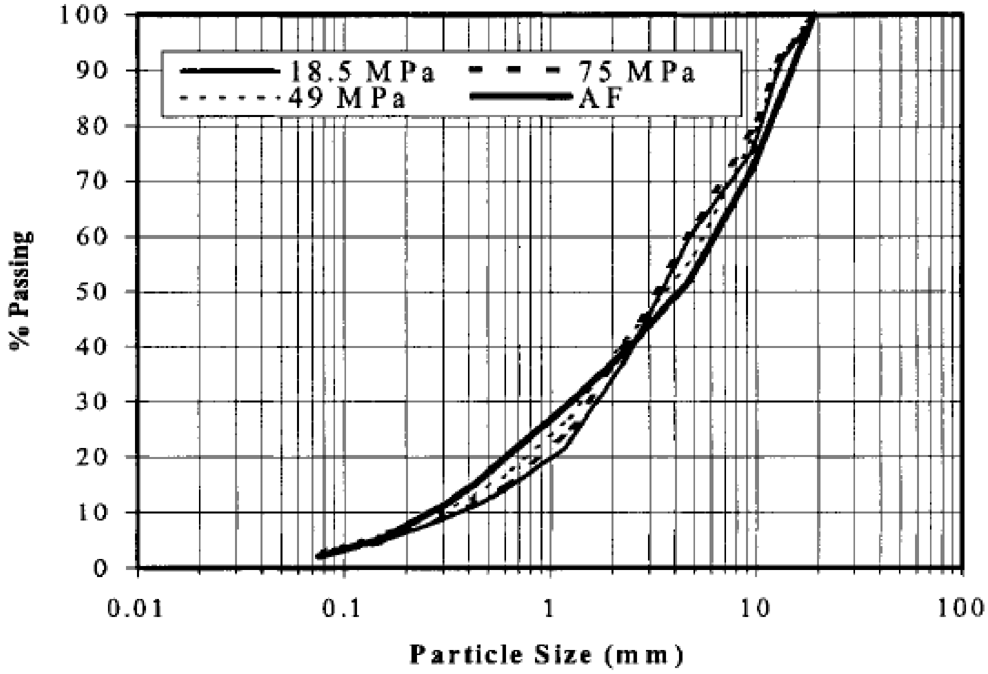


Figure A.16. Sieve analysis results of RCAs evaluated by Nataatmadja et al.

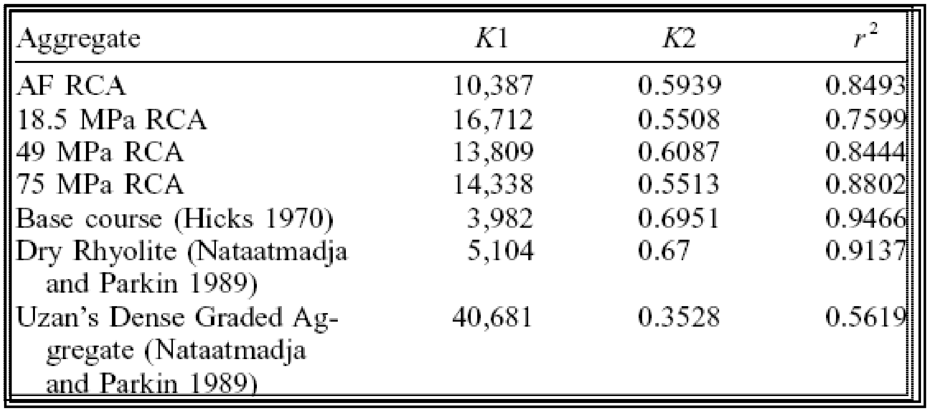
Table A.5. Basic properties of RCAs evaluated by Nataatmadja et al.

Properties	AF	18.5 MPa	45.0 MPa	75.0 MPa
LA Abrasion Loss (B), %	30	22	25	21
LA Abrasion Loss (K), %	27	24	21	24
Aggregate Crushing Value, %	24	23	22	22
10% fines test, kN	149	158	166	187
Flakiness Index	6	12	9	14

Nataatmadja et al. determined that with an increase in the strength of the original PCC, the flakiness of the produced RCA tends to increase. The LA abrasion and aggregate crushing value (ACV) test results indicate the AF aggregate (RCA and brick) to be the least strong. Data in Table 2.5 suggest that the standard tests of LA abrasion and ACV were unable to differentiate between the four aggregates. On the other hand, the 10% fines test, which is a variation of the ACV test, was able to differentiate between the four aggregates. The results of the 10% fines test indicate that the compressive strength of the original PCC is directly related to the hardness of the produced RCA particles.

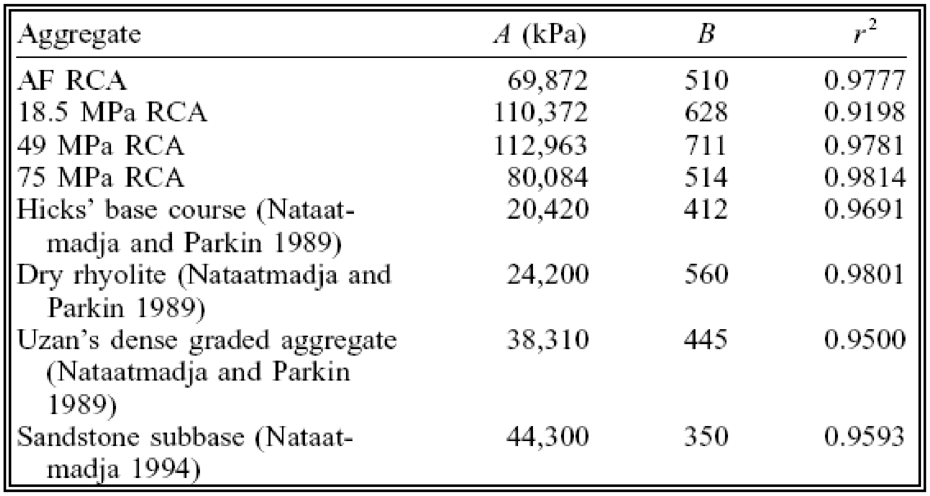
The comparison of RCA with different virgin aggregates in terms of M_R are shown in Table A.6 (K-™ model) and Table A.7 (two-parameter model).

Table A.6. RCA performance using the K-™ model (after Nataatmadja et al.)



Aggregate	$K1$	$K2$	r^2
AF RCA	10,387	0.5939	0.8493
18.5 MPa RCA	16,712	0.5508	0.7599
49 MPa RCA	13,809	0.6087	0.8444
75 MPa RCA	14,338	0.5513	0.8802
Base course (Hicks 1970)	3,982	0.6951	0.9466
Dry Rhyolite (Nataatmadja and Parkin 1989)	5,104	0.67	0.9137
Uzan's Dense Graded Aggregate (Nataatmadja and Parkin 1989)	40,681	0.3528	0.5619

Table A.7. RCA performance using the two-parameter model (Nataatmadja et al.)



Aggregate	A (kPa)	B	r^2
AF RCA	69,872	510	0.9777
18.5 MPa RCA	110,372	628	0.9198
49 MPa RCA	112,963	711	0.9781
75 MPa RCA	80,084	514	0.9814
Hicks' base course (Nataatmadja and Parkin 1989)	20,420	412	0.9691
Dry rhyolite (Nataatmadja and Parkin 1989)	24,200	560	0.9801
Uzan's dense graded aggregate (Nataatmadja and Parkin 1989)	38,310	445	0.9500
Sandstone subbase (Nataatmadja 1994)	44,300	350	0.9593

Nataatmadja et al. (2001) also suggested that, depending upon the quality of the RCA, significant degrading of the particles can occur under field conditions. Flakiness index appears to the most significant factor contributing to this phenomenon, as shown in Figure A.17. They recommended keeping the flakiness of RCA below 10 percent to maximize the M_R and to minimize permanent deformation.

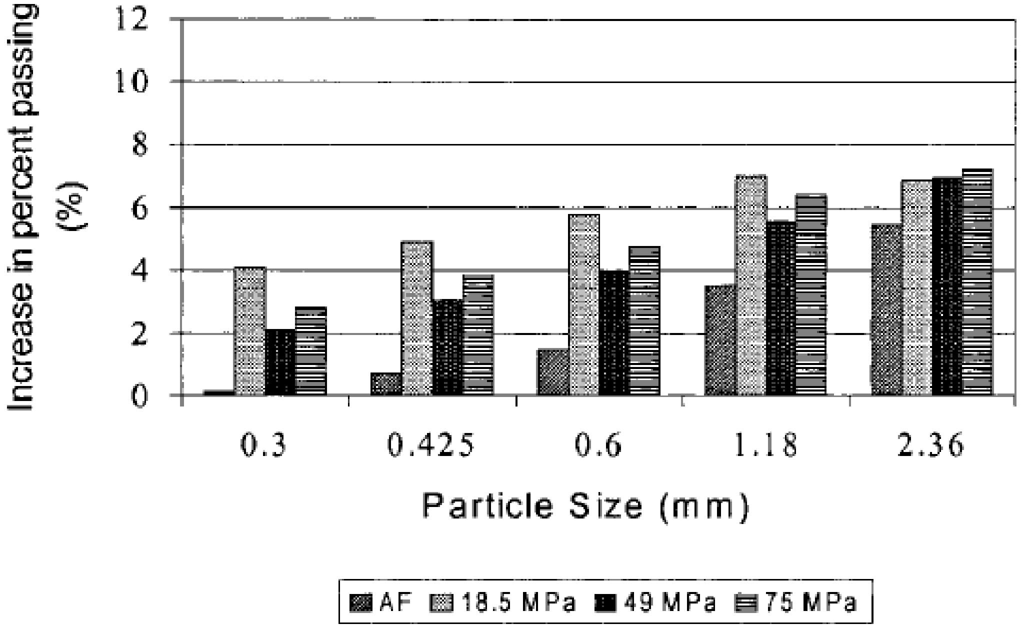


Figure A.17. Increase in percent passing after 50,000 cycles of repeated loading.

Research conducted by Nataatmadja and Tan (2001) can be summarized as follows:

- M_R is affected by the original concrete compressive strength, the soft material in the RCA, and the flakiness index of the RCA
- The degrading of the aggregate matrix was found to be affected by the crushing of softer and flaky materials
- Performance of RCA is comparable to that of virgin aggregate base materials
- Well-graded RCA may even result higher M_R under low deviator stress

Park (2003) presented a study performed in South Korea to investigate the performance of two virgin aggregates (crushed stone and gravel) used as concrete pavement base compared to RCA in dry and wet conditions. The following performance-related parameters were evaluated: compactibility, stability, shear resistance, and particle breakage of the RCA. The RCA was obtained from a pavement replacement project and was crushed to meet the Indiana DOT requirements for No. 53 compacted aggregate, as shown in Figure A.18. The physical properties of RCA-A (relatively coarse), RCA-B (relatively fine), limestone crushed stone aggregate (CSA), and gravel are shown in Table A.8. The RCA was visually determined to be rough and composed of 70 to 90 percent natural aggregate. Figure A.19 compares the moisture-density relationships for RCA and CSA. It was found that RCA, CSA and gravel have similar compactibility; the moisture-density relationship of RCA from this study is sharp contrast to results obtained by others (especially, Rathje et al. [2002] and Nattatmadja et al. [2001]) that tend to suggest that RCA moisture-density relationship does not resemble that of virgin aggregate. RCA-A and RCA-B were combined for further physical and mechanical tests.

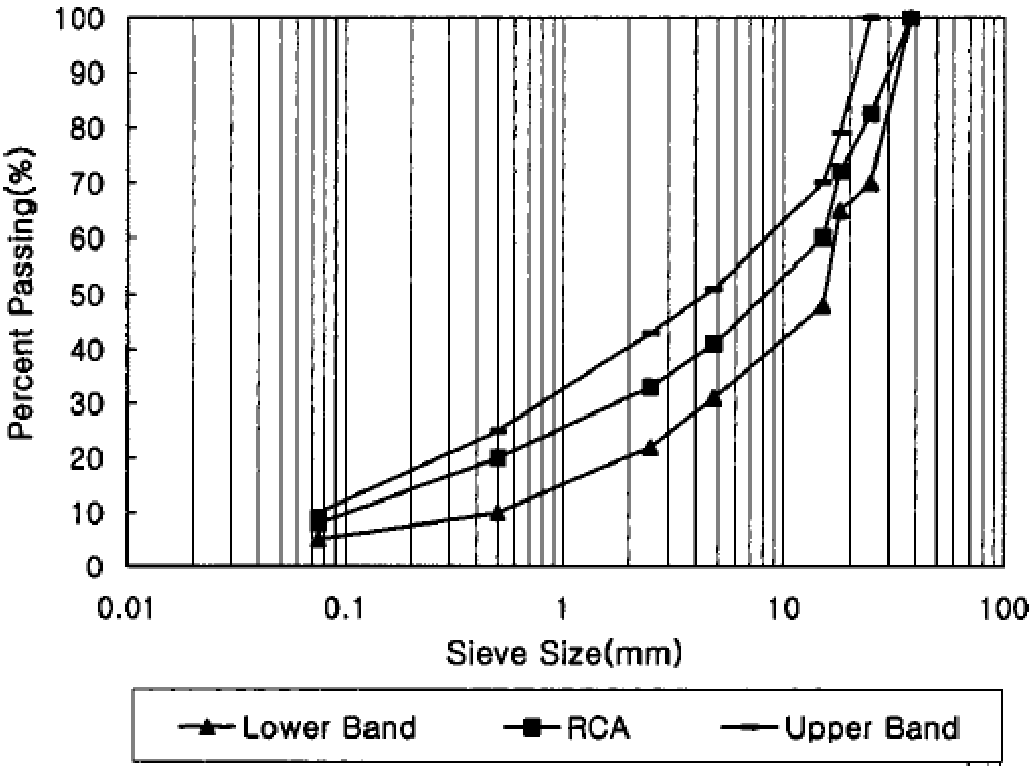


Figure A.18. Grading of RCA meeting the No. 53 aggregate requirements (after Park).

Table A.8. Physical properties of RCA and virgin aggregate (after Park).

Tests	RCA-A	RCA-B	Crushed Stone	Gravel
Bulk SG (fine)	2.527	2.539	2.623	2.642
Water absorption (%)	1.43	1.77	1.8	1.3
LA Abrasion loss (%)	32.9	43.6	31.2	N/A

A significant finding was that the energy and effort required to compact RCA is very similar to CSA and gravel aggregates (Park 2003). This conclusion was based on comparison of Corps of Engineers Gyratory Compaction Index for each aggregate, as shown in Figure A.20.

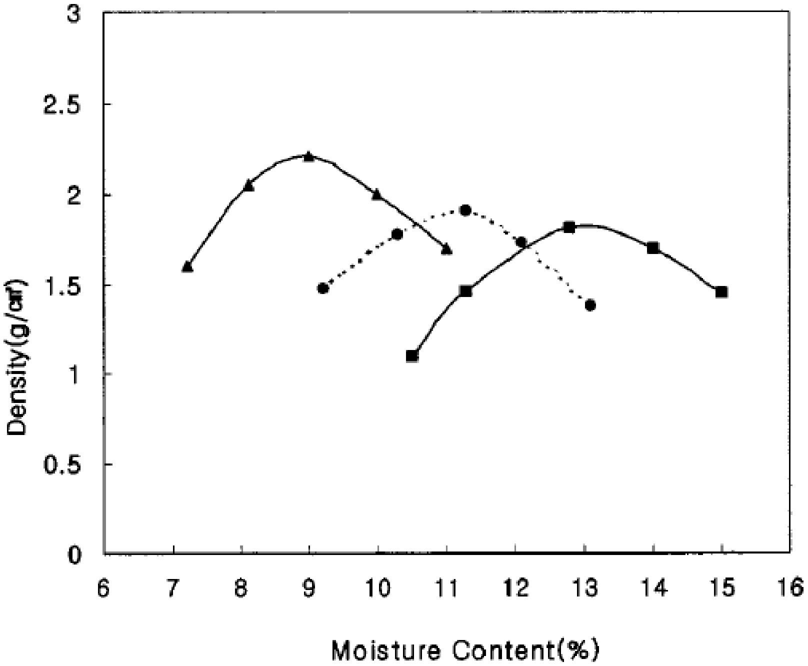


Figure A.19. Density and moisture relationship for RCA and CSA.

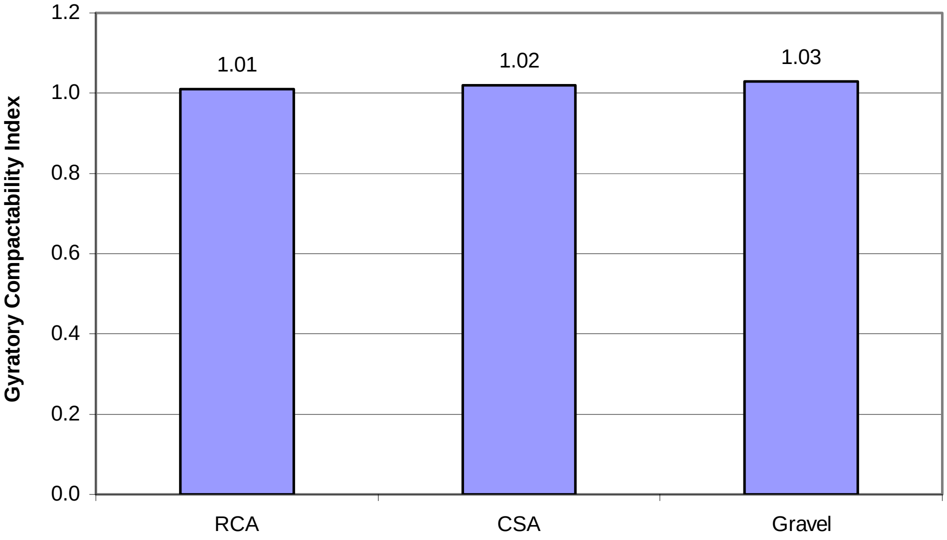


Figure A.20. Comparison of compactive effort using the gyratory compactability index.

The shear resistance of the materials was studied using the gyratory shear factor using the Corps of Engineers Gyratory Test Machine (GTM). The stability and shear resistance of dry RCA were higher than gravel and similar or better than crushed stone, as well as higher than wet RCA, as shown in Figure A.21. The GTM can also be used to study breakage of base/subbase aggregates with continuing service time (increase in traffic repetitions). A progressive reduction in the elasto-plastic index with cycles of GTM revolutions accompanies aggregate deterioration caused by aggregate breakdown. The higher the internal friction, the closer the elasto-plastic index approaches unity. The variation of elasto-plastic index with increasing the GTM revolutions is shown in Figure A.22. RCA is generally not as stable as the CSA. However, above 200 revolutions, its elasto-plastic index decreases significantly. This could be indicative of long-term field performance problems, as well as inappropriate testing.

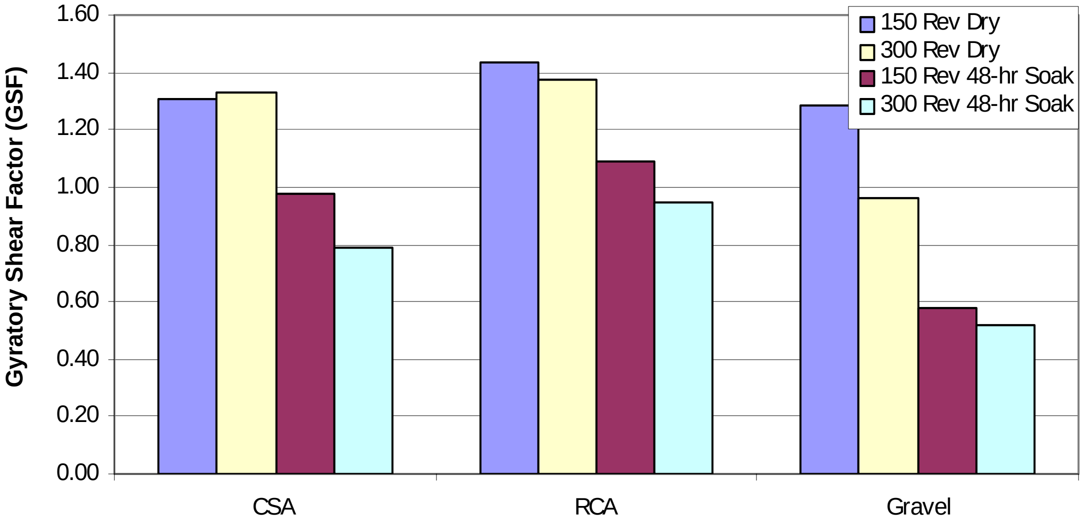


Figure A.21. Comparison of gyratory shear factor by Park (2003).

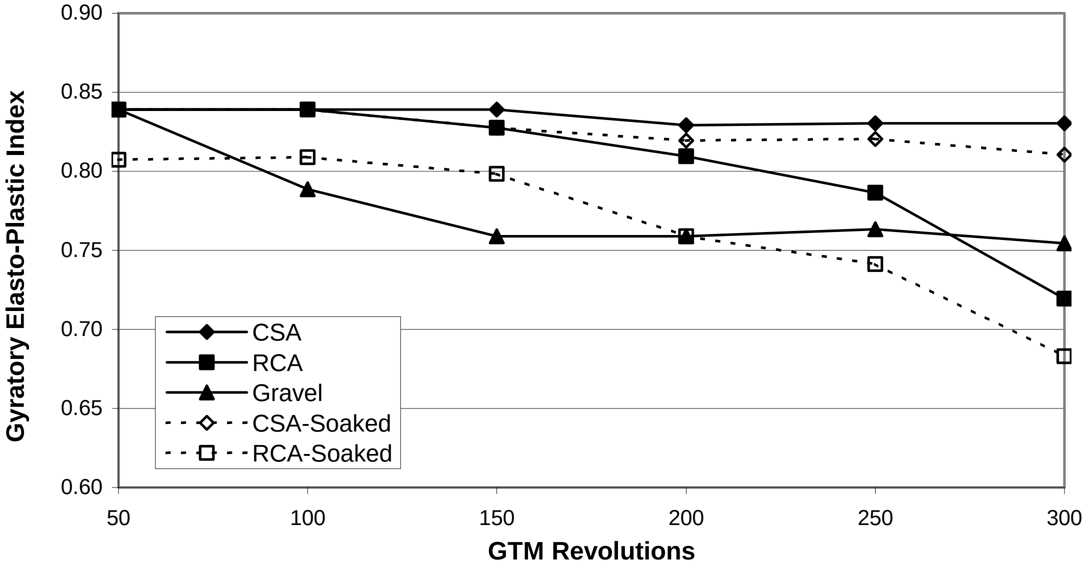


Figure A.22. Evaluation of field performance potential using the GTM.

Field tests were also performed to compare mechanical properties of RCA base with virgin CSA base. This analysis was based on deflections measured in the field using an FWD. It was found that deflections of RCA sections are similar to those of CSA sections. As a result, both produce a similar radius of relative stiffness (Figure A.23) and modulus of subgrade reaction, assuming the same concrete slab system. In conclusion, RCA can substitute for crushed stone as base material in a concrete pavement system successfully.

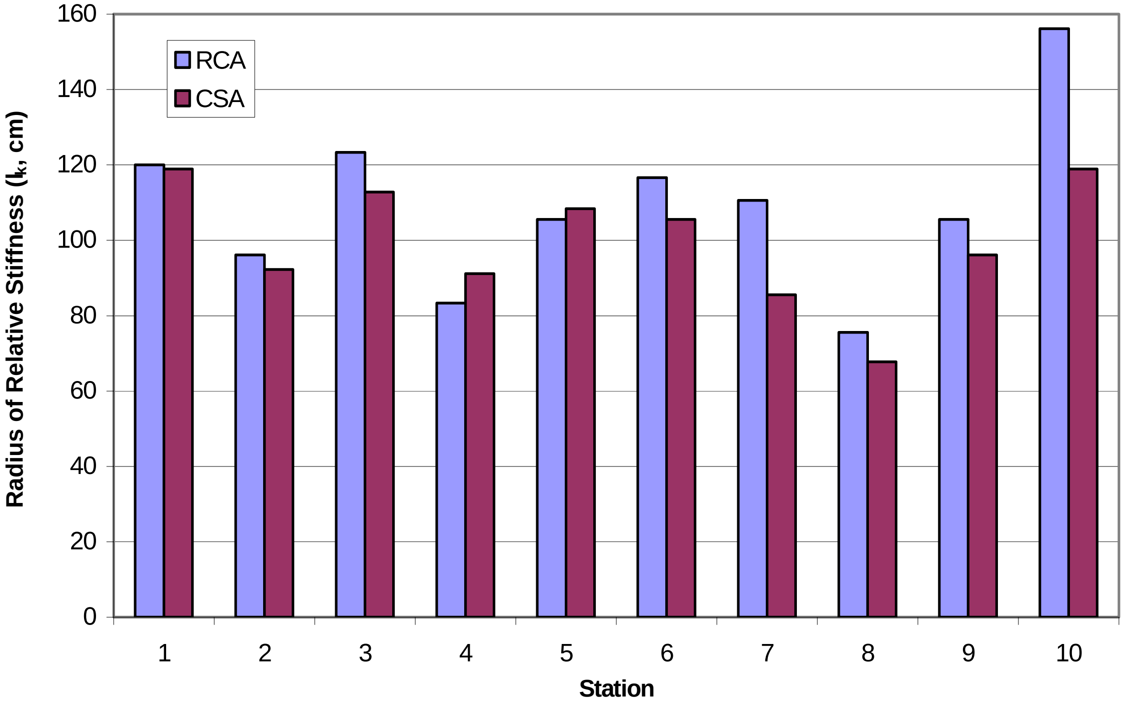


Figure A.23. Comparison of radius of relative stiffness (after Park, 2003).

A.8 RCA RECYCLING CONCERNS

Prior to the use of RCA in pavement layers, there are some performance-related and environmental concerns that should be studied and addressed as necessary. The main environmental concern of using RCA is the possibility of environmental contamination due to the leaching of hazardous components. The performance-related issues are related to the effect of calcium carbonate precipitate and fines on the drainage system, as well as possible expansion caused by sulfate attack. On those concretes with existing ASR that are recycled, ASR is not likely to continue on unbound RCA individual particles. The end result is of no significance relative to the stability of a base.

A.8.1 ENVIRONMENTAL IMPACT

RCA environmental concerns are perceived as being less pronounced than those of recycled asphalt pavement (RAP) because of the concern over the asphalt binder. Thus, few environmental tests on RCA are reported in the literature. However, this does not suggest that RCA poses a lower risk to the environment than the other recycled materials.

Some agencies have limited the use of RCA as aggregate in unbound pavement layers because of the higher pH levels measured for RCA. However, the point of sampling is very critical in determining whether the pH levels exceed most regulatory limits. Nevertheless, the use of RCA in pavement base may cause an increase in the pH of effluent groundwater, especially when it is subjected to intermittent wetting and drying or even constant flow. There is potential that harmful contaminants, although extremely unlikely to be present, can leach into the groundwater (Saeed and Hudson, 1997). As a result, the evaluation of leaching potential of RCA base should focus on leaching conditions during intermittent infiltration (wetting and drying and oxygen and carbon dioxide uptake). This will only be an issue if the original concrete was used to stabilize a hazardous waste, which is not likely.

Nelson et al. (2001) studied the potential for leaching of chemical constituents from highway construction materials, including PCC. They developed a methodology to predict the transport of toxic constituents of highway construction materials and to evaluate their impact on surface and ground water toxicity. This study, however, did not specifically address the effect of recycled materials compared to virgin materials.

Snyder (1996) evaluated the environmental impact of the relatively high pH of the effluent derived from RCA layers based on existing studies. This evaluation was not conclusive but indicated that although RCA base effluent were initially very alkaline, it was almost never reported to be enough to be considered hazardous to the environment. In addition, since the effluent is diluted within a short distance from the drain outlet, the environmental impact is confined to a small area.

Snyder (1996) reported some areas of vegetation kill (Figure A.24) near drain outlets; however, he also observed frogs and insects living in the water around the drains indicating the water to be non-toxic.

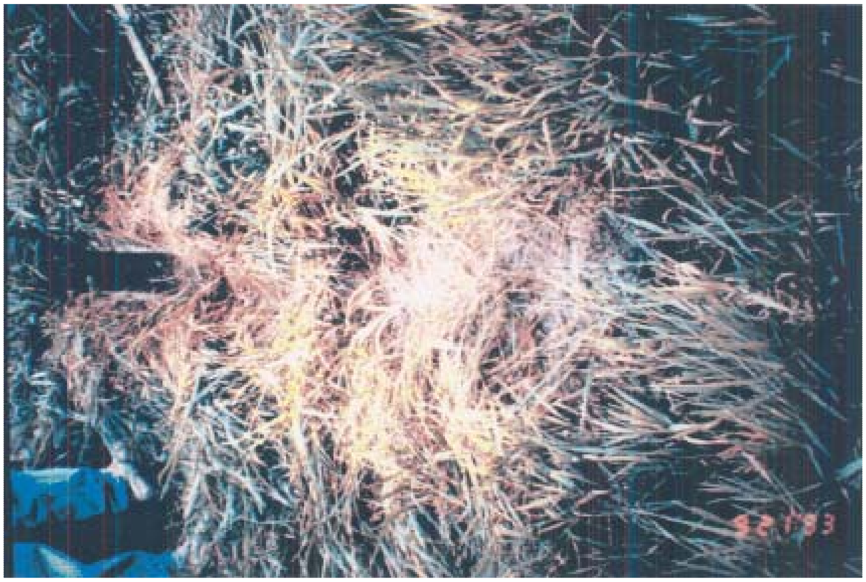


Figure A.24. Vegetation kill on I-90 near Austin, MN (Snyder, 1996).

Kuo et al. (2001) analyzed the presence of heavy metals (cadmium, chromium, aluminum, nickel, iron, zinc, copper, and lead) in RCA in Florida. It was found that only lead exceeded the EPA-set limit of 5 parts per million (ppm), as shown in Table A.9. In this case, the source of lead was household paint, which is not a problem nowadays for RCA from highway pavements. In contrast, this could be a surface problem for an existing pavement prior to recycling, however, only a small portion of the RCA would even remotely be an issue.

Table A.9. Heavy metal concentrations (ppm) in RCA in Florida (Kuo et al., 2001).

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
District 1								
December	ND	ND	ND	5200	ND	6200	140	ND
January	ND	ND	ND	3500	ND	18000	39	ND
February	ND	ND	ND	5100	ND	5400	26	ND
March	ND	ND	ND	3700	ND	4100	16	ND
April	ND	ND	ND	4800	ND	6000	29	ND
May	ND	ND	ND	4200	ND	4400	ND	ND
District 2								
December	ND	ND	ND	4408	ND	4200	99	ND
January	ND	ND	ND	4000	ND	13000	ND	ND
February	ND	ND	ND	2800	ND	3100	ND	ND
March	ND	ND	ND	4800	ND	4000	ND	ND
April	ND	ND	ND	4400	ND	4833	ND	ND
May	2	ND	13	3973	3	3980	47	22
District 4								
July	12*	ND	16	2252	4	2525	84	15
August	ND	ND	ND	4600	ND	4600	78	ND
September	ND	ND	ND	4500	ND	4600	380	ND
* Lead concentration in excess of EPA limit of 5 ppm.								
District 5								
December	ND	ND	ND	5400	ND	7300	120	ND
January	ND	ND	ND	3600	ND	4600	25	ND
February	ND	ND	ND	4600	ND	5200	33	ND
March	ND	ND	ND	4600	ND	5300	26	ND
District 6								
July	ND	ND	16	5501	12	4103	80	16

Note: Metal concentrations in excess of EPA limits are indicated by an * and described as such.
ND: Not detectable.

Cho and Yeo (2003) found that RCA did not release any metallic ions in alkaline conditions, but released them when placed in acidic solutions. The paste structure was destroyed and some ions, as expected, were released; test results are shown in Figure A.25. The RCA Greek specification limits the amount of foreign, organic, and sulfate ingredients to 1.0, 0.5, and 1.0 percent, respectively (Oikonomou, 2004).

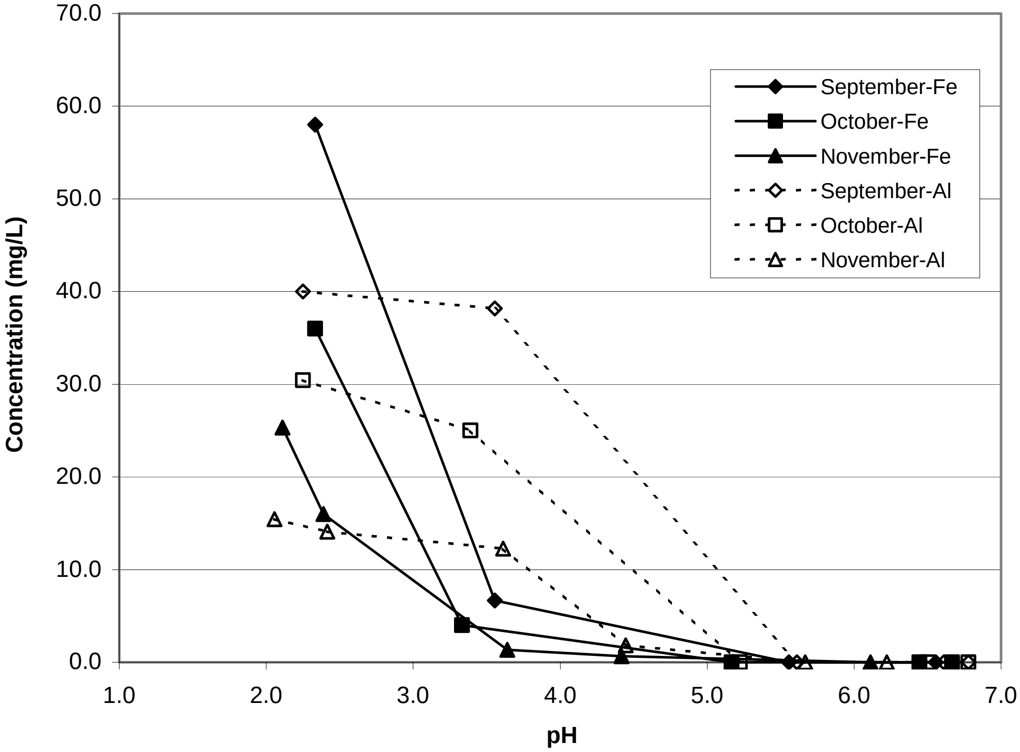


Figure A.25. Leaching evaluation of RCA (after Cho et al., 2003).

A.8.2 DRAINAGE PERFORMANCE OF PAVEMENT BASES CONTAINING RCA

Snyder (1996) reviewed six field and five laboratory studies addressing performance and environmental concerns regarding the use RCA for pavement. The main objective of this review was to evaluate the effect of calcium carbonate precipitate and other fines derived from RCA drainage performance. Snyder concluded that RCA had sufficient calcium hydroxideto be leached and precipitated in the presence of atmospheric carbon dioxide to form calcium carbonate. In addition, all RCAs were able to produce various amounts of precipitate depending on the amount of freshly exposed surface of cement mortar. Snyder concluded that washing RCA to reduce the amount of dust and other fines produced during the crushing process or blending RCA with virgin aggregates in selective portions would minimize calcium carbonate precipitate potential but would not eliminate it. According to Snyder (1996), Minnesota DOT studies indicated that the accumulation of precipitate and insoluble residues can significantly reduce the permittivity of typical filter fabrics but is not enough to affect the performance of pipe drains. As a result, Snyder suggested using filter fabrics with initial permittivity high enough to filter precipitate and other fines without affecting significantly the drainage system. Snyder suggested that the use of RCA fines passing in the No.4 sieve should not be used on layers connected to drainage structures, including drainage layers. Snyder recommended to place the filter fabric so the flow is parallel to its surface and as such can never clog.

Snyder (1996) endorsed the Michigan DOT suggestion of using calcium ion concentration tests to estimate the precipitate potential of RCA, although other methods were being evaluated including the use of pH-based tests. Snyder believed that the calcium ion concentration test better represented the precipitate mechanisms, but he recognized the need for a criterion to accept or reject tested samples.

Dollimore et al. (2000) used thermal analysis and X-ray powder diffraction (XRD) data to identify the components of concrete pavement with RCA. Dollimore et al. showed that it is possible to identify the percentage of portlandite, dolomite, and calcite through thermogravimetric (TG-DTG) analysis. The conclusions of this study focused on the secondary precipitation of calcite in structures containing RCA. This secondary calcite can affect the tendency of a structure to drain water. Concrete with RCA contains finer material and, consequently, more surface area is available for the reactions that result in calcite dissolution from the RCA and secondary precipitation. Dollimore et al. concluded that the calcium content from carbonate components in the aggregates and the in the cement paste seemed to affect the calcite precipitation the most, but that the calcium derived from the small amount of portlandite remaining in the cement paste would not significantly affect the amount of secondary calcite precipitation.

A.8.3 SULFATE ATTACK

Sulfate attack occurs when a chemical reaction between sulfate and calcium aluminate hydrate in the presence of water occurs resulting in ettringite, which has at least double the volume of the original constituents (Rollings and Rollings, 2003). Sulfate-resistant cements (Types II or V) are usually used to minimize the possibility of such attack. Protection against sulfate attacks, however, is not guaranteed when sulfate-resistant cement is used. According to Rollings et al. (1999), there are two forms of sulfate attack. In type I, the conventional sulfate attack, the calcium and alumina originate from portland-cement hydration, whereas in type II, the clay-based attack, the calcium originates from portland-cement hydration but the alumina comes from the clay minerals in the soil. As a result, sulfate attack type II may occur even sulfate-resistant cement is used.

According to Ansari et al. (2000), one of the deleterious effects of recycled concrete is the detrimental expansive reaction of the gypsum in the concrete rubble with the cement matrix because of the external introduction of sulfate ions. In addition, the chlorides from deicing salts are considered deleterious because most SHA allow 5% impurities which commonly contain sulfates. They believe these contaminants do not impose risk since they can be removed using some techniques (washing and density separation).

Rathje et al. (2002) performed durability tests indicating that expansion after compaction seems to be a problem only when RCA contains significant amounts of sulfates. They tested compacted crushed concrete in six molds for expansion. These samples were prepared from prisms that had previously experienced sulfate attack; the results are shown in Figure A.26. Samples 1 through 3, which were stored in water, showed an average expansion of 3.70 percent after 69 days. Samples 4 through 6, stored in a 5 percent sulfate solution, showed an average expansion of 2.85 percent. The results indicated that RCA from PCC that had previously experienced sulfate attack would continue to expand after crushing and compaction when exposed to a very strong sulfate environment. They believed that the amount of sulfate in the field, however, was not expected to cause significant expansion.

Tests conducted by Rathje et al. (2002) on commercially available RCA also showed similar results when exposed to a 5 percent sulfate solution (see Figure A.27) as would be expected for any Type I, III, or IV cement. In this case, the expansion limit of 0.1 percent was exceeded after 57 days. However, they noted that exposure to a 5 percent sulfate solution is very aggressive, and this concentration is almost impossible to achieve in field conditions.

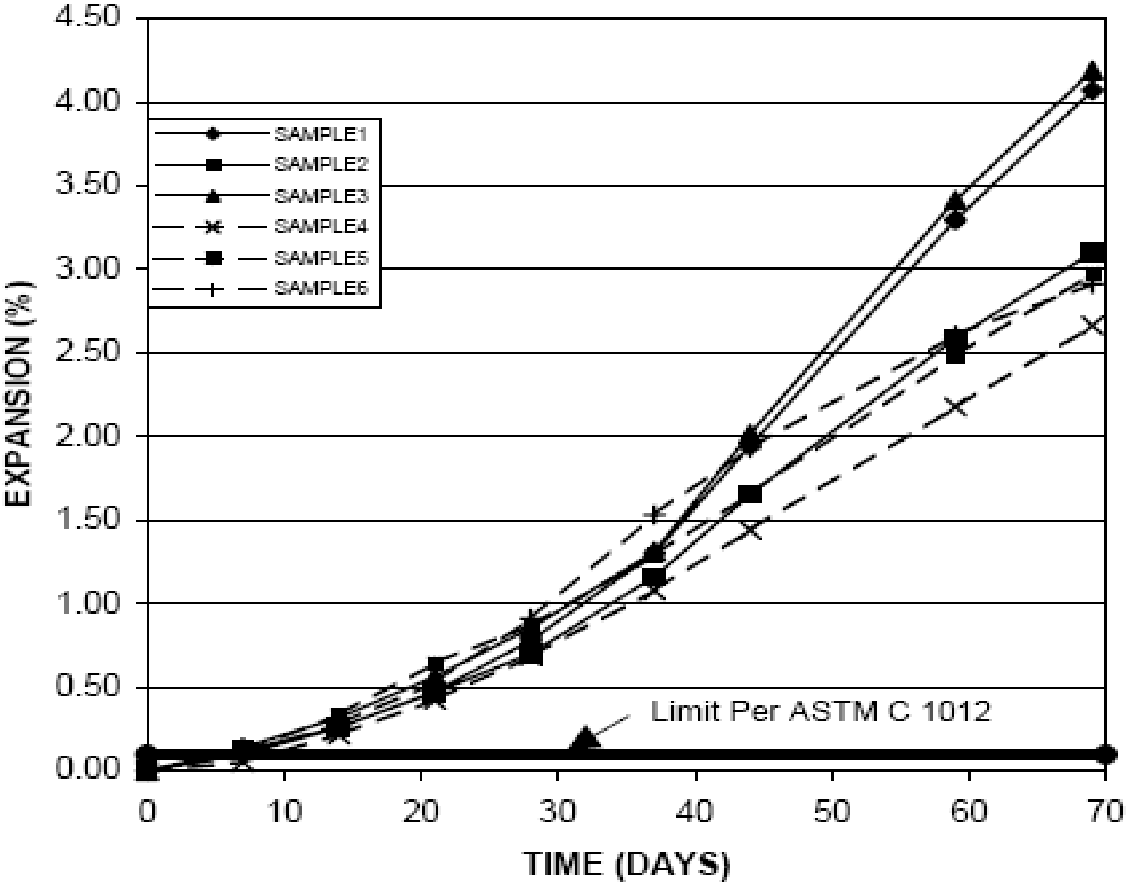


Figure A.26. RCA expansion due to sulfate attack (Rathje et al., 2002).

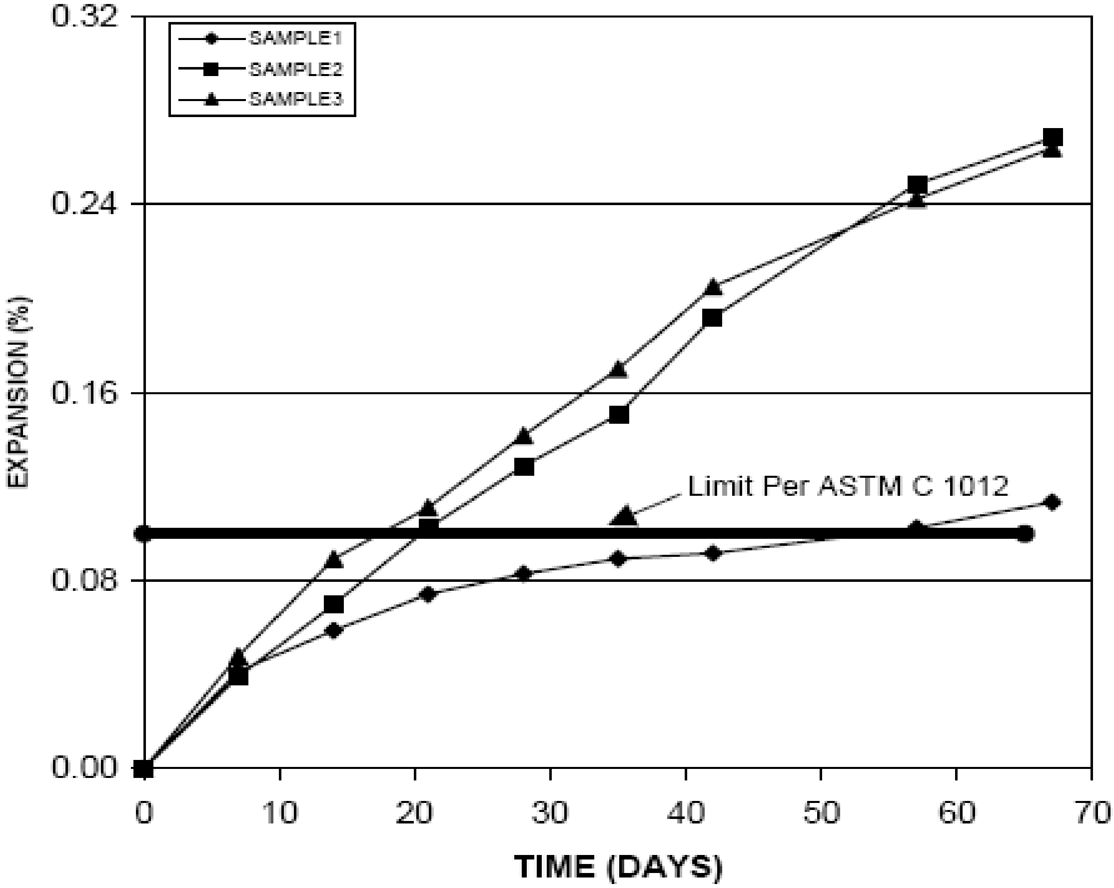


Figure A.27. Expansion of commercial RCA due to sulfate attack (Rathje et al., 2002).

Rollings and Rollings (2003) presented a review of the Corps of Engineers laboratory research on sulfate attack on lime- and cement-stabilized bases. They presented six study cases of actual roads, airfields, and port pavement failures caused by sulfate attack on stabilized materials. One of these cases, the German Air Force Phase 1 (GAF1) in New Mexico, used RCA as unbounded base and fill throughout the GAF1 project. The RCA originated from a concrete pavement with structural problems and no indication of sulfate attack or any durability problems; the sieve analysis results of RCA used in the base course construction are shown in Figure A.28. As water table was high and soil sulfate exposure is very high in New Mexico, all concrete structure near the ground use sulfate-resistant cement Type V. In addition, chemical tests indicated the RCA was sulfate resistant. Shortly after construction the heaving began. Three inspections indicated that heaving was becoming more severe and widespread over time. The elevation differences between the areas with and without RCA layers became apparent. It was reported that upheaval occurred in a variety of structures founded on RCA layers including concrete pavement, asphalt pavement, foundation slabs and sidewalks. There were cases where the upheaval was in excess of 3 in., as shown in Figure A.29. Rollings et al. (2003) reported the detailed investigation of this case suggesting the following three possible reasons for this sulfate attack on a sulfate-resistant unbonded RCA layer: severe exposure conditions due to a much higher permeability, soil contamination during construction and formation of thaumasite, which reacts with the silicate phase and not the aluminate phase of the RCA. As a result, sulfate attack may occur on unbound RCA layer even if the conditions for such attack do not seem appropriate. Sulfate attack should certainly be a concern when considering the use of RCA for unbound pavement layers in addition to layers stabilized with cement or lime.

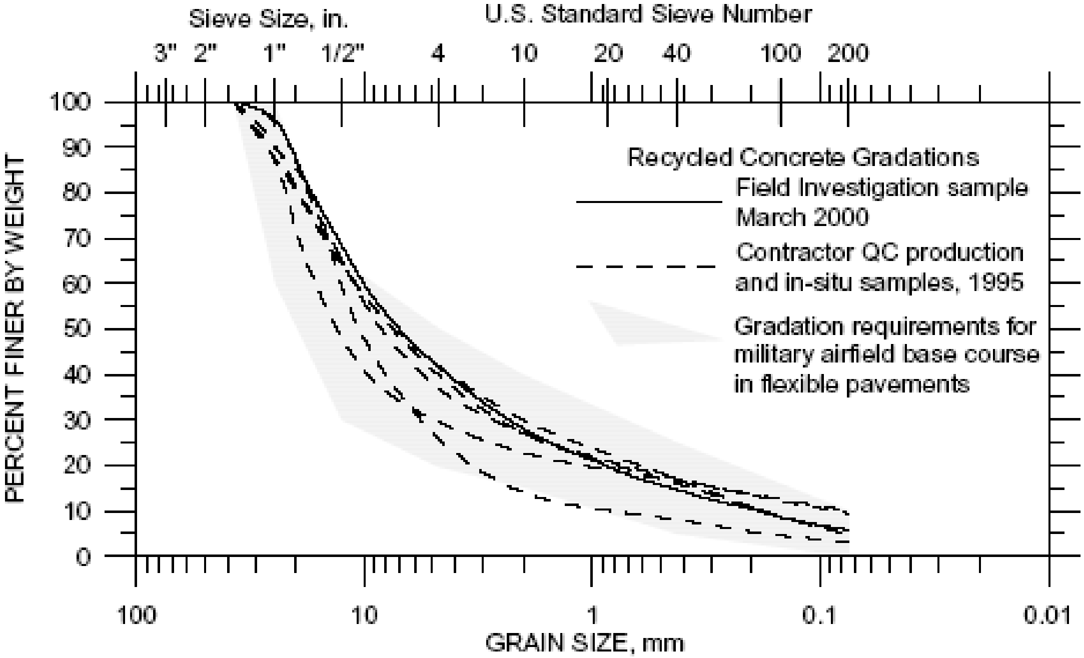


Figure A.28. Grading of RCA used at GAF1 (Rollings et al., 2003).

Figure A.29. Example of sulfate attack heaving on RCA base (Rollings et al., 2003).

A.8.4 ALKALI-SILICA REACTIVITY

ASR is a chemical reaction between certain forms of silicate minerals in the aggregate and the alkalis in the pore water in PCC. This reaction forms a gel around and within the aggregate particle. This gel absorbs water and causes internal swelling within PCC. The end result is a volume increase in PCC with resultant expansion (shoving), damage to adjacent structures, cracking, spalling, and popouts. ASR has been a recognized phenomenon since the 1940s, and countermeasures mandating the use of low-alkali cements with reactive aggregates were widely prescribed. Another chemical reaction between the alkalis and certain dolomitic aggregates, alkali-carbonate reaction (ACR), also occurs. It is relatively rare and is more poorly understood. It will not be addressed further other than to say PCC undergoing ACR should not be considered for recycling until more is understood about the process.

PCC is inherently alkaline. The effects of higher energy costs and emission requirements have combined to encourage manufacturing changes that make modern portland cements much more alkaline than in the past. In addition, modern PCC routinely use more admixtures and supplementary cementing materials that are potential sources of additional alkalis than in the past. The increasing alkalinity of modern cements, combined with trends such as decreasing availability of aggregates, reduced government testing of materials, and discovery that certain modern deicing chemicals can greatly exacerbate the ASR reaction have resulted in a significant increase in the number of ASR-reacting concrete pavements.

ASR is a complex subject beyond the scope of this study, and it is the topic of extensive research, including several ongoing projects by the IPRF. However, because we now have a considerable quantity of unsatisfactory ASR-reacting PCC, it would be an economical boon if we could safely recycle these reacting PCC into aggregate for base, subbase, fill, or drainage layers.

The ASR reaction in PCC will continue as long as alkalis, reactive minerals, and water are present. Once any of these are consumed, the reaction should end, and the material should then be stable. At present, we do not have the technical understanding to predict reliably when the alkali-silica reaction will end or even ascertain for a specific PCC if it has ended without detailed laboratory evaluation and testing. If the ASR-reacting PCC is recycled, it will be crushed to a grading appropriate for its use and will be used under a pavement surfacing.

If the ASR continues, gel will continue to form and imbibe water, causing a slight volume increase. This is occurring at an aggregate particle level so that a particle of RCA contains one or more reacting fine or coarse aggregate particles within a cementitious matrix that may contain other non-reacting aggregate particles. Hence, the ASR-induced volume change that occurs is within the individual RCA particles. This may lead to several consequences:

1. Expansion of the RCA layer. The individual expanding reacting RCA particles work in concert to cause the recycled layer to heave vertically and expand laterally, much as with conventional reacting PCC. The increased pore space of the RCA layer compared to conventional PCC will provide excess volume within the RCA that may negate this volume expansion. This will depend on the grading used (e.g., a dense-graded base course grading versus an open-graded drainage layer) and the amount of reaction to be accommodated (e.g., some aggregates react very vigorously and are a major problem while others have slow, limited reactions and are more a nuisance than a real problem). In addition, there is some level of confinement provided by the overlying pavement and adjacent structures or fill that must be overcome before vertical or lateral distortions can be overcome. Nevertheless, highly reactive PCC has been known to expand in terms of several feet, buckle slabs, damage building columns and foundations, and crack reinforced concrete trenches. Hence, one should not underestimate the forces ASR-reacting PCC can potentially develop. There are certainly some ASR-reacting concretes that could be safely recycled for specific applications without adverse volume changes in the final structure. But there are also likely highly reactive ASR-reacting concretes that may cause volume change problems. We simply do not have adequate criteria at present to separate one from the other.

2. Deterioration of RCA particles. As the individual RCA particles undergo internal volume increases, RCA particles may break into smaller particles. The end result would be a sandier and siltier grading in the RCA layer over time. This could adversely affect RCA layer strength values (especially under wet conditions if

fines increase), decrease permeability, or lead to pumping. Much probably depends on the nature of the specific reaction, the grading, and what is reacting (fine or coarse particles). Some ASR-reacting concretes could probably be safely recycled, but some may cause significant problems.

Carbon dioxide in the atmosphere reacts with cementitious compounds in PCC to form calcium carbonate in a process known as carbonation. This impacts a number of PCC properties, but of significance to ASR, it can decrease the pH of the PCC from about 12 to about 8. This reduction in alkalinity inhibits the continuation of the ASR process in the zone of carbonation. Normally, carbonation is a very slow process, taking years or decades in conventional PCC. However, the more permeable nature of RCA in pavement structures may allow carbonation processes to mitigate some adverse ASR effects.

Pozzolans, ground granulated blast-furnace slag, silica fume, and lithium admixtures have been used to mitigate ASR in new concrete mixtures. It may be feasible to do some mitigation using these or other technologies with ASR-reacting RCA but such would require further research.

Abou-Zeid et al. (2004) found that RCA had higher reaction to alkali-silica than conventional concrete. Rathje et al. (2002) observed minor expansion on RCA prone to develop ASR when soaked in water. They prepared a total of 33 prisms for ASR testing. Prisms 1 through 18 were moist cured for one day before being subjected to the ASTM C 1293 accelerated ASR prism expansion test at an elevated temperature of 140 ºF. This exposed these prisms to expansion levels above the 0.04% expansion limit set in the ASTM standard. These were then crushed to produce RCA to represent RCA that had undergone extensive ASR attack. Prisms 19 through 33 were moist cured at 23ºC until the accelerated expansion test on the first set of ASR prisms was completed; RCA produced from these prisms represented concrete that had not been exposed to ASR. The expansion results of both sets of prisms are shown in Figure A.30.

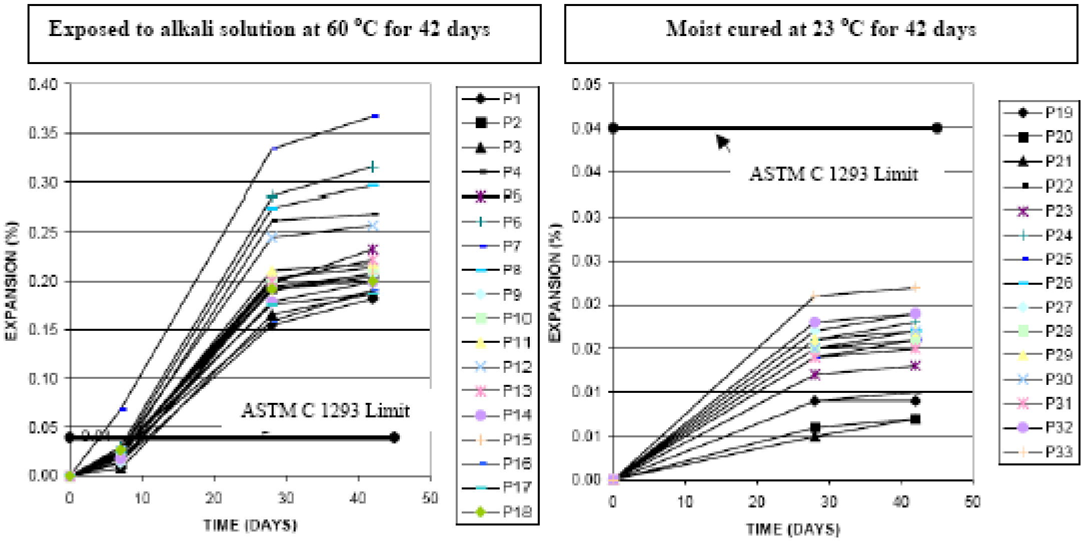


Figure A.30. Expansion of prisms subjected to expansion tests (Rathje et al., 2002).

Mold samples were then prepared using RCA obtained by crushing prisms 1 through 18 and 19 through 33 separately. Compacted RCA samples were placed in both water and a 1N-NaOH solution and stored 38 ^{o}C to evaluate expansion due to ASR attack. The test apparatus used by Rathje et al. (2002) to measure expansion of compacted RCA samples is shown in Figure A.31. Figure A.32 shows the expansion results of RCA manufactured from ASR-exposed PCC and Figure A.33 shows the expansion results of RCA manufactured from PCC that did not have any ASR exposure. The expansion in both cases was observed to be greater than the limit set forth by ASTM C 1293; however, these expansion values were considered to be insignificant by Rathje et al (2002) in cases of unbound use of RCA.

Figure A.31. Apparatus used by Rathje et al. (2002) to evaluate ASR-related expansion.

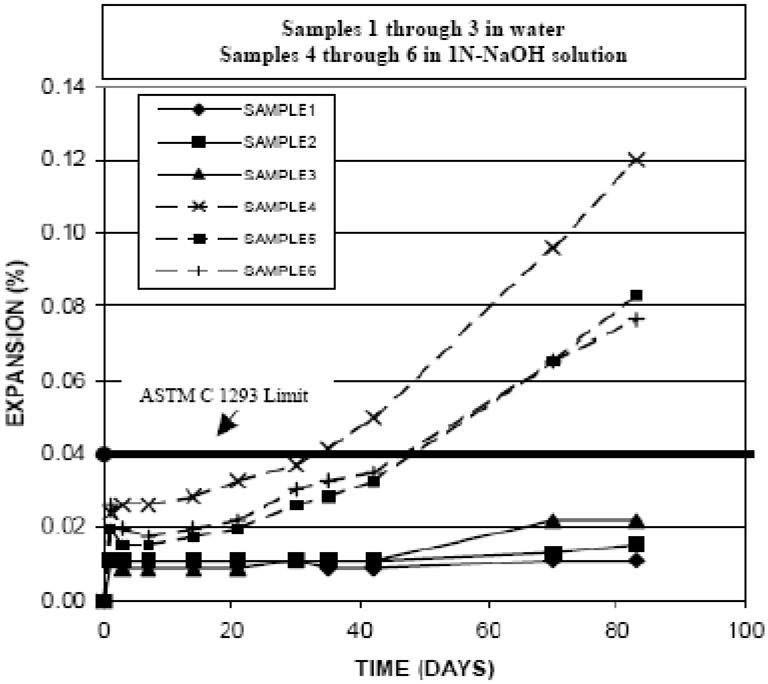


Figure A.32. Expansion of ASR exposed RCA at 38 °C (Rathje et al., 2002).

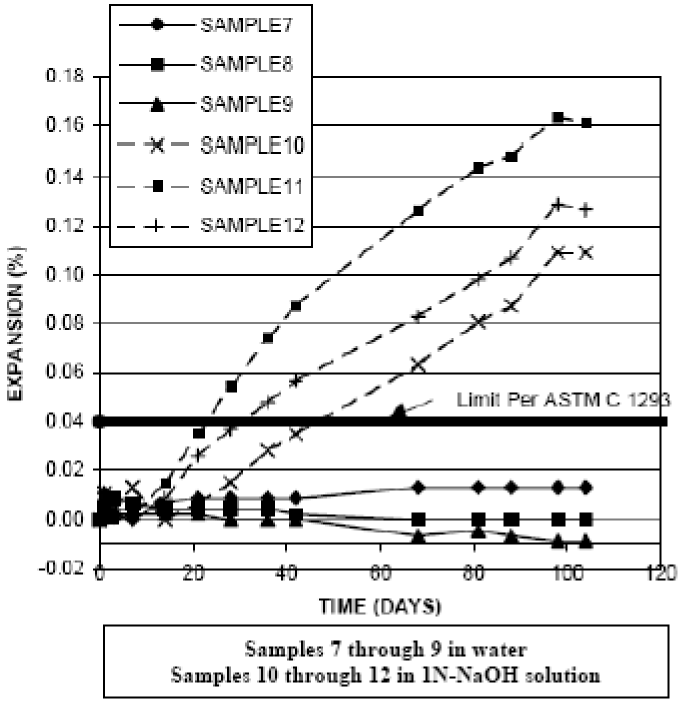


Figure A.33. Expansion of non-ASR exposed RCA at 38 °C (Rathje et al., 2002)

Gress and Kozikowski (2000) evaluated available techniques and procedures for assessing ASR expansion potential of RCA. They found that the use of concrete cubes greatly accelerated ASR compared to standard prism casting. Sealing prisms in evacuated plastic bags with water also effectively accelerated ASR expansion. Modified versions of AASHTO T303 and ASTM 1293 were also found to effectively accelerate ASR in concrete standard prisms compared to their respective standard versions. The level of equivalent alkali used in the test affected the 28-day expansion of the AASHTO T303 but not the expansion at 14 days.

A.8.5 D-CRACKING

Certain, primarily sedimentary, aggregates have pore structures that make them vulnerable to damage if frozen while they are critically saturated. These cyclic freezing forces crack the aggregate, and PCC pavements containing these freezing-susceptible aggregates develop a characteristic pattern of fine cracks paralleling slab joints. This cracking is known as Durability- or D-cracking.

D-cracking is a function of aggregate size, and depending on the specific individual aggregate pore structure, there is a maximum-size aggregate below which D-cracking ceases to be a problem. In many cases, recycling PCC inherently reduces the actual aggregate size within any individual RCA particles. Controlling the recycling process to produce RCA particles with maximum-aggregate sizes within the fragment below the minimum critical size for D-cracking is probably a simple way of ensuring no further D-cracking after placement. According to the U.S. Army and Air Force (1988), experience has shown that crushing recycled concrete to pass the 0.75-in sieve prevents D-cracking.

A.8.6 REHYDRATION POTENTIAL OF RCA

Published literature indicates that RCA can be used as unbound base material with relatively few problems. However, there has always been a perception that RCA as an unbound base can rehydrate and get stronger. Rehydration has not been shown as a chemical phenomenon, and there is some other physical change occurring that explains the apparent stiffening of RCA in unbound condition. The following discussion on rehydration of RCA is summarized from internal research conducted by the Waterways Experiment Station (WES, now ERDC) and reported by Poole et al. (2004).

When producing RCA, hydrated cement paste or mortar adheres to coarse aggregate pieces. The amount of adhering material increases with increasing cement content and increasing fine aggregate content of original PCC (Tavakoli and Soroushian, 1996a; Hansen, 1992). This residue affects the physical and durability properties of RCA. Adhering material gives RCA harshness, particularly when RCA size is small (Hansen, 1992), that requires additional mixing water to maintain workability. The adhering material includes a part of the cement–aggregate interface that has the properties of the original concrete.

A.8.6.1 Presence of Unhydrated Cement

Crusher dust, material <150 micrometer fraction in RCA contains a much higher proportion of hydrated or partially hydrated cementitious materials, relative to aggregate, than do the larger fractions. Accordingly, there may be some potential in this very fine fraction for residual hydraulic or pozzolanic activity that might have useful applications (Roy, 1981; Mather, 1981; Frohnsdorff, 1981; Hansen, 1990).

Residual hydraulic potential could exist if the portland cement was incompletely hydrated. This could happen if water-cement ratios were low enough that all of the originally water filled space filled up with reaction product, thus stopping the hydration reaction, or if the PCC dried out in service before all of the portland cement had hydrated. Mather (1981) stated that PCC made with modern cements probably would not contain much residual hydraulic activity because these cements typically contain much higher fractions of phases that hydrate relatively rapidly. Hansen and Narud (1983) found little residual hydraulic activity in crushed concrete fines when using a Type III portland cement (ASTM C 150). This is expected, as the extreme fineness typical of these cements should have largely depleted its hydraulic activity.

In addition to containing unhydrated portland cement phases, the paste fraction of old PCC contains significant fractions of calcium hydroxide. Depending upon the chemistry of the specific cement, calcium hydroxide can be 15 to 25 percent by mass of fully hydrated cement paste. This is would amount to 2 to 3 percent of PCC but would be somewhat higher in the very fine fraction of RCA. Calcium hydroxide is one of the reactants in the pozzolanic reaction, in which the amorphous silica fraction of a pozzolan reacts with calcium hydroxide, in water, to make a calcium-silicate hydrate that is very similar to the reaction product formed during portland cement hydration.

Hansen (1990) found that crushing the very fine fraction of RCA to the fineness of portland cement results in a material that would react with fly ash very slowly. In very old PCC, much of this calcium hydroxide near the surface (top 3/8") may be converted to calcium carbonate by exposure to atmospheric carbon dioxide, and consequently the small portion of RCA would not be reactive with pozzolans.

Other than references to the likelihood that residual hydraulic activity might or might not be significant, only Hansen and Narud (1983) reported actual investigations into the matter. Therefore, a small pilot project was conducted at WES to evaluate the hydration potential of the very fine RCA material.

A.8.6.2 Summary of WES Research Results

Research conducted at WES indicated that the major unhydrated cementitious phases of the cement, Ca_3SiO_5 (C_3S) and Ca_2SiO_4 (C_2S), are distributed fairly evenly among the size fractions with a slightly higher amount in the finest fractions of RCA. The amount of calcium hydroxide is greater in the finer fractions compared to the coarser ones. This phase is formed as a result of the hydration of the portland cement. The amount of quartz decreases with decreasing size of the material. The amount of quartz is particularly diminished in the minus 75-µm-size fraction. This phase is mostly present due to the sand in the mortar.

Poole et al. (2004) confirmed the effect of mortar or paste that adhered to aggregate in crushed material on water demand and harshness reported in the literature. The results of WES work also support the results reported by Hansen (1983) that, even though there was measurable residual hydraulic activity, there is too little to be useful in new construction. The cements used by WES represented cements commonly used in general-purpose construction. WES demonstrated that the residual potential for pozzolanic activity was too small to be of practical use in conventional PCC, but there could be some useful effect in low strength materials. However, tests for this potential would need to be conducted for any contemplated application, since the experimental conditions of this work were probably close to optimal for the development of this potential. RCA is more likely to be carbonated to the point that this potential would not exist. Further research was recommended to fully to investigate this potential. Evaluation of RCA use in pavement base courses by Pomeroy (1981), Hansen (1992), and Kibert (1994) indicated that RCA materials often tend to form crusts that could give a false impression of stiffening. These crusts, called tufa, also have the potential to inhibit drainage.

A.8.7 TECHNICAL EVALUATION OF RCA

A major FHWA research study on recycling (Chesner et al., 1998) recommended that the decision to recycle materials for construction should be based on the evaluation of engineering, environmental, occupational health and safety, recyclability, economic, and implementability considerations. A 6-step evaluation framework to assist on this decision was suggested. The following were the recommended steps:

1. Identify all potential issues associated with the recycled product.
2. Establish acceptance criteria based on laboratory testing.
3. Perform tests and evaluate results based on acceptance criterion.
4. Product modification should be considered prior to rejection of non-compliant products.
5. Identify implementability constraints.
6. Determine the need for a field demonstration.

Many U.S. agencies and European countries use the same acceptance criteria, tests, and specifications for recycled and virgin aggregate materials. For instance, the FHWA requires that the performance of recycled materials be similar or better than the performance using conventional materials (Simon et al., 2000). Yrjanson (1989) also recommended that the tests for RCA should be the same as those for conventional aggregates. However, it is a concern in the U.S. and Europe that traditional tests do not predict the field performance of recycled materials (Schimmoller et al., 2000). In fact, there are instances when testing procedures for virgin and recycled materials should not be the same. For example, Saeed and Hall (2004) stated that there is an excessive disintegration of RCA during the sodium sulfate test because of chemical reaction between sodium sulfate and RCA; thus, test results are not representative of the real world. Despite some concern about testing procedures, there is consensus that engineering, environmental, and economic aspects of both virgin and recycled aggregates are essential issues to be addressed. In general, RCA has similar or better engineering properties, in addition to similar or more positive environmental and economic impacts.

Chesner et al. (1998) consider the following engineering RCA properties important for pavement layers: grading, particle shape, absorption, specific gravity, plasticity, stability, strength, durability, and permeability. Strength and durability can be estimated from M_R and abrasion resistance, respectively. Saeed and Hall (2004) grouped some of these properties into the following three sets of evaluation tests for recycled aggregates:

- Screening (grading, specific gravity, density)
- Strength (shear strength, CBR)
- Miscellaneous (toughness, durability, permeability)

Saeed et al. (2001) evaluated the performance of unbound granular pavement layers and identified the granular base elements that affect performance of concrete pavements. Distresses related to poor performance of the unbounded granular layer in concrete pavements include pumping, faulting, cracking, and frost heave. Saeed et al. concluded that the performance of unbound granular pavement layers is greatly affected by shear strength and, consequently, by stiffness. Other aggregates properties that affect performance of unbonded aggregate layer include frost susceptibility, toughness and abrasion, durability, and permeability. The following laboratory tests were suggested for performance evaluation of unbonded granular layer:

- Classification/screening tests
    - Sieve Analysis
    - Atterberg Limits
    - Moisture-Density Relationship
    - Specific Gravity and Absorption
    - Flat and Elongated Particles
    - Uncompacted Voids)
- Durability (Magnesium Sulfate Soundness)
- Shear strength (Triaxial and California Bearing Ratio)
- Stiffness (M_R)
- Toughness and abrasion (Micro-Deval)
- Frost susceptibility (Tube Suction)

According to Oikonomou (2004), the tests for RCA characterization should be divided into four categories: historical data, physical, mechanical, and environmental characteristics. Historical data refer to information about the origin of the RCA, including composition and petrography analysis. Physical characteristics are properties as water absorption, specific gravity, amount of chlorides and sulfate, presence of foreign materials, and reactivity to alkali-silica. Mechanical characteristics include properties such as LA abrasion loss and percentage of soft granules. Finally, environmental characterization is mostly concern with the possible formation of leachates.

A.9 CURRENT RCA BASE/SUBBASE SPECIFICATIONS

The following properties are required in the Greek specifications for RCA (Oikonomou, 2004):

- Specific gravity of at least 2.2
- Water absorption of at most 3 percent
- Los Angeles (LA) abrasion loss of at most 40 percent
- Soundness loss of at most 10 percent

Chini et al. (1998) also recommended a maximum LA abrasion loss of 40 percent for RCA to be used as base course. In addition, they recommended a maximum plasticity index of 6 percent, limited the amount of flat or elongated particles to 8 percent, and required a LBR of at least 100 percent; the sodium sulfate soundness test for RCA was waived. Finally, Chini et al. recommended that RCA should meet the same grading specification as natural aggregate. Mack et al. (1993) also recommended the sulfate soundness test to be waived for RCA. U.S. Army and Air Force (1988) recommended RCA meet all the same requirements and use the same testing procedures as natural aggregates.

The Unified Facility Guide Specification (UFGS) proposed the specification UFGS-02709, "Portland Cement-Stabilized Base or Subbase Course," that accounts for the use of RCA for cement-stabilized and lean concrete base or subbase courses prepared by the U.S. Army Corps of Engineers (UFGS, 2004a). Other UFGS specifications prepared by the Naval Facilities Engineering Command (NAVFAC) are also available for stabilized base, including the UFGS-02712 (UFGS, 2004b) for lean concrete base and the UFGS-02713 (UFGS, 2004c) for cement-stabilized base. The UFGS also has specifications for granular base, but they are specified for use under flexible pavement only. The specification prepared by the USACE is the UFGS-02704 (UFGS, 2004d), whereas the NAVFAC prepared the UFGS-02722 (UFGS, 2004e). However, none of the above specifications directly accounts for or mention the use of RCA.

A research project was conducted between the Florida DOT and the University of Central Florida to developed guidelines and specifications to account for recycled material. Kuo et al. (2001) published a report on this research project, and part of it was also published in 2002 (Kuo et al., 2002). Some of the laboratory tests recommended to be performed on RCA included grading, LBR, LA abrasion, soundness by sodium sulfate, sand equivalent, optimum moisture content, maximum dry unit weight, permeability, impurities, and M_R. Kuo et al. also recommended that RCA should have similar compressive and shear strength to virgin aggregate, in addition meeting grading and provide proper workability. Finally, RCA should not contain detrimental impurities such as lead and asbestos. The specification proposed by Kuo et al. (2002) is shown in Table

A.10, along with average results from laboratory tests and the current Florida DOT specification for conventional aggregate.

Table A.10. Comparison of base specifications by Kuo et al. (2002).

Type of Test	**Average Test Results**	**Proposed Specification**	**FDOT Specification**	**Specification**
Grading Test	Average Grading	Grading Limits	Grading	FM 1-T027
2 in	100	100	100	
1 1/2 in	99.5	98 – 100	95 – 100	
3/4 in	83.2	65 – 100	65 – 90	
3/8 in	61.2	40 – 83	45 – 75	
No. 4	44.8	27 – 63	35 – 65	
No. 10	34.4	20 – 49	25 – 45	
No. 50	15.7	8 – 24	5 – 25	
No. 200	3.8	2 – 6	0 – 10	
LBR Test	181.71	Min. 120	100	FM - 515
LA Abrasion Loss	44%	< 48%	< 45	FM 1-T096
Sodium Sulfate Test	52%	< 50%	15%	15%
Sand Equivalent	70.50%	> 70%	≥ 28%	AASHTO T - 104
Heavy Metals	0 – 12 ppm	5 ppm	5 ppm	EPA - 96
Asbestos	Free of Asbestos	Free of Asbestos	Section 112 EPA	EPA - 89
Optimum Moisture Content	11.2% – 12.1%	10% – 12%	Not Specified	FM 5 - 521
Maximum Dry Unit Weight	113.8 lb/ft^3 – 114.8 lb/ft^3	108 lb/ft^3 – 120 lb/ft^3	98% of Max. Dry Density	FM 5 - 521
Permeability	0.72 (ft/day)	0.10 to 1.40 (ft/day)	Not Specified	FM 5 - 513
Impurities	1.99% by weight	< 2.0% by weight	Substantially free of impurities	FM 1 T - 194
Structural Coefficient	0.34	0.30	0.15	–
Thickness Requirement	4 in.	Min. 8.0 in	Min. 8.0 in	–

The FAA requires that the construction of airfield pavements follows AC 150/5370-10A, “Standards for Specifying Construction of Airports” (FAA, 1989), which was originally published on February 17, 1989. Since then, it had many modifications related to pavement construction. Currently, AC 150/5370-10A is under complete revision, which should be finalized at the end of calendar year 2004 as AC 150/5370-10B (FAA, 2004). It does not seem that the use of RCA is going to be addressed in the new specification. A summary of the current specification requirements for P-208 (aggregate) and P-209 (crushed aggregate) base courses is shown in Table A.11. This table illustrates the acceptance and control procedures for granular bases. The control procedures are separated depending on the time relative to layer placement (before, during and after). The specified tests to be conducted prior (and sometime during) placement are shown in

Table A.12. Chesner et al. (1998) provided the list of standard test methods to evaluate traditional granular materials for pavement layers, as shown in Table A.13.

Table A.11. Summary of the FAA specification for P-208 and P-209.

Acceptance/control	Properties	Specified value
Control prior to placement	See Table 2.12	-
Control during placement	Moisture	Within ± 1.5% omc
Acceptance	Density*	100% of the maximum laboratory density ASTM D 1556 or D 2167
Control after placement	Thickness**	At most 0.5 in. less than design thickness
	Smoothness	3/8 inches max tested using a 16-ft straigthedge
* Density is accepted on a lot basis, which consists of 2400 sy max and each lot has 2 equal sublots. One test should be performed for each sublot.		
** For P-208, one thickness test (depth or core) should be performed every at least 300 sy. For P-209, four thickness determinations should be performed per lot, as defined under density acceptance.		

Table A.12. FAA specification control prior to granular layer placement.

Layer	Test	Specified value	ASTM testing
P-208	Los Angeles (LA) wear at 500 revolutions	Uncrushed (45% max) and crushed (55% max)	C 131
	Fractured faces (FF) of material retained on No.4 sieve	60% min of 2 FF and 75% min of 1 FF (draft spec)	-
	Grading		C 117 and C 136
P-209	Los Angeles (LA)	45% max	C 131
	Fractured faces (FF) of coarse material retained on No.4 sieve	90% min of 2 FF and 100% min of 1 FF (by weight)	-
	Grading		C 117 and C 136
	Flat or elongated particles: + No.4 sieve	15% max by weight	D 693
	Sodium sulfate soundness loss	12% max after 5 cycles	C 88
	LL and PI of minus No.40 material	LL: 25 max and PI: 4 max	D 4318
	Sand equivalent value for fine aggregate	35 min	D 2419
	Percent passing (PP) No.200 sieve	60% max of PP the No.30 sieve	-

Table A.13. Granular aggregates test procedures (Chesner et al., 1998).

Property	**Test Method**	**Reference**
General Specifications	Graded Aggregate Material for Bases or Subbases for Highways or Airports	ASTM D2940
Grading	Sizes of Aggregate for Road and Bridge Construction	ASTM D448 / AASHTO M43
	Sieve Analysis of Fine and Coarse Aggregate	ASTM C136 / AASHTO T27
Particle Shape	Flat and Elongated Particles in Coarse Aggregate	ASTM D4791
	Uncompacted Voids Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)	AASHTO TP33
	Index of Aggregate Particle Shape and Texture	ASTM D3398
Base Stability	California Bearing Ratio	ASTM D1883 / AASHTO T193
	Moisture-Density Relations of Soils Using a 5.5 lb (2.5 kg) Rammer and a 12-in. (305 mm) Drop	ASTM D698 / AASHTO T99
	Moisture- Density Relations of Soils Using a 10-lb (4.54 kg) Rammer and an 18-in. (457 mm) Drop	AASHTO T180
Permeability	Permeability of Granular Soils (Constant Head)	ASTM D2434 / AASHTO T215
Plasticity	Determining the Plastic Limit and Plasticity Index of Soils	ASTM D4318 /AASHTO T90
	Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test	ASTM D2419 / AASHTO T176
Abrasion Resistance	Resistance to Degrading of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C535
	Resistance to Degrading of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	ASTM C131 / AASHTO T96
Resilient Modulus	Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46	AASHTO T274

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APPENDIX B

Proposed Specifications for Item X-XXX, Recycled Concrete Aggregate Base Course

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PROPOSED SPECIFICATIONS FOR ITEM X-XXX, RECYCLED CONCRETE AGGREGATE BASE COURSE

DESCRIPTION

XXX-1.1 This item consists of a base course composed of recycled concrete aggregate, crushed to meet a particular grading, constructed on a prepared course in accordance with these specifications and in conformity to the dimensions and typical cross sections shown on the plans.

MATERIALS

XXX-2.1 AGGREGATE. Recycled concrete aggregate shall consist of portland cement concrete or other concrete containing pozzolanic binder material and be derived exclusively from concrete pavements. The recycled concrete material shall be free of reinforcing steel, expansion material, and other foreign material. Asphalt concrete overlays shall be removed from the PCC surface prior to pavement removal and crushing. Also, full-slab asphalt concrete panels (used as a replacement for a removed PCC slab) shall be removed. An incidental amount of recycled asphalt concrete pavement may be present in the recycled concrete aggregate.

Recycled concrete aggregate shall be free from coatings of clay, silt, organic matter, and other objectionable materials. Fine aggregate passing the No. 4 (4.75-mm) sieve shall consist of fines from the operation of crushing the recycled concrete aggregate. If necessary, fine aggregate may be added to produce the correct grading. The fine aggregate shall be produced by crushing stone, gravel, slag, or recycled concrete that meet the requirements for wear and soundness specified for coarse aggregate.

> **
>
> To the extent possible, recycled concrete aggregate should be produced from distress-free (material related) concrete. Published literature and limited laboratory testing have indicated that alkali-silica reactivity (ASR) is not a concern for crushed aggregate base course. The pavement designer should exercise due care in evaluating site conditions and other factors to ensure the proper use of ASR prone PCC.
>
> The engineer shall gather and analyze available information on the history and performance of the ASR-distressed PCC to be used to manufacture base material. The results of this investigation will justify why this material will provide an acceptable level of safety, economy, and durability. The designer is also advised to consult with experts (geologists, concrete petrographers, materials engineers, etc.) on the degree of reactivity of aggregates from the source(s) used to construct the original PCC.

Recycled concrete aggregate shall not be used in locations with high sulfate content soils.

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The amount of flat and elongated particles in recycled concrete aggregate shall not exceed 20 percent for the fraction retained on the 0.5 inch (13 mm) sieve nor 20 percent for the fraction passing the 0.5 inch (13 mm) sieve when tested in accordance with ASTM D 4791. A flat particle is one having a ratio of width to thickness greater than 3; an elongated particle is one having a ratio of length to width greater than 3. In the portion retained on each sieve specified, the recycled concrete aggregate shall have at least 90 percent by weight of particles with at least two fractured faces and 100 percent with at least one fractured face. The area of each face shall be equal to at least 75 percent of the smallest midsectional area of the piece. When two fractured faces are contiguous, the angle between the planes of fractures shall be at least 30 to count as two fractured faces.

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Recycled concrete aggregate shape depends on the characteristics of the recycled concrete, plant type, and plant operation speed. A number of trial batches may have to be produced before crushed recycled concrete aggregate meeting the shape and grading requirements is produced.

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The percentage of wear shall not be greater than 45 percent when tested in accordance with ASTM C 131. The sodium sulfate soundness test (ASTM C 88) requirement is waived for recycled concrete aggregate.

The fraction passing the No. 40 (0.42-mm) sieve shall have a liquid limit no greater than 25 and a plasticity index of not more than 4 when tested in accordance with ASTM D 4318. The fine aggregate shall have a minimum sand equivalent value of 35 when tested in accordance with ASTM D 2419.

a. Sampling and Testing. Recycled concrete aggregate samples for preliminary testing shall be furnished by the Contractor prior to the start of base construction. All tests for initial aggregate submittals necessary to determine compliance with the specification requirements will be made by the Engineer at no expense to the Contractor.

   Samples of recycled concrete aggregate shall be furnished by the Contractor at the start of production and at intervals during production. The sampling points and intervals will be designated by the Engineer. The samples will be the basis of approval of specific lots of recycled concrete aggregate for the quality requirements.

Samples of recycled concrete aggregate to check grading shall be taken at least once daily. Sampling shall be in accordance with ASTM D 75, and testing shall be in accordance with ASTM C 136 and C 117.

b. Grading Requirements. The grading (job mix) of the final mixture shall fall within the design range indicated in Table 1, when tested in accordance with ASTM C 117 and C 136. The final grading shall be continuously graded from coarse to fine and shall not vary from the low limit on one sieve to the high limit on an adjacent sieve or vice versa.

Table 1. Requirements for grading of recycled concrete aggregate.

Sieve Size	Percentage by Weight Passing Sieves	Job Mix Tolerances Percent
2 in (50.8 mm)	100	--
1-1/2 (37.5 mm)	95 - 100	+/- 5
1 in (25.0 mm)	70 - 95	+/- 8
3/4 in (19.0 mm)	55 - 85	+/- 8
No. 4 (4.75 mm)	30 - 60	+/- 8
No. 30 (0.60 mm)	12 - 30	+/- 5
No. 200 (0.075 mm)	0 - 5	+/- 3

The job mix tolerances in Table 1 shall be applied to the job mix grading to establish a job control grading band. The full tolerance still will apply if application of the tolerances results in a job control grading band outside the design range.

EQUIPMENT

XXX-3.1 GENERAL. All equipment necessary to mix, transport, place, compact, and finish the recycled concrete aggregate base course shall be furnished by the Contractor as to design, capacity, and mechanical condition. The Contractor shall provide written certification to the Engineer that all equipment meets the requirements for this section. The equipment shall be inspected by the Engineer at the job site prior to the start of construction operations.

XXX-3.2 MIXING EQUIPMENT. Base course shall be thoroughly mixed in a plant suitable for recycled concrete aggregate. The mixer shall be a batch or continuous-flow type and shall be equipped with calibrated metering and feeding device that introduce the aggregate and water into the mixer in specified quantities. If necessary, a screening device shall be installed to remove oversized material greater than 2 in (50 mm) from the recycled concrete aggregate feed.

Free access to the plant shall be provided to the Engineer at all times for inspection of the plant's equipment and operation and for sampling the mixed recycled concrete aggregate materials.

XXX-3.3 HAULING EQUIPMENT. The mixed recycled concrete aggregate base course shall be transported from the plant to the job site in hauling equipment having beds that are smooth, clean, and tight. Truck bed covers shall be provided and used to protect the mixed recycled concrete aggregate base course from rain during transport.

XXX-3.4 PLACING EQUIPMENT. Recycled concrete aggregate shall be placed using a mechanical spreader or machine capable of receiving, spreading, and shaping the material without segregation into uniform layer or lift. The placing equipment shall be equipped with a strike off plate that can be adjusted to the layer thickness. The placing equipment shall have two end gates or cut off plates, so that the recycled concrete aggregate may be spread up to a lane width.

XXX-3.5 COMPACTION EQUIPMENT. Recycled concrete aggregate base course compaction shall be accomplished using one or combination of the following pieces of equipment:

- Steel-wheeled roller
- Vibratory roller
- Pneumatic-tire roller
- Hand-operated power tampers (for areas inaccessible to rollers)

XXX-3.6 FINISHING EQUIPMENT. Trimming of the compacted recycled concrete aggregate to meet surface requirements shall be accomplished using a self-propelled grader or trimming machine, with a mold board cutting edge of 12 ft (3.7 m) minimum width automatically controlled by sensors in conjunction with an independent grade control from a taut string line. String line will be required on both sides of the sensor controls for all lanes.

CONSTRUCTION METHODS

XXX-4.1 WEATHER LIMITATIONS. Construction is allowed only when the atmospheric temperature is at or above 35 ^{o}F (2 ^{o}C). When the temperature falls below 35 ^{o}F (2 ^{o}C), the contractor shall protect all completed areas against detrimental effects of freezing. Areas damaged by freezing, rainfall, or other weather conditions shall be corrected.

XXX-4.2 PREPARING UNDERLYING COURSE. The underlying course shall be checked by the Engineer before placing and spreading operations are started. Any ruts or soft yielding places caused by improper drainage conditions, hauling, or any other cause shall be corrected at the Contractor's expense before the base course is placed thereon. Material shall not be placed on frozen material.

To protect the existing layers and to ensure proper drainage, the spreading of the recycled concrete aggregate base course shall begin along the centerline of the pavement on a crowned section or on the greatest contour elevation of a pavement with a variable uniform cross slope.

XXX-4.3 GRADE CONTROL. Grade control between the edges of the recycled concrete aggregate base course shall be accomplished by grade stakes, steel pins, or forms placed in lanes parallel to the centerline and at intervals of 50 ft (15 m) or less on the longitudinal grade and 25 ft (7.5 m) or less on the transverse grade.

XXX-4.4 MIXING. The recycled concrete shall be uniformly blended during crushing operations and mixed with water in a mixing plant suitable for recycled concrete aggregate. The plant shall blend and mix the materials to meet the specifications and to secure the proper moisture content for compaction.

XXX-4.5 PLACING. The recycled concrete aggregate base material shall be placed on the moistened subgrade or base in layers of uniform thickness with an approved mechanical spreader.

The maximum depth of a compacted layer shall be 6 inches (150 mm). If the total depth of the compacted material is more than 6 inches (150 mm), it shall be constructed in two or more layers. In multi-layer construction, the material shall be placed in approximately equal-depth layers.

The previously constructed layer shall be cleaned of loose and foreign material prior to placing the next layer. The surface of the compacted material shall be kept moist until covered with the next layer.

Adjustments in placing procedures or equipment shall be made to obtain grades, to minimize segregation grading, to adjust the water content, and to ensure an acceptable recycled concrete aggregate base course.

XXX-4.6. EDGES OF BASE COURSE. The recycled concrete aggregate shall be placed so that the completed section will be a minimum of 5 ft (1.5 m) wider, on all sides, than the next layer that will be placed above it. Approved fill material shall be placed along the free edges of the recycled concrete aggregate in sufficient quantities to compact to the thickness of the course being constructed, or to the thickness of each layer in a multiple course, allowing in each operation at least a 2-ft (0.6-m) width of this material to be rolled and compacted simultaneously with rolling and compacting of each layer of base course. If this base course material is to be placed adjacent to another pavement section, then the layers for both of these sections shall be placed and compacted along the edge at the same time.

XXX-4.7 COMPACTION. Immediately upon completion of the spreading operations, the recycled concrete aggregate shall be compacted. The number, type, and weight of rollers shall be sufficient to compact the material to the required density.

Each layer of the recycled concrete aggregate base course shall be compacted to the required density using the compaction equipment. The moisture content of the material during placing operations shall not be below, nor more than 1-1/2 percentage points above, the optimum moisture content as determined by ASTM [ ].

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> The Engineer shall specify ASTM D 698 for areas designated for aircraft with gross weights of 60,000 pounds (27 200 kg) or less and ASTM D 1557 for areas designated for aircraft with gross weights greater than 60,000 pounds (27 200 kg).
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Rolling shall begin at the outside edge of the surface and proceed to the center, overlapping on successive trips at least one-half the width of the roller. Alternate trips of the roller shall be slightly different lengths. Speed of the roller shall be such that displacement of the recycled concrete aggregate does not occur. In all places not accessible to the rollers, the base course material shall be compacted with hand-operated power tampers. The compaction shall continue until each layer has a degree of compaction that is at least 100 percent of the laboratory maximum density through the full depth of the layer. The contractor shall make adjustments in compacting or finishing techniques to obtain true grades, to minimize segregation and degradation, to reduce or increase water content and to ensure a satisfactory base course. Any materials found to be unsatisfactory shall be removed and replaced with satisfactory material or reworked, so that the requirements of this specification are met.

XXX-4.8 ACCEPTANCE SAMPLING AND TESTING FOR DENSITY. Recycled concrete aggregate shall be accepted for grading and density on a lot basis.

A lot will consist of one day's production where it is not expected to exceed 2,400 square yards (2,000 square meters) per lift. A lot will consist of one-half day's production, where a day's production is expected to consist of between 2,400 and 4,800 square yards (2,000 and 4,000 square meters) per lift.

Each lot shall be divided into two equal sublots. One test shall be made for each sublot. Sampling locations will be determined on a random basis in accordance with statistical procedures contained in ASTM D 3665.

Each lot will be accepted for grading when it falls within the limits and tolerances shown in Table 1 when tested in accordance with ASTM C117 and C 131. If the proper grading is not attained the grading test will be repeated. The entire lot shall be rejected and replaced by the Contractor at the Contractor’s expense.

Each lot will be accepted for density when the field density is at least 100 percent of the maximum density of laboratory specimens prepared from samples of the base course material delivered to the job site. The specimens shall be compacted and tested in accordance with ASTM [ ]. The in-place field density shall be determined in accordance with ASTM D 1556 or D 2167. If the specified density is not attained, the entire lot shall be reworked and two additional random tests made. This procedure shall be followed until the specified density is reached.

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> The Engineer shall specify ASTM D 698 for areas designated for aircraft with gross weights of 60,000 pounds (27 200 kg) or less and ASTM D 1557 for areas designated for aircraft with gross weights greater than 60,000 pounds (27 200 kg).
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In lieu of ASTM D 1556 or D 2167 method of field density determination, acceptance testing may be accomplished using a nuclear gage in accordance with ASTM D 2922. The gage should be field calibrated in accordance with paragraph 4 of ASTM D 2922. Calibration tests shall be conducted on the first lot of material placed that meets the density requirements.

Use of ASTM D 2922 results in a wet unit weight, and when using this method, ASTM D 3017 shall be used to determine the moisture content of the material. The calibration curve furnished with the moisture gages shall be checked as described in paragraph 7 of ASTM D 3017. The calibration checks of both the density and moisture gages shall be made at the beginning of a job and at regular intervals.

If a nuclear gage is used for density determination, two random measurements shall be made for each sublot.

XXX-4.9 FINISHING. The surface of the recycled concrete aggregate base course shall be finished by equipment designed for this purpose.

In no case will thin layers of material be added to the top of base course to meet grade. If the elevation of the layer is 1/2 inch (12 mm) or more below grade, the layer shall be scarified to a depth of at least 3 inches (75 mm), new material added, and the layer shall be recompacted. If the finished surface is above plan grade, it shall be cut back to grade and rerolled.

Should the surface become rough, corrugated, uneven in texture, or traffic marked prior to completion, the unsatisfactory portion shall be scarified, and recompacted or replaced at Contractor’s expense.

XXX-4.10 SURFACE TOLERANCES. The finished surface shall not vary more than 3/8 inch (9 mm) when tested with a 16-ft (4.8-m) straightedge applied parallel with or at right angles to the centerline. The Contractor shall correct any deviation in excess of this amount, at the Contractor’s expense.

XXX-4.11 THICKNESS CONTROL. The completed thickness of the base course shall be within 0.5 inch (13 mm) of the design thickness. Four determinations of thickness shall be made for each lot of material placed. Each lot shall be divided into four equal sublots. One test shall be made for each sublot. Sampling locations will be determined on a random basis in accordance with procedures contained in ASTM D 3665. Where the thickness is deficient by more than 0.5 inch (13 mm), the Contractor shall correct such areas at no additional cost by excavating to the required depth and replacing with new material. Additional test holes may be required to identify the limits of deficient areas.

XXX-4.12 TRAFFIC. Equipment used in construction may be routed over completed portions of the base course, provided no damage results and provided that the equipment is distributed evenly over the full width of the base course to avoid rutting or uneven compaction.

XXX-4.13 MAINTENANCE. The base course shall be maintained until the base course is completed and accepted. Maintenance will include immediate repairs to any defects and shall be repeated as often as necessary to keep the completed work intact. Any recycled concrete aggregate base course that is not paved over prior to the onset of winter, shall be retested before paving to verify that it still complies with the requirements of this specification. Any area of the recycled concrete aggregate base course that is damaged shall be reworked as necessary.

METHOD OF MEASUREMENT

XXX-5.1 The quantity of recycled concrete aggregate base course to be paid will be determined by measurement of the number of square yards (square meters) of material actually constructed and accepted as complying with the plans and specifications.

BASIS OF PAYMENT

XXX-6.1 Payment shall be made at the contract unit price per square yard (square meter) for recycled concrete aggregate base course. This price shall be full compensation for furnishing all materials, for preparing and placing these materials, and for all labor, equipment tools, and incidentals necessary to complete the item.

Payment will be made under:

Item X-XXX-6.1
Recycled Concrete Aggregate Base Course — per square yard (square meter)

TESTING REQUIREMENTS

ASTM C 29	Unit Weight of Aggregate
ASTM C 117	Materials Finer than 75μm (No. 200) Sieve in Mineral Aggregates by Washing

ASTM C 131	Resistance to Abrasion of Small Size Coarse Aggregate by Use of the Los Angeles Machine
ASTM C 136	Sieve or Screen Analysis of Fine and Coarse Aggregate
ASTM D 75	Sampling Aggregate
ASTM D 693	Crushed Stone, Crushed Slag, and Crushed Gravel for Dry-or Water-Bound Macadam Base Courses and Bituminous Macadam Base and Surface Courses of Pavements
ASTM D 698	Moisture-Density Relations of Soils and Soil - Aggregate Mixtures Using 5.5-lb (2.49-kg) Rammer and 12-in (305-mm) Drop
ASTM D 1556	Density of Soil in Place by the Sand - Cone Method
ASTM D 1557	Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-lb (4.5-kg) Rammer and 18-in (457-mm) Drop
ASTM D 2167	Density of Soil in Place by the Rubber-Balloon Method
ASTM D 2419	Sand Equivalent Value of Soils and Fine Aggregate
ASTM D 2922	Density of Soil and Soil-Aggregate in Place by Nuclear Methods
ASTM D 3017	Moisture Content of Soil and Soil-Aggregate in Place by Nuclear Methods
ASTM D 3665	Random Sampling of Paving Materials
ASTM D 4318	Liquid Limit, Plastic Limit, and Plasticity Index of Soils

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APPENDIX C

Recommended Future Research

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C.1 RECOMMENDED FUTURE RESEARCH

Published literature provided information on a number of issues but had limited information on others. Appendix B discusses additional research that would aid and expand the use of RCA in airport pavement structures.

- Sulfates and RCA: Sulfates in soil or ground water or from external sources in contact with RCA in pavement structures can lead to sulfate attack of the RCA with consequent heaving and expansion of the pavement structure. This was true in one case even when the RCA was from sulfate-resistant PCC. Research is needed to understand the potential for sulfate attack of RCA in pavement structures, to set safe exposure limits of sulfates, and to identify possible countermeasures to control sulfate attack.

- RCA Toughness: LA Abrasion tests should be conducted on a range of RCA, produced from both distressed and distress-free PCC, to determine the range of material loss. PCC with different strength and different aggregate (limestone, granite, etc.) should be included in the investigation.

- RCA Quality: RCA is at least equal to virgin aggregate material. However, detailed information comparing strength and stiffness characteristics of RCA to virgin aggregate is not available. Such information should be developed using a controlled laboratory investigation to properly characterize RCA and generate input parameters for pavement design purposes.

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