COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

PENN DOT RESEARCH

GUIDANCE DOCUMENT FOR RECLAIMED PORTLAND
CEMENT CONCRETE

STATE-WIDE OPEN END CONTRACT No. 440128
Assignment 13

FINAL REPORT

January 2003

By: Jelena Vukov, P.E.

Apex Environmental, Inc.
220 North Park Road
Reading, PA 19610
(610) 371-8400
GUIDANCE DOCUMENT
FOR
RECLAIMED PORTLAND CEMENT CONCRETE

State-Wide Open End Contract
No. 440128
Assignment 13

Prepared for:

Commonwealth of Pennsylvania
Department of Transportation
PENNDOT Chief Engineer’s Office
Strategic Environmental Management Program Office
400 North Street, 7th Floor
Harrisburg, Pennsylvania 17120-0094

Prepared by:

Apex Environmental, Inc.
220 North Park Road
Reading, PA 19610

Apex Job No. 9023.013

January 2003
TABLE OF CONTENTS

EXECUTIVE SUMMARY ................................................................................................................................. 1

1.0 BACKGROUND ........................................................................................................................................... 2
  1.1 Sources of Reclaimed Portland Cement Concrete (RPCC) ................................................................. 2
  1.2 Current Use of RPCC Materials ........................................................................................................... 3
  1.3 Recycling of RPCC ................................................................................................................................. 6
  1.4 Production of RPCC Aggregates .......................................................................................................... 7

2.0 PROPERTIES OF RPCC MATERIALS ..................................................................................................... 10
  2.1 Grading of RPCC Aggregates ............................................................................................................... 10
  2.2 Storage and Stockpiling ....................................................................................................................... 11
  2.3 Physical Properties of RPCC Aggregates ........................................................................................... 12
  2.4 Durability of RPCC Aggregates ......................................................................................................... 14

3.0 CONCRETE PROPERTIES WITH RPCC AGGREGATES ..................................................................... 17
  3.1 Strength of RPCC Concrete ................................................................................................................... 17
  3.2 Tensile and Flexural Strength ............................................................................................................. 23
  3.3 Modulus of Elasticity, Creep ................................................................................................................ 23
  3.4 Durability and Frost Resistance ......................................................................................................... 24

4.0 DISCUSSIONS ON PROVISIONAL SPECIFICATIONS DEVELOPMENT ............................................... 25
  4.1 RPCC Aggregates Used for Recycled Cement Concrete Pavement .................................................... 25
  4.2 RPCC Aggregates Used for Rip-Rap or Rock Lining ........................................................................... 29
  4.3 RPCC Aggregates Used for Gabions .................................................................................................... 30
  4.4 RPCC Aggregates Used for Miscellaneous Drainage ......................................................................... 31
  4.5 Other Applications of RPCC ............................................................................................................. 31

5.0 REFERENCES ........................................................................................................................................... 32

6.0 APPENDIX ............................................................................................................................................... 34

LIST OF TABLES

Table 1: Overview of State Research, Use and Available Specification on Various RPCC Materials ............. 3
Table 2: Overall Grading of Crusher Products, Experimental Data .......................................................... 11
Table 3: Typical Physical Properties of Recycled Concrete Material ......................................................... 13
Table 4: Typical Mechanical Properties of Recycled Concrete Materials ................................................. 15
Table 5: Compressive Strength of Original and Recycled Aggregate Concretes ........................................... 18
Table 6: Compressive Strength of Natural and Recycled Aggregate Concretes ........................................... 19
Table 7: Compressive Strengths of Recycled Aggregate Concrete Produced from Concrete of Varying Quality .20
Table 8: Concrete Test Results from Lehigh University ............................................................................. 21

LIST OF FIGURES

Figure 1: Flow Chart of Typical Secondary Generation Processing of Building and Demolition Wastes .......... 9
Figure 2: Correlation Between Crusher Setting and Particle Size Distribution of Crusher Products ........... 10
Figure 3: Comparison Between Compressive Strength of Test Specimen Made with Natural and Recycled Aggregates ........................................................................................................... 22
Figure 4: Comparison Between Splitting Tensile Strength of Test Specimen Made with Natural and Recycled Aggregates ........................................................................................................... 22
Figure 5: Modulus of Elasticity as a Function of Water Cement Ratio of Original and Recycled Aggregate Concrete ......................................................................................................................... 24
APPENDIX

Use Guidelines and Provisional Special Provisions for:

- Recycled Concrete Pavement Incorporating RPCC Aggregates
- RPCC Aggregate in Rip-Rap and Rock-Lining
- RPCC Aggregates in Gabions
- RPCC Aggregate in Miscellaneous Drainage
EXECUTIVE SUMMARY

This report is intended to facilitate the material use approval process of Reclaimed Portland Cement Concrete (RPCC) aggregates by the Pennsylvania Department of Transportation (PENNDOT) as an alternative to conventional aggregates in select applications. At many transportation project sites in Pennsylvania, the cost of construction may be potentially reduced by utilizing RPCC materials.

This report presents an overview of the significance of the properties, limitations and proposed specifications for the use of RPCC in cement concrete, rip-rap, gabion, and miscellaneous drainage applications. In 2001, under the Transportation Materials Partnership Research Program, Lehigh University and Howard University were contracted by PENNDOT’s Bureau of Planning and Research (Contract #359630, Work Order #5) for the Development of Product and Materials Use Approval for Reclaimed Portland Cement Concrete for State and Local Projects. Additionally, laboratory trials of RPCC mixture designs were conducted by Lehigh University [Sabnis, 2001]. Lehigh University’s report was used as a starting point for this report that was subsequently revised by Apex Environmental, Inc., for the SEM Program Office.

The literature review indicated that RPCC aggregates are being used in several applications in several states. Existing information on the properties of RPCC aggregates and recycled concrete made with these aggregate blends was reviewed. For example, the Federal Highway Administration (FHWA) has published user guidelines on the use of RPCC materials in several applications, including concrete pavements, base courses, subbase courses, and drainage applications. Some studies have been conducted on the actual field performance of RPCC materials, predominantly on highway pavement reconstruction projects. Information was limited for other applications.

In general, RPCC materials have significant potential as substitutes for conventional materials in many applications. Perhaps the most obvious and least sophisticated of these applications is the use of RPCC as embankment fill. On the other end of the application spectrum, RPCC materials can be used to produce high quality concrete with proper quality control procedures. RPCC materials also have the engineering properties which allow for direct substitution in other engineering applications such as miscellaneous drainage, gabion and rip-rap. Provisional special provisions for these applications are presented in the Appendix.
1.0 BACKGROUND

1.1 Sources of Reclaimed Portland Cement Concrete (RPCC)

Each year approximately 4.6 billion tons of solid (non-hazardous) waste is generated in the United States. As the volume of waste and byproduct materials and the cost of disposal continue to rise, there is increased motivation to recover and recycle these materials in secondary applications. All states have adopted legislation aimed at recycling certain types of non-hazardous wastes, with 40 percent of the states instituting mandatory recycling. Reusing such materials reduces disposal volumes and conserves natural resources. Apart from regulatory mandates, economic incentives to recycle are stronger today than ever, especially with the significant increases to waste disposal and transportation costs.

The National Cooperative Highway Research Program (NCHRP) summarized the recycling and use practices of waste materials and byproducts in highway construction [Collins et al., 1994]. The study noted that of the total solid waste generated, industrial waste is estimated to account for 350-400 million tons per year. Industrial waste streams include coal ash, blast-furnace, steel mill and non-ferrous slags, foundry wastes, construction and demolition debris, highway pavement, and other waste streams. The largest industrial waste category, reclaimed asphalt pavement (RAP), is estimated to be approximately 100 million tons per year. Coal ash, another large industrial waste category, represents approximately 72 million tons per year. Demolition debris, cement and lime kiln dust and industrial slags each ranged from 16 to 24 million tons per year.

Construction and demolition (C&D) debris and broken concrete pavement are potential sources of RPCC. C&D debris is generated at approximately 25 million tons per year, while removed concrete pavement constitutes a smaller, but significant portion of this waste stream, at 3 million tons per year.

Highway construction requires large quantities of materials and likewise generates a high quantity of solid waste. For highway and bridge construction only, over 2 billion tons per year of crushed stone, sand, and gravel are consumed [Yrjanson, 1989]. The increased expense of transporting raw materials and diminished localized supplies (particularly in urban areas) are additional factors that encourage the use of recycled materials in highway applications. Thus, highway agencies have become frequent participants in efforts to recycle or reuse diverse waste materials.
1.2 Current Use of RPCC Materials

In 1991, FHWA conducted a comprehensive survey of state highway and environmental agencies on recycling and use of waste materials and by-products in highway applications. Agencies were asked for feedback on research, specifications and the use of more than two dozen different waste materials and industrial by-products. The findings were published in the NCHRP Synthesis of Highway Practice Report No. 199 [Collins et al., 1994].

Experience in using reclaimed materials varies considerably. Some materials have been actively used for many years, such as reclaimed asphalt pavement (RAP), while others are in various phases of experimental research, testing and development. Recycled materials often provide unique or improved engineering properties when viewed in the context of the desired engineering function. Examples of such materials are silica fume, which when used as an admixture to Portland cement concrete, provides a denser, more impermeable mix that attains significantly higher compressive strength and corrosion resistance. Class F fly ash is a partial replacement for Portland cement in concrete mixes and is an admixture in low strength controlled material, i.e., flowable fill. The fly ash has been shown to increase the workability and sulfate resistance of concrete, while simultaneously reducing the alkali-silica reactivity and the heat of hydration.

Among the materials surveyed as part of the NCHRP study were RPCC materials from three main source categories: concrete pavement, C&D debris and broken concrete. Table 1 provides an overview of research, specifications and use of RPCC materials [Collins et al., 1994]. Though substantial, state research and use of RPCC materials in asphalt pavement (recycled asphalt pavement or RAP) are not presented in Table 1, as it is not the focus of this report.

Table 1 - Overview of state research, use and available specification on various RPCC materials
[adapted from Collins et al., 1994]

<table>
<thead>
<tr>
<th>STATE</th>
<th>PAVING &amp; BUILDING DEBRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reclaimed Concrete Pavement</td>
</tr>
<tr>
<td>Arizona</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>California</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>Colorado</td>
<td>Aggregate base coarse (R,U,S)</td>
</tr>
<tr>
<td>Connecticut</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>Delaware</td>
<td>Embankment borrow (R,U)</td>
</tr>
<tr>
<td>STATE</td>
<td>PAVING &amp; BUILDING DEBRIS</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td><strong>Reclaimed Concrete Pavement</strong></td>
</tr>
<tr>
<td>Iowa</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>Kansas</td>
<td>Concrete aggregate (R,U,S)</td>
</tr>
<tr>
<td>Louisiana</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>Missouri</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>Montana</td>
<td>Concrete aggregate (S)</td>
</tr>
<tr>
<td>Nebraska</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>New Jersey</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>New York</td>
<td>Recycled pavement (R)</td>
</tr>
<tr>
<td>North Dakota</td>
<td>Aggregate base coarse (U)</td>
</tr>
<tr>
<td>Ohio</td>
<td>Aggregate base coarse (U)</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>Concrete aggregate (S)</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Concrete aggregate (R,U)</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>Subbase materials (U)</td>
</tr>
<tr>
<td>South Carolina</td>
<td>Aggregate base coarse</td>
</tr>
<tr>
<td>South Dakota</td>
<td>Recycled pavement (U)</td>
</tr>
<tr>
<td>Texas</td>
<td>Aggregate base coarse (R,U)</td>
</tr>
<tr>
<td>Wyoming</td>
<td>Concrete aggregate (R,U,S)</td>
</tr>
</tbody>
</table>

Note: Only reclaimed concrete applications were included in this table, with the exception on asphalt pavement uses.

Reclaimed concrete pavement has been researched and used for highway base and subbase material and as concrete aggregate, as shown in Table 1. As reported by the American Concrete Pavement Association (ACPA), roughly 3 million tons of concrete pavement are recycled annually [Collins et al., 1994].

Other sources of RPCC materials, such as C&D debris, are predominantly used in embankment, rip-rap and subbase applications [Yrjanson, 1989]. The NCHRP study estimated that approximately 20 to 30 million tons of C&D debris are generated annually in the United States. C&D debris is routinely crushed and processed into aggregate made of concrete, bricks, glass and old asphalt at processing locations, mainly in large metropolitan locations.

As part of the FHWA survey, state agencies were also asked to provide information on existing recycled material specifications. State specific or detailed specifications were not included in the NCHRP report. However, some state DOTs were contacted to obtain copies of specifications and were interviewed on recycled material use practices. Table 1 also identifies the states that have adopted RPCC material specifications in selected applications [Collins et al., 1994]. Based on the age of this study, it is likely that the list of states and number of specification to date has expanded. In Europe, Denmark, Germany, the Netherlands and France have active programs promoting the use of recycled materials in road construction applications [FHWA, 2000].

In 1999, Germany reported an overall 35 percent recycling rate of industrial waste into road construction applications. Blast furnace slag and steel slag is 92-100 percent recycled in such applications as embankments, backfilling, soil stabilization, and bases with and without hydraulic binders. Power plant residual wastes are recycled at a rate of 75-100 percent. Other wastes recycled in highway applications include: 6.6 million tons of recovered asphalt; and, approximately 16.5 million tons of crushed road materials and rubble.

The Netherlands’s recycling program captured and reused 73 percent of its total generated waste in 1999. One hundred percent of asphalt concrete (8.5 million tons) and asphalt rubble (3.3 million tons) were reused in road applications. Other waste streams recycled into highway construction include blast furnace slag (83 percent recycled) for cement production, and building and demolition waste (10 million tons) were used for new base courses.

France recycles old pavements (estimated at 1.1-2.2 million tons in 1999) as wearing courses and base materials, demolition materials are used as aggregates, and 20-25 percent of all generated blast furnace slag and coal fly ash are reintroduced in road construction.
1.3 Recycling of RPCC

Portland cement concrete is formed from a hardened mixture of Portland cement, water, fine and coarse aggregates, air and admixtures. The plastic mix is placed and consolidated in the formwork or on prepared surfaces, and then is cured to facilitate the chemical hydration reaction of the water/cement mix, resulting in hardened concrete. The finished product has high compressive strength predominantly provided by the aggregates and hardened cement paste. Well-graded fine and course aggregates comprise approximately 60 to 80 percent of the total volume of cement concrete. Hardened concrete typically has a low tensile and shear strength. As such, tensile and shear reinforcement is typically added in sections of structures to provide adequate tensile and shear strength, when needed.

As mentioned earlier, RPCC is generated from recycled concrete elements of roads, runways, buildings and other structures (sidewalks, utility excavation or demolition operations). Moreover, ACPA estimated that approximately 6,000 tons of concrete could be reclaimed from every mile of demolished concrete pavement [Collins et al., 1994]. RPCC also results from cleanup operations associated with natural disasters such as earthquakes, avalanches and other structural failures.

RPCC generated from the demolition and crushing of concrete structures typically results in similar elements as the original concrete: coarse and fine aggregates, mortar, steel reinforcements and possibly deleterious materials, depending on its source. Deleterious materials are typically introduced into RPCC during the demolition or collection process. For example, RPCC generated from road demolition operations may include subbase soil materials and elements of asphalt pavement. RPCC generated from the demolition of building structures may contain reinforcement steel, commingled wood, gypsum (plaster), glass and other structural elements. If the exact source of RPCC is unknown, or if it is from mixed sources, specific handling approaches or processing may be required to control the quantity and type of deleterious materials. To date, most studies on RPCC materials from mixed demolition rubble have focused on sulfate bearing materials such as gypsum plaster. Deleterious materials are of relevance for RPCC intended for new concrete applications, but are of little importance for applications such as backfill, rock lining, and gabion fill, except for esthetic reasons. However, when the source of RPCC is known, deleterious materials and their potential effects on the final RPCC application can be anticipated and mitigated. Experience has shown that by implementing some simple procedures during the demolition and collection process, the quantity of deleterious materials can be minimized. This is especially applicable for reclaimed concrete pavement, where large quantities of practically homogeneous material is generated, thus improving the recycling value of the RPCC [Yrjanson, 1989].

Over the years, the recycling of concrete pavements and other elements has become more cost competitive due to the development of improved methods and equipment for processing concrete pavements, crushing, and removal of steel reinforcement and deleterious materials [Yrjanson, 1989]. Some challenges include:
Effective removal of asphalt top courses to expose the underlying concrete pavements.
Several methods have been used by different state highway agencies to effectively remove asphalt pavement from the underlying concrete courses [Yrjanson, 1989]. Asphalt pavement is typically crushed by diesel hammers, removed by backhoes and motor graders with front-end loaders. Some projects required several passes of equipment to completely remove the asphalt course. Additionally, brooming of exposed concrete courses has been conducted to minimize introducing asphalt materials in the collected RPCC.

Selection of most effective concrete slab-fracturing and removal equipment.
The first pavement breakers featured pile-driving hammers mounted onto the rear of backhoes or loaders. Most highway demolition projects still use conventional pavement breakers such as diesel hammers that fractures old concrete slabs at predetermined impact strengths and intervals, shattering the slabs into manageable pieces. After the old slab is sufficiently fractured, a "rhino horn" (a large curved pointed hard-steel picker tooth) mounted on a hydraulic excavator is used to remove reinforcement from the shattered concrete by pulling the tooth up and through the concrete. Minimal collection of underlying subbase soils can be achieved using standard equipment. Hydraulic shears are also used to cut and pull out loose steel reinforcement. Cutting torches may be employed to cut the exposed steel from the concrete rubble. Crushed slabs are then loaded into dump trucks for transport to RPCC processing facilities.

Effective screening and stockpiling of crushed RPCC.
Generally, the same engineering principles apply to storing and stockpiling of RPCC materials as with conventional aggregates. The moisture adsorption and possible alkaline solutions (elevated pH) associated with RPCC aggregates will be discussed in later sections.

Generation of RPCC from other sources, such as construction and demolition projects varies by project, but similarly, demolition of concrete structural elements is done by impact hammers, or other crushing equipment, such as wrecking balls. Embedded steel is removed during crushing operations. Occasionally wrecking balls have been used to further break concrete pieces into more manageable sizes.

1.4 Production of RPCC Aggregates
Once concrete rubble or RPCC, regardless of source, is broken in manageable pieces, it is transported to a crushing and screening facility. Facilities or plants for the production of RPCC are similar to those plants for production of virgin aggregates. Production facilities incorporate various types of crushers, screens, transfer equipment, and various devices used for removal of foreign matter. In general, concrete crushing plants may be classified as first or second generation processing plants.
First generation plants typically have no facilities removal of deleterious materials, with the exception of reinforcing steel and other ferrous materials. Accordingly, first generation plants are more suited for processing relatively clean RPCC, such as crushed highway concrete slabs. Removal of foreign matter is mechanically or manually accomplished before crushing, and by cleaning the crushed product by dry or wet classification. If non-highway sources of RPCC are being processed, the incoming RPCC will likely contain foreign matter as metal, wood, hardboard, plastics, cladding and roofing materials.

Second generation processing plants typically incorporate debris removal steps. Figure 1 shows a flow diagram of a second generation processing plant. Large concrete pieces from demolition sites are typically reduced to a maximum size of 16-28 inches (0.4-0.7 m). Large pieces of steel, wood, plastics, and paper are removed by hand. The materials are then sent over a primary screen (scalping screen) to remove dirt, gypsum and other fine materials, and are then crushed by a primary crusher (jaw or impact type). Following the primary crushing step, the RPCC materials are passed through magnetic separators to remove ferrous materials. Secondary crushing, washing and screening then remove lightweight materials such as plastic, paper, wood and gypsum. Processed RPCC aggregates usually contain less than one percent impurities, which is considered good enough for new road construction applications, although not for all concrete applications (i.e., prestressed concrete, lightweight, structural grade concrete). Typically, RPCC aggregates produced from highway pavement are usually clean enough to meet specifications for concrete aggregates without additional washing.

Jaw crushers have been found to provide the best grain-size distribution of recycled aggregate for concrete production, while cone crushers are found to be suitable as secondary crushers [Hansen, 1985]. Impact crushers generally provide better grain-size distribution of aggregate for road construction purposes. A Japanese study conducted on crushers concluded that physical properties of recycled aggregates such as specific gravity, water absorption, sulfate soundness, and Los Angeles abrasion loss percentage were not significantly influenced by crushers types and crusher settings [summarized in Hansen, 1985]. However, the same study also concluded that grain-size distribution was strongly influenced by the use of different crushers. Although difficult to compare, some equipment (concrete shredders) produced almost twice as much material finer than 4.8 mm (undesirable) for the same maximum size of produced coarse recycled aggregates (25 mm) compared to jaw crusher results. The balance between coarse aggregate production and minimize fines production can be optimized by adjusting crushers and settings.
Figure 1 - Flow Chart of Typical Secondary Generation Processing of Building and Demolition Waste (from ACI-555-94)

Selective Demolition
(reduce individual fragments of broken concrete to a maximum of 16-28 in.)

Separate storage of concrete, brick rubble, and mixed demolition debris which is heavily contaminated with wood, iron, plastics and gypsum

Manual or Mechanical Pre-screening
(removal of large pieces of paper, wood and plastics)

Primary Screening
(removal of all minus 0.5 in. fine material such as soil, gypsum and etc.)

Primary Crushing

Magnetic Separation
(removal of remaining ferrous matter)

Secondary Screening

Manual or Mechanical Removal of Remaining Contaminants
(removal of lightweight matter such as plastics, paper and wood)

Secondary Crushing

Washing, Screening or Air-sifting
(removal of remaining contaminants such as plastics, paper, wood and gypsum)

Fraction of concrete demolition waste and brick rubble less than 1.5 in.

Final Screening
(into size fraction according to customer’s requirement)
2.0 PROPERTIES OF RPCC MATERIALS

This Chapter presents an overview of the engineering properties of RPCC aggregates.

2.1 Grading of RPCC Aggregates

The crushing characteristics of hardened concrete are not significantly different from those of natural rock, and are essentially independent of the original recycled concrete’s quality over a wide range of water-cement ratios [Hansen, 1985]. The linear particle size distribution used to predict crushed natural rock sizes (Figure 2) is also applicable for predicting RPCC gradations.

Table 2 shows the gradation results of RPCC aggregate undergoing a one-pass jaw crusher during experimental testing [modified from Hansen, 1985]. As shown, a well-graded coarse aggregate distribution can be obtained. Highway reconstruction projects have been successful in achieving desirable gradations of RPCC materials using conventional aggregate processing equipment [FHWA, 1997]. Of course, crushing characteristics depend on the selected crusher just as with any aggregate production. Typically, as with conventional aggregate production, impact crushers and swing hammer mills have higher reduction factors than jaw or cone crushers. With the selection of the appropriate crusher settings, RPCC aggregates can meet the same gradation distributions as natural aggregates.
Crushed RPCC aggregates are more angular and coarser than crushed natural rock. According to Hansen [1985], fine RPCC aggregates (<5 mm in diameter) are somewhat more coarse and angular than natural sands. This can cause difficulties during mixing of the fresh concrete made with fine RPCC aggregates. However, demonstration projects in several states have overcome this problem by substituting the RPCC fines with natural sands.

### 2.2 Storage and Stockpiling

The methods and equipment used to store and stockpile RPCC are the same as for conventional aggregates. Sound engineering controls should be similarly applied, such as segregating and storing larger and smaller aggregates separately to minimize "in process segregation," which occurs when different size particles are stockpiled together. Coarser aggregates tending to roll down the side of a stockpile and accumulate at the bottom of the stockpile, leaving finer aggregates in the center. For use of RPCC aggregates in rip-rap, gabion fill or backfill applications this is not an issue. However, it is recommended to separately store RPCC aggregates generated from different concrete sources or crushing methods to ensure uniformity of RPCC aggregate properties when intended for concrete applications [FHWA, 1997]. Currently, the Minnesota Department of Transportation is the only organization that provides guidelines of segregating and storing of RPCC materials [Chesner, 2001].
FHWA, in its *User Guidelines for Waste and By-Product Materials in Pavement Construction* [1997] recommends that RPCC collected from different sources or types of concrete be blended with other aggregates, or be separately processed and placed in stockpiles to ensure uniformity of RPCC aggregate properties.

### 2.3 Physical Properties of RPCC Aggregates

Processed RPCC aggregates normally yield consistent physical properties. Variations in physical and mechanical properties of crushed RPCC aggregates will largely be based upon the source of recycled concrete. For example, aggregate from precast concrete is typically smaller in size, and aggregates from construction projects may contain higher levels of deleterious substances. This section presents typical physical properties of RPCC aggregates.

**Shape**

Processed RPCC aggregates are more angular in shape and coarse than crushed natural rock, due in part to the adhesion of mortar to the aggregates from the original concrete, resulting in a rougher surface texture [Hansen, Ref. 4]. The shape of the original aggregate particles also influences the shape of RPCC aggregates. Most RPCC aggregates appear to fracture in the crushing process in such a manner as to produce block, or non-flat and elongated particles [Chesner, 2001].

When RPCC aggregates are targeted for new concrete applications, it should be noted that both the particle shape and surface texture RPCC aggregates have a significant influence on the workability of the new concrete mix and the properties of the new concrete. Specifically, rough textured, angular, or elongated particles require more water to produce workable concrete than smooth, rounded, compact aggregates, and as a result, these mixes require more cementing materials to maintain the same water-cement ratio. As with conventional aggregates, when angular or poorly graded aggregates are used, the produced concrete may be more difficult to pump and finish [FHWA, 1997]. One candidate solution calls to limit the use of RPCC fine aggregates in new cement mixes, while other solutions altogether substitute fine RPCC aggregates with natural sand [Hansen, 2001].

On the other hand, the same angular properties allow RPCC aggregates to interlock well in granular base and other applications. RPCC aggregate provides good load transfer when placed on weaker subgrade and high frictional strength. Rip-rap and other lining applications benefit from this property.
Specific Gravity
Specific gravity is a measure of material density, and it affects the unit weight of porous media. RPCC aggregates typically have a lower specific gravity than conventional aggregates and as aggregate size decreases, there is a corresponding decrease in the specific gravity and increase water absorption in comparison to similarly-sized conventional aggregates. This is due to the adhesion of the mortar to the aggregates. Studies have shown that approximately 20 percent of the old mortar remains attached to coarse RPCC aggregates. Fine RPCC aggregates contain an estimated 45 to 65 percent of the old mortar component [Hansen, 1985]. Fine RPCC aggregates (passing 4.75 mm (No. 4) sieve) are particularly affected, while coarser aggregates are less affected. As would be expected, the strength characteristics of recycled concrete can be affected by the adhering mortar, especially on the finer RPCC aggregate fractions.

Table 3 lists several properties for coarse and fine RPCC aggregates [Hansen, 1985]. One advantage of the lower specific gravity of RPCC aggregates (lower compacted unit weight) compared with conventional mineral aggregates is higher yield (greater volume for the same weight) of produced aggregate.

<table>
<thead>
<tr>
<th>Property</th>
<th>Recycled Concrete Material</th>
<th>Test Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse Particles (16 to 32 mm)</td>
<td>Coarse: 2.2 to 2.5</td>
<td>ASTM C127; AASHTO T85</td>
</tr>
<tr>
<td>Fine Particles (4 to 8 mm)</td>
<td>Fine: 2.0 to 2.3</td>
<td>ASTM C128; AASHTO T84</td>
</tr>
<tr>
<td>Density (SSD) kg/m³</td>
<td>Coarse: 2,430 to 2,490 kg/m³</td>
<td>ASTM C127; AASHTO T85</td>
</tr>
<tr>
<td></td>
<td>Fine: 2,310 to 2,340 kg/m³</td>
<td>ASTM C128; AASHTO T84</td>
</tr>
<tr>
<td>Absorption, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse Particles</td>
<td>2 to 6</td>
<td>ASTM C127; AASHTO T85</td>
</tr>
<tr>
<td>Fine Particles</td>
<td>4 to 8*</td>
<td>ASTM C128; AASHTO T84</td>
</tr>
<tr>
<td>Magnesium Sulfate Soundness Loss, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse Particles</td>
<td>Coarse: ≤ 4</td>
<td>ASTM C88;</td>
</tr>
<tr>
<td>Fine Particles</td>
<td>Fine: &lt; 9</td>
<td>AASHTO T104</td>
</tr>
</tbody>
</table>

ASTM C88 – Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
* Values as high as 11.7 have been detected.
Density
Studies show that generally the density of RPCC aggregates is somewhat lower than the density of conventional aggregates. As with specific gravity, this property is due to the low density of the old mortar attached to original aggregate particles [Hansen, 1985]. However, the density of RPCC aggregates is not found to vary widely, even for a wide range of water-cement ratios in the original concrete. When RPCC aggregates are intended for use in new concrete mixes, the saturated surface dry (s.s.d.) density should be tested according to ASTM C127 or C128.

Absorption
Higher water absorption is one of the most marked differences between the physical properties of RPCC and conventional aggregates. The noticeable increase of absorption is due to the higher absorption properties of the adhering mortar. Fine RPCC aggregates are especially affected because old mortar is attached in higher percentages to its surfaces. Some studies have shown that approximately 20 percent of the old cement paste is attached to 20-30 mm RPCC aggregates, while the 0-0.3 mm fraction (fine) RPCC aggregates contain 45-65 percent mortar [Hansen, 1985]. Because of high absorption characteristics, fine RPCC aggregates are often precluded from use in new concrete applications, thus limiting the amount of water extracted from the design mix. An alternative approach is to presoak RPCC aggregates before mixing in new concrete applications. RPCC applications sensitive to absorption characteristics should be tested according to ASTM C127 or C128.

2.4 Durability of RPCC Aggregates

Los Angeles Abrasion
The Los Angeles (LA) abrasion loss test procedure (AASHTO T 96-68 – Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals) is used to measure the resistance to abrasion of coarse aggregates. It is expressed as a percentage of the original mass of the test sample. The LA abrasion loss ranges from 22 to 41 percent for RPCC coarse aggregates derived from high and low strength parent concrete, respectively. On average, the LA abrasion loss percentage ranges from 25 to 45 percent for RPCC aggregates, somewhat higher than for high-quality conventional aggregates. Concrete aggregates may not exceed a LA abrasion of 50 percent for use in Portland cement concrete for highway applications per AASHTO TP33. Chesner [2001] reports that several state DOTs have specified LA abrasion requirements for coarse RPCC aggregates intended for use in Portland cement highway applications, ranging from maximum limits of 40 to 50 percent. A six-year Long Island, NY study of uncontrolled stockpiles of RPCC aggregates intended for use as a granular subbase or base, revealed that physical properties including LA abrasion loss fell within predictable and acceptable ranges [FHWA, 1997]. Table 4 shows some typical mechanical properties of RPCC materials.
Table 4 - Typical Mechanical Properties of Recycled Concrete Materials [FHWA, 1997]

<table>
<thead>
<tr>
<th>Properties &amp; Test Procedures</th>
<th>Material</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural Aggregate</td>
<td>Recycled Aggregate</td>
</tr>
</tbody>
</table>
| LA Abrasion, %               | 20 to 25          | 20 to 45        | ASTM C131  
| Coarse Particles            |               |                | ASTM C33  
|                              |               |                | AASHTO T96-681 |
| Magnesium Sulfate Soundness Loss, % | ≤ 3 | ≤ 4 | ASTM C88  
| Coarse Particles            | 6 to 8          | < 9            | AASHTO T104 |
| Fine Particles              |                |                |              |
| California Bearing Ratio (CBR), % | 130 to 180  | 94 to 148      | PTM 106* |

ASTM C131 – Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals  
* PTM – Pennsylvania Test Method

Sulfate Soundness

The durability of aggregates, a measure of the aggregate’s freeze-thaw resistance, is monitored for aggregates used in concrete applications. ASTM C33 involves exposing an aggregate to five cycles of alternate soaking and drying in an aqueous sulfate or magnesium sulfate solution and establishes weight loss limits to the aggregates. When sodium sulfate solutions are used, a maximum 12 percent weight loss (for coarse aggregates) and 10 percent weight loss (for fine aggregates) is acceptable per ASTM T104. For magnesium sulfate solutions, 18 percent and 15 percent limits are allowed, respectively for coarse and fine aggregates, per ASTM T104. The average magnesium sulfate soundness loss of RPCC coarse aggregates using ASTM C33 was found in the range of 4 percent or less [FHWA, 1997]. The corresponding loss in fine RPCC aggregates was noted less than 9 percent, well within allowable limits. Overall, studies on the durability characteristics of RPCC aggregates show comparable results to conventional aggregates [Hansen, 2001].

Some problems have been encountered in using sulfate solutions on RPCC aggregates. The mortar on RPCC aggregates is susceptible to sulfate attack, thus overstating the susceptibility of the aggregate to freeze-thaw degradation. The exact cause is still undetermined, but several factors have been suggested including, type of aggregates used in concrete, type of Portland cement, amount of mortar still adhering to RPCC aggregates, or even reactions occurring between the solid phase and sulfate solutions. More representative results were obtained with magnesium sulfate solutions, although there were some problems with this test also [Chesner, 2001]. Alternatively, the weathering and durability characteristics of RPCC aggregates may be evaluated using cycles of wetting, freezing or thawing. These approaches include ASTM C88 and AASHTO T103.
Alkali-Silica or Alkali-Carbonate Reactivity

The potential for certain aggregate types to react with the alkali components present in Portland cement to form expansive compounds is widely documented [FHWA, 1997] and includes alkali-silica reactivity, alkali-carbonate reactivity that manifests itself in D-cracking (see below). Limited information is available on the effect RPCC aggregates may have on new concrete applications. Chesner [2001] recommends RPCC aggregates be tested for potential alkali reactive aggregates if it is a standard requirement for conventional aggregates. Test method ASTM C289 is recommended for alkali-silica reactivity testing. Alternatively, Type II cement can be used to limit or mitigate future reactivity in new concrete applications. [Hansen, 1985].

D-Cracking of Cement Concrete Pavement

D-cracking is a form of pavement distress caused by poor-quality aggregates that absorb moisture and deteriorate through freeze-thaw action. Sulfate and chloride ions and alkali-reactive aggregates can promote D-cracking to occur in concrete pavements. Thus, these impurities must be controlled to ensure the finished concrete has consistent strength and durability characteristics. Studies show that the durability of new concrete made with RPCC aggregates taken from D-cracked concrete shows substantial improvement in D-cracking resistance [Yrjanson, 1989].

Chloride Ions

RPCC aggregates produced from highway construction may be impacted by deicing salts. Chloride ions may also be entrained in the original fresh concrete by accelerating admixtures, poorly washed marine aggregates or desert sand. Chloride ions induce corrosion of steel. As such, it is recommended that RPCC aggregates be tested for chloride ion content. A threshold value of 2.4 kg/m$^3$ (4 lbs/yd$^3$) has been recommended by ACPA. The quantity of chloride typically found in old concrete pavement is below critical threshold values [Hansen, 1985; Yrjanson, 1989].

Alkalinity

The old mortar component of RPCC aggregates has a substantial influence on RPCC's alkalinity. Cement paste, or mortar, consists of a series of calcium-aluminum-silicate compounds, including calcium hydroxide [Ca(OH)$_2$], which is highly alkaline. The pH of RPCC-water mixtures can exceed 11. Elevated pH may induce corrosion of aluminum or galvanized steel pipes placed in direct contact with RPCC materials in the presence of moisture, though this is no different than would be encountered with fresh concrete. Elevated pH should be taken into consideration when RPCC aggregates are used as fill materials or placed directly in contact with aluminum or galvanized piping. However, Ca(OH)$_2$ is often used as soil stabilizing agent. Furthermore, some jurisdictions (Ontario, Canada) have restricted stockpiling and placement of RPCC crushed materials near watercourses to minimize the impact of the alkaline leachate on water quality.
3.0 CONCRETE PROPERTIES WITH RPCC AGGREGATES

This Chapter presents an overview of the properties of recycled concrete made with various blends of RPCC aggregates. It also presents the difference between concrete made from conventional and RPCC aggregates.

3.1 Strength of RPCC Concrete

Compressive strength characteristics of concrete made with RPCC aggregates are influenced by several main factors: the strength of the original concrete, the composition of RPCC aggregates in the new concrete; properties of the RPCC aggregates, and the water-cement ratio. It is generally accepted that the cement paste from the original concrete that has adhered to the RPCC aggregates (especially the fine RPCC aggregates) plays an important role in the performance of the concrete made with RPCC aggregates. Studies show that recycled concrete generally produced lower compressive strengths than control mixes of concrete made with conventional aggregates. The loss in compressive strength ranged from 10 to 25 percent, with some test results showing strength loss as high as 39 percent. Fine RPCC aggregates were identified as a significant contributor to the loss of recycled concrete’s compressive strength, an important factor if targeted for new concrete applications. However, when tests were conducted on concrete made when some or all RPCC fine aggregate was substituted by natural sand, the compressive strengths of this recycled concrete substantially improved, and in some cases exceeded the strengths of the concrete made with conventional aggregates [Hansen, 1985].

Table 5 shows the results of a series of compressive strength tests conducted on three original concretes (low, medium and high strength) made with conventional aggregates and with RPCC aggregates from the same original samples.
Table 5 - Compressive Strength of Original and Recycled Aggregate Concretes
After 38 Days of Accelerated Curing [adapted from Hansen, 1985]

<table>
<thead>
<tr>
<th></th>
<th>Compressive Strength of Concrete using Natural and Recycled Aggregate Concrete, MPa, (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>56.4 (8.870)</td>
</tr>
<tr>
<td>H/H</td>
<td>61.2 (8.870)</td>
</tr>
<tr>
<td>H/M</td>
<td>58.5 (8.790)</td>
</tr>
</tbody>
</table>

Legend:
H = High Strength Concrete made using natural aggregate (w/c=0.40)
M = Medium Strength Concrete made using natural aggregate (w/c=0.70)
L = Low Strength Concrete made using natural aggregate (w/c=1.20)
H/H = High Strength Concrete made with recycled aggregate from high strength concrete
H/M = High Strength Concrete made with recycled aggregate from medium strength concrete
H/L = High Strength Concrete made with recycled aggregate from low strength concrete
*,** = Original low concrete and corresponding higher strength recycled concrete
NA = For H/M, L/H and L/M, there were only one set of values

The results show that the compressive strength of concrete using RPCC aggregates is dependent on the strength of the original concrete. Also, Hansen [1985] stated that the strength is also largely controlled by the water-cement ratio of the original concrete and the water-cement ratio of the RPCC concrete when other factors were essentially identical. It is interesting that concrete made with RPCC aggregates produced higher compressive strengths than the original concrete, when using a lower water-cement ratio (see * in Table 5).

Hansen [1985] reports a study conducted by Rasheeduzzafar and Khan [1984] that generally confirms these findings. High-strength concrete (40 MPa or higher) was produced from a medium-strength (23 MPa) coarse recycled aggregate. When the fine RPCC aggregates were removed and substituted with natural fine aggregates, the strength of recycled concrete exceeded the original concrete.

Table 6 illustrates that the recycled concrete compressive strength was negatively affected by RPCC fines in controlled samples at different water-cement ratios [Hansen, 1985].
Other studies suggest that recycled concrete made with coarse RPCC aggregates blended with natural fine aggregates had higher compressive strengths than concrete incorporating only RPCC aggregates [Hansen, 1985]. As such, it appears advantageous to eliminate or limit the use of fine RPCC aggregates. For example, Hansen [1985] recommends that all fine materials below 2 mm (0.08 in.) be excluded from concrete mixes.

Results presented in Table 7 imply that there may not be great variations in the compressive strengths of RPCC concrete under controlled laboratory conditions and using selected sources of RPCC aggregates. However, in practice, a larger variation is compressive strengths may be observed due to variations in water absorption capacities of RPCC aggregates. Presoaking RPCC aggregates is one method to minimize the variability of compressive strengths.

### Table 6 – Compressive Strength of Natural and Recycled Aggregate Concrete Made from the Same Original Concrete Using Recycled Coarse Aggregate and Various Proportions of Recycled Fine Aggregate and Natural Sand [adapted from Hansen, 1985]

<table>
<thead>
<tr>
<th>Water Cement Ratio</th>
<th>Natural coarse and fine aggregate</th>
<th>Recycled coarse aggregate and 100% natural sand</th>
<th>Recycled coarse aggregate, 50% recycled fine aggregate, and 50% natural sand</th>
<th>Recycled coarse aggregate and 100% recycled fine aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>37.5 (5,446)</td>
<td>37.0 (5,360)</td>
<td>34.0 (4,930)</td>
<td>30.0 (4,350)</td>
</tr>
<tr>
<td>0.55</td>
<td>28.9 (4,190)</td>
<td>28.5 (4,130)</td>
<td>25.0 (3,620)</td>
<td>21.5 (3,120)</td>
</tr>
<tr>
<td>0.68</td>
<td>22.0 (3,190)</td>
<td>21.0 (3,040)</td>
<td>17.5 (2,540)</td>
<td>13.0 (1,880)</td>
</tr>
</tbody>
</table>
Table 7 – Compressive Strengths of Recycled Aggregate Concrete Produced From Concrete of Varying Quality [Hansen, 1985]

<table>
<thead>
<tr>
<th>Water Cement Ratio of Original Concrete</th>
<th>Compressive Strength of 15 year old Concrete, MPa (psi)</th>
<th>Water Cement Ratio of Concrete with Recycled Aggregate</th>
<th>Compressive Strength of Concrete with Recycled Aggregate at 28 Days, MPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.53</td>
<td>75.1 (10,900)</td>
<td>0.57</td>
<td>49.1 (7,120)</td>
</tr>
<tr>
<td>0.67</td>
<td>51.5 (7,470)</td>
<td>0.57</td>
<td>40.3 (5,840)</td>
</tr>
<tr>
<td>0.65</td>
<td>59.3 (8,600)</td>
<td>0.57</td>
<td>43.1 (6,250)</td>
</tr>
<tr>
<td>0.80</td>
<td>38.9 (5,640)</td>
<td>0.57</td>
<td>38.0 (5,510)</td>
</tr>
<tr>
<td>0.50</td>
<td>73.1 (10,600)</td>
<td>0.57</td>
<td>47.4 (6,870)</td>
</tr>
<tr>
<td>0.59</td>
<td>62.4 (9,050)</td>
<td>0.57</td>
<td>43.3 (6,280)</td>
</tr>
<tr>
<td>0.65</td>
<td>37.9 (9,850)</td>
<td>0.57</td>
<td>41.8 (6,040)</td>
</tr>
<tr>
<td>0.81</td>
<td>42.1 (6,100)</td>
<td>0.57</td>
<td>32.0 (4,640)</td>
</tr>
<tr>
<td>0.50</td>
<td>61.9 (8,980)</td>
<td>0.57</td>
<td>39.8 (5,700)</td>
</tr>
<tr>
<td>0.50</td>
<td>84.8 (12,300)</td>
<td>0.57</td>
<td>36.8 (5,340)</td>
</tr>
<tr>
<td>0.53</td>
<td>73.4 (10,600)</td>
<td>0.57</td>
<td>44.0 (4,380)</td>
</tr>
<tr>
<td>0.50</td>
<td>64.1 (9,240)</td>
<td>0.57</td>
<td>35.2 (5,100)</td>
</tr>
</tbody>
</table>

Tavakoli and Soroushian [1996] reported the properties of RPCC aggregates and concrete made of RPCC aggregates on two paving projects (U.S. 22 and I-75 projects in Michigan). All fine recycled aggregates were substituted with natural aggregates. Compressive, splitting tensile, and flexural strengths were compared between concrete made with coarse RPCC aggregates and concrete made using natural crushed stone. Some conclusions of these studies are:

Recycled aggregate concrete may have higher compressive strength than the control concrete if the compressive strength of the original concrete is higher than the control concrete (conventional aggregate).

Higher LA abrasion and water absorption values were associated with RPCC aggregates, generally attributed to the properties of adhering mortar to RPCC aggregates.

The compressive strength of recycled concrete was reduced, and this was partly attributed to the presence of old mortar component on RPCC aggregates.

Splitting tensile and flexural strengths of recycled aggregate concrete can be higher or lower than those of the natural concrete, depending on the water-cement ratio and dry mixing period, and;

The basic trends in behavior of field-demolished RPCC aggregate are not significantly different from those of the laboratory-made recycled aggregate as far as compressive, tensile, and flexure strengths are concerned.
Lehigh University also completed compressive and tensile strength tests on conventional and recycled concrete samples. Four 8-inch standard cylinders were prepared according to ASTM C33 and using a 0.45 water-cement ratio (by weight) as an average and typical value for both RPCC and conventional concrete mixes. Curing times were 3, 7, 14, and 28 days for compressive and tensile strength testing as specified in ASTM C39 and ASTM C496, respectively. Table 8 summarizes the compressive strength and splitting tensile strength data. The compressive strengths of the RPCC concrete samples were consistently higher than the concrete made with natural aggregate, while the splitting tensile strength of recycled concrete was slightly lower, approximately 4 percent less than the natural aggregate specimens in a 28-day testing period.

<table>
<thead>
<tr>
<th>Specimen Age (days)</th>
<th>Compressive Strength (psi)</th>
<th></th>
<th>Splitting Tensile Strength (psi)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RPCC</td>
<td>Natural</td>
<td></td>
<td>RPCC</td>
</tr>
<tr>
<td>3</td>
<td>4,334</td>
<td>3,562</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>7</td>
<td>5,100</td>
<td>4,203</td>
<td>498</td>
<td>519</td>
</tr>
<tr>
<td>14</td>
<td>5,385</td>
<td>4,748</td>
<td>518</td>
<td>537</td>
</tr>
<tr>
<td>28</td>
<td>5,975</td>
<td>4,974</td>
<td>545</td>
<td>563</td>
</tr>
</tbody>
</table>

Figures 3 and 4 show an explicit gain in strength from 3 to 28 days for both concretes. One explanation of the early RPCC concrete strength gain is attributed to the old mortar acting as a good bonding agent between the RPCC aggregates and new cement paste. Test results show that the RPCC concrete is comparable in strength to conventional concrete, and that the RPCC aggregates satisfy the requirements of ASTM C33.
Figure 3 – Comparison Between 28-day Compressive Strength of Test Specimen Made with Natural and Recycled Aggregate

Figure 4 – Comparison Between 28-day Splitting Tensile Strength of Test Specimen Made with Natural and Recycled Aggregate
3.2 Tensile and Flexural Strength

Research on the tensile and flexural strength of recycled concrete is limited. Most studies report insignificant differences between flexural strength for recycled and conventional concretes [Hansen, 1985]. The tensile strength of RPCC concrete is generally reported slightly lower (10 to 20 percent) than concrete made with conventional aggregates.

3.3 Modulus of Elasticity, Creep

The Modulus of Elasticity ($E$) is a measure of the inherent rigidity or stiffness of a material. Materials with a large $E$ deforms less under the same loading conditions. Hansen [1985] summarizes a Japanese study that found $E$ to be lower in RPCC concrete when compared with control concrete samples, see Figure 5. RPCC concrete made of both fine and coarse RPCC aggregates has the largest reduction in $E$, followed by RPCC concrete made with coarse RPCC and natural fine aggregates. Hansen [1985] reports similar results, where the average $E$ was found to be 25 to 40 percent lower for concrete made with fine and coarse RPCC aggregates compared to concrete made with conventional aggregates. When the fine RPCC aggregates were replaced by natural fine aggregates (keeping the coarse RPCC aggregates), the average $E$ was reduced by only 10 to 30 percent compared to concrete made with conventional aggregates. As the old mortar and fine RPCC aggregate fractions increase, there is a corresponding decrease in $E$. 
Studies of the creep of RPCC concrete are limited. Hansen [1985] summarized that the creep of RPCC concrete is typically found to be 30 to 60 percent higher than measured in conventional concrete. As creep is proportional to the mortar content in a concrete, it can be expected that creep will be the highest when both fine and coarse RPCC aggregates are used.

### 3.4 Durability and Frost Resistance

Concrete permeability is probably the key factor in determining the durability of structural concrete. Studies have shown that RPCC concrete generally has a higher permeability compared to comparable control samples based on measured water absorption values. As discussed earlier (Section 1.3) the old mortar fraction adhering to RPCC aggregates plays a large role in the recycled concrete's water absorptive qualities. However, studies also indicated that by controlling the RPCC concrete's water-cement ratio and RPCC aggregate fractions, a comparative permeable RPCC concrete can be produced.

NCHRP reports that the freeze-thaw resistance of concrete made from RPCC aggregates exceeds those of concrete made with conventional aggregates [Yrjanson, 1989]. Concrete made with RPCC aggregates taken from a pavement that exhibited D-cracking also outperformed the original concrete in the same application.
4.0 DISCUSSIONS ON PROVISIONAL SPECIFICATIONS DEVELOPMENT

Chapters 2 and 3 presented the engineering properties of RPCC aggregates and concretes made with various blends of conventional and recycled materials. When specifications are considered, the differences between conventional and RPCC aggregates and concretes must be understood within the context of the intended application. For example, in order to use RPCC aggregates in concrete mixes one must take into consideration a broad range of factors including both in RPCC aggregate properties and the design mix criteria to produce a quality concrete. Care must be taken when using concrete with RPCC aggregates for use in structural concrete where E and creep are principal design considerations, i.e., beams. However, there are many examples in which high compressive strength and modulus are not required, such as embankment material, backfill, rip-rap, etc. Here, concrete strength and rigidity has little bearing on its functionality and performance.

Discussions on RPCC aggregate use in concrete, rip-rap, gabion, and miscellaneous drainage applications are presented below. Based on this information, Appendix A provides Use Guidelines and Provisional Special Provisions for each application listed above. This chapter presents the discussion, rationale and justifications for the development of the Provisional Special Provisions.

4.1 RPCC Aggregates Used for Recycled Cement Concrete Pavement

FHWA endorses the use of RPCC materials in reconstruction projects. RPCC aggregates have been used since 1975 in state highway projects. The FHWA published a report summarizing a review and findings of eight state highway projects in which cement concrete pavements were reclaimed in highway reconstruction projects [Yjranson, 1989]. Most documented uses of RPCC aggregates have been in normal weight Portland cement concrete. A consistent finding is that fine RPCC aggregates (passing 4.75 mm (No. 4) sieve) should be restricted or excluded from recycled concrete mixes due to potential problems.
Material Handling of RPCC Materials

RPCC materials collected from different sources or types of concrete should be either blended with other aggregates, or separately processed and placed in stockpiles to ensure uniformity of RPCC aggregate properties (specific gravity, percentage of non-RPCC materials, absorption). The same methods and equipment used to store or stockpile conventional aggregates are applicable for RPCC materials.

Segregating and Stockpiling

Currently, only Minnesota DOT requires for smaller and larger RPCC aggregates to be separately stockpiled to avoid "in process segregation". Aggregate sizes susceptible to segregations, such as #357 and #467, can be separated during storage as a best practice method - allowing a better controlled gradation of selected aggregate sizes when blending operations are considered.

The moisture content of RPCC aggregate stockpiles should be monitored to identify concrete water requirements. Sprinkling RPCC aggregate stockpiles is an effective method of minimizing their potential to absorb moisture from the concrete mix [FHWA, 1997].

RPCC aggregates may exhibit higher pH values than conventional aggregates. If so, care should be given to the selection of storage locations in order to minimize stormwater runoff impacting waterways. Ontario (Canada) has restricted stockpiling RPCC aggregates near watercourses [Chesner, 2001].

Blending RPCC aggregates with Other Aggregates

Practice and research has shown that RPCC blending can be successfully completed, but satisfactory workability and improved quality (higher compressive strength and higher resistance to D-cracking) can be obtained [Hansen, 1985; Tavakoli et al., 1996; Yjranson, 1989]. A pre-submitted blend combination, and defined blending percentage of any combination of natural or different sources of RPCC aggregates are recommended. Any changes in blending will require a revised mix design. Mechanical interlock blending or conveyor belt blending of aggregates are recommended techniques.

Gradation of RPCC aggregates

Most states have stipulated the same gradation requirements for RPCC aggregates as for natural aggregate materials [Chesner, 2001]. Studies and demonstration projects have shown that processing plants have the ability to produce any desired gradation [Collins et al., 1985].

Fines and Deleterious Components

Across the board, State DOTs have restrictioned the inclusion of fines (less than 75 µm (No. 200 sieve) within cement concrete applications. AASHTO M80 is considered the most appropriate requirement, setting limits of no more than 1.0 percent material finer than 75 µm (No. 200 sieve), unless the fines are
generated as part of the crushing process, in which case this limit is increased to 1.5 percent by some states [Chesner, 2001].

The presence of deleterious materials may affect desired concrete quality. FHWA [1997] stipulates that aggregate should be free of potentially deleterious materials such as clay lumps, shales, or other friable particles, and other materials that could affect its chemical stability, weathering resistance, or volumetric stability. ASTM C40, ASTM 295, ASTM C142, and ASTM D2419 are listed as appropriate testing procedures. Accordingly, RPCC aggregates should be limited to no more than 0.3 percent (by mass) of deleterious materials such as vegetable matter, plastics, plaster, paper, gypsum board, metals, fabrics, wood brick, tile, glass and bituminous materials, in accordance with ASTM C295. Mixes containing coarse RPCC aggregates and natural sand produce the most desirable characteristics [Hansen, 1985]. It appears prudent to exclude fine RPCC aggregates (passing 4.75 mm (No. 4) sieve) from concrete designs. Fine RPCC aggregate should be substituted with natural sand [Hansen, 1985].

**Shape**
The original aggregate source predominantly dictates the RPCC aggregate shape. Crushed RPCC aggregates are typically more coarse and angular in shape than conventional aggregates. FHWA [1997] identifies no ASTM or AASHTO limits for flat and elongated particles for RPCC aggregates.

**Specific Gravity**
The specific gravity of RPCC aggregates is typically lower than with conventional aggregates in the range of 2.0 to 2.5, primarily due to the adhesion of old mortar to the RPCC aggregates. Fluctuations in specific gravity are undesirable because concrete is batched on the principle of weighing the components. Potential variation can affect the yield of the mix, cement factor and the engineering properties of the cement concrete mixture. Chesner [2001] reports that specific gravity be monitored and controlled either through a source approval method or through the monitoring the properties of fresh Portland cement concrete, including yield, to determine if specific gravity various result in property changes. Standard practices of batch weight adjustment should be followed. Use ASTM C128/AASHTO T84 to test the specific gravity of coarse RPCC aggregates.

**Absorption**
Absorption of RPCC aggregates is higher than that of conventional aggregates because of the old mortar content. As discussed in Chapter 2, this property is particularly noticeable with fine RPCC aggregates (passing 2.36 µm (No. 8) sieve). Absorption of coarse RPCC aggregates is less pronounced and is reported to be in the 2 to 6 percent range. Natural aggregates typically have an absorption value of less than 2 percent. High absorption values will result in elevated water demands during the mixing process. Chesner [2001] and FHWA [1997] recommend that RPCC aggregates be saturated with water for a
sufficient time before introduction in the concrete mix. Saturation by sprinkling system or other approved methods has been recommended. FHWA [1997] recommends using ASTM C128/AASHTO T84 or equivalent to test and monitor the absorption values of RPCC aggregates.

**LA abrasion**
Los Angeles abrasion has been estimated to be in the range of 25 to 45 percent for RPCC aggregates. This is lower than the ASTM C33 limit of 50 percent for conventional aggregates, and therefore it can be expected that RPCC aggregates can meet these standard limitations. ASTM C535 or equivalent may be used to test LA abrasion loss in RPCC aggregates, if desired.

**Durability**
Many states have established freeze-thaw (soundness) criteria for RPCC aggregate [Chesner, 2001]. However, FHWA reports that RPCC aggregates typically exhibit good soundness characteristics and have similar properties as conventional aggregates [1997]. Using traditional testing methods, ASTM C88/AASHTO T104 on RPCC aggregates may not yield representative results [Chesner, 2001].

**Chloride Ions**
RPCC aggregates produced from highway demolition may contain chloride ions from deicing salts. Presence of chloride ions may lead to corrosion of steel. Connecticut and New York DOT agencies have set maximum permissible chloride content values of 0.5 lb/cu yd and 0.6 lbs/cu yd, respectively, as specified in AASHTO T260, or equivalent test method [Chesner, 2001]. Michigan, Minnesota and Wisconsin DOTs adopted the 2.4 kg/m³ (4 lbs/cu yd) chloride threshold value as recommended by the American Concrete Pavement Association (ACPA) [Hansen, 1985].

**Alkali-Silica or Alkali-Carbonate Reactivity**
The potential for certain aggregate types to react with alkali components in Portland cement to form expansive compounds is widely documented. This includes alkali-silica reactivity, alkali-carbonate reactivity resulting in D-cracking; and other unwanted manifestations. RPCC materials from unknown sources may be alkali-silica reactivity tested based upon judgment of the engineer. Suggested testing methods include: AASHTO T299, AASHTO T303, ASTM C295, ASTM C289, ASTM C342, ASTM C441, ASTM C589, ASTM C666 and ASTM C856.

**RPCC Concrete Design Mix Guidelines**
In principle, the same mix methods can be applied to recycled concrete as with conventional concrete. Experience has shown that RPCC concrete can use conventional approaches for batching, mixing, transporting, placement, compaction and finish. Close monitoring of the compressive strength variability,
water-cement ratio, and presence of deleterious materials may be required [Hansen, 1985]. Some modifications are recommended when designing the recycled concrete mix, and are presented below:

When natural sand is used in lieu of fine RPCC aggregates in a design mix, it may be assumed that the free water-cement ratio for a required compressive strength is the same as with conventional concrete. However, if trial mixes show a lower compressive strength, the water-cement ratio must be increased.

Base the mix design on the measured density of the RPCC aggregates.

Adjust the free water content in trial mixes to obtain the required slump.

A maximum RPCC aggregate size of 0.75 to 1.5-inches may be required to obtain satisfactory freeze-thaw resistance.

Use the same sand to (RPCC) aggregate ratio as with conventional concrete mixes.

Expect more variation of compressive strength between mixes when using RPCC aggregates produced in a processing facility which accepts concrete rubble from many different demolition sites simultaneously.

If fine RPCC aggregates are used in the concrete mix, limit fine RPCC aggregates to 30 percent of all fine aggregate (sand) portion. Otherwise, concrete may result in lower compressive strength and be difficult to work with.

Prewet RPCC aggregates to minimize their absorption of water from the concrete mix.

Conduct screening of RPCC aggregates to minimize sulfate and chloride ion contamination.

**Quality Control**

The same quality control procedures for conventional concrete are required for concrete made with RPCC aggregates. The slump, air content, and temperature of the plastic concrete should be monitored at the time of placement, and compressive strength cylinders cast for compressive strength determinations in ASTM C39. Flexural strength and splitting tensile tests should be conducted, as appropriate. Due to the sensitivity of concrete pavement performance and durability to water-cement ratio, and the potential variability of RPCC gradation, specific gravity, and absorption, particular attention should be given to these RPCC aggregate properties in concrete pavement mixtures, and the mixing water component should be adjusted accordingly.

4.2 **RPCC Aggregates Used for Rip-Rap or Rock Lining**

Well-graded rock has been traditionally used in rip-rap or rock lining applications. Table 1 (in Section 1.2) shows that several state DOTs (Colorado, Kansas, Missouri and New York) use RPCC concrete aggregates in rip-rap or rock lining applications. This material must demonstrate satisfactory quality requirements such as good bearing strength, durability, angularity and should be relatively free of foreign substances.
Materials suited for these applications are typically larger in size (anywhere from 2 to 40 inches in size). Coarse fractions of RPCC aggregates can meet these quality performance standards.

The maximum dimensions of RPCC aggregates is controlled by its original pour dimensions. PENNDOT’s Publication 408, Section 850 stipulates a 1:3 size aspect ratio for rock applications (neither width nor thickness less than one-third its length). For practical purposes, RPCC aggregates will fall into Rock Class R-3 through R-5 size, although if blended with rock, can meet the R-3 through R-8 rock size classifications.

As RPCC materials are processed, depending on its source, foreign substances such as asphalt, soil, gypsum and other materials may be present. New York DOT limits foreign substances to 5 percent by weight (NYDOT Specification Sections 203 and 304). Missouri DOT stipulates a maximum limit of 10 percent for earth, sand, shale and non-durable rock content (MODOT Specification Section 611.30).

PENNDOT Pub. 408, Section 850 specifies a minimum specific gravity of 2.5 for rock lining materials. Coarse RPCC materials have been shown to typically have specific gravities in the 2.2 to 2.5 range, owing to the old mortar component still attached to the RPCC aggregates. RPCC aggregates typically should exhibit their original (old concrete application) bearing capacity and durability characteristics, and thus meet the performance criteria of this application. In addition, RPCC aggregates, because of their old mortar component may even exhibit greater angularity, adding to their interlocking behavior.

In a typical rock lining configuration, geotextiles are first placed along areas in ground contact. Rocks are then placed over the geotextiles in specified nominal layers. RPCC aggregates (of the sized used for rock lining) may still contain embedded reinforcement bars or mesh. Exposed steel reinforcement can puncture and tear geotextiles. For this and aesthetic reasons, New York DOT limits the exposed length of reinforcement to 25 mm (1 inch) in rock lining applications. For RPCC aggregates placed directly next to geotextiles no exposed reinforcement should be present. Exposed reinforcement in RPCC in small amounts should not structurally affect the application. However, due to aesthetics it is recommended that RPCC aggregates be visually screened for reinforcement and the exposed length steel be limited to a maximum of 25 mm (1 inch) for all RPCC aggregates used in these applications.

### 4.3 RPCC Aggregates Used for Gabions

RPCC aggregates can fully meet the physical and quality requirements for gabion applications. RPCC aggregates are durable and well draining. No information was found on the use of RPCC materials as gabion fill. RPCC aggregates are non-plastic and are not susceptible to frost.
Due to its potential high alkalinity, RPCC aggregates may result in corrosion to galvanized steel materials, such as gabion wire mesh, when exposed to moisture [FHWA, 1997]. Therefore, RPCC aggregates should be screened for alkalinity, with a recommended acceptable pH value range of 5-10. Alternatively, use RPCC aggregates only with corrosion resistant gabions.

### 4.4 RPCC Aggregates Used for Miscellaneous Drainage

RPCC aggregates are suitable for use in miscellaneous drainage applications. RPCC materials can fully meet the physical and quality requirements for this application as specified for PENNDOT Pub. 408, Section 703.2, Type C, No. 1 and No. 57 coarse aggregates. RPCC aggregates are highly angular, durable and well draining. RPCC aggregates are non-plastic and are not susceptible to frost.

Due to its potential high alkalinity, RPCC aggregates can potentially result in corrosion to galvanized steel materials, such as galvanized steel piping. Therefore, it is recommended that RPCC aggregates not be placed in areas that would be unacceptable for fresh concrete due to pH considerations.

RPCC aggregates may still contain remains of embedded reinforcement bars or mesh. Minimal quantities of reinforcement would not structurally impair the purpose of its use, however, due to aesthetic reasons it is recommended that RPCC aggregates be visually screened for reinforcement and limit the exposed length of reinforcement to 25 mm (1 inch) for all RPCC aggregates used in these applications.

### 4.5 Other Applications of RPCC

Flowable backfill, also known as Controlled Low-Strength Material (CLSM) has been developed as an alternative to conventional backfill. The American Concrete Institute (ACI) has defined CLSM as a self-compacting, cementitious material primarily used as backfill in lieu of compacted fill [PENNDOT, 1985]. CLSM is composed of aggregate, cementitious material and water. Often, fly ash is incorporated into the mixture to increase flowability and pore refinement and to increase the cementitious content of the mixture. RPCC aggregates can be used in substitution of the conventional aggregates. Currently, PENNDOT has developed four types of flowable fill, Special Provision (SP) Item 9220-Flowable Backfill (PENNDOT, 1995). Pub. 408, Section 703.2, Types B and C aggregates allows the use of bottom ash or coarse aggregate or fine aggregates.
5.0 REFERENCES


AASHTO M6-81, Fine Aggregate for Portland Cement Concrete
AASHTO M43, Sizes of Coarse Aggregate for Highway Construction
AASHTO M80, Coarse Aggregate for Portland Cement Concrete
AASHTO T27, Sieve Analysis of Fine and Coarse Aggregate
AASHTO T84, Specific Gravity and Absorption of Fine Aggregate
AASHTO T85, Specific Gravity and Absorption of Coarse Aggregate
AASHTO T96-681, Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
AASHTO T103, Soundness of Aggregates by Freezing and Thawing
AASHTO T104, Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
AASHTO T260, Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials
AASHTO T299, Rapid Identification of Alkali Silica Reaction Products in Concrete
AASHTO T303, Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction
AASHTO TP33, Uncompacted Voids Content of Fine Aggregate


ASTM C33-02, Standard Specification for Concrete Aggregate
ASTM C39-01, Compressive Strength of Cylindrical Concrete Specimens
ASTM C40-99, Organic Impurities in Fine Aggregate for Concrete
ASTM C88-99, Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
ASTM C127-01, Standard Test Method for Specific Gravity and Absorption for Coarse Aggregates
ASTM C128-01, Standard Test Method for Specific Gravity and Absorption for Fine Aggregates
ASTM C131-01, Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
ASTM C136-01, Sieve Analysis of Fine and Coarse Aggregate
ASTM C142-97, Clay Lumps and Friable Particles in Aggregates
ASTM C289-02, Potential Alkali-Silica Reactivity of Aggregates
ASTM C295-98, Petrographic Examination of Aggregates for Concrete
ASTM C342, Potential Volume Change of Cement Aggregate Combinations
ASTM C441-97, Mineral Admixtures to Prevent Alkali Silica Reaction
ASTM C496-96, Splitting Tensile Strength of Cylindrical Concrete Specimens
ASTM C535, Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
ASTM C589, Potential Reactivity of Carbonate Aggregates
ASTM C666-97, Resistance of Concrete to Rapid Freezing and Thawing
ASTM C856-95, Petrographic Examination of Hardened Concrete
ASTM C1252-98, Uncompacted Voids Content of Fine Aggregates
ASTM D2419-95, Plastic Fines in Graded Aggregates and Soils by Use of the Equivalent Test
ASTM D3398-00, Index of Aggregate Particle Shape and Texture
ASTM D4791-99, Flat and Elongated Particles in Coarse Aggregate
ASTM T103, Soundness of Aggregates by Freezing and Thawing
ASTM T104, Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate

General Literature


Missouri Department of Transportation Specifications, available at [www.modot.state.mo.us](http://www.modot.state.mo.us).

New York State Department of Transportation Specifications, available at [www.dot.state.ny.us](http://www.dot.state.ny.us).


6.0 APPENDIX

Use Guidelines and Provisional Special Provisions
DATE: December 23, 2002

SUBJECT: Provisional Special Provision
Reclaimed Portland Cement Concrete Aggregates in concrete, rip-rap, rock-lining, gabion and drainage applications.

TO: DISTRICT ENGINEERS/ADMINISTRATOR

FROM: Gary L. Hoffman, P.E.
Chief Engineer
Highway Administration

Attached please find a special provision and use guidelines for Reclaimed Portland Cement Concrete Aggregates (RPCC) in concrete, rip-rap, rock-lining, gabion and drainage applications. RPCC has demonstrated satisfactory performance in these applications, and is currently used in twenty states (including AZ, CA, CO, FL, IA, IN, LA, MA, MD, MN, MI, NJ, NY, ND, OH, RI, SC and TX).

The provisional special provisions for RPCC in concrete, rip-rap, rock-lining, gabion and drainage applications have been issued as follows:

<table>
<thead>
<tr>
<th>Specification Version</th>
<th>Special Provision Number</th>
<th>ITEM NUMBERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPCC-concrete pavement</td>
<td>METRIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ENGLISH</td>
<td></td>
</tr>
<tr>
<td>RPCC rip-rap/rock lining</td>
<td>METRIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ENGLISH</td>
<td></td>
</tr>
<tr>
<td>RPCC-gabions</td>
<td>METRIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ENGLISH</td>
<td></td>
</tr>
<tr>
<td>RPCC-misc. drainage</td>
<td>METRIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ENGLISH</td>
<td></td>
</tr>
</tbody>
</table>

The provisional status of these provisional special provisions will allow the use of this type of product on projects in accordance with the attached guidelines. In the use of any provisional special provision, the District is requested to monitor performance and report any problems with the specification to the Engineering Technology and Information Division, Bureau of Construction and Materials at (717) 787-7287.

Use RPCC aggregates obtained in accordance with Publication 408, Section 703.2(a)7, or as otherwise approved by the MTD prior to use.
Any problems regarding environmental compliance of RPCC aggregates should be reported to the Chief Engineer’s Office, SEM Program Office, Pollution Prevention Division at (717) 783-3616. If you have any questions, please call Mr. Ken Thornton at (717) 783-3616.

c. M.M. Ryan, P.E.
   K.J. Thornton, P.G.
   J.A. Cheatham, P.E., FHWA
   A.C. Bhajandas, P.E.
   S.B Zimmerman
   D.A Schreiber, P.E.
   T.E. Bryer, P.E.
   R. J Peda, P.E.
   N. Krise
   District ADE’s for Design
   District ADE’s/ADA for Maintenance
   District ADE’s for Construction
   District Experimental Coordinators
   L.E. Holley, PADEP
Attached is a new Provisional Special Provision for the use of Reclaimed Portland Cement Concrete (RPCC) aggregate as coarse aggregate in normal, high strength, Portland cement concrete pavement.

RPCC aggregates are generated from crushing of concrete elements. RPCC aggregates closely resemble natural aggregates, except for a coating of old mortar. RPCC aggregates are more coarse and angular than natural aggregates and exhibit higher water absorption values and lower specific gravities. RPCC materials may contain elements of reinforced steel or mesh and other deleterious materials depending on its source. RPCC materials generated from concrete pavements may contain soil collected during removal and collection. Typically, RPCC aggregates produced from highway pavement are usually clean enough to meet specifications for concrete aggregates without further processing. Other RPCC sources, such as C&D debris, will likely contain metal, wood, hardboard, plastics, cladding and roofing materials. This requires other processing to remove deleterious materials. The RPCC supplier should certify that the processed RPCC aggregates contain deleterious materials less than 0.3 percent by weight (mass).

Fine RPCC aggregate (passing 4.75 mm (No. 4) sieve should be excluded and/or substituted by natural sand, or other approved material. RPCC aggregates produced from highway demolition may be adversely impacted by chloride ions from deicing operations. RPCC aggregates exceeding a chloride ion value of 2.4 kg/m³ (4 lbs/yard³) should be disallowed.

In principle, the same quality control and methods for batching, mixing, transporting, placement, compaction and finishing can be applied to recycled concrete, as with conventional concrete. The major design differences include replacing the fine RPCC aggregates with conventional aggregates, and closely monitoring the compressive strength variability, water-cement ratio, and deleterious materials.

Particular attention should be given to the specific gravity and absorption properties of the RPCC and to the water-cement ratio in concrete design mixtures. Trial mixes should be made to adjust the free water content necessary to obtain the required slump. Pre-wetting RPCC aggregates is recommended to minimize absorption of water from the concrete mix.

Until widespread experience is gained using RPCC aggregate in concrete designs statewide, this product will retain provisional status. Provisional status also requires the use of recycled concrete to be monitored by the District, and the Engineering Technology and Information Division (ETID), Bureau of Construction and Materials. Monitoring by the Districts will be limited to advising the ETID of where RPCC aggregates are used in recycled pavement and any problems encountered during construction, and of any problems observed during the life of the project. Monitoring is limited to visual inspection of the recycled concrete pavement, and should continue every six months over five years. If further experience gained by the Districts demonstrates a problem with the recycled concrete pavement, the Provisional Special Provision will be withdrawn immediately. Any problems regarding the engineering performance or environmental compliance of recycled concrete pavement should be reported to the Strategic Environmental Management (SEM) Program Office in the Chief Engineers Office at 717-772-0831.
RECYCLED CEMENT CONCRETE PAVEMENT INCORPORATING RECLAIMED PORTLAND CEMENT CONCRETE AGGREGATES

I. DESCRIPTION--  This work is the use of Reclaimed Portland Cement Concrete (RPCC) aggregate as a coarse aggregate in normal, high strength, Portland cement concrete pavement. Do not use RPCC aggregates in lightweight, high density, or other specialty Portland cement concrete applications.

II. MATERIAL – Section 704.1(b) and as follows:

(b) RPCC aggregate

1. Quality requirements – Section 703, Table B, Type A quality, and as follows:
   a. Provide RPCC aggregates with less than 0.3 percent (by mass) of deleterious material, including, but not limited to: vegetable matter, plastics, plaster, paper, gypsum board, metal, fabrics, wood brick, tile, glass and bituminous materials, in accordance with ASTM C295 or other acceptable methods.
   b. Provide RPCC aggregates with a maximum water absorption between 2 to 6 percent as determined by PTM 622, ASTM C27 (AASTHO T27) or other acceptable method. Pre-wet RPCC aggregates to a saturated surface dry condition prior to use.
   c. Provide RPCC aggregates with a minimum specific gravity of 2.0. Provide specific gravity and bulk specific gravity measurements in accordance with PTM 506 (ASTM C127, AASHTO T85) and PTM 507, respectively.
   d. Provide RPCC aggregates with a maximum chloride ion value of 2.4 kg/m$^3$ (4 lbs/yd$^3$) according to AASHTO T260.

2. Gradation - Section 703.2, Table C. Eliminate RPCC materials passing the 4.75 mm (No. 4) sieve, or replace with natural sand or other materials suitable for concrete mix design.

III. DESIGN BASIS – Section 704.1(c)

IV. TESTING AND ACCEPTANCE – Section 704.1(d)

V. MEASUREMENT OF MATERIAL – Section 704.1(e)

VI. MIXING CONDITIONS – Section 704.1(f)

VII. REVIEW OF QUALITY CONTROL PLAN – Section 704.1(g)

VIII. MIXING DESIGNS USING POTENTIALLY REACTIVE AGGREGATE – Section 704.1(h)

IX. MEASUREMENT OF MATERIAL – Section 704.1(e)
Attached is a new Provisional Special Provision for the use of Reclaimed Portland Cement Concrete (RPCC) aggregate as an alternate material for rock in rip-rap or rock lining applications.

RPCC aggregates are generated from crushing of concrete elements. The main sources of RPCC aggregates are: concrete pavement, and construction and demolition (C&D) debris. RPCC materials typically contain reinforced steel or mesh and other deleterious materials, depending on its source, which can effectively be removed.

Coarse RPCC aggregates are suitable for use in this application and can meet quality performance standards of Section 850 - Rock Lining. The maximum dimension of produced RPCC aggregate is generally controlled by its original concrete pour dimensions. For practical purposes, RPCC aggregates will likely fall into Rock Classes R-3 through R-5, although when blended with rock, can meet R-3 through R-8 rock size classifications.

Limit foreign substances in RPCC aggregate to a maximum of 5 percent, by weight. RPCC aggregates have specific gravities in the 2.2 to 2.5 range, slightly lower than natural aggregates, owing to the old mortar component still attached to the surfaces of processed RPCC aggregates. This property should not affect performance in this application, as the RPCC aggregates usually exhibit their original bearing capacity and durability characteristics, and may exhibit better interlocking due to their greater angularity.

Place no RPCC materials with exposed steel reinforcements or mesh in direct contact with geotextiles because exposed reinforcement can puncture and tear geotextiles. For other areas limit exposed reinforcement to 25 mm (1 inch) length for aesthetic reasons.

Until widespread experience is gained using RPCC aggregate in rip-rap or rock lining applications statewide, this product will retain provisional status. Provisional status also requires the use of RPCC material to be monitored by the District, and the Engineering Technology and Information Division (ETID), Bureau of Construction and Materials. Monitoring by the Districts will be limited to advising the ETID of where RPCC aggregates are used in rip-rap or rock lining applications and any problems encountered during construction, and of any problems observed during the life of the project. Monitoring is limited to visual inspection of the rip-rap or rock lining, and should continue every six months over five years. If further experience gained by the Districts demonstrates a problem with the application, the Provisional Special Provision will be withdrawn immediately. Any problems regarding the engineering performance or environmental compliance should be reported to the Strategic Environmental Management (SEM) Program Office in the Chief Engineers Office at 717-772-0831.
I. DESCRIPTION – This work is the construction of rip-rap or rock lining using Reclaimed Portland Cement Concrete (RPCC) aggregate.

II. MATERIAL – Section 850.2, and as follows:

(a) RPCC aggregate.

Provide RPCC aggregates with less than 5 percent (by weight) of foreign materials.
Provide RPCC aggregates with a minimum specific gravity of 2.0.
Provide RPCC aggregates with exposed reinforcements or mesh less than 25 mm (1 inch) in length.
Provide RPCC aggregates with a pH greater than 5 and less than 10.

III. CONSTRUCTION – Section 850.3, Standard Drawings, and as follows:

Substitute RPCC aggregates for rock or blended with rock in all proportions. Do not place RPCC aggregates with exposed metal reinforcements in direct contact with geotextiles.

IV. MEASUREMENT AND PAYMENT – Section 850.4, and as follows:

(a) RPCC aggregate. Square Meter (Square Yard) or Cubic Meter (Cubic Yard)
USE GUIDELINES

RECLAIMED PORTLAND CEMENT CONCRETE AGGREGATES
IN GABIONS

Attached is a new Provisional Special Provision for the use of Reclaimed Portland Cement Concrete (RPCC) aggregate for fill of gabions.

RPCC aggregates are generated from crushing of concrete elements. The main sources of RPCC aggregates are: concrete pavement, and construction and demolition (C&D) debris. RPCC materials typically contain reinforced steel or mesh and other deleterious materials, depending on its source, which can effectively be removed.

Coarse RPCC aggregates are suitable for use in this application and can meet physical requirements of Section 626 - Gabions. The maximum dimension of RPCC aggregate is generally controlled by its original concrete pour dimensions. Coarse RPCC aggregates can easily meet the 75 mm (3 inches) to 200 mm (8 inches) size requirements.

Limit foreign substances in RPCC aggregate to a maximum of 5 percent, by weight. RPCC aggregates have specific gravities in the 2.2 to 2.5 range, slightly lower than natural aggregates, owing to the old mortar component still attached to the surfaces of processed RPCC aggregates. This property should not affect performance in this application, as the RPCC aggregates usually exhibit their original bearing capacity and durability characteristics, and may exhibit better interlocking due to their greater angularity.

Different materials are used for the gabion wire baskets, including steel (galvanized steel, zinc coated steel) or other corrosion resistant variant (polyvinyl coated). RPCC aggregates may exhibit higher pH values than conventional aggregates, acceptable range being 5 to 10. Due to RPCC’s alkalinity, RPCC aggregates may potentially contribute to corrosion of gabion wire mesh. Therefore, RPCC should be screened for alkalinity, or only be used with corrosion resistant gabions.

Until widespread experience is gained using RPCC aggregate in gabion applications statewide, this product will retain provisional status. Provisional status also requires the use of RPCC material to be monitored by the District, and the Engineering Technology and Information Division (ETID), Bureau of Construction and Materials. Monitoring by the Districts will be limited to advising the ETID of where RPCC aggregates are used in gabion applications and any problems encountered during construction, and of any problems observed during the life of the project. Monitoring is limited to visual inspection of the gabions, and should continue every six months over five years. If further experience gained by the Districts demonstrates a problem with the application, the Provisional Special Provision will be withdrawn immediately. Any problems regarding the engineering performance or environmental compliance should be reported to the Strategic Environmental Management (SEM) Program Office in the Chief Engineers Office at 717-772-0831.
I. DESCRIPTION – This work is the furnishing, assembling, and filling of open mesh wire baskets with Reclaimed Portland Cement Concrete (RPCC) aggregate, forming gabions of the type indicated.

II. MATERIAL – Section 626.2, and as follows:

(a) RPCC aggregate.

   Provide RPCC aggregates with less than 5 percent (by weight) of foreign materials.
   Provide RPCC aggregates with a minimum specific gravity of 2.0.
   Provide RPCC aggregates with exposed reinforcements or mesh less than 25 mm (1 inch) in length.
   Provide RPCC aggregates with a pH greater than 5 and less than 10.

III. CONSTRUCTION – Section 626.3

IV. MEASUREMENT AND PAYMENT – Section 626.4:

(a) RPCC aggregate. Cubic Meter (Cubic Yard)
Attached is a new Provisional Special Provision for the use of Reclaimed Portland Cement Concrete (RPCC) aggregate for miscellaneous drainage.

RPCC aggregates are generated from crushing of concrete elements. The main sources of RPCC aggregates are: concrete pavement, and construction and demolition (C&D) debris. RPCC materials typically contain reinforced steel or mesh and other deleterious materials, depending on its source, which can effectively be removed.

Coarse RPCC aggregates are suitable for use in this application and can meet Section 613 – Stone Backfill for Miscellaneous Drainage. The maximum dimension of RPCC aggregates is generally controlled by its original concrete pour dimensions, and can easily meet the AASHTO No. 1 and No. 57 gradation requirements.

Limit foreign substances in RPCC aggregate to a maximum of 5 percent, by weight. RPCC aggregates have specific gravities in the 2.2 to 2.5 range, slightly lower than natural aggregates, owing to the old mortar component still attached to the surfaces of processed RPCC aggregates. This property should not affect the performance in this application, as the RPCC aggregates usually exhibit their original bearing capacity and durability characteristics, and may exhibit better interlocking due to their greater angularity.

Place no RPCC materials with exposed steel reinforcements or mesh in direct contact with geotextiles because exposed reinforcement can puncture and tear geotextiles. For other areas limit exposed steel reinforcement to 25 mm (1 inch) length for aesthetic reasons.

Until widespread experience is gained using RPCC aggregate in miscellaneous drainage applications statewide, this product will retain provisional status. Provisional status also requires the use of RPCC material to be monitored by the District, and the Engineering Technology and Information Division (ETID), Bureau of Construction and Materials. Monitoring by the Districts will be limited to advising the ETID of where RPCC aggregates are used miscellaneous drainage applications and any problems encountered during construction, and of any problems observed during the life of the project. Monitoring is limited to visual inspection of the drainage application, and should continue every six months over five years. If further experience gained by the Districts demonstrates a problem with the application, the Provisional Special Provision will be withdrawn immediately. Any problems regarding the engineering performance or environmental compliance should be reported to the Strategic Environmental Management (SEM) Program Office in the Chief Engineers Office at 717-772-0831.
I. DESCRIPTION – This work is the furnishing and placing of Reclaimed Portland Cement Concrete (RPCC) aggregate for miscellaneous drainage.

II. MATERIAL – Section 613.2, and as follows:

(a) RPCC aggregate-- of the gradation indicated, and as follows:

Provide RPCC aggregates with less than 5 percent (by weight) of foreign materials.
Provide RPCC aggregates with a minimum specific gravity of 2.0.
Provide RPCC aggregates with exposed reinforcements or mesh less than 25 mm (1 inch) in length.
Provide RPCC aggregates meeting the requirements of Section 703.2, Type C quality.
Provide RPCC aggregates with a pH greater than 5 and less than 10.

III. CONSTRUCTION – Section 613.3, and as follows:

Do not place RPCC aggregates with exposed steel reinforcements or mesh immediately adjacent to geotextiles.

IV. MEASUREMENT AND PAYMENT – Section 613.4:

(a) RPCC aggregate. Cubic Meter (Cubic Yard)