Recycled Concrete Aggregate in Portland Cement Concrete

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Submitted By

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16. Abstract

Aggregates can be produced by crushing hydraulic cement concrete and are known as recycled concrete aggregates (RCA). This report provides results from a New Jersey Department of Transportation study to identify barriers to the use of RCA in new Portland cement concrete and to provide a recommendation as to whether this material should be permitted on Department of Transportation projects. The report includes a review of previous studies of RCA, a summary of the experiences of other transportation agencies with the material, and summary of the additional laboratory and field trials performed as a part of this study. A recommendation is made to allow RCA to be used in non-structural roadway applications. Recommended specifications are provided.

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EXECUTIVE SUMMARY

Diminishing supplies of natural coarse aggregates and increasing interest in sustainable design have motivated New Jersey Department of Transportation to investigate the use of crushed hydraulic cement concrete as a source of aggregate in new Portland cement concrete. The two likely sources of recycled concrete aggregates (RCA) are Class B recycling facilities currently taking in waste concrete and crushing it for use as roadway aggregate base and concrete precasting facilities that have an interest in crushing and reusing surplus material from the end of a production run and from damaged cast pieces. Prior to making a decision on whether to allow RCA to be used in concrete NJDOT required more information on the opportunities and barriers for use of this material.

The objective of this work was to study the barriers to the use of RCA in new PCC. As part of the study, recommendations were to be made regarding whether the material should be used, and recommendations and specifications developed for the use of RCA if its use is warranted.

The research approach included review of published literature on the use of RCA, review of the experiences from other state transportation agencies in North America, review of other state specifications, a limited laboratory program for evaluation of recycled aggregate samples and Portland cement concrete prepared from these samples, and field trials of concrete made with RCA. Results of the literature review, contacts with other STAs, evaluation of the regional recycled aggregate product, and results of field trials were used to develop specifications for the use of RCA in PCC.

Because there is an extensive body of literature already available, laboratory experimentation was limited. The purpose of any experimental laboratory work was to validate the RCA product available in the region is comparable to that used in previous studies so that those prior results may be extrapolated with confidence. Laboratory work was also used to determine the consistency of RCA stockpiles throughout the region, looking at both variability between sources and variability within a stockpile. Finally, laboratory work was performed to optimize mixes used in field trials. The field installations included as part of this work were limited to lower risk applications that allow the specifications and recommendations to be tested in a controlled manner.

As identified through the literature review, RCA is produced through the crushing of concrete pavements or other waste concrete after removal of any reinforcing steel. Required gradations are produced through crushing and screening in much the same way aggregates are produced from virgin materials. To be used as aggregate, RCA requires most of the same tests performed on virgin aggregates. However, important distinctions between RCA and virgin aggregates have been identified. The presence of cement paste or mortar adhering to the recycled aggregates reduces density, increases porosity, increases mix water demand, and increases drying shrinkage of PCC. It can also impact compressive strength and elastic modulus. An additional concern when Class B recycling facilities are to be the source of RCA is lack of knowledge of the source aggregates including susceptibility to alkali-silica reactivity. However, for each of the issues identified as potential problems when RCA is used, effective mitigation

measures were also identified and RCA is being used as a coarse aggregate for hydraulic cement concrete.

There are numerous examples cited in which RCA has been used in pavement concrete however most of the states allowing its use have limited the applications to nonstructural concrete such as curbs, gutters, and roadway barriers. Some require the source of the original aggregate of the RCA be known and all require a DOT approved source. Aggregate from a non-approved source can be used but only after comprehensive testing and by approval from the design engineer. Aggregate should be of a uniform quality throughout and be free from contaminants such as wood, clay, and steel rebar. The allowable contaminant level seems to vary from state to state but generally falls within a fixed range. In general, it is common that RCA should be only used to produce coarse aggregate. However, Texas does allow 20 percent replacement of fines providing the recycled fine fraction conforms to specified limits.

The laboratory testing performed for this project was primarily used to establish the range of properties that will be found for the RCA produced through the available sources in New Jersey. These measured properties were in line with values noted in published literature and had similar variability. The testing was also used to characterize the aggregate properties for the RCA that was used in the field trials.

As noted, the adhered mortar reduces the specific gravity and increases the absorption of RCA. The measured bulk dry specific gravity in this study ranged from 2.1 to 3.4 with an average of 2.35. The measured absorption ranged from 5 percent to 7 percent in the RCA tested. Measured residual mortar contents ranged from 23.4 percent to 39.2 percent with a mean value of 31.6 percent.

Initially the project team planned to use one of the Class B recycling facilities as the source for recycled concrete aggregates for the remainder of the lab and field trials. However, none of the facilities were willing to produce a #57 gradation for the project because they were set up for production of DGAB material and were regularly turning over their stockpiles of this material. As an alternative a mobile crushing unit was contracted to produce the material by crushing plant waste from the Modern Precast facility in Ottsville, Pennsylvania. Unfortunately, the screens were not properly set to produce a #57 aggregate. Instead the material was primarily bound by the 3/8" and 3/4" sieves and lacked smaller sizes. It was also noted there was observable contamination of the aggregate with small pieces of wood and plastic. It is assumed these came from the wagon wheels and other mechanisms used to hold rebar in position in the precast pieces the material originally came from. The research team was able to prepare acceptable concrete mixes (normal slump and self-consolidating) using this material and these mixes were used for field trials.

The field trials of concrete installations using RCA consisted of the following:

- A concrete apron was place March 18, 2011 (approximately 4 cubic yards)

- A twenty foot length of sidewalk was placed along Carpenter St. on the Rowan campus (5.5 cubic yards) using the RCA with slag mix on June 30, 2011 and a companion section of sidewalk with virgin aggregate was placed on July 2, 2011.
- A test slab was placed outside of Wilson Hall on the Rowan campus on August 2nd, 2011 with virgin aggregate and the companion slab using the RCA mix without slag was placed August 4th, 2011. Each of these was approximately 4.0 cubic yards.
- A test section using the RCA with slag mix was placed August 29th, 2011 outside Robinson Hall on the Rowan campus. This area was a placement of sidewalk with monolithic curb.
- A precast stormwater box, a pedestrian barrier, three parking bumpers, and four 6 ft x 6 ft x 8 in precast slabs were cast at Old Castle Precast, Holmdel, NJ on May 18, 2012.

The intention was that all of the cast-in-place items would be monitored for a period of at least a year with special interest in how they held up through winter freeze-thaw cycles and de-icing salt application. The winter of 2011-2012 was extremely mild and little de-icing salt was used on campus. Monitoring will continue beyond the end of the project. At this point all of the field installations are performing well.

Based on the work performed in this study the following recommendations are made

1. The New Jersey Department of Transportation should allow the use of recycled concrete as coarse aggregate for concrete.
2. Applications should be limited to non-structural or roadway concrete items, excluding surface and base courses. Precasting roadway concrete items with SCC using RCA should also be permitted.
3. Although many states require that the original source of the recycled concrete be known and that the original concrete met DOT standards, implementation of this standard would be problematic in New Jersey. A system of regional recycling centers has developed across the state that is currently supplying RCA for dense graded aggregate base and RAP for asphalt applications. The source of the concrete being recycled is not usually known and this requirement would force the recyclers to develop parallel crushing operations for traceable and non-traceable materials. It is doubtful the recycling centers would be willing or have the space to do this. This is not an issue for precast concrete operations electing to recycle their own waste concrete.
4. In cases of large pavement removal and replacement operations, reuse of the aggregates could be approved on a job basis with satisfactory test results of the recycled material.
5. Many authors suggested the many problems associated with the use of RCA were alleviated by limiting the aggregate replacement rate to 30 percent or less.

There is not a consensus on this and states are successfully allowing 100 percent replacement rates. It is suggested that no limit be placed on the replacement rate. Available supply of RCA will likely dictate whether contractors choose to use a blend of virgin aggregate and RCA or a 100 percent replacement. Precast facilities would likely use a blend.

6. An alternative mix design process has been proposed elsewhere with the claim that it eliminates many of the problems associated with using RCA in new concrete. In this project more traditional mix design methods worked well and the alternative mix design method should not be required.

7. Because of the unknown history of material reaching Class B recyclers, it is recommended that ASR mitigation methods be required for all mixes using RCA unless the source aggregate is known such as in the case of precasting operations.

8. Slabs fabricated with recycled aggregates could be used in a chloride ponding study to further evaluate long term durability of the material.

9. The precasting trials were promising and used 100 percent aggregate replacement. It would be instructive to blend recycled material and natural aggregates together. A blend of RCA and natural aggregate is a more realistic scenario in the precast environment.

Additions to existing NJDOT specifications are recommended in order to permit the use of crushed hydraulic cement concrete to be used as recycled concrete aggregate in new Portland cement concrete. The suggested specifications can be found in Volume 2 of this report.

BACKGROUND

In the state of New Jersey, diminishing virgin aggregate supplies has motivated the New Jersey Department of Transportation (NJDOT) to further investigate the use of recycled materials as aggregates for use of PCC. In recent years, sources of coarse aggregates in southern New Jersey have been diminishing, leading to an increased cost of transporting aggregates from other regions. In the past, demolished concrete would find its way to landfills as a waste product subject to high tipping fees. Currently, some waste concrete is diverted to Class B recycling facilities where it is crushed and used aggregates for roadway base courses. Potentially, these Class B recyclers could also be sources of recycled aggregates for use in Portland cement concrete. In addition, precast concrete producers have an interest in crushing and reusing surplus material from the end of a production run and from damaged cast pieces. As of 2005, 38 states recycled concrete as dense graded aggregate base for pavement; however, only 11 states recycled it as aggregate in new PCC. [1]

Currently, the NJDOT and many other states do not allow the use of recycled concrete aggregate (RCA) in new PCC. Some states have found that RCA provides engineering, economic and environmental benefits however approval for use of RCA in concrete requires testing and performance comparable to that of virgin aggregates. RCA is produced through the crushing of concrete pavements or other waste concrete after removal of any reinforcing steel. Required gradations are produced through crushing and screening in much the same way aggregates are produced from virgin materials. To be used as aggregate, RCA requires most of the same tests performed on virgin aggregates. However, important distinctions between RCA and virgin aggregates have led state transportation officials in New Jersey and much of the rest of the country to be cautious in the adopting RCA as an acceptable aggregate for PCC. The presence of cement paste or mortar adhering to the recycled aggregates reduces density, increases porosity, and increases drying shrinkage of PCC. Additional concerns include problems with the quality of the original concrete being recycled, and the presence of contaminants.

OBJECTIVES

The objective of this work was to study the barriers to the use of RCA in new PCC. As part of the study, recommendations were to be made regarding whether the material should be used, and recommendations and specifications developed for the use of RCA if its use is warranted.

INTRODUCTION

In order to achieve the project objectives a series of tasks were identified and included literature reviews, collection of experiences from other state transportation agencies in North America, review of other state specifications, laboratory evaluation of recycled aggregate samples and Portland cement concrete prepared from these samples, and field trials of concrete made with RCA.

The research identifies the benefits and barriers to the use of recycled concrete as aggregate in PCC through literature reviews and discussions with state transportation agencies currently using this material. Because there is an extensive body of literature already available, laboratory experimentation was limited. The purpose of any experimental laboratory work was to validate the RCA product available in the region is comparable to that used in previous studies so that those prior results may be extrapolated with confidence. Laboratory work was also used to determine the consistency of RCA stockpiles throughout the region, looking at both variability between sources and variability within a stockpile. Finally, laboratory work was performed to optimize mixes used in field trials.

The field installations included as part of this work were limited to lower risk applications that allow the specifications and recommendations to be tested in a controlled manner. Field trials included various slabs cast on the campus of Rowan University and precast elements including a culvert box, a safety barrier, parking bumpers, and slabs. These field trials are continuing to be monitored beyond the end of the original project period.

Results of the literature review, contacts with other STAs, evaluation of the regional recycled aggregate product, and results of field trials were used to develop specifications for the use of RCA in PCC.

SUMMARY OF THE LITERATURE REVIEW

General Background (Sources of RCA)

Natural aggregates can vary from source to source depending on the age, the geographic location, the method of processing and impurities present, and the mineralogy of the source. Hardened concrete that has been crushed and reused as an aggregate in new concrete mixes is referred to as recycled concrete aggregate (RCA). Because recycled aggregates originate from a multitude of sources, the most common source being demolition projects of pavements and buildings [2], there will be variability in the properties of RCA. Whether the demolition is domestic or industrial, the composition and characteristics of recycled concrete aggregates deserve serious consideration regarding their use in new PCC. As concrete is reduced in size for further handling and eventual distribution, it becomes evident that the source of the concrete greatly affects the composition and properties of the material. Pavement typically yields little variation in composition or impurities since its aggregate sources are likely of a natural quarry. Impurities like wood, tile and poly vinyl carbonate however, can be found in small amounts in some sources, indicating demolition of domestic dwellings.

Disposal of concrete from demolition projects or precast facility waste is a challenge both economically and environmentally, which leads contractors to pioneer ways to recycle waste materials such as concrete. Regional sources of RCA include landfills, precasters, paving contractors and construction material recycling plants, all of which can produce RCA with varying qualities and compositions depending on the demolition sites they receive their material from.

RCA Production Process

Due to the inherent variability in RCA and its dependence on properties of the original concrete, the RCA production process is an important subject and was investigated for this report. ACI Committee 555 provides a description of the production process. [2] RCA production begins with the breaking up and removing of old concrete. Different uses of concrete include pavement, vertical structures, reinforced concrete, prestressed concrete and more. The many concrete applications along with the wide variety concrete properties, like compressive and flexural strength, have encouraged the development of a multitude of different methods for concrete demolition. In general, concrete can be broken up using hand tools, vehicle-mounted equipment, explosives, chemical agents, heat methods, or water blasting.

Hand-held tools can be pneumatic, hydraulic, electrical, or gasoline-powered. These tools include jackhammers, drills, and saws. They are useful for small jobs and confined areas. They usually are sources of dust and vibration, which for small jobs may not be much of a concern. For larger jobs, vehicle-mounted demolition attachments are often used. These can include the impact hammer-related tools, but also wrecking balls for cranes, hydraulic crushers, rippers, and rotating cutter heads. With these methods, noise, vibration, and dust become large factors which must be considered in project planning. The large area needed to operate them, especially wrecking balls, must also be accounted for. Explosive blasting involves obvious related risks, and licensed experts must be present, but is an option for entire building demolition. Diamond wire saws may be useful for thick sections of concrete or where noise and vibration are a problem. Chemical demolition agents may also be used. This process involves drilling holes into the concrete, and pouring the chemical agent into the holes. The chemical agent expands, forcing crack propagation. Several heat methods exist, including jet-flame cutters and thermal lances. Finally, water-jet blasting has been used successfully, and greatly reduces dust and fire risk. The method of demolition is selected based on the properties of the concrete, available space, and considerations such as dust, noise, and vibration.

After demolition, RCA production continues by further processing the old concrete. Further processing includes crushing and removing impurities. The process begins at the demolition site. Hydraulic hammers and vehicle-mounted equipment are used break the large concrete sections into smaller pieces. Large hooks, shears, and torches are used to remove most of the rebar from the rubble. This steel can also be collected and recycled separately. The crushed concrete is then transported to an RCA processing plant, which may be a construction demolition facility or separate recycling center. At the plant, the concrete is passed through crushers, which are usually of the jaw crusher variety. The concrete is passed through a primary crusher, reducing the size to approximately 2-1/2 to 3 inches. At this point, the remaining rebar is removed, which can be accomplished manually or with a strong magnet. The concrete is then passed through secondary crushers, producing aggregate with a maximum size of 3/4 to 1 in. [2]

It is important to note that the aforementioned crushing method uses a very large amount of energy. Research has shown that an alternative which uses significantly less energy could be crushing by a lightning charged impulse. [3] In this method, a plasma current flows along the grain boundary between the aggregate and mortar paste, causing cracking. However, it has yet to be determined whether this method is feasible on a larger scale.

Quan showed that the manufacturing method influences the amount of adhered or residual mortar on the aggregate surface. [4] Production methods employing crushing produced aggregates with more residual mortar and lower density than methods that employed rubbing and heating. As noted earlier, the presence of residual mortar influences density, porosity, and strength among other properties as is further discussed below.

Even after the rebar is removed, the recycled aggregate may contain impurities, especially construction debris. Remnant impurities can include brick, wood, plastic, and other materials, depending on the source of the concrete. Although manual sorting is possible for large impurities, further processing may be necessary if the impurities are varied or abundant. Fine impurities such as gypsum may be removed by screening.

Once the aggregate is sufficiently processed, it must be properly graded. It has been shown that recycled aggregate can be sized with gradation methods similar to those employed in virgin aggregate methods, with satisfactory results. Reduction of fines in the aggregate may require washing.

Stockpiling

RCA stockpiles tend to be slightly high in alkalinity due to extracted $Ca(OH)_2$ leachate from the cement of crushed concrete. [5] Alkalinity of individual stockpiles may vary depending on the source of origin and corresponding metal/contaminant content. Though high alkalinity levels can produce hazardous solutions, the acidic nature of the rain that acts as an agent in the $Ca(OH)_2$ leachate extraction can reduce the alkalinity or completely neutralize the stockpile, thereby eliminating the alkalinity problem with typical RCA stockpiles. In terms of stockpiling, there are no strong counterarguments to using RCA as an alternative to virgin aggregates in new PCC. In addition to increased alkalinity, the $Ca(OH)_2$ revealed from the crushing process of recycled concrete can react with CO_2 to form calcium carbonate precipitate which can clog drains and sewers. [5] In terms of handling and maintaining RCA, the American Concrete Pavement Association suggests prewashing the recycled aggregates to reduce leachate at the site of construction. [6]

Energy and Greenhouse Gases

Use of RCA reduces the use of natural aggregates and reduces the stream of construction waste being landfilled. There has been little work to characterize whether there are further environmental benefits through the reduction of energy use and greenhouse gas emissions. In one study, life-cycle models incorporating varying levels of coarse aggregate replacement were developed. It was found that when virgin and recycled aggregates are available locally, only using recycled aggregates at a 20 percent or lower replacement rate is beneficial in terms of greenhouse gas reduction. Larger replacement rates are only beneficial when virgin aggregate must be transported large distances. [7]

Aggregate Properties

Density and Porosity

Although density and specific gravity are not important indicators of aggregate quality, they are integral for concrete mix design. Specific gravity is the parameter conventionally used in mix design. Four types of specific gravities are defined based on how voids in the aggregate particles are considered in PCC mix design; however the bulk dry specific gravity is typically reported in the literature review. General results showed that the bulk dry specific gravity of recycled aggregate ranged from 2.2 for fine aggregate to 2.6 for coarse aggregate. [8], [9], [10], [11] In comparison to natural aggregates, these values are much lower; typically virgin coarse aggregate and fine aggregates have specific gravities between 2.40 and 2.90. Lower values in RCA can be attributed to the adherence of old residual mortar to the crushed recycled concrete aggregate which tends to have a lower specific gravity of (2.1-2.4). [6] The old mortar contains voids that were formed by air pockets in the original concrete. The mortar filled with air voids adds additional volume to the aggregate with very little additional weight, resulting in lower specific gravities.

Absorption is a measure of the porosity of aggregates and is considered the best factor to judge the suitability of recycled aggregate in new PCC. Apart from the effect on specific gravity, the air voids present in the residual mortar paste also have a direct effect on the porosity and absorption of the recycled concrete aggregate. Although aggregates are inert, they can capture water in surface and air voids of the residual paste from the original concrete. The amount of water that the aggregates absorb is important in the design of PCC since moisture captured in the voids is not available to improve the workability of the concrete or to react with the cement in the mix. There is no specific level of aggregate absorption specified for design of PCC (although some state specifications may place limits on aggregate absorption), but aggregates are evaluated for absorption and porosity in order to determine the amount of water required for a specified mix design. [12] Generally, absorption of recycled concrete aggregate was found to be regularly higher than that of virgin aggregate. [8], [13], [14] The absorption rates for recycled aggregates were found to be very rapid with 75 percent of the 24 hour absorption capacity occurring in the first 30 minutes of soaking. [10] Studies have also found that recycled coarse aggregate with a maximum size of 30 mm had a bulk specific gravity of 2.19 and water absorption of 6.5 percent. Traditional coarse virgin aggregates of the same size have absorption of ranging from 0.2 percent to 4 percent. [15], [16] Literature reviews also indicated that overall recycled fine aggregates were more absorptive than coarse aggregates due to the fine mortar and dust particles included in the fine portion of aggregates, which could prohibit their use in new PCC. [17] Furthermore, residual cement from the original concrete was found to be 6.5 percent for coarse aggregate and 25 percent for fine aggregate, yielding absorption of 3.2 percent and 12 percent, respectively. [18] Typically fine aggregates have absorption of roughly 8-10 percent. [19] The effect of absorption in recycled coarse aggregates can be moderately reversed if the aggregates are soaked in water prior to concrete mixing to ensure that most of the surface and air voids are filled with water resulting in a saturated surface-dry condition. [20], [16] It has also been noted that impact crushers tend to produce a high percentage of aggregates without adhered mortar. [20], [21] Increasing the absorption capacity has been found to decrease the workability and finishability of mixes containing RCA. However, pre-soaking the aggregate stockpiles or limiting the amount of recycled fines in new PCC mixes has been found to correct this issue.

LA Abrasion

The ability of aggregates to resist damaging effect of loads is related to the hardness of the aggregate particles and is described as the toughness or abrasion resistance. This is important because aggregates must be able to resist crushing, degradation and disintegration when stockpiled, compacted, or exposed to loads. The Los Angeles Abrasion Test, [22], [23] evaluates the aggregates resistance to abrasion. In this test, a washed and weighed amount of coarse aggregate is placed in a large steel drum with standard sized steel balls. The drum rotates for typically 500 revolutions and the aggregate coarser than a No. 12 is then weighed. The LA abrasion number is then reported as the percent weight loss. This value is empirical, meaning that it does not have any scientific basis but can be used to compare results of other aggregates' LA abrasion performance. Generally, the greater the abrasion loss, the less suitable for concrete the aggregate is. Literature reviews indicated that typical recycled coarse aggregates' abrasion losses were found to range from 20 percent to 45 percent. [8], [13] Though RCA abrasion losses are usually within ASTM standards, they are consistently higher than those of virgin aggregates. Higher abrasion loss in RCA than in natural aggregates can be attributed to the soft mortar attached to the aggregates and the presence of only partially fractured particles due to improper or uneven crushing. [6] Abrasion resistance is important because old mortar is by nature weaker than the aggregates themselves making it more likely to be abraded from the aggregate. A concern with recycled aggregate is that when subjected to loads such as those encountered during mixing and stockpiling, fines could be produced and a higher percent weight loss could occur compared to virgin aggregates. These fines can upset the amount of fines and cement paste required for the particular mix design. Abrasion losses can also cause the gradation of a stockpile to change which can also affect the components required in a mix design.

Sulfate Soundness Testing

Sulfate soundness testing provides a way for engineers to gauge an aggregate's resistance to weathering and deformation due to freeze-thaw without actually observing freeze-thaw cycles on a sample. The process includes submerging an aggregate sample in either magnesium sulfate or sodium sulfate for an extended period of time. A reaction occurs, causing salt crystals to form within the pores and cracks of the aggregates, thereby simulating the formation of ice crystals similar to what is observed during a freeze-thaw cycle. A Washington DOT literature review on the use of recycled concrete aggregate in new PCC mixes concluded that RCA usually fails the sodium test. [24] However, it usually passes the magnesium test. This discrepancy in testing outcomes raises concern as to whether or not sulfate soundness testing is applicable to RCA. The discrepancy, though still under investigation, was enough for the Idaho Department of Transportation to drop its endorsement for the use of RCA in new PCC.

Angularity

The shapes of aggregates determine how well the material will pack or the mobility of the stones within a mix. Generally, aggregates which are angular with many sharp corners produce bulk materials which have higher stability than rounded aggregates. However, rounded aggregates are easier to work into place compared to angular aggregate. This is because angular aggregates have sharp faces which make it difficult for them to slide across each other. In regards to PCC, it is desirable to use aggregates which are round and smooth to improve the workability of a fresh concrete mix. However, rounded particles are more difficult to obtain, so in New Jersey it is common for angular aggregates to be used in PCC. During the processing of old concrete to make recycled concrete aggregate, the aggregate undergoes crushing. Because the aggregate is stronger than the paste of the aggregate, the concrete breaks apart primarily in the cement portions of the concrete, conserving the original angular shape of the original aggregate. However, the paste now adhering to the coarse aggregate affects the texture of the coarse aggregate, making it less smooth which could then decrease the workability of a mix. In terms of fine aggregate, recycled fines are generally very angular compared to natural fines like sand which is undesirable. [8] One problem with excessive angularity of RCA is the potential for PCC mixes to be harsh which can affect workability and finishability.

Contaminants

Contaminants or deleterious substances are any materials that can adversely affect the quality of Portland Cement Concrete made with the aggregate. In PCC, deleterious material typically includes clay lumps, soft or friable particles and coatings. In RCA, contaminants primarily include clay brick, timber, metal and ceramics. These contaminants are undesirable in RCA because they can reduce the strength and cohesiveness of PCC mix. The NJDOT currently allows the use of RCA as a dense graded aggregate and specifies allowable limits for contaminants as can be seen in table 1 (table 901.10.02-1 of NJDOT specifications).

Table 1. NJDOT specification for allowable contaminants in DGA

Composition Requirements for RCA		
Aggregate Property	**Minimum Percent**	**Maximum Percent**
Concrete[1]	90	
HMA		10
Brick, cinder block, schist, concrete washout, and other friable material		4
Reactive material		0
Wood		0.1

As can be seen from table 1, the NJDOT's limits for allowable contaminants allows up to 10 percent of the material to be other than concrete including HMA, brick, cinder block, concrete washout and other friable material. The NJDOT specifications limit broken stone or washed gravel used as coarse aggregate to 5 percent weathered or deleterious stone. One study showed that RCA consisted of 92.1 percent crushed concrete (49.1 percent of original aggregate plus adhered mortar and 43 percent of original aggregates), 1.6 percent of ceramic aggregates, 5.3 percent of bituminous material and 0.8 percent of other material which is comparable to the limits for DGA. [25] One major difficulty in specifying allowable limits of contaminants allowed in RCA for use in PCC is the variability of the quality control of concrete sources. Compared with the properties of virgin material, those of recycled concrete are not as easily controlled.

The material may be contaminated from various sources. As a result, it is typically of lower quality compared to virgin material. [17]

Gradation

Gradation describes the particle size distribution of the aggregate which is an important attribute when designing a PCC mix. Construction considerations such as equipment capability, dimensions of construction members, clearance between reinforcing steel and layer thickness all limit the maximum aggregate size. The maximum aggregate size is simply the smallest sieve size through which 100 percent of the sample aggregate passes. In terms of structural concrete, size 57 and 67 aggregate gradations are most commonly used and accepted. The NJDOT currently specifies a gradation for dense graded aggregate as can be seen in table 2. It can be seen that roughly half of the aggregate is 1.5 in. to ¾ in. which is too large for usage in structural PCC. Therefore, Class B recyclers would need to purchase additional screens and modify operations to handle additional stockpiles with gradations suited to PCC. Studies show that recycled aggregates can be specified to the same gradation ranges as virgin materials. [8] Crushing equipment can easily be programmed to produce aggregates of desired gradation as long as accumulation of fines is kept at an acceptable level. [6] Furthermore, some studies found that similar gradation of RCA could be produced by crushing concrete in comparison to crushed aggregates as long as proper screening is performed. [25]

Table 2. NJDOT gradation for DGA

Gradation Requirements for DGA	
Sieve Size	**Percent Passing**
1-1/2"	100
3/4"	55 - 90
No. 4	25 - 50
No. 50	5 - 20
No. 200	3 - 10

During field sampling, a consultant from Winzinger Inc. in Franklinville, NJ confirmed that RCA could be produced meeting the 57 and 67 size gradation. The consultant went on to say that the estimated time required to prepare the sieve equipment for a size 57 or 67 aggregate would only take roughly a day.

Table 3. ASTM C-33 gradation specifications

Coarse Aggregate Grading Requirements for Concrete (ASTM C-33)									
Amounts Finer Than Each Laboratory Sieve (Square Openings), Weight Percent									
Size No.	**Nominal Size**	**1.5 in. (37.5mm)**	**1 in. (25.0mm)**	**3/4 in. (19.0mm)**	**1/2 in. (12.5mm)**	**3/8 in. (9.5mm)**	**No. 4 (4.75mm)**	**No. 8 (2.36mm)**	**No. 16 (1.18mm)**
57	1 in. to No. 4 (25.0 to 4.75mm)	100	95 to 100	—	25 to 60	—	0 to 10	0 to 5	—
67	3/4 in. to No. 4 (19.0 to 4.75mm)	—	100	90 to 100	—	20 to 55	0 to 10	0 to 5	—

Fluid Properties and Issues

As in concrete mixes using natural aggregates, the addition of water to cementitious material containing recycled aggregates creates a slurry-like mixture which eventually forms concrete if consolidated properly. Quality concrete mixes harden due to a chemical process called hydration. Hydration is what allows construction workers to spread and form concrete in desired shapes and positions. Rate of hydration and compressive strength are two major properties a construction worker must consider in terms of producing quality concrete. Several indicators that help predict rate of hydration and compressive strength in fresh concrete mixes include workability, pumpability, air content, absorption and use of admixtures.

Workability and Pumpability

Workability is defined as the ease of placing, consolidating and finishing freshly mixed concrete and can be an indicator of how well a concrete mix has been designed as concrete mixes should not be too fluid or too thick during either of these processes. Workability in recycled aggregate concrete (RAC) is different from workability of natural aggregate concrete (NAC) in that the angularity of recycled aggregates inhibit fluidity. A prominent indication of workability is the slump test [26] (although not applicable for self-consolidating concretes), which consists of filling a truncated cone with a concrete sample mix, removing the cone and measuring the change in height the concrete slumps. Extremely high or extremely low slump values may indicate poor workability. [26]

Katz conducted a study that analyzed the effects of recycled aggregates in fresh concrete mixes using original Portland cement and white Portland cement in separate instances. [18] The slump of PCC using RCA using 28 day-old aggregate was found to be 15 mm (8.82 percent) greater than that of a test concrete using natural aggregates.

The slump gain observed in the laboratory prompted Katz to add sand to the mixture to help maintain workability. Other studies found the workability of a mix decreased significantly as the replacement rate of RCA in a mix increased. [10], [11] Various admixtures can be used to modify these findings.

Pumpability refers to the ease with which a concrete mix can be pumped and delivered to forms. It is also important to note that concrete becomes compacted as it is pumped and can lose some of its initial slump. Economical and scheduling issues may arise if the pumped concrete stops flowing and creates a blockage within the piping of the delivery system. Pumpability is often considered as a close indicator of the workability of a mix.

A Japanese research study evaluated the pumpability of a RAC mix using a transportation test. [27] A concrete sample was pumped through transportation piping, 58 m in horizontal length and 3 m in vertical length. The RCA replacement ratios were 0, 15 and 30 percent, while the water–cement ratio was 50 percent and the slump value was 18 cm. The head loss in the piping was slightly higher for the RACs than for the ordinary concrete. The difference was considered negligible and no observed difference in slump after transport was observed.

Water Content & Workability

About 5 percent more water is needed to produce similar workability to that of typical PCC mixes. This is due to the excess mortar content which tends to absorb water that would otherwise add to the workability of the mix. The addition of water to a concrete mix raises the water-to-cement ratio of the mix and subsequently reduces the potential hardened strength. [6] Recycled aggregates can be washed prior to batching to reduce excess fine content and help reduce the water demand of the batch, thereby reducing the chance of large reductions in hardened strength.

Air Content

Air content and air entrainment require consideration whenever a concrete product is subject to harsh weather; specifically cold weather conditions that encourage freeze-thaw effects on the concrete. Air content and air entrainment also affect the workability of a mix, in that entraining a mix with air will yield a more workable mix. Concrete mixes can be designed to perform in three exposure levels. The exposure levels are defined as follows: [28]

> *Mild Exposure - Indoor* or outdoor service in which concrete is not exposed to freezing and deicing salts.
>
> *Moderate Exposure* – Some freezing exposure occurs, but concrete is not exposed to moisture or free water for long periods of time.

Severe Exposure – Concrete is exposed to deicing salts, saturation, or free water. Examples include pavements, bridge decks, curbs, gutters, canal linings, etc.

Katz also investigated the effect of air content on PCC with recycled aggregate and normal aggregate. [18] The results indicated air content for the RAC was 4 to 5.5 percent higher than the reference concrete. The cause of the increased air content was not clear. However, increased air content is known to occur in lightweight aggregate concrete, which exhibits some similarities with recycled aggregate concrete. [29] Another study indicated entrapped air in excess mortar of recycled aggregates, air contents are up to 0.6 percent higher than that of conventional concrete mixes that use virgin aggregates. [6] It has been suggested that aggregate correction factors can be employed to correct for air voids during batching. In general, air content in RCA is much higher than that of virgin aggregates due to the porous nature of RCA.

Curing

Curing is the process of maintaining satisfactory moisture content and temperature in the concrete for a definite period of time. [28] Curing allows continued hydration and gains in concrete strength. There is no specific curing method in terms of hydration and maximum strength gains in RAC as compared to NAC. Ultimate strength and quality of RACs depend primarily upon mix design and aggregate preparation.

Hardened Properties

Compressive Strength

Generally, the older studies of RAC have found that as the percent replacement of aggregate with RCA increases for a concrete mix, the compressive strength decreases. Most investigations consider the optimal RCA replacement level to be 30 percent or less. [30], [31], [9], [10] However, it has been found that RCA replacement levels of up to 50, 70 and 100 percent can be achieved by varying the w/c ratio at the expense of lower wear and absorption resistance levels. [21], [32] The strengths of hardened concrete made with 100 percent replacement recycled coarse aggregates can be inferior to those of control mixes made with all natural materials. The situation is made worse when the natural fines are replaced by 100 percent recycled fines. [12] The strength of concrete made with recycled coarse and natural sand was found to be between 11 percent and 20 percent lower than a control at 168 days. When natural sand is replaced by recycled fines the deficit becomes 21 percent to 38 percent. [33] As a result, use of recycled fines is not considered beneficial to concrete strength. Additional studies have confirmed the typical strength losses in PCC when 100 percent coarse RCA is substituted for virgin aggregate. One study found that the strength loss can range from 20 to 25 percent lower than strengths of virgin concretes. [20] Slight differences in strength losses can be attributed to the effect that specific mix designs have on concrete.

However, there is evidence that coarse RCA can be used as a partial replacement of virgin coarse aggregate in PCC. One study found that up to 30 percent replacement of

RCA had no significant effect on the 28 compressive strength of concrete. A gradual reduction in 28 day compressive strength resulted from the increase of RCA content above 30 percent. [31], [9] Corresponding studies found that PCC made with 25 percent replacement had the same strength (30-45MPa) as virgin aggregate concrete with the same quantities and effective water to cementitious material ratio. [20] It is clear that strength reductions can occur at any level of aggregate replacement with RCA (e.g. 8 percent reduction with 25 percent replacement) [34] and results are dependent on the specific mix design. Recommended uses for concrete with 30 percent replacement of RCA were found to be driveways, parking lots, external pavements, foundations in non-aggressive soils, and curb bedding. [30]

While many studies found the need to limit coarse aggregate replacement to 30 percent, others have found comparable results with 100 percent replacement with recycled aggregates. [35], [11], [36] In other cases, the use of a 100 percent replacement rate may result in reduced compressive strength compared to a comparable mix with virgin aggregates, however the strength achieved is still suited to the purpose of the mix. [37], [38], [39]

The performance of concrete made with RCA can also be improved by the addition of supplementary cementitious admixtures. Fly ash, a byproduct of the coal industry, is the most commonly used pozzolan in civil engineering structures. When introduced to concrete, fly ash extends the hydration process, allowing a greater strength development and reduced porosity. The addition of fly ash to 100 percent recycled coarse aggregate mixes was found to increase the compressive strengths between 28 and 90 days compared to mixes prepared without fly ash. [40] Additional studies have confirmed these conclusions. [41], [42], [16], [43] Due to the weaker composition and increased number of bonded interfaces of recycled aggregates, decreases in hardened compressive and tensile strengths are typically lower in recycled aggregate concrete than in conventional PCC. [6] The higher air content that results from the increased number of bonded interfaces of recycled aggregates has also been found to decrease the compressive strength of recycled aggregate concrete products. Up to 24 percent less compressive strength and 10 percent less tensile strength have been observed, but modifying the mix to reduce the w/c or adding fly ash have been found to produce hardened concretes with compressive and tensile strengths similar to that of conventional PCC. Furthermore, the addition of silica fume to RCA mixes was found to increase the strength of RCA concrete beyond the strengths of virgin concrete. Concrete with a coarse RCA replacement resulted in a 28 day strength of 25 MPa compared to an equivalent Natural aggregate mix of 30 MPa. Addition of fly ash to the RCA mix yielded 28 day strengths of 30 MPa and addition of silica fume yielded strengths of 40 MPa, as seen in figure 1 below. [44] The increase in strength due to the addition of fly ash and silica fume can be attributed to the densifying effects and pozzolanic activity of the cementitious admixtures. Slag has also been found to be effective in increasing the compressive strength of RAC. [45]

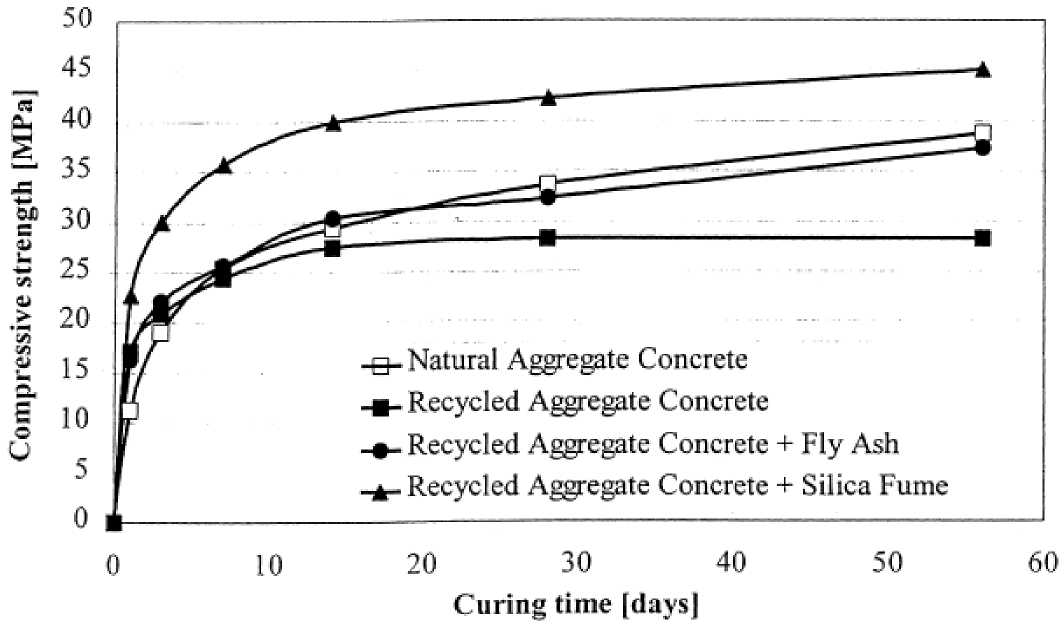

Figure 1. Effects of Fly Ash and Silica Fume in RAC [44]

Modulus of Elasticity

The modulus of elasticity is commonly used in designing concrete structures. Because the stress-strain relationship is not linear, the classic definition of modulus of elasticity (Young's modulus) is not applicable. Instead, the chord modulus (also often referred to as the modulus of elasticity) in compression is more commonly used for concrete and is determined according to ASTM C469. [46] The method requires three or four loading and unloading cycles, after which the chord modulus is determined between a point corresponding to a very small strain value and a point corresponding to either 40 percent of the ultimate stress or a specific strain value. Normal-weight concrete typically has a modulus of elasticity of 14 GPa to 40 GPa. [12]

It was generally found that when recycled aggregate is substituted for natural aggregate in concrete, the hardened concrete experiences a decrease in modulus of elasticity which can cause an increase in fatigue rates in concrete products and increased deflection in pavement panels. This decrease in elastic modulus, compared to similar mixes made with natural aggregates, was on average about 15 percent, but varied from 3 percent to 50percent. The decrease in elastic modulus between recycled aggregate concretes and conventional PCCs can be attributed to the excess mortar, attached to recycled aggregate, having lower elastic modulus than the aggregate itself. However, one study found an increase in elastic modulus of 14 percent when 31 percent of natural aggregates were replaced with recycled aggregates. [47] This was achieved with concrete that was mixed with a two-stage mixing process. This suggests that equal or higher elastic moduli can be achieved with RCA, either by altering the mixing process or mix design. Similarly, a study demonstrated that elastic modulus of RCA concrete can be increased with the addition of fly ash. [40] The inclusion of recycled fines was found to have a detrimental effect on modulus of elasticity. [48] As with other properties, elastic modulus of RCA concrete improves with better quality concrete used for the aggregate.

Porosity

Porosity is a property of hardened concrete which is strongly related to durability. Porosity is a measure of the amount of pores and voids in concrete, and corresponds to the permeability. These tiny pores are what allow fluids to migrate, whether by flow, diffusion, or sorption, through concrete. This can cause problems for multiple reasons. Any water that permeates concrete and freezes will induce internal stresses and possibly cracking. Any aggressive agents such as chlorides that permeate the concrete can corrode the rebar. Therefore, for concrete to be durable, porosity should be minimized. Because porosity is a measure of pores and voids, porosity is inversely related to concrete density. Permeability in recycled aggregate concretes has been found to be up to 500 percent of that of typical virgin aggregate concretes. [6] By reducing the w/c by 5 to 10 percent, the permeability and absorption can be compensated for.

The porosity of concrete containing RCA is of concern because, due to the presence of old mortar, RCA itself is more porous than natural aggregate. A study investigating freeze-thaw of RCA concrete found that while concrete density decreased (and porosity increased) with the use of RCA, the associated problems could be addressed with proper mix design. [49] Fly ash can be used to increase the density of RAC. [50] Some properties affected by porosity are explored in more depth below.

Freeze Thaw

When water freezes, it expands approximately 9 percent in volume. As the water in moist concrete freezes, it produces pressure in the pores of the concrete. If the pressure developed exceeds the tensile strength of the concrete, the cavity will dilate and rupture. The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause expansion and cracking, scaling, and crumbling of the concrete. Concrete containing RCA may be susceptible to cracking related to freeze thaw because of the high porosity of RCA.

Resistance to freezing and thawing was found to drop with increasing RCA content in PCC. [51] For concrete mixes with low water to cementitious ratios, expansion pressure due to freezing of water brought into the concrete by RCA could not be alleviated through the pores due to the dense mix. As a result, internal cracking occurred caused by the freezing water. [49] However, the addition of fly ash and air entrainment was found to increase the resistance to freeze thaw. The relative dynamic modulus for recycled aggregate concrete containing fly ash was found to only decrease 16 percent at 320 cycles. The use of air entrainment was far more effective with the relative dynamic modulus of concrete containing RCA showing no loss after 300 cycles with air entrainment. [52] Berube confirms the recommendation. [13] Using ¾" RCA has also been found to help reduce D-cracking. [6] Wei suggests the addition of 2 percent calcined diatomite to reduce permeability and increase freeze-thaw resistance or RAC mixes.[53] Xu found the internal structure of RAC led to decreased strength following freeze-thaw cycling.[54]

Chlorides and Chloride Permeability

Also related to the porosity and durability of hardened concrete is chloride penetration. The penetration of chloride ions into concrete causes corrosion of the reinforcement and deterioration of the concrete. It is particularly a problem in marine environments or roads and bridges where deicing salts are used. The concern with RCA is that chloride penetration could be more prevalent due to the greater porosity, and that RCA containing chlorides could be used in new concrete, accelerating corrosion. In addition to the corrosion of steel reinforcement, high chloride content may also affect the durability of new concrete. It has been considered most reasonable to check the chloride content of any recycled material that may contain excessive salt, and then estimate the corresponding chloride content of the resulting mixture.[6] Estimating the chloride content of a sample can be challenging, but chloride penetration can easily be tested by immersing concrete in a salt solution for a period of time, and then measuring the depth of penetration. Alternatively, the sample can be subjected to a series of immersion/drying cycles. In the different studies reviewed, chloride penetration of concrete made with RCA varied from a slight increase to a 100 percent increase when compared to conventional concrete. The variability is likely attributable to varying mix designs and the different possible sources of RCA. High chloride content can affect the durability of new concrete. If chloride levels are found to be unreasonably high, a few possible solutions include the use of epoxy-coated reinforcing steel and washing the RCA fines to reduce the chloride content.[6] However, it was noted that proper mix design can significantly decrease chloride penetration. A low water-cement ratio and the addition of fly ash proved effective in decreasing chloride penetrability.[40] Washing aggregate stockpiles is a good option as well.

It has been found that incorporation of slag in mixes with RCA reduces that rate of chloride diffusion.[45] Similarly, incorporating fly ash into mixes also has been shown to reduce the rate of chloride penetration by reducing the volume of macro-pores.[36], [55] Even in cases of 100 percent replacement of coarse aggregate with RCA, it was found that adequate resistance to chloride penetration could be achieved and this was improved with the addition of fly ash.[37]

Other studies have shown that concrete produced from RCA obtained from rejected precast elements can possess good durability properties, namely resistance to chloride ingress, chloride-induced corrosion, freeze-thaw and abrasion, similar to the corresponding natural aggregate concrete mixes. This suggests that coarse RCA, obtained from rejected precast elements, can be used in high performance concretes.[9]

Shrinkage

When cement paste is still plastic it undergoes a slight decrease in volume of about 1 percent. This shrinkage is known as plastic shrinkage and is due to the loss of water from the cement paste, either from evaporation or from the suction by dry concrete below the fresh concrete. Plastic shrinkage may cause cracking but it can be prevented by controlling water loss during the curing process. In addition to shrinkage during the plastic stages, another form of volume change occurs after setting, especially at early ages. If concrete is not properly cured and is allowed to dry, it will shrink. This type of shrinkage is called drying shrinkage, which is of particular concern for use of RCA in PCC. Shrinkage takes place over a long period of time, but the rate of shrinkage is high early, and then decreases rapidly with time. In normal weight virgin aggregate concrete, about 15 percent to 30 percent of the shrinkage occurs in the first two weeks, while 65 percent to 85 percent occurs in the first year. [12] Many other studies have also reported increased shrinkage with the use of RCA. [56], [36], [57] Shrinkage and shrinkage-induced cracking are increased by several factors, including lack of curing, high water-cementitious materials ratio, high cement content, low coarse aggregate content, existence of steel reinforcement, and aging.

The most prominent cause of drying shrinkage in PCC containing RCA is the high absorption of RCA. Studies show that like virgin aggregate concrete, RAC shrinkage occurs more rapidly and is more prevalent in the early life of the concrete and eventually slows down over time. Replacement values of over 30 percent RCA showed a rapid increase in shrinkage up to and over 2.5 times the rates for replacement percentages of 30 percent or less. [58], [59], [9] The lifespan of the original concrete used to make RCA for use in PCA was also found to have an effect on the drying shrinkage. PCC containing RCA that had been crushed at 28 days had significantly higher shrinkage than aggregates crushed at 1 and 3 days. [18] However, for RCA produced from concrete with long life-spans, this effect could be negligible. Note that RCA from Class B recyclers is likely to be much older however that at a precast plant will likely be young. Other research found that shrinkage during the first 10 days of curing in RAC was less than that of a virgin aggregate concrete, but that the shrinkage after 10 days was much higher than that of the control concrete. [34] Corinaldesi found the lower stiffness of RAC somewhat compensates for increased shrinkage resulting in similar amounts of shrinkage cracking. [44]

Shrinkage is clearly when RCA is used in concrete. However, research has shown that the addition of fibers to RCA concrete mixes can both delay and limit crack formations caused by shrinkage. The addition of Polypropylene fibers was found to decrease the value of shrinkage for an RCA specimen by about 6 percent after 600 days curing. Furthermore, Fibraflex metallic fibers were found to reduce the value of shrinkage by 15 percent after 600 days curing. RAC concrete with fiber content greater or equal to 0.25 percent was found to reduce crack widths substantially. [60] The addition of water reducing admixtures based on polycarboxylate polymer incorporating a drying shrinkage reducing group was also determined to be an effective means to reduce drying shrinkage. [42] The Washington State Department of Transportation recommends that in the event that excess fines are present in a RCA stockpile, the aggregate should be washed to minimize susceptibility to drying shrinkage. [24]

Creep

Creep is defined as the gradual increase in strain, with time, under sustained compressive loading. Creep of concrete is a long term process and it takes place over many years. Although the amount of creep in concrete is relatively small compared to other materials, it can affect the performance of structures. In reinforced concrete, creep can cause additional stress and strains in the steel reinforcements leading to gradual transfer of load from concrete to steel. Creep can also lead to the loss of prestressing force in prestressed concrete structures. Literature reviews suggest that the behavior of RCA in PCC, in terms of creep, is comparable to typical creep behavior of NAC if the coarse aggregate replacement is 30 percent or less. Generally, it was found that creep strains tended to increase with RCA content. [9] Meinhold found that with 100 percent coarse aggregate replacement with RCA, creep was noticeably greater than the reference specimen to the RAC specimens but all values were within acceptable range of creep values in ordinary concrete. [12] Similarly, Domingo-Cabo found using 100 percent RCA for coarse aggregate resulted in increased creep deformation by 51 percent to 70 percent. [57] Kou found the addition of fly ash as a partial cement replacement reduced creep deformation. [40]

Thermal Expansion

Due to the variation in the origin and composition of recycled aggregates and cements, coefficients of thermal expansion have varied from 0 percent to 30 percent higher than typical coefficients. [6] In contrast, another study found 50 percent replacement of with RCA reduced thermal expansion by 40 percent compared to a 100 percent natural aggregate mix. [61] Thermal expansion can be a problem with concrete slabs when it lead to excessive curling due to temperature gradients through the slab or if restraint combine with contraction leads to cracking. In pavement applications, it has been suggested that reducing the panel span can reduce the chance of cracking due to thermal expansion.

ASR

Another area of concern related to the durability of concrete is alkali silica reaction (ASR). Three factors must be present for ASR to occur. First, a source of alkali is needed, which is provided by the highly alkaline cement paste. Second, sufficient amounts of reactive silica must be present, which is often found in aggregates. Finally, the presence of water is needed to facilitate the reaction and form the gel which is produced. If the reaction occurs within the concrete, it forms a swelling gel which creates an internal pressure, possibly causing spalling and loss of strength. Due to the angular nature of RCA, the available surface area is much greater than the surface area of typical virgin aggregates which increases the potential for ASR.

A study conducted by Shayan found no increase in alkali silica reactivity in concrete made with RCA. [62] However, it was noted that RCA should still be tested for ASR for sources can greatly vary. If a recycled aggregate source already had ASR problems, the new concrete containing the RCA would likely be more susceptible to further ASR. Other studies concluded that if RCA were known to contain reactive aggregate, ASR could be controlled by using cements with a reduced alkali level. Using Type II cement has been found to reduce the potential for ASR. The potential for ASR is affected by the alkali levels of the original concrete, the remaining potential for ASR of the recycled aggregate and the alkali content of the new concrete. An ACPA research project on the use of RCA in PCC concluded that adding elements such as fly ash and slag to RCA concrete mixes can significantly reduce the potential for ASR. [6] Also, reducing the amount of RCA fines and permeability of a mix can reduce the potential for ASR. A study conducted by the WSDOT indicated that blending virgin aggregates with RCA as the coarse aggregate in mixes can also inhibit ASR. [24]

Residual Mortar Content and Equivalent Mortar Volume Method for Mix Proportioning

The presence of mortar adhering to the original aggregate causes RCA to be less dense than natural aggregate. Many studies have shown that with proper mix design PCC can be produced with RCA that has equivalent strength to that produced with natural aggregates. However, the mortar also affects properties such as creep and shrinkage, elastic modulus, chloride permeability, and carbonation. Researchers have found ways to overcome the deficiencies caused by RCA; for example shrinkage compensating admixtures have been shown to be effective in limiting the shrinkage of PCC with RCA. Presoaking the aggregates prior to mixing has also helped to reduce water demand and shrinkage. These mix modifications however increase the cost of the mix due to the need for additional admixtures or additional material processing in comparison to natural aggregates.

The amount of mortar adhering to the original aggregate in RCA is quantified as the residual mortar content. To determine the mortar content of the RCA a representative sample is oven-dried for 24 hours at 105^o C and then immersed for 24 hours in 26 percent by weight sodium sulfate solution. The RCA samples, while still immersed, are then subjected to 5 days of alternating freezing and thawing (16 hours at -17^o C and 8 hours at 80^o C. After the last cycle the solution is drained from the sample and the sample is washed with tap water over a #4 sieve. The sample is then dried for 24 hours at 105^o C after which it is weighed. The process frees the mortar allowing the relative portions to be determined. [63] The residual mortar content is found by

$$RMC = \left(\frac{W_{RCA} - W_{OVA}}{W_{RCA}}\right) x\ 100$$

where W_{RCA} is the initial oven-dried mass of the sample and W_{OVA} is the final oven-dried mass of the original virgin aggregates after removal of the residual mortar through the freeze-thaw cycling.

A range of recommended limits to residual mortar content from various research studies include 44 percent [64] and 15 percent [4]. Based on the results of the field and laboratory work performed as part of this study and described later, the 15 percent limit is not realistic for the RCA sources and production methods currently available in New Jersey.

Fathifazl has suggested a new proportioning method for PCC that uses RCA as some or all of the coarse aggregate and reported properties of concretes prepared with this method. [65], [66], [67], [68] The conventional approach to mix design with RCA has been to treat the recycled aggregates as a homogenous material with characteristic absorption and density properties. Fathifazl instead proposes that the RCA be treated as a two-phase system consisting of mortar and aggregate. If proportioned with conventional methods, the new concrete will then have a larger total mortar volume than concrete made with natural aggregates. This extra mortar likely leads to some of the inferior performance that has been reported. If the relative volume of mortar and aggregate in RCA can be determined, then the new concrete mix can be designed to have the same total mortar volume as a mix using natural aggregates. The method ensures that the total volume of aggregate (natural and the aggregate component of the RCA) is equivalent to that in a natural aggregate mix. The method therefore results in a design with less new cement and new paste than a natural aggregate paste because some of the mortar volume already exists from the RCA that is used.

Fathifazl reports the mix design procedure, shows a method to determine the maximum theoretical replacement rate of natural aggregate with RCA. He reports the resulting mixes had strength and elastic modulus, slump, shrinkage, flexural strength, and freeze-thaw resistance all similar to natural aggregate mixes. [66], [65]

Highway Pavements

Two studies evaluated the long term performance of pavements constructed with concrete using recycled concrete aggregates. The first study looked at sections of IH-10 between Loop 610 W and IH-45 in Houston constructed using 100 percent replacement of coarse and fine aggregates with RCA. [39] The project findings were

1. Compared to virgin aggregates recycled aggregates had a lower specific gravity, higher water absorption, greater loss in sulfate soundness, and LA abrasion loss.
2. There was little to no variation in the paving operation between the different aggregates.
3. The reconstructed CRCP had an excellent performance both short and long term with tight crack widths and very little spalling.
4. There is little or no difference in the thermal coefficient or the permeability of the concretes.
5. The RCA has significantly different modulus of elasticity, compressive and indirect tensile strength, and water absorption from natural aggregate.
6. Good pavement performance for RCA appears to be dependent on a low modulus of RCA and a good bond between the RCA and new mortar.
7. After more than 10 years of service under heavy traffic, the CRCP section containing 100 percent RCA is still providing excellent performance with no single structural distress.

In the second study 16 sections of pavement made with RCA in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming were surveyed and compared to conventional concrete. The pavements were originally surveyed in 1994 and the surveys were updated in 2006. The findings included: [69]

1. *"There was no clear correlation between the higher total mortar content of RCA concrete pavements and cracking distresses in either survey, although one RCA concrete pavement did exhibit more cracking than the control pavement.*
2. *There was little difference between the 1994 and 2006 surveys.*
3. *Rehabilitation techniques normally applied to conventional concrete work effectively on recycled pavements (dowels).*
4. *Field cores showed that 10 of the 16 pavements surveyed exhibited evidence of alkali-silica reactivity. Eight of these pavements were shown to have significant remaining expansion potential and are expected to continue expanding.*
5. *All pavements constructed with RCA from concrete showing alkali-silica reactivity and D-cracking exhibited field performance equivalent to their controls and pavements without distress.*
6. *The recycled pavements have generally performed comparably with their controls."*

Findings from other Transportation Agencies

<u>FHWA</u>

In 2003 The Federal Highway Administration (FHWA) conducted a National Review in an attempt to evaluate using recycled concrete aggregate in new Portland cement concrete. [70] While newer information is available from additional years of in-service RAC and additional laboratory studies, the findings of the study are still relevant. Specific applications of the aggregate were identified as well as any barriers or benefits associated with its implementation. Aggregate production methods, specifications and construction processes were also documented. Of the 11 states which implement RCA in PCC at the time, California, Michigan, Minnesota, Texas, and Virginia were chosen for an in-depth review of their recycled concrete aggregate program.

It was concluded that RCA should be used in PCC only if it matched the performance of virgin aggregate material in the final product. The aforementioned states approved the use of RCA as a partial coarse aggregate replacement for PCC use in curbs, gutters, valley gutters, sidewalks, concrete barriers, driveways, temporary pavements, interchange ramps and shoulders. Specific findings related to engineering, economics, and environmental aspects as well as recommendations from the FHWA review are found below.

Engineering

- D-Cracking of PCC pavements containing RCA can be reduced by crushing of the old concrete to smaller aggregate sizes.

- RCA was found to decrease the resilient modulus of PCC and increase the creep. The implementation of RCA should be used sparingly only when it benefits its specific application.
- RCA that originated from concrete with rounded aggregate yields a new product with particles having fractured angular shapes. This property increases the bonding between the RCA and the paste ultimately increasing the compressive strength.

Economic

- RCA usage in new PCC was found to reduce the final cost of the project.
- Usage was found to be more economical in urban areas since sources of aggregate from demolition are more readily available and virgin aggregate sources are not as plentiful.
- Decreased haul distance of aggregates from other regions leads to less costly transportation.

Environmental

- Use of RCA leading to a reduction of hauling distances was found to reduce overall fuel and energy consumption, as well as improve air quality and reduce mobile carbon emissions.
- RCA replacement in PCC yields a reduction of land fill material as well as waste piles.
- RCA usage results in preservation of Natural virgin aggregate sources which are currently becoming depleted.

Recommendations of FHWA Study

- Recycled concrete aggregates should be washed prior to use in PCC in order to eliminate excess fines.
- Lower compressive strengths of PCC containing RCA were attributed to the usage of recycled fines; prior to the review, the maximum replacement of recycled fines was determined to be 20 percent.
- Problems concerning the workability of the mix were accredited to the absorbency of the recycled concrete aggregate and the difficulty maintaining a uniform saturated surface dry condition of the aggregates.
- Saturated surface dry condition of the aggregates can be maintained by more consistent process control of stockpiles which includes watering and monitoring moisture content of the aggregates in the stockpile.
- PCC containing RCA should not be utilized in structural concrete due to the issues involving creep and shrinkage.
- Suppliers and stockpiles should be certified by STA's in order to ensure quality control.
- RCA from reconstruction projects should be used to ensure a consistent source and reuse of original aggregate.

Survey of State Transportation Agencies

The New Jersey Department of Transportation assisted in the distribution of a brief survey of other state transportation agencies to determine their experiences with recycled concrete aggregates in Portland cement concrete. Thirty-two responses were received and are summarized below. The information is specific to state transportation agencies' specifications and use of RCA. There may be private sector use not reflected here. Further details can be found in Appendix A.

Table 4. Response to survey regarding use of RCA in PCC

States allowing RCA in PCC	Notes
Alabama	Does allow RCA use in PCC. RCA has not been use in PCC. The crushed concrete used as an aggregate shall meet the requirements given in this Section and the requirements given in Articles 801.01, 801.02 and 801.03. The RCA must meet the respective Division 800 articles, a source of RCA must be listed as an approved aggregate producers and must meet the same requirements as other approved aggregate types (Abrasion, Soundness, Gravities, BPN, Silica, F/E, absorption, etc.). RCA is not allowed in structural concrete, only PCC pavement. Currently there is no approved source of PCC aggregate.
Colorado	No comments.
Florida	RCA can be used as coarse aggregate in non-structural applications. Currently considering allowing RCA for roadway barrier walls, but this has yet to be included in the specification.
Kansas	Does allow RCA use in PCC (so far done on a case-by-case basis). Most uses have been an experiment to measure how it would perform. Although the experiments have been promising there is not a large need for the use because most reclaimed concrete is being used to construct bases for the PCCP, not leaving a lot of waste concrete.
Minnesota	Does allow RCA use in PCC (at the discretion of the Concrete Engineer based on the history of the recycled material). The recycled concrete needs to be washed as well as meet all state requirements.
New York	Does allow RCA in PCC. The source of the RCA must be known to evaluate the ASR potential. Prefer recycled aggregate from highway application with a known history and less potential for brick and other undesired materials. The RCA stockpiles need to be soaked and drained to get the RCA into a SSD condition. Although permitted, RCA has not been use in PCC on any New York DOT projects.
North Carolina	Does allow RCA use in PCC (since 1990's) RCA has been largely used for subdivision, low volume roads (small projects), or detour routes (due to the lack of availability of large volumes of material required for projects performed on higher volume roads). Use of aggregate from crushed concrete has been allowed for use in Class B concrete mixes (non-structural/incidental, 2500psi) (*no supplier has submitted a mix design for approval using crushed concrete to this date)

	*Crushed concrete is not allowed for use in any other class of concrete.
Ohio	Does allow RCA in PCC with recently created specification. Has not been used yet. There are requirements for evaluation of the source pavement's condition for signs of D-cracking and ASR. The mix design has to be tested for shrinkage, freeze thaw, etc.
South Carolina	Does allow RCA use in PCC RCA was used approximately 10 years ago on I-95 and will be used again with a project on I-20. Both cases were for the purpose of widening the road and will use the existing concrete as coarse aggregate in the reconstruction. Fine aggregate is not permitted for use and RCA that is not from the existing road is not allowed in construction. The concrete materials of the road had no performance issues. Would be very hesitant to allow RCA from parent sources that are not well known. RCA is only used when reconstructing an existing PCC pavement with PCC, which is not often done.
Tennessee	Does allow RCA in PCC. RCA has to meet the specifications for the specific class of concrete. RCA has not been used in PCC yet.
Texas	Does allow RCA use in PCC. RCA can only be used in non-structural concrete (paving concrete, sidewalks, anchors, etc.) Any percent of coarse aggregate can be used, but only 20 percent of RCC fine aggregate is allowed in PCC. 100 percent coarse aggregate is used in pavement in multiple cases.
West Virginia	Does allow RCA use if it meets WVDOH specifications. RCA has not been use in PCC in West Virginia.
States that do not allow RCA in PCC	
Arizona	Does not allow RCA use in PCC.
Delaware	Does not allow RCA use in PCC. Concerns: 1. Incorporating ASR in the RCA into a new PCC mix and the effects that it would have on the new mix. 2. Introducing potentially reactive aggregates into mixes. Supply of one source of aggregate are not large enough to establish an ASR test history since the stockpiles will be exhausted very quickly. 3. Variability in the material stream characteristics (weak RCA -> weaknesses in the PCC -> variability in the break results) Have enough other uses for RCA (unbound aggregate layers) to exhaust our local supplies.
District of Columbia	Does not allow RCA use in PCC.
Georgia	Does not allow RCA use in PCC.
Indiana	Does not allow RCA use in PCC. Currently studying the use of Recycled concrete with Purdue University.
Kentucky	Does not allow RCA use in PCC.

Louisiana	Previously allowed use of RCA in PCC however no longer does because of observed quality control/quality assurance problems.
Maryland	Does not allow RCA use in PCC. Currently researching RCA literature and information. Concerned about the ASR (alkali silica reaction), the presence of unknown by-products and material constituents in the recycled material (especially in the absence of historical & quality assurance data from the original time of placement), Concerned about general material quality control and quality assurance of the new product containing the RCA.
Missouri	Does not allow RCA use in PCC (currently). MoDOT advised several contractors that were interested in using recycled concrete aggregates in new concrete pavement, that they would allow the use provided the concrete meets the same specification requirements as for concrete without recycled concrete aggregates.
Mississippi	Does not allow RCA use in PCC.
Montana	Has not used RCA in PCC.
Nebraska	Does not allow RCA use in PCC.
Nevada	Has not used RCA in PCC.
New Hampshire	Does not allow RCA use in PCC.
New Mexico	Does not allow RCA use in PCC. Concerned about the issues of ASR reactions.
Ontario	Does not currently use RCA in PCC (are interested). Currently monitoring a field trial installation to assess performance. Trial: The trial was constructed this past fall (2011) using returned concrete (i.e. concrete from concrete making operations that was returned to the ready-mix plant, separated and crushed), and the plastic and early-age hardened properties of the concrete were assessed; long term properties including durability will also be monitored. The trial installation is in a sidewalk application where it is exposed to freeze-thaw action and use of deicing salts. Two different replacement levels of recycled concrete aggregate were used (15 percent and 25 percent, approximately). Depending on the success of the trial, plans will be made regarding future work and potential for broader use of returned concrete in MTO construction operations. This trial is a cooperative effort with an Ontario building materials producer (Holcim) and an academic partner (Professor R. D. Hooton of the University of Toronto). MTO has no plans for use of recycled concrete from demolition, at this time.
Pennsylvania	Does not allow RCA use in PCC.
Rhode Island	Does not allow RCA use in PCC.
Utah	Does not allow RCA use in PCC.
Washington	Has not used RCA in PCC. Are interested in the possibility.

Other State Transportation Authorities RCA Specifications

Alabama

The Alabama specifications allowing crushed concrete as an aggregate in concrete pavement are found in "*Approved General Application Special Provisions For The 2012 ALDOT Standard Specifications For Highway Construction, 03/26/12"* under the section *Portland Cement Concrete Pavement*. The specifications states "*Crushed concrete may be used as an aggregate if this is shown to be allowed on the plans. The crushed concrete used as an aggregate shall meet the requirements given in this Section and the requirements given in Articles 801.01, 801.02, and 801.03."* These specifications include a requirement for a specific gravity of 2.55 or greater however there is a statement that this requirement applies to gravel only. Articles 801.01, 801.01, and 801.03 of the specification address producer qualifications, deleterious materials, and physical tests of coarse aggregates specifically. Crushed concrete aggregates must meet all of the same requirements as other coarse aggregates with the exception of specific gravity.

Colorado

While the survey indicated Colorado allows RCA in PCC, nothing was found in the specifications addressing this.

Florida

The DOT specifies that reclaimed Portland cement concrete can be reused in nonstructural concrete applications. The reclaimed Portland cement concrete should be from a source which was produced and placed in accordance with applicable Specifications. The material should be crushed and processed to provide a clean, hard, durable aggregate having a uniform gradation free from adherent coatings, metals, organic matter, base material, joint fillers, and bituminous materials. The allowable limits for contaminants and deleterious materials are consistent for virgin and reclaimed aggregates. The maximum loss as determined by the Los Angeles Abrasion (FM 1-T 096) should not exceed 50 percent. Furthermore, the Contractor's (Producer's) crushing operation should produce an aggregate meeting the applicable gradation requirements set forth by the DOT.

Kansas

Although Kansas allows RCA in PCC on a case-by-case basis, this is done primarily in the form of research studies and no specifications have been developed.

Michigan

The Michigan Department of Transportation specifies crushed concrete coarse aggregate may **only** be used in concrete mixtures for curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps with commercial ADT (average daily traffic) below 250, and concrete shoulders. The construction of reinforced pavement containing RCA has been a major concern for the Michigan DOT due to its susceptibility to transverse cracking. The combination of smaller aggregates, which result from the crushing process used to make the RCA, along with the increased mortar content of RCA, which reduces abrasion resistance, has made it a challenge for JRCP to withstand cracking as observed in a Michigan DOT case study.[24] Therefore, the Michigan DOT has limited the use of RCA in new PCC to the aforementioned, low risk applications.

In order to ensure aggregate quality, crushed concrete must originate from concrete sources owned by the DOT as part of the contracted project. Crushed concrete should also be processed to avoid contamination by foreign material such as joint sealants, HMA patching, base layer aggregate or soil. However, the inclusion of the aforementioned materials is permitted if its occurrence on the 1 inch sieve does not exceed 3 percent of the total weight of the aggregate sample. Furthermore, crushed concrete stockpiles with any presence of non-DOT sources such as building-brick, wood or plaster are completely rejected for use in new PCC. Steel reinforcement is allowed in crushed concrete stockpiles as long as it meets the specified aggregate grading without necessary hand removal. Additionally, the fine portion of the allowable gradations should not exceed a liquid limit of 25 percent and plasticity limit of 4.0.

Crushed aggregate should be produced by means of crushing methods that ensure uniformity of aggregate properties: specific gravity ±0.05, absorption ±0.40 percent with no apparent segregation. After crushing, the resulting aggregate should be separated according to the original coarse aggregate type. Exceptions include:

1. Different aggregate types may exist in the same stockpile if the quantities by weight of each aggregate type retained on the No. 4 sieve do not differ by more than ± 10 percent from the average quantity obtained from at least three representative samples.
2. When aggregate is produced from concrete pavement with only one aggregate type that has been repaired with concrete patches with a different aggregate type.

Michigan Class 6A, 17A and 26A aggregates must also be tested according to Michigan testing methods for Abrasion resistance and freeze thaw resistance. Acceptable test results pertaining to the stated gradations can be found in table 5.

Table 5. Michigan Physical Requirements for Coarse Aggregates, Dense-Graded Aggregates, and Open-Graded Aggregates

Material	Series/ Class	Gravel, Stone, and Crushed Concrete						Slag (a)		All Aggregates
		Crushed Material, % min (MTM 110,117)	Loss, % max, Los Angeles Abrasion (MTM 102)	Soft Particles, % max (MTM 110)	Chert, % max (MTM 110)	Sum of Soft Particles and Chert, % max (MTM 110)	Freeze-Thaw Dilation, % per 100 cycle max (MTM 115) (d)	Sum of Coke and Coal Particles, % max (MTM 110)	Freeze-Thaw Dilation, % per 100 cycles max (MTM 115) (d)	Flat and Elongated Particles, ratio - % max (ASTM D 4791)
Coarse Aggregates	4 AA (b)		40			2.0 (c)	0.020	1.0	0.020	3:1—15.0 (l)
	6 AAA		40	2.0 (e)	2.5	4.0	0.040 (f)	1.0	0.040 (f)	
	6 AA (g)		40	2.0 (e)		4.0	0.067 (h)	1.0	0.067	
	6 A (g)		40	3.0 (e)	7.0	9.0	0.067	1.0	0.067	
	17 A (g)		40	3.5 (e)	8.0	10.0	0.067	1.0	0.067	
	25 A	95	45	8.0 (i)		8.0		1.0		3:1—20.0 (m)
	26 A (g)		40	2.0 (e)		4.0	0.067	1.0	0.067	
	29 A	95	45	8.0 (i)		8.0		1.0		3:1—20.0 (m)
Dense-Graded Aggregates (j)	21 AA	95	50							
	21 A	25	50							
	22 A	25	50							
	23 A	25	50							
Open-Graded Aggregates	2 G	90	45 (k)							
	3 G	95	45 (k)							
	4 G	95	45 (k)							
	34 R	20 max	45 (k)							
	34 G	100	45 (k)							

Minnesota

The Minnesota Department of Transportation specifies that RCA can be used as a coarse aggregate for Portland Cement Concrete (PCC) for any structural use. It is permitted as the sole coarse aggregate for PCC mixtures as well as in blends with other classes of approved virgin aggregates. Recycled concrete aggregate is classed as "R", and is the product of crushing old concrete to meet a specified gradation. The aggregate must be handled and stockpiled in a manner to prevent contamination with foreign material. Furthermore, crushing operations should be conducted in a manner which avoids problems associated with the presence of reinforcing steel. The fine fraction of the crushed RCA (passing the No. 4 (4.75mm) sieve size) should be removed and disposed of accordingly. The original source of the aggregate must be known so that the engineer can determine if the aggregate is suitable for an intended use. Typical virgin aggregate quality control requirements specified in 3137.2D of the Minnesota specification shall not apply directly, however the engineer, using good judgment, may consider any of these requirements when determining suitability of the aggregate. All other general requirements including aggregate washing requirements and gradation requirements are identical for virgin and recycled aggregates. The MNDOT has also found it beneficial to add fly ash to new mixes as it increases the workability without the use of excess water and also reduces the chance of susceptibility to D-Cracking.

Texas

The Texas department of transportation specifies that coarse aggregates preferably be obtained from sources listed in the Department's Concrete Rated Source Quality Catalog (CRSQC). Aggregates from non-listed sources can be used only when tested and approved by the Engineer before use. At no point should approved and unapproved sources be mixed. Coarse recycled hydraulic cement concrete can be used as the sole coarse aggregate or as a blend with various virgin classifications as long as the aggregate is free from frozen material and from harmful amounts of salt, alkali, vegetable matter, or other objectionable material, either free or as an adherent coating. A uniform quality should be attained throughout the aggregate.

Deleterious material or contaminants should at most contain 0.25 percent by weight of clay lumps, 1.0 percent by weight of shale, and 5.0 percent by weight of laminated or friable particles. When tested for abrasion resistance by means of the LA abrasion test, wear must not be more than 40 percent. Texas requires coarse aggregates to lose less than 18 percent in a 5-cycle magnesium-sulfate soundness test however the specifications state this test is not to be used for crushed hydraulic cement aggregate. The aggregate must conform to the same gradations as natural coarse aggregates.

It should be noted that the TxDOT does permit the use of recycled fine aggregates as a 20 percent replacement of fines in new PCC as long as the loss by decantation, plus the allowable weight of clay lumps, does not exceed 1.0 percent or the value shown on the engineering plans, whichever is smaller.

Recycled crushed hydraulic cement concrete as a coarse or fine aggregate can only be used in class A, B, D, E, and P concrete. The specified classes along with typical uses of the concrete classes can be seen in table 6.

The Texas Department of Transportation has found that wetting RCA stockpiles has helped to solve moisture control problems like low densities and high absorptiveness in new concrete mixes. RCA pavements have been found to perform as well as virgin aggregate pavements though RCA pavements typically have lower compressive and tensile strength than normal PCC pavements. No major difference in spalling or cracking rates between RCA pavements and virgin aggregate pavements has been observed in any TxDOT project.

Table 6. Texas department of transportation concrete classes

Class of Concrete	Design Strength, Min. 28-day f'_c (psi)	Maximum W/C Ratio[1]	Coarse Aggregate Grades[2,3]	General Usage[4]
A	3,000	0.60	1–4, 8	Inlets, manholes, curb, gutter, curb & gutter, conc. retards, sidewalks, driveways, backup walls, anchors
B	2,000	0.60	2–7	Riprap, small roadside signs, and anchors
C[5]	3,600	0.45	1–6	Drilled shafts, bridge substructure, bridge railing, culverts except top slab of direct traffic culverts, headwalls, wing walls, approach slabs, concrete traffic barrier (cast-in-place)
D	1,500	0.60	2–7	Riprap
E	3,000	0.50	2–5	Seal concrete
F[5]	Note 6	0.45	2–5	Railroad structures; occasionally for bridge piers, columns, or bents
H[5]	Note 6	0.45	3–6	Prestressed concrete beams, boxes, piling, and concrete traffic barrier (precast)
S[5]	4,000	0.45	2–5	Bridge slabs, top slabs of direct traffic culverts
P	See Item 360	0.45	2–3	Concrete pavement
DC[5]	5,500	0.40	6	Dense conc. overlay
CO[5]	4,600	0.40	6	Conc. overlay
LMC[5]	4,000	0.40	6–8	Latex-modified concrete overlay
SS[5]	Note 7	0.45	4–6	Slurry displacement shafts, underwater drilled shafts
K[5]	Note 6	0.45	Note 6	Note 6
HES	Note 6	0.45	Note 6	Note 6

1. Maximum water-cement or water-cementitious ratio by weight.
2. Unless otherwise permitted, do not use Grade 1 coarse aggregate except in massive foundations with 4-in. minimum clear spacing between reinforcing steel bars. Do not use Grade 1 aggregate in drilled shafts.
3. Unless otherwise approved, use Grade 8 aggregate in extruded curbs.
4. For information only.
5. Structural concrete classes.
6. As shown on the plans or specified.
7. Cementitious material content shall be minimum 658 lb/cy of concrete.

Virginia

Crushed hydraulic cement concrete is permitted for use as a coarse aggregate provided it conforms to the physical requirements specified and shows no adverse chemical reaction. Crushed hydraulic cement concrete will not be permitted in the following: reinforced cement concrete, in combination with other materials in contact with geotextile fabric when such fabric is used as a drainage item, and in backfill or bedding for perforated pipe. When tested for soundness in accordance with AASHTO T103 or T104, weight loss must not exceed 12 percent when subjected to Magnesium Sulfate and 5 percent when submitted to 100 free thaw cycles. The amount of deleterious material should not be more than the limits specifies in table 7. The aggregate can be produced in any of the gradations specified in table 8. There do not appear to be any restrictions as to the original source of the material as long as it meets the same qualification procedures the natural aggregates meet.

Table 7. Virginia DOT allowable limits of deleterious material

Material	% by Weight	AASHTO Test Method
Coal and lignite	0.25	T113
Clay lumps	0.25	T112
Material passing No. 200 sieve by washing[1]	1.00	T11

[1]When the material passing the No. 200 sieve by washing is dust of fracture, the percentage of deleterious material may be increased to 1.50 percent.

Table 8. Virginia DOT approved RCA gradations

Va. Size	Amounts Finer Than Each Laboratory Sieve (Square Openings) (% by Weight)														
No.	4 in.	3 1/2 in.	3 in.	2 1/2 in.	2 in.	1 1/2 in.	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 50	No. 100
1	Min. 100	90–100		25–60		Max. 15		Max. 5							
2			Min. 100	90–100	35–70	Max. 15		Max. 5							
3				Min. 100	90–100	35–70	0–15		Max. 5						
357				Min. 100	95–100		35–70		10–30		Max. 5				
5						Min. 100	90–100	20–55	Max. 10	Max. 5					
56						Min. 100	90–100	40–85	10–40	Max. 15	Max. 5				
57						Min. 100	95–100		25–60		Max. 10	Max. 5			
67							Min. 100	90–100		20–55	Max. 10	Max. 5			
68							Min. 100	90–100		30–65	5–25	Max. 10	Max. 5		
7								Min. 100	90–100	40–70	Max. 15	Max. 5			
78								Min. 100	90–100	40–75	5–25	Max. 10	Max. 5		
8									Min. 100	85–100	10–30	Max. 10	Max. 5		
8P									Min. 100	75–100	5–30	Max. 5			
9										Min. 100	85–100	10–40	Max. 10	Max. 5	
10										Min. 100	85–100				10–30

North Dakota

The North Dakota Department of Transportation specifications include a section for Recycled Portland Cement Concrete Pavement. There does not seem to be exclusion to using the material for curbs, sidewalks, etc but the material would not meet the requirements of structural concrete. The concrete is a Class A (6 bags of cementitious and 5.35 gallons water per yard) air entrained mix. The coarse aggregate must meet North Dakota Number 4 (table 9) with the additional requirement that the source material should be crushed to maximize the amount retained on the #8 sieve while still meeting the #4 gradation requirements. A spray bay is also required at the end of the crusher operation to pre-wet the aggregate prior to stockpiling. Finally, the specifications require that at least 20 percent of the coarse aggregate be virgin aggregate.

Table 9. North Dakota #4 Coarse Aggregate Gradation Requirements

Sieve Size	Percent
1-1/2"	-
1"	100
¾"	90-100
½"	-
3/8"	20-55
#4	0-10
#8	0-5
#200	1 (Max)

South Carolina and West Virginia

Although identified in the FHWA reports as allowing RCA in new concrete, South Carolina and West Virginia specifications appear to only allow RCA in base courses. They may be permitted in PCC on a case-by-case basis.

Illinois

The Illinois Department of Transportation studied the 20 year performance of continuously reinforced concrete pavement and found that pavement containing RCA performed as well as CRCP containing virgin aggregates. If RCA samples pass freeze-thaw and ASR testing specifications, the use of RCA in new PCC is highly recommended. The Illinois Department of Transportation also recommends moist curing since it promotes prevention of premature cracking.

Sections 1003 and 1004 of the Standard Specifications for Road and Bridge Construction include crushed concrete as an acceptable source of aggregate material. Quality and gradation requirements must not be compromised and freeze-thaw tests are required if the crushed concrete is to be used as Portland cement concrete pavement. The aggregate source can be either through acceptance of a recycled source on a project basis or through a central recycling plant.

For acceptance on a project basis, the existing concrete must be sampled from a minimum of three locations and submitted to IDOT for quality testing. If the material is to be used in concrete pavement, base course, or base course widening it must be subjected to freeze-thaw testing. Recycled Asphalt Pavement (RAP) is not considered as Other Deleterious when crushed concrete is used as aggregate shoulders but shall not exceed 2.0 percent when used in Class A concrete.

Material from a central recycling plant must have a quality sample for each 10,000 tons per specific gradation. The crushed concrete from central recycling plants is not accepted for IDOT Class A quality use, Class B quality use, or Class C quality hot-mix asphalt use.

Idaho

The Idaho Department of Transportation (IDT) did allow the use of RCA however IDT never saw it used. After looking at the ASR issues within Idaho it was decided that allowing RCA in new concrete was a risk they were unwilling to take. Portions of the state, mainly eastern Idaho and the Snake River Plain, have extremely reactive aggregates and there was significant concern with putting those reactive aggregates into a new mix with more alkali available from new paste. Because the state generally has very good access to high quality virgin aggregate sources, the decision to not allow RCA has minimal impact on ITD (Clint Hoops, Field Services Engineer, Idaho Department of Transportation, personal communication).

Discussion of State Specifications

Most states that allow the use of RCA restrict it to nonstructural concrete in typical uses such as curbs, gutters, and roadway barriers. Some require the source of the original aggregate of the RCA be known and all require a DOT approved source. Aggregate from a non-approved source can be used but only after comprehensive testing and by approval from the design engineer. Aggregate should be of a uniform quality throughout and be free from contaminants such as wood, clay, and steel rebar. The allowable contaminant level seems to vary from state to state but generally falls within a fixed range. Essentially, coarse aggregate can be produced from RCA to conform to the same gradations as virgin aggregates; Michigan is the lone exception. In general, it is common that RCA should be only used to produce coarse aggregate. However, Texas does allow 20 percent replacement of fines providing the recycled fine fraction conforms to specified limits.

LABORATORY AND FIELD TEST RESULTS

Chloride Ion Testing of Coarse RCA

The AASHTO Standard Test T 260 was performed on samples from each of the Class B recyclers used in this study to determine the chloride content within the aggregate. [71] This testing was performed due to the concern that recycled aggregates may introduce high levels of chlorides into new concrete.

The measured water-soluble chloride ion content for the aggregate suppliers can be found in table 10. All measured chloride ion contents were relatively low, ranging from 0.0148 percent to 0.0305 percent. Table 11 shows ACI 222R recommendations for maximum water soluble chloride content incorporated from the mix ingredients for new construction (as repeated in section 4.3.1 of the 318-08 Building Code). [72] The measured water-soluble chloride contents are all below these limits.

Table 10. Chloride Ion Analysis of aggregate suppliers

Region	Aggregate Source	Adjusted*		Non-Adjusted	
		Titration Endpoint (mL)	Cl^- Percent	Titration Endpoint (mL)	Cl^- Percent
South Jersey	South State	4.273	0.0032**	6.035	0.0240
	Winzinger	5.960	0.0228	5.938	0.0222
	Pierson	5.870	0.0216	5.844	0.0216
Central Jersey	Stavola	5.512	0.0177	5.312	0.0155
	Central Jersey	5.299	0.0151	5.259	0.0148
	Fanwood	5.510	0.0173	5.777	0.0210
North Jersey	Tilcon	5.970	0.0231	5.762	0.0203
	Rockcrete	6.626	0.0305	6.145	0.0252
	Grasselli	6.328	0.0267	5.670	0.0191

*samples adjusted for blast-furnace slag or other sulfide-bearing materials

** Suspect measurement

Table 11. ACI 318-08 chloride limits for new construction

Construction type and condition	Water soluble chloride limit, percent by mass
Prestressed concrete	0.06
Reinforced concrete wet in service	0.08
Reinforced concrete dry in service	0.15

Specific Gravity and Absorption of Coarse RCA
Standard Specification: ASTM C 127-88(1993)

Although specific gravity and absorption are not always important indicators of aggregate quality, they are integral for concrete mix design. Specific gravity is the parameter conventionally used in mix design. Four types of specific gravities are defined based on how voids in the aggregate particles are considered in PCC mix design; however the bulk dry specific gravities were usually reported in the literature review. As can be seen in the data in table 12, the bulk dry specific gravity of the aggregates from all nine suppliers ranged from 2.1 to 3.4 with an average of 2.35.

Absorption is a measure of the porosity of aggregates. The air voids present in RCA capture water thereby reducing the amount of water available to improve the workability of the concrete or to react with the cement in the mix. Typically, virgin coarse aggregates have absorption values from 0.2 percent up to 4 percent. As expected, all sources of RCA were found to have greater absorption values due to the presence of adhered mortar. The measured absorption ranged from 5 percent to 7 percent in the RCA tested.

Table 12. Specific Gravity and Absorption Values of Coarse RCA a) Sampling Round One, b) Sampling Round 2

a)

Aggregate Source	BSG	BSG (SSD)	App. SG	Absorption (%)
Fanwood	2.35	2.48	2.69	5.44
Stavola	2.34	2.49	2.76	6.56
Winzinger	2.31	2.44	2.65	5.51
South State	2.31	2.43	2.62	5.08
Pierson	2.30	2.44	2.67	6.04
Grasselli	2.29	2.44	2.68	6.40
Tilcon	2.29	2.43	2.67	6.22
Rockcrete	2.20	2.35	2.60	6.93
Central Jersey	2.11	2.26	2.47	6.91

b)

Aggregate Source	BSG	BSG (SSD)	App. SG	Absorption (%)
Fanwood	2.34	2.47	2.68	5.35
Stavola	2.38	2.49	2.68	4.74
Winzinger	2.28	2.42	2.66	6.33
South State	NA	NA	NA	NA
Pierson	2.33	2.46	2.67	5.38
Grasselli	NA	NA	NA	NA
Tilcon	2.37	2.49	2.68	4.79
Rockcrete	2.31	2.44	2.66	5.68
Central Jersey	2.36	2.49	2.72	5.70
Modern	2.31	2.43	2.63	5.36
Avg	2.34	2.46	2.67	5.42

Determination of Equivalent Mortar Volume of Recycled Concrete Aggregate

Fathifazl introduced a new proportioning method for PCC using RCA as some or all of the coarse aggregate. [65], [66] It has been reported throughout the literature, the presence of mortar adhering to the original aggregate causes RCA to be less dense than natural aggregate. This adhering mortar results in a lower density aggregate and affects concrete properties such as creep and shrinkage, elastic modulus, chloride permeability, and carbonation. Fathifazl proposes that the RCA be treated as a two-phase system consisting of mortar and aggregate. If proportioned with conventional methods, the new concrete will then have a larger total mortar volume than concrete made with natural aggregates. This extra mortar likely leads to some of the inferior performance that has been reported. If the relative volume of mortar and aggregate in RCA can be determined, then the new concrete mix can be designed to have the same total mortar volume as a mix using natural aggregates.

Abbas proposed a method determine the residual mortar content of the RCA. [63] The aggregates sampled from New Jersey recyclers were tested using the proposed method. To determine the residual mortar content a representative sample of the aggregate is oven-dried for 24 hours at 105^o C and then immersed for 24 hours in 26% by weight sodium sulfate solution. The RCA samples, while still immersed, are then subjected to 5 days of alternating freezing and thawing (16 hours at -17^o C and 8 hours at 80^o C. After the last cycle the solution is drained from the sample and the sample is washed with tap water over a #4 sieve. The sample is then dried for 24 hours at 105^o C after which it is weighed. The process frees the mortar allowing the relative portions to be determined. [63] The residual mortar content is found by

$$RMC = \left(\frac{W_{RCA} - W_{OVA}}{W_{RCA}}\right) x\ 100$$

where W_{RCA} is the initial oven-dried mass of the sample and W_{OVA} is the final oven-dried mass of the original virgin aggregates after removal of the residual mortar through the freeze-thaw cycling.

For this study the RCA from each source was sorted to produce a #57 gradation comparable to that a local concrete producer as coarse natural aggregate. The sample size for each was approximately 3000 g. The samples were soaked in a sodium sulfate solution, subjected to cycles of freezing and thawing, and then washed as described above. The residual mortar contents measured for each sample are reported in table 13. The process of stripping the residual mortar from the aggregates also provided the opportunity to characterize the underlying aggregates. Table 13 also provides the descriptions of the aggregates.

Table 13. Residual mortar content measurements

Aggregate Source	RMC (%) Round One Sampling	RMC (%) Round Two Sampling	Description of Underlying Aggregate
South State	39.2	NA	Combination of quartz nodules, sandstone, mica schist (shiny) and limestone
Stavola	37.2	24.2	Predominantly shale
Grasselli	36.5	NA	Combination of limestone, quartz nodules, and shale
Tilcon	31.4	22.3	Combination of sandstone, limestone, and shale
Pierson	29.7	27.4	Combination of quartz nodules, sandstone, mica schist (shiny), limestone, and shale
Central Jersey	26.4	25.4	Combination of quartz nodules, sandstone, mica schist (shiny), limestone, and shale
Winzinger	24.4	30.6	Combination of quartz nodules, sandstone, mica schist (shiny) and limestone
Fanwood	23.4	21.0	Combination of quartz nodules, sandstone, mica schist (shiny) and limestone
Rockcrete	36.1	19.8	Combination of quartz nodules, sandstone, mica schist (shiny) and limestone
Modern Precast	NA	33.8	Predominantly shale

Measured residual mortar contents from Round 1 sampling ranged from 23.4 percent to 39.2 percent with a mean value of 31.6 percent. Similar results were found in the second round of testing although those results do show there can be significant variance between samples taken at different times. The underlying aggregates generally consisted of either a mix of quartz nodules, sandstone, mica schist, and limestone or consisted of primarily shale. The difference likely is determined by whether the crushing plant was receiving material from a single source or mixed sources of concrete at the time of sampling.

There is some question to the accuracy of the residual mortar test as currently proposed. It was observed that in some cases not all of the mortar was separated from the aggregate at the end of five freeze/thaw cycles. It was also observed that in some cases the mortar that was separated from the aggregates remained intact at a size large enough to be retained on the #4 sieve and was thus considered aggregate in the residual mortar calculation. This would likely occur if sulfate resistant cement was used in the original concrete. Figure 2 shows samples of the underlying aggregates and examples of remaining adhered mortar or large sized mortar pieces. Despite these concerns, the test at least provides a means to approximate the residual mortar content as a starting point for a modified mix design for RCA concretes.

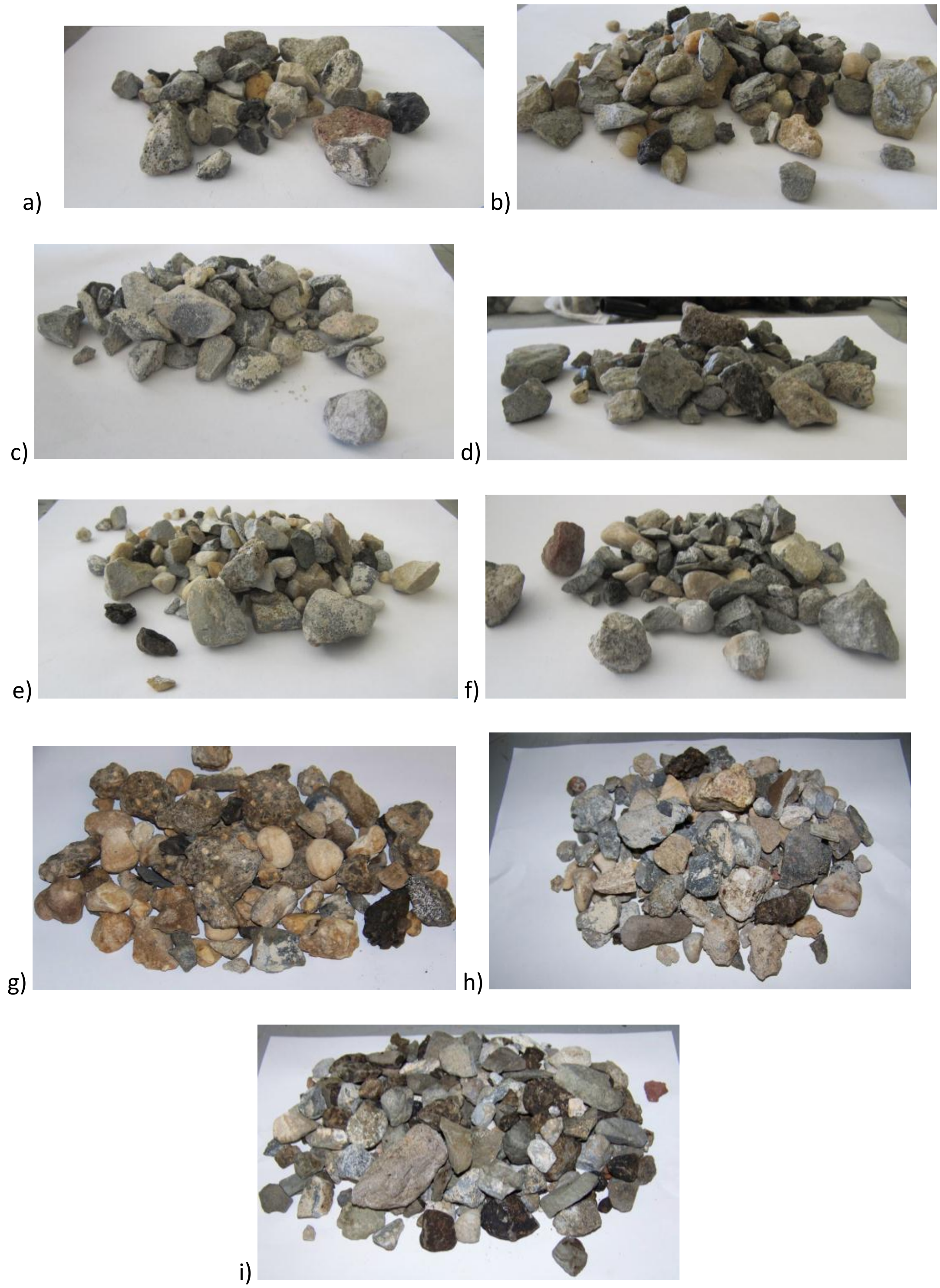

Figure 2. Underlying aggregate post RMC testing of sample from a) Winzinger, b) Pierson, c) Stavola, d) Tilcon, e) South State, f) Grasselli, g) Central Jersey, h) Rockcrete, i) Fanwood

Aggregates Used in the Remainder of the Laboratory and Field Trials

Initially the project team planned to use one of the Class B recycling facilities as the source for recycled concrete aggregates for the remainder of the lab and field trials. However, none of the facilities were willing to produce a #57 gradation for the project because they were set up for production of DGAB material and were regularly turning over their stockpiles of this material. As an alternative a mobile crushing unit was contracted to produce the material by crushing plant waste from the Modern Precast facility in Ottsville, Pennsylvania. Unfortunately, the screens were not properly set to produce a #57 aggregate. Instead the material was primarily bound by the 3/8” and 3/4” sieves and lacked smaller sizes as seen in figure 3. It was also noted there was observable contamination of the aggregate with small pieces of wood and plastic. It is assumed these came from the wagon wheels and other mechanisms used to hold rebar in position in the precast pieces the material originally came from. The research team was able to prepare acceptable concrete mixes (normal slump and self-consolidating) using this material as described below.

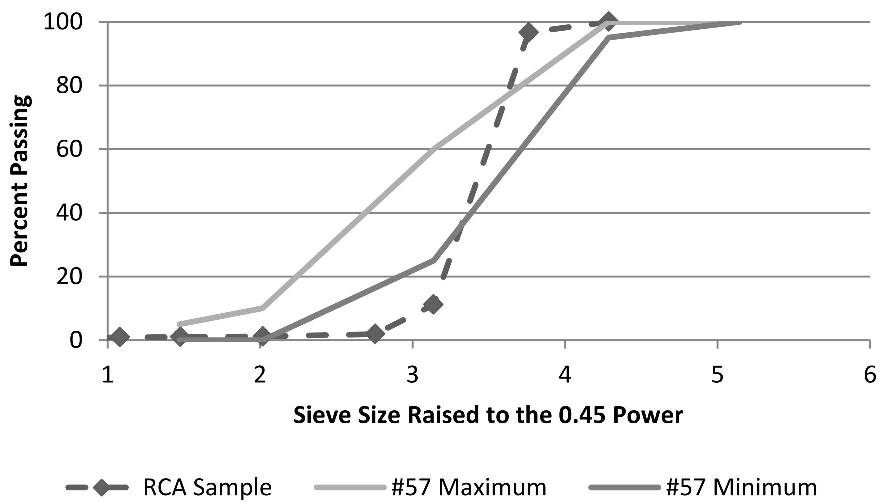

Figure 3. Gradation of the RCA used in the Field Trials

pH and Turbidity of Aggregate Runoff Water

The Ohio Department of Transportation has concerns with recycled concrete as aggregate for road base material due to measured high pH values. [73], [74] A test was devised to observe and evaluate the effects of rainfall on stockpiles of recycled concrete aggregate (RCA). This experiment was based upon the Ohio Department of Transportation’s “Box Test” however new water was used for each test cycle. The purpose of this experiment was to determine if the runoff from an RCA stockpile would have a harmful effect on the environment surrounding the pile. The samples collected from the test described below were tested for pH and turbidity.

Set-up and Procedure

The box test consisted of three rectangular side-by-side compartments constructed with plywood, shown in figure 4. The compartments were lined with plastic on the inside to prevent water loss through the wood and mold growth. The apparatus was placed on the laboratory bench top and sloped so that all of the water in each compartment would drain out. One hole was drilled in the bottom of each compartment with a PVC pipe for drainage. The pipes had small holes drilled in them where the pipe met the bottom of the box. Long flexible tubing was attached to the bottoms of the PVC pipes. The tubes led to three 5-gallon buckets for water collection.

Three different aggregate types were used. In one compartment, a virgin aggregate was used for a control in this experiment. The second compartment contained RCA from two Class B recycling facilities (Pierson and Stavola). The third compartment contained RCA produced from material crushed at Modern Precast. All three types used had the same gradation.

The buckets were filled with enough tap water so that there was enough water to completely cover the aggregate in each compartment. The initial pH and turbidity of the tap water were measured. The water in each bucket was then poured gently into their respective compartments. The water was allowed to freely drain back into the buckets. After the majority of the water was drained, the buckets were mixed to disturb the settled solids and samples were collected. The samples were measured again for pH and turbidity. To simulate rainfall runoff, the effluent water was dumped out and new tap water was used for each run of the test.

The pH results from the box test are shown in table 14 and figure 5. The turbidity results are presented in table 15 and figure 6. The pH from the Modern aggregate was noticeably higher than the tap water and the other aggregate. The EPA limits runoff pH to 9.0. The sample from Modern Precast initially exceeds this value. The other RCA samples had runoff pH below 9.0.

The virgin aggregate runoff was initially extremely turbid. The turbidity of the virgin aggregate runoff had decreased drastically by the tenth run of the experiment, but remained the most turbid. Additionally, the turbidity of the Modern Precast and Class B recycler RCA decreased to about the turbidity of tap water.

Table 14. Tabulated pH results

Number	pH			
	Initial (Tap Water)	Modern	Stavola/Pierson	Virgin
1	7.230	9.396	8.343	7.606
2	7.030	9.739	8.221	7.498
3	7.188	9.579	8.279	7.836
4	7.350	9.505	8.245	7.803
5	7.169	9.874	8.522	8.118
6	7.055	9.570	8.404	8.040
7	6.991	9.730	8.198	7.298
8	7.219	9.348	8.005	7.692
9	7.139	9.232	7.975	7.685
10	7.318	9.171	8.016	7.530
11	7.315	9.174	7.952	7.550
12	7.247	9.242	8.104	7.829
13	7.485	8.880	8.036	7.913
14	7.248	8.904	8.043	7.801
15	7.209	8.853	7.908	7.365
16	7.317	8.791	7.887	7.330
17	7.243	8.739	7.820	7.606
18	7.191	8.747	7.905	7.625

Figure 4. Apparatus used in the box test

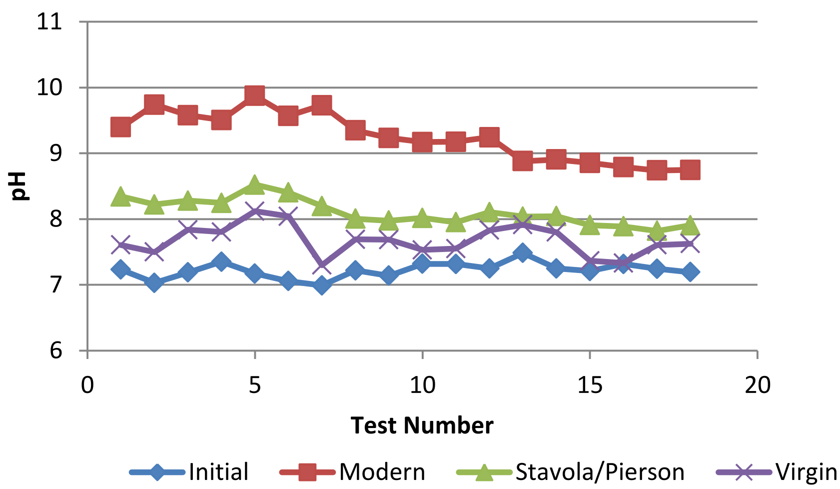

Figure 5. Graph of effluent pH over time

Table 15. Tabulated turbidity results

Number	Turbidity (Ntu)			
	Initial (Tap Water)	Modern	Stavola/Pierson	Virgin
1	-	-	-	-
2	-	34.2	48.1	190.0
3	2.57	41.2	65.7	370.0
4	1.10	25.6	39.4	362.0
5	1.01	10.1	41.7	227.0
6	0.70	8.50	14.6	139.0
7	0.32	3.18	7.01	77.4
8	0.30	4.92	13.2	131.0
9	3.75	4.97	17.8	52.8
10	0.35	3.08	16.6	56.1
11	0.62	2.52	19.0	77.8
12	1.35	6.67	10.6	59.8
13	1.17	3.12	6.48	34.4
14	1.06	2.75	7.1	43.5
15	0.56	4.13	6.38	31.1
16	0.56	2.68	7.65	31.1
17	0.73	2.50	5.18	45.6
18	0.42	1.74	8.44	36.9

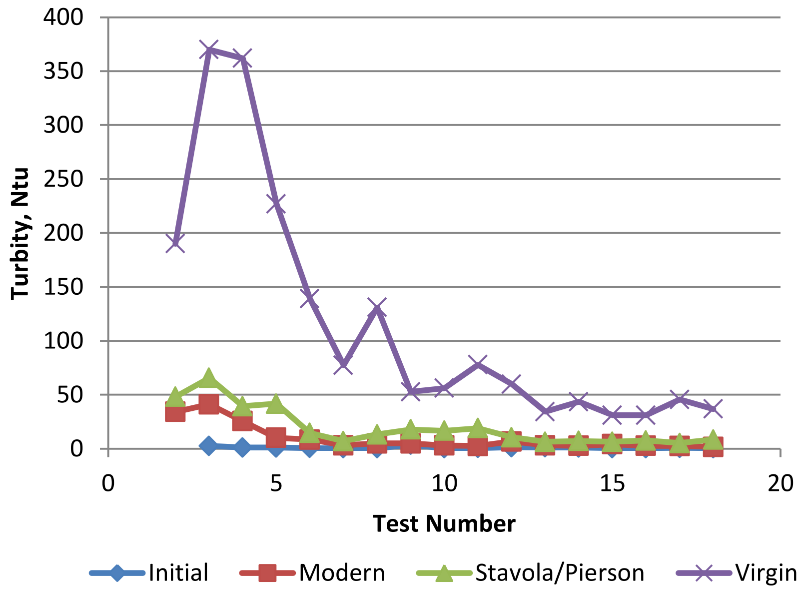

Figure 6. Graph of effluent turbidity over time

Lab Mixes

Concrete mixes employing RCA were developed for cast-in-place applications and for precast applications. Initially the team employed the Residual Mortar Volume Method of proportioning. [66], [65] Standard mixes from the Ready-Mix and Precast contractors that were to be used in the field trials were modified using the method. While the developer of the method has had success, this team was unable to produce a satisfactory mix. The mixes were found to be very stiff and difficult to consolidate. In many of the trials it was observed there did not appear to be enough paste to adequately coat the aggregate.

An absolute volume method of proportioning was used as an alternative with a slight increase in sand content to replace the fines missing in the coarse RCA. Ultimately the mixes were selected for the natural aggregate and RCA (slag and no slag mix) cast-in-place mix and for the self-consolidating mix used for precast trials. The mixes could be consistently produced with predictable fluid and cured properties. The mix designs are shown in table 16 below. The mixes were designed with target air content of 6% and slump of 5 inches for cast-in-place and a spread of 24 inches for the SCC mix.

Table 16. Mixes developed for field trials

Mix	Component	Quantity per Cubic Foot
Natural Aggregate Mix		
	Water	9.6 lb
	Cement	18.4 lb
	Slag	4.6 lb
	Sand	53 lb
	Coarse Aggregate	61.1 lb
	Water Reducer	60 ml
	Air Entrainment	1.5 ml
Recycled Aggregate Mix (w/slag)		
	Water	11.1 lb
	Cement	18.4 lb
	Slag	4.6 lb
	Sand	50.1 lb
	Coarse RCA	51.9 lb
	Water Reducer	60 ml
	Air Entrainment	1.5 ml
Recycled Aggregate Mix (no slag)		
	Water	11.1 lb
	Cement	23 lb
	Sand	50.1 lb
	Coarse RCA	51.9 lb
	Water Reducer	60 ml
	Air Entrainment	1.5 ml
Recycled Aggregate Precast Mix		
	Water	11 lb
	Cement	25 lb
	Sand	51 lb
	Coarse RCA	46 lb
	Water Reducer	50 ml
	Air Entrainment	5 ml

Chloride Permeability

Two mixes were prepared, one including slag and one without, using the recycled aggregates from Modern Precast in a #57 gradation. The mix proportions for each on a cubic foot basis were 52 lb coarse aggregate, 23 lb cement (18.4 lb cement and 4.6 slag in the slag mix), 11.4 lb water, 50.1 lb sand, 47 ml mid-range water reducer, and 1.4 ml air entraining agent. Slump of the slag mix was 7 inches and slump of the no slag mix was 1.5”. Each had an air content of 7 percent. A rapid chloride permeability test was performed on samples from each mix at age of approximately 56 days. The reading for the no slag mix was 3073 coulombs and for the slag mix it was 2326 coulombs. NJDOT does not have a requirement for rapid chloride permeability for conventional concrete mixes however these readings fall within the range typically measured for New Jersey's conventional mixes. Neither reading meets NJDOT standards of 1000 coulombs for high performance concrete.

Laboratory Measured Shrinkage of Concrete Beams

Four small beams (36 in x 7 in x 3.5 in) were cast; two using an RCA mix and two using a natural aggregate mix. The natural aggregate and RCA slag mix designs from table 16 were used. Inserts were set into the beam at approximately 10" spacing. The beams were placed on a bed of small glass beads to minimize axial restraint. A dial gage with a 0.0001" resolution is used to monitor the change in the distance between these points over time. The dial gage was compared to a standard kept at the same temperature as the beams to eliminate temperature effects. Figure 7 shows the comparison of the average shrinkage measured over a period of 195 days. Shrinkage in the beams cast with recycled concrete aggregates was nearly twice as large as that with natural aggregates.

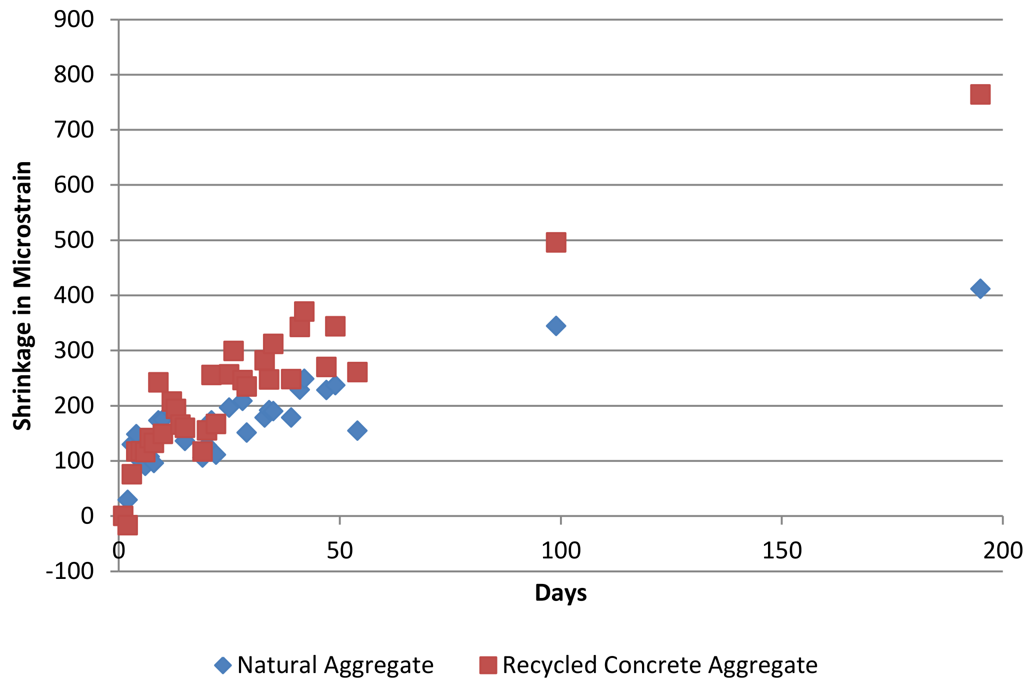

Figure 7. Comparison of shrinkage measured in beams cast with natural aggregate and recycled concrete aggregate

Field Results

The field trials of concrete installations using RCA consisted of the following:

- A concrete apron was place March 18, 2011 (approximately 4 cubic yards)
- A twenty foot length of sidewalk was placed along Carpenter St. on the Rowan campus (5.5 cubic yards) using the RCA with slag mix on June 30, 2011 and a companion section of sidewalk with virgin aggregate was placed on July 2, 2011.
- A test slab was placed outside of Wilson Hall on the Rowan campus on August 2nd, 2011 with virgin aggregate and the companion slab using the RCA mix without slag was placed August 4th, 2011. Each of these was approximately 4.0 cubic yards.
- A test section using the RCA with slag mix was placed August 29th, 2011 outside Robinson Hall on the Rowan campus. This area was a placement of sidewalk with monolithic curb.
- A precast stormwater box, a pedestrian barrier, three parking bumpers, and four 6 ft x 6 ft x 8 in precast slabs were cast at Old Castle Precast, Holmdel, NJ on May 18, 2012.

The intention was that all of the cast-in-place items would be monitored for a period of at least a year with special interest in how they held up through winter freeze-thaw cycles and de-icing salt application. The winter of 2011-2012 was extremely mild and little de-icing salt was used on campus. Monitoring will continue beyond the end of the project.

All of the cast-in-place items were also instrumented with control points similar to the methods described above to monitor shrinkage and compare results to companion pavement sections that were constructed with natural aggregates. The team found these measurements were highly influenced by temperature and moisture changes and no conclusions could be drawn.

Concrete Apron

The apron was cast as an extension to a loading area at Rowan Hall on the Rowan University campus. The concrete was placed March 18, 2011. The air temperature was 66 degrees F and the concrete temperature was 72 degrees F at placement. The measured air content was 5 percent and slump was 5 inches. No placement issues were noted by the field crew and the mix was easy to finish. No distress is currently observed in the pavement.

Table 17. Mix proportions for concrete apron (quantities/cubic yard) and strength data

Cement	620 lb
Water	31 gallons
Sand	1353 lb
Coarse RCA	1404 lb
Water Reducer	Axim 3000 GP 7oz/100
Air Entrainment	AER .2 oz/100
7 day strength	3980 psi
28 day strength	5750 psi

a) b) c) d)

Figure 8. Apron casting on March 18, 2011 and condition on August 9, 2012

Carpenter Street Sidewalk

The sidewalk was placed June 30, 2011. The air temperature was 82 degrees F and the concrete temperature was 84 degrees F at placement. The measured air content was 6.2 percent and slump was 5 inches. No placement issues were noted by the field crew and the mix was easy to finish. No distress is currently observed in the pavement.

Table 18. Mix proportions for Carpenter Street sidewalk (quantities/cubic yard) and strength data

Cement	496 lb
Slag	124 lb
Water	27 gallons
Sand	1353 lb
Coarse RCA	1404 lb
Water Reducer	Axim 3000 GP 7oz/100
Air Entrainment	AER .2 oz/100
28 day strength	4900 psi


a)


b)


c)


d)

Figure 9. Carpenter Street placement on June 30, 2011 and condition on August 9, 2012

Wilson Hall Pavement Replacement

A section of paved area near Wilson Hall was replaced on August 4, 2011. The air temperature was 71 degrees F and the concrete temperature was 82 degrees F at placement. The measured air content was 6.5 percent and slump was 5.5 inches. The field crew felt the mix was a little difficult to float and could have had additional water. This mix did not have slag and the crew preferred the slag mix with RCA. No distress is currently observed in the pavement.

Table 19. Mix proportions for pavement replacement (quantities/cubic yard) and strength data

Cement	620 lb
Water	28 gallons
Sand	1353 lb
Coarse RCA	1404 lb
Water Reducer	Axim 3000 GP 7oz/100
Air Entrainment	AER .2 oz/100
28 day strength	4750 psi

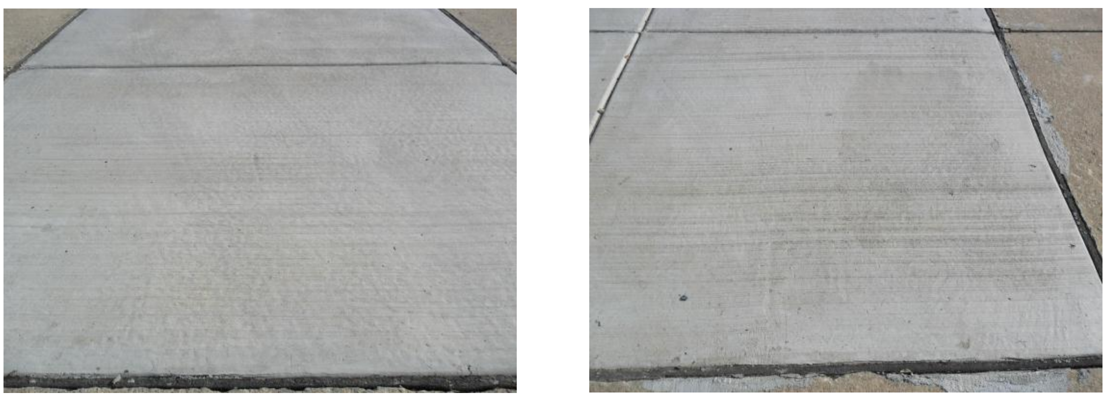

Figure 10. Pavement replacement near Wilson Hall condition on August 9, 2012. The figure on the left is a section using a RCA mix and the section on the right is a companion section that used natural aggregate

Robinson Hall Sidewalk Replacement

The sidewalk was placed August 29, 2011. The air temperature was 82 degrees F and the concrete temperature was 84 degrees F at placement. The measured air content was 6.2 percent and slump was 5 inches. No placement issues were noted by the field crew and the mix was easy to finish. No distress is currently observed in the pavement.

Table 20. Mix proportions for Robinson Hall sidewalk (quantities/cubic yard) and strength data

Cement	496 lb
Slag	124 lb
Water	27 gallons
Sand	1353 lb
Coarse RCA	1404 lb
Water Reducer	Axim 3000 GP 7oz/100
Air Entrainment	AER .2 oz/100
8 day strength	3750 psi
29 day strength	5230 psi

Figure 11. Condition of sidewalk in front of Robinson Hall on August 9, 2012

Precast Trials

On May 18, 2012 precast trials were performed. The items cast included three parking bumpers, a pedestrian barrier, four precast slabs (6 ft x 6 ft x 8 in), and a stormwater system box with various opening. The items were selected to represent a range of low risk applications in which RCA might be acceptable.

During laboratory trials to develop the self-consolidating concrete mix for use in the precast trials it was noted that the RCA had small wood and plastic pieces remaining after crushing of the precast waste from Modern Concrete. There was concern regarding how this would affect the quality of the new precast sections. This did not prove to be an issue in the field trials. The concrete spread was 23.5 inches and the air content was 5.7 percent. The mix proportions used are shown in table 21 and the finished products are shown in figure 12. The laborers at the precast plant did not report any issues with placement of the material incorporating recycled concrete aggregates. These items, with the exception of the concrete box, will be put into service on the Rowan University campus and monitored beyond the end of the project.

Table 21. Mix proportions and strength results for precast trials

Water	35 gal
Cement	675 lb
Sand	1377 lb
Coarse RCA	1242 lb
Water Reducer	Sika Viscocrete 6100 6 oz/100
Air Entrainment	Sika Air .5 oz/100
14 day strength	6265 psi
26 day strength	6600 psi

Figure 12. Items precast using recycled concrete aggregates

RECOMMENDATIONS

Based on the extensive review of available literature and the experiences of other state transportation agencies the following recommendations are made

1. The New Jersey Department of Transportation should allow the use of recycled concrete as coarse aggregate for concrete.
2. Applications should be limited to non-structural or roadway concrete items, excluding surface and base courses. Precasting roadway concrete items with SCC using RCA should also be permitted.
3. Although many states require that the original source of the recycled concrete be known and that the original concrete met DOT standards, implementation of this standard would be problematic in New Jersey. A system of regional recycling centers has developed across the state that is currently supplying RCA for dense graded aggregate base and RAP for asphalt applications. The source of the concrete being recycled is not usually known and this requirement would force the recyclers to develop parallel crushing operations for traceable and non-traceable materials. It is doubtful the recycling centers would be willing or have the space to do this. This is not an issue for precasting operations electing to recycled their own waste concrete.
4. In cases of large pavement removal and replacement operations, reuse of the aggregates could be approved on a job basis with satisfactory test results of the recycled material.
5. Many authors suggested the many problems associated with the use of RCA were alleviated by limiting the aggregate replacement rate to 30 percent or less. There is not a consensus on this and states are successfully allowing 100 percent replacement rates. It is suggested that no limit be placed on the replacement rate. Available supply of RCA will likely dictate whether contractors choose to use a blend of virgin aggregate and RCA or a 100 percent replacement. Precast facilities would likely use a blend.
6. An alternative mix design process has been proposed elsewhere with the claim that it eliminates many of the problems associated with using RCA in new concrete. In this project more traditional mix design methods worked well and the alternative mix design method should not be required.
7. Because of the unknown history of material reaching Class B recyclers, it is recommended that ASR mitigation methods be required for all mixes using RCA unless the source aggregate is known such as in the case of precasting operations.
8. Slabs fabricated with recycled aggregates could be used in a chloride ponding study to further evaluate long term durability of the material.

9. The precasting trials were promising and used 100 percent aggregate replacement. It would be instructive to blend recycled material and natural aggregates together. A blend of RCA and natural aggregate is a more realistic scenario in the precast environment.

RECOMMENDED SPECIFICATIONS

Additions to existing NJDOT specifications are recommended in order to permit the use of crushed hydraulic cement concrete to be used as recycled concrete aggregate in new Portland cement concrete. The suggested specifications can be found in Appendix B of this report.

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Appendix A - Details of Transportation Official Survey

RCA Survey

A survey was sent out to the DOT of each U.S. State, Capital and other territories. Thirty-two DOTs responded.

This section is split into the Following Sections:

States that do allow RCA use in PCC
States that do allow RCA use in PCC (has not been used as of yet)
States that do not allow RCA use in PCC
States that do not allow RCA use in PCC (no reason provided)
States that have no policy on RCA usage in PCC
States that did not respond to the survey

States that do allow RCA use in PCC

Colorado
Does allow RCA use in PCC
Contact: Patrick Kropp (Concrete and Physical Properties Program Manager)
Contact Information: 303-398-6541

Florida
Does allow RCA use in PCC
RCA can be used as coarse aggregate in non-structural applications
Currently considering allowing RCA for roadway barrier walls, but this has yet to be included in the specification
Link:
ftp://ftp.dot.state.fl.us/LTS/CO/Specifications/SpecBook/2010Book/901.pdf
Contact: Mike Bergin
Contact Information: 352-955-6666
michael.bergin@dot.state.fl.us

Kansas
Does allow RCA use in PCC (so far done on a case-by-case basis)
Most uses have been an experiment to measure how it would perform
Although the experiments have been promising there is not a large need for the use
*Most reclaimed concrete is being used to construct bases for the PCCP, not leaving a lot of waste concrete
Contact: Andrew Gisi, PE
Contact Information: AGisi@ksdot.org
785-291-3856

Nevada
Does allow RCA use in PCC
RCA must meet the states base aggregate specifications.
Has been used by a contractor who used a blend of recycled concrete with base aggregates and had no problem getting acceptable results for gradation and compaction (along with meeting our source acceptance requirements prior to using this blend). (Note: this response appears to be dealing with base material rather than use in concrete)
Contact: Reid G. Kaiser, P.E., CPM (Chief Materials Engineer | Nevada Department of Transportation)
Contact Information: (775) 888-7520 phone
(775) 720-4532 cell
(775) 888-7501 fax
rkaiser@dot.state.nv.us | www.nevadadot.com
Mailing address: 1263 South Stewart Street, Carson City, Nevada 89712
Contact: Rick Bosch
*Would be a good person to contact, he was our Resident Engineer on the project where we used it. I have attached his contact information

North Carolina
Does allow RCA use in PCC (since 1990's)
RCA has been largely used for subdivision, low volume roads (small projects), or detour routes (due to the lack of availability of large volumes of material required for projects performed on higher volume roads)
RCA was also used for three limited access routes where existing concrete pavement and structures where crushed with the resulting aggregate used as base under the new concrete pavement (this does not include rubbelized or crack and seat concrete that has been covered with asphalt).
Use of aggregate from crushed concrete has been allowed for use in Class B concrete mixes (non-structural/incidental, 2500psi) (*no supplier has submitted a mix design for approval using crushed concrete to this date)
*Crushed concrete is not allowed for use in any other class of concrete.
Contact: W. Cabell Garbee, II, PE (Field Operations Engineer, NCDOT Materials and Tests Unit)
Contact Information: cgarbee@ncdot.gov
919-329-4224 office
919-906-6294 cell
*One contractor in the state utilizes crushed concrete as aggregate in concrete for their driveway/parking lot specialty division (private, non-DOT projects).

South Carolina
Does allow RCA use in PCC
RCA was used approximately 10 years ago on I-95 and will be used again with a project on I-20 beginning this month
Both cases were for the purpose of widening the road and will use the existing concrete as coarse aggregate in the reconstruction
Fine aggregate is not permitted for use and RCA that is not from the existing road is not allowed in construction
The concrete materials of the road had no performance issues
Would be very hesitant to allow RCA from parent sources that are not well known
* RCA is only used when reconstructing an existing PCC pavement with PCC, which is not often done
Contact: Andrew M. Johnson, Ph.D., P.E. (State Pavement Design Engineer, Office of Materials and Research, South Carolina Department of Transportation)
Contact Information: Phone: (803) 737-6683
Fax: (803) 737-6649
e-mail: JohnsonAM@scdot.org
Mailing Address: P.O. Box 191
Columbia, SC 29202-0191

Texas
Does allow RCA use in PCC
RCA can only be used in none structural concrete (paving concrete, sidewalks, anchors, etc.)

Any percent of coarse aggregate can be used, but only 20% of RCC fine aggregate is allowed in PCC
100% coarse aggregate is used in pavement in multiple cases
Publications/Websites:
ftp://ftp.dot.state.tx.us/pub/txdot-info/gsd/concrete_0-1753.pdf
http://www.txdot.gov/business/contractors_consultants/recycling/concrete_aggregate.htm
Contact: Elizabeth (Lisa) Lukefahr (CST – M&P, Rigid Pavement and Concrete Materials TxDOT)
Contact Information: (512) 506-5858
elizabeth.lukefahr@txdot.gov

States that do allow RCA use in PCC (has not been used as of yet)
Alabama
Does allow RCA use in PCC
RCA has not been use in PCC in New York
If allowed by the plans Crushed concrete may be used as an aggregate
The crushed concrete used as an aggregate shall meet the requirements given in this Section and the requirements given in Articles 801.01, 801.02 and 801.03.
The RCA must meet the respective Division 800 articles, an approved source of RAC must be listed on our approved aggregate producers List I-1 and must meet all same requirements as other approved aggregate types (Abrasion, Soundness, Gravities, BPN, Silica, F/E, absorption, etc.).
RCA is not allowed in structural concrete, only PCC pavement
Currently there is no approved source of PCC aggregate
Contact: Mr. Chris Strickland, P.E. (ALDOT Aggregate Engineer)
Contact Information: Office: (334) 206-2420
Email: stricklandc@dot.state.al.us

Contact: Mr. Shannon Golden, P.E. (ALDOT Concrete Engineer)
Contact Information: Office: (334) 206-2410
Email: goldens@dot.state.al.us

Minnesota
Does allow RCA use in PCC (at the discretion of the Concrete Engineer based on the history of the recycled material)
The recycled concrete needs to be washed as well as meet all state requirements
*It was suppose to be used in 1997 in a concrete pavement but the contractor struggled with controlling the w/c ratio of the mix and ending up switching to virgin aggregate for 100% of the mix
It is unsure if the MnDOT has ever used RCA in PCC
Contact: Maria Masten (Concrete Engineer)
Contact Information: 651-366-5572
maria.masten@state.mn.us

New York
Does allow RCA in PCC
RCA has to meet the specifications of NYDOT
The source of the RCA must be known to have the ASR potential.
Prefer recycled aggregate from highway application than urban areas (Higher transportation and building waste in urban concrete poorer expected performance)
The RCA stockpiles need to be soaked and drained to get the RCA into a SSD condition (RCA is treated as a light weight source)
RCA has not been use in PCC in New York
Contact: Donald Streeter
Contact Information: dstreeter@dot.state.ny.us

*People wont recycle the concrete because of the conditions imposed

Ohio
Does allow RCA in PCC (recently)
RCA has to meet the requirements for evaluation of the pavement's condition (looking for D cracking and ASR before reuse)
The RCA mix design has to also be tested for shrinkage, freeze thaw, etc…
RCA is used in PCC because it is not allowed for use as a roadbase granular material (due to environmental run off and issues with freeze thaw breakdown of the aggregate agglomerate)
*Cementatious action between the concrete pavement and an RCA aggregate base that has caused cracking and pavement failures or durability issues
Contact: Lloyd Welker PE (Administrator, Office of Materials Management, Ohio Department of Transportation)
Contact Information: 614 275 1351
Mailing Address: 1600 West Broad Street
Columbus, Ohio 43223

Tennessee
Does allow RCA (crushed concrete) in PCC
RCA has to meet the specifications for the specific class of concrete
RCA has not been use in PCC in Tennesse
Contact: Bill Trolinger (C.E. Manager II, Materials & Tests, TnDOT)
Contact Information: 615-350-4105(cell)
615-3504128 (fax)
Bill.Trolinger@tn.gov

West Virginia
Does allow RCA use if it meets WVDOH specifications. The link below is section 501.2.1 of WVDOH standard specifications.
http://www.transportation.wv.gov/highways/contractadmin/specifications/Documents/2010%20Standard%20Specifications%20Roads%20and%20Bridges/Complete%20Publications/2010StandardRoadsnBridges.pdf
RCA has not been use in PCC in West Virginia
Contact: Mike Mance
Contact Information: 304-558-9846
*Have no experiences or observations to report

States that do not allow RCA use in PCC

Delaware

Does not allow RCA use in PCC

Concerned about the introduction of the ASR from the RCA into the PCC and the possible effects

Concerned about the introduction of Reactive RCA into PCC (The supply of one source aggregate are not large enough to establish an ASR test history since the stockpiles will be exhausted very quickly)

Concerned about the variability of the RCA characteristics (Such as RCA weakening the PCC causing accelerated breaking results)

Contact: Greg Hainsworth, P.E. (Materials and Research)

Contact Information: 302-760-2401 (Phone)
302-739-5270 (Fax)

*Local supplies of RCA are exhausted in use for unbound aggregate layers

Maryland

Does not allow RCA use in PCC

Currently researching RCA literature and information

Concerned about the ASR (alkali silica reaction), the presence of unknown by-products and material constituents in the recycled material (especially in the absence of historical & quality assurance data from the original time of placement), Concerned about general material quality control and quality assurance of the new product containing the RCA.

If the concerns are someday addressed and material quality and longevity of RCA can be established it is possible that RCA may be used in PCC

Contact: Michelle Armiger (Division Chief, Maryland State Highway Administration, Office of Materials Technology, Concrete Technology Division)

Contact Information: marmiger@sha.state.md.us
(443) 572-5133

Mailing Address: 7450 Traffic Drive
Hanover, MD 21076

New Mexico

Does not allow RCA use in PCC

Concerned about the issues of ASR reactions.

Contact: Bryce Simons (Materials Testing Engineer)

Contact Information: 505-827-5191 (Office)
505-470-7902 (Cell)

States that do not allow RCA use in PCC (no reason provided)

Arizona
Does not allow RCA use in PCC.
No reason given.
Contact: Bill Hurguy
Contact Information: BHuruguy@azdot.gov

District of Columbia
Does not allow RCA use in PCC.
No reason given.
Contact: Wasi Khan
Contact Information: None provided

Georgia
Does not allow RCA use in PCC.
No reason given.
Contact: Myron K. Banks (Materials & Research Branch Chief – Concrete Construction Division)
Contact Information: 404-608-4876 (Office)
*Allow RCA usage in base material

Indiana
Does not allow RCA use in PCC
Currently studying the use of Recycled concrete with Purdue
Recycled concrete can currently be used in subgrade applications
Contact: Tony Zander (Concrete Engineer)
Contact Information: azander@indot.in.gov

Kentucky
Does not allow RCA use in PCC.
No reason given.
Contact: Allen H. Myers, P. E. (Director, Division of Materials, Department of Highways, Kentucky Transportation Cabinet)
Contact Information: 502-564-3160 (phone)
502-564-7034 (fax)
Allen.Myers@ky.gov
Street Address: 1227 Wilkinson Boulevard
Frankfort, KY 40601-1226

Louisiana
Does not allow RCA use in PCC (had allowed it previously)
John Eggers has more information about the problems with RCA usage and why the RCA use was restricted
Contact: John Eggers (an HQ Area Engineers)
Contact Information: John.Eggers@la.gov
225-379-1505 (Phone)

Missouri
Does not allow RCA use in PCC (currently)
*MoDOT advised several contractors that were interested in using recycled concrete aggregates in new concrete pavement, that they would allow the use provided the concrete meets the same specification requirements as for concrete without recycled concrete aggregates
Contact: Brett Trautman (Field Materials Engineer, Construction, Materials and Research Division, Missouri Department of Transportation)
Contact Information: (573) 751-2926
email - brett.trautman@modot.mo.gov

Mississippi
Does not allow RCA use in PCC.
No reason given.
Contact: Adam Browne (Concrete Field Engineer, Mississippi Department of Transportation, Materials Division)
Contact Information: 601-359-1761

Nebraska
Does not allow RCA use in PCC.
No reason given.
Contact: Mick Syslo, P.E. (Materials & Research Engineer, Nebraska Dept. of Roads)
Contact Information: (402) 479-4750 (Office)

New Hampshire
Does not allow RCA use in PCC.
No reason given.
Contact: Alan Rawson
Contact Information: ARawson@dot.state.nh.us

Pennsylvania
Does not allow RCA use in PCC.
No reason given.
Contact: Timothy L. Ramirez, P.E. (Engineer of Tests, PA department of Transportation)
Contact Information: 717-783-6602 (Phone)
717-783-5955 (Fax)
www.dot.state.pa.us

Rhode Island
Does not allow RCA use in PCC.
No reason given.
Contact: Mark Felag
Contact Information: mfelag@dot.ri.gov

Utah

Does not allow RCA use in PCC.
No reason given.
Contact: Bryan N. Lee, P.E. (Materials Engineer for Concrete and Steel) (UDOT Central Materials Division)
Contact Information: (801) 965-3814
633-6262 (cell)
bryanlee@utah.gov

States that have no policy on RCA usage in PCC

Montana
Has not used RCA in PCC
No Concerns or conditions were given
Contact: Matthew R. Strizich, P.E. (Materials Engineer, Montana Department of Transportation)
Contact Information: 406-444-6297

Ontario
Does not currently use RCA in PCC (are interested)
Currently monitoring a field trial installation to assess performance.
Trail:

> The trial was constructed this past fall using returned concrete (i.e. concrete from concrete making operations that was returned to the ready-mix plant, separated and crushed), and the plastic and early-age hardened properties of the concrete were assessed; long term properties including durability will also be monitored. The trial installation is in a sidewalk application where it is exposed to freeze-thaw action and use of deicing salts. Two different replacement levels of recycled concrete aggregate were used (15% and 25%, approximately). Depending on the success of the trial, plans will be made regarding future work and potential for broader use of returned concrete in MTO construction operations. This trial is a cooperative effort with an Ontario building materials producer (Holcim) and an academic partner (Professor R. D. Hooton of the University of Toronto).

MTO has no plans for use of recycled concrete from demolition, at this time.
Contact: Mr. Tom Kazmierowski (Manager of the Materials Engineering and Research Office of the Ontario Ministry of Transportation)
Contact: Jana Konecny (Senior Concrete Engineer, Concrete Section)
Contact Information: jana.konecny@ontario.ca
(416) 235-3711

Washington
Has not used RCA in PCC
No Concerns or conditions were given
Contact: Thomas E. Baker, P.E. (WSDOT, State Materials Engineer)
Contact Information: 360-709-5401

360-480-9406 (cell)
360-709-5588 (fax)
Mailing Address: PO Box 47365
Olympia WA 98504-7365
Street Address: 1655 South Second Ave
Tumwater WA 98512-6951
*Have not used it, but are interested in the possibility

States that did not respond to the survey
Alaska
Arkansas
California
Connecticut
Hawaii
Idaho
Illinois
Iowa
Maine
Massachusetts
Michigan
Oklahoma
Oregon
South Dakota
Wisconsin
Wyoming

Appendix B – Recommended Specifications for use of Recycled Concrete Aggregates in Hydraulic Cement Concrete

Recommended modifications to allow the use of recycled concrete aggregates in hydraulic cement concrete are provided. The changes or additions to the current specifications have been underlined.

DIVISION 900 – MATERIALS
SECTION 901 – AGGREGATES

901.01 SOURCE

Use aggregates from a single source and geological classification in any 1 construction item unless otherwise authorized. Use only sources of aggregate that are listed on the QPL.

The ME may allow aggregates from different sources if they are of the same geological classification and have similar specific gravities and aggregate properties.

Use test methods for gradation according to the appropriate provisions of AASHTO T 11 or T 27, unless otherwise noted. Gradations of aggregates in the various tables of this and other Sections are the percentages passing by weight.

The aggregate producer shall submit annually, to the ME for approval, a quality control plan for the aggregate products. The aggregate producer may obtain guidelines for developing the quality control plan from the ME upon request.

901.02 STOCKPILES

Provide an area for each stockpile of adequate size, reasonably uniform in cross-section, well drained, and cleared of foreign materials.

At concrete and HMA mixing plants, stockpile a sufficient quantity of aggregate to provide for a minimum of 1 day's operations. Place the aggregate stockpiles on a firm, hard surface, such as a compacted aggregate, HMA, or concrete surface. Construct the stockpile by placing the aggregates in layers of not more than 3 feet thick.

Locate the piles so that there is no contamination by foreign material and no intermingling of aggregates from adjacent piles. Do not use steel-tracked equipment on the stockpiles.

Do not store aggregates from different sources, geological classifications, or of different gradings in stockpiles near each other unless a bulkhead is placed between the different materials. If blending aggregates of different gradings and from different sources, proportion through weigh hoppers. The ME may allow loader blending of aggregate stockpiles if included in the approved aggregate producer's quality control plan. The Department will reject aggregates found segregated or contaminated. If a stockpile is rejected for segregation, the Contractor may reconstruct it for further evaluation. Use methods that prevent segregation when charging aggregates from stockpiles.

Do not use washed aggregates sooner than 24 hours after washing or until the surplus water has drained out and the material has uniform moisture content.

Do not stockpile RAP higher than 15 feet. Cover or otherwise protect stockpiles of RAP for use in HMA to prevent buildup of moisture.

901.03 COARSE AGGREGATE

Obtain coarse aggregate as specified in 901.01. Use coarse aggregate that is broken stone or washed gravel graded as specified Table 901.03-1. Stockpile coarse aggregate as specified in 901.02. The ME will sample coarse aggregate as specified in Table 901.03-2.

Table 901.03-1 Standard Sizes of Coarse Aggregate

		Amounts finer than each laboratory sieve, percentage by weight														
No.	**Nominal Size**	**4"**	**3-1/2"**	**3"**	**2-1/2"**	**2"**	**1-1/2"**	**1"**	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 50**	**No. 100**
1	**3-1/2" - 1-1/2"**	100	90-100		25-60		0-15		0-5							
2	**2-1/2" - 1-1/2"**			100	90-100	35-70	0-15		0-5							
3	**2" - 1"**				100	90-100	35-70	0-15		0-5						
4	**1-1/2" - 3/4"**					100	90-100	20-55	0-15		0-5					
5	**1" - 1/2"**						100	90-100	20-55	0-10	0-5					
57	**1" - No. 4**						100	95-100		25-60		0-10	0-5			
67	**3/4"- No. 4**							100	90-100		20-55	0-10	0-5			
7	**1/2" - No. 4**								100	90-100	40-70	0-15	0-5			
8	**3/8" - No. 8**									100	85-100	10-30	0-10	0-5		
9	**No. 4 - No. 16**										100	85-100	10-40	0-10	0-5	
10	**No. 4 - No. 200**										100	85-100				10-30

Table 901.03-2 Coarse Aggregate Sampling		
Coarse Aggregate, No.	**Sample Size (pounds)**	**Frequency**
1	150	1000 tons or 830 cubic yards
2	100	1000 tons or 830 cubic yards
3	90	1000 tons or 830 cubic yards
4	70	1000 tons or 830 cubic yards
5 & 57	50	500 tons or 415 cubic yards
67	30	500 tons or 415 cubic yards
7	20	250 tons or 200 cubic yards
8, 9, & 10 (stone sand)	10	250 tons or 200 cubic yards

901.03.01 Broken Stone

Use broken stone that is uniform in texture and quality and that conforms to the requirements specified in Table 901.03.01-1.

Table 901.03.01-1 Requirements for Broken Stone		
Aggregate Property	**Test Method**	**Maximum Percent**
Weathered and deleterious stone	NJDOT A-3	5
Broken stone other than that classification approved for use	NJDOT A-3	5
Flat and elongated pieces for graded material No. 67 and larger length greater than 5 times the thickness or width)	ASTM D 4791	10
Absorption in cold water:		

No. 9 and larger	AASHTO T 85	1.8
Stone sand only (No. 10)	AASHTO T 84	2.0
Sodium sulfate soundness, loss	AASHTO T 104	10
Adherent fines in coarse aggregates:		
HMA	NJDOT A-4	1.5
Concrete	NJDOT A-4	1.0
Percentage of wear (Los Angeles Abrasion Test):		
HMA surface course	AASHTO T 96	40
HMA intermediate or base course	AASHTO T 96	45
Concrete surface course and bridge decks	AASHTO T 96	40
Concrete, other	AASHTO T 96	50
Dense-graded aggregate base course	AASHTO T 96	50

The geologic classifications are as follows:

1. **Argillite.** A thoroughly indurated and cohesive rock composed predominantly of silt size or smaller particles of clay, quartz, and feldspar or the fine-grained thermal recrystallization products of this assemblage (hornfels). Ensure rock is bedded thickly enough so as not to break into thin pieces at planes of stratification.

2. **Carbonate Rock.** A thoroughly indurated and cohesive rock composed predominantly of calcite and dolomite, bedded thickly enough so as not to break into thin pieces at planes of stratification. Minerals insoluble in hot hydrochloric acid are discrete grains of quartz, clay, and mica.

3. **Gneiss.** A metamorphic rock consisting principally of quartz and feldspar. Ensure rock has a dense structure, with a uniform distribution of minerals that will not break into thin pieces at lines of stratification.

4. **Granite.** An equigranular or porphyritic igneous rock consisting principally of quartz and feldspar.

5. **Quartzite.** A metamorphic rock composed principally of quartz. Quarry rock so that only the nonarkosic, uniformly compacted quartzites are included in the graded products. Ensure quartzite is not schistose in structure.

6. **Trap Rock.** An igneous rock, locally, either basalt or diabase, with a uniform distribution of constituent minerals. Amygdaloidal or vesicular basalt is not considered trap rock and is considered a deleterious material for testing purposes.

901.03.02 Washed Gravel

Use washed gravel that is either crushed or uncrushed as specified and that conforms to the requirements specified in Table 901.03.02-1.

Table 901.03.02-1 Requirements for Washed Gravel		
Aggregate Property	**Test Method**	**Maximum Percent**
Weathered and deleterious gravel	NJDOT A-3	5
Sodium sulfate soundness, loss	AASHTO T 104	10
Soft particles as determined by scratch hardness test	NJDOT A-5	5
Absorption in cold water:		
No. 9 and larger	AASHTO T 85	1.8
Stone sand only (No. 10)	AASHTO T 84	2.0
Clay lumps, organic material, coal and other foreign or deleterious matter (Percent by weight or volume, whichever is greater)	AASHTO T 112	0.5
Chloride content	AASHTO T 260	0.06
Crushed gravel material with at least 1 fractured face (Nicked gravel is not considered crushed)	ASTM D 5821	60
Adherent fines in coarse aggregates:		
HMA	NJDOT A-4	1.5
Concrete	NJDOT A-4	1.0

Quartz gravel is composed of natural pebbles, of which the majority is coarsely crystalline quartz. Ensure that the individual crystals within each pebble are intergrown into a tenacious, nonporous, interlocking texture that fractures as a single unit. Ensure that the percent of wear determined according to the Los Angeles Abrasion Test is as specified for the various uses, except that the percent maximum loss for quartz gravel is 50 percent.

When the sodium sulfate soundness and scratch hardness tests total 10 percent or more, the ME will perform a petrographic analysis to determine the amount of unsound and weathered material.

901.06 AGGREGATES FOR CONCRETE, MORTAR, AND GROUT

The ME will test aggregates used in concrete according to AASHTO T 303 for potential expansion due to alkali-silica reactivity. The ME will classify aggregates that produce expansion of 0.1 percent or more after 14 days in solution as potentially reactive. Use potentially reactive aggregate in concrete only in conjunction with remedial agents such as fly ash, slag, or low alkali cement at the minimum addition rates specified in 903.03.01.

901.06.01 Coarse Aggregate

Added text to allow RCA as coarse aggregate in concrete.

Use coarse aggregate that is broken stone or washed gravel or recycled concrete aggregates conforming to 901.03.01 or 901.03.02 or 901.06.04, respectively, except do not use carbonate rock for concrete surface courses, bridge approach, or bridge decks. Recycled concrete aggregates may only be used in roadway items identified in Table 903.03.06-1 with the exception of surface course and base course concrete. Use coarse aggregate that is the size or sizes shown in Table 903.03.06-1 and Table 903.03.06-2. Wash the coarse aggregate at least 24 hours before use.

Allowing for most roadway items but not for surface course and not for structural concrete.

901.06.02 Fine Aggregate

NO CHANGES WERE PROPOSED TO THIS SECTION

901.06.03 Lightweight Aggregate

NO CHANGES WERE PROPOSED TO THIS SECTION

New specification section including properties.

901.06.04 Recycled Concrete Aggregate (crushed hydraulic cement concrete) for use in PCC

The Contractor may produce coarse aggregate for use in PCC from crushed hydraulic cement concrete that conforms to the gradation and plasticity requirements specified in 901.10.01 and to the following:

1. **Composition.** Ensure that the composition, as determined according to NJDOT A-3, conforms to the requirements specified in Table 901.06.04-1.

Table 901.06.04-1 Composition Requirements for RCA in PCC		
Aggregate Property	**Minimum Percent**	**Maximum Percent**
Concrete[1]	95	_
HMA		5
Brick, cinder block, schist, concrete washout, and other friable material	_	2
Reactive material		0
Wood		0.1

[1] To meet the minimum requirement for concrete, the Contractor may add broken stone or crushed gravel. Use broken stone conforming to 901.03.01 or crushed gravel conforming to 901.03.02, except that it need not be washed

These requirements are tighter than for DGA RCA.

2. Physical Properties

Use crushed hydraulic cement concrete that is uniform in texture and quality and that conforms to the requirements specified in Table 901.06.04-2.

Table 901.06.04-2 Requirements for Recycled Concrete Aggregate in PCC		
Aggregate Property	***Test Method***	***Maximum Percent***
Flat and elongated pieces for graded material No. 67 and larger length greater than 5 times the thickness or width)	*ASTM D 4791*	*10*
Absorption in cold water:		
No. 9 and larger	*AASHTO T 85*	*8.0*
Sodium sulfate soundness, loss	*AASHTO T 104*	*10*
Residual Mortar Content	*Proposed NJDOT Test A-7*	*44*
Adherent fines in coarse aggregates:		

Concrete	NJDOT A-4	1.0
Percentage of wear (Los Angeles Abrasion Test):		
Concrete, other	AASHTO T 96	50
Chloride content	AASHTO T 260	0.06

3. **Stockpiles.** Ensure that stockpiles conform to the requirements of 901.02. In addition, regularly wet recycled concrete aggregate (RCA) stockpiles to maintain the material in a near SSD condition. The Contractor may blend recycled concrete aggregate with virgin aggregate as described in 901.02.

Inserted to encourage keeping the stockpile wet to alleviate some shrinkage issues.

4. **Reporting of Recycled Materials Usage.** Report the tonnage of concrete aggregate being recycled to the Solid Waste Management District of origin, according to N.J.A.C 7:26A.

901.10 DENSE-GRADED AGGREGATE (DGA)

Use a DGA that is listed on the QPL. For gradation acceptance, the ME will sample DGA according to AASHTO T 2 for each 500 cubic yards. The ME will apply the gradation requirements to the material after it has been placed and compacted on the Project.

901.10.01 Virgin

Produce virgin DGA from broken stone conforming to 901.03.01, crushed gravel conforming to 901.03.02, or blast furnace slag conforming to 901.04, except that at least 90 percent of all fragments shall contain at least 1 fractured face. Ensure that the DGA conforms to the following requirements and gradation:

1. **Moisture Content.** Ensure that the moisture content of DGA immediately before placement is 6 ± 2 percent based on dry weight. If dense-graded aggregate is to be paid for on a weight basis, do not deliver DGA to the Project with the moisture content exceeding 8 percent.

2. **Plasticity and Gradation.** When tested according to AASHTO T 90, ensure that the portion passing the No. 40 sieve is non-plastic. Ensure that the gradation conforms to the requirements specified in Table 901.10.01-1.

Table 901.10.01-1 Gradation Requirements for

DGA	
Sieve Size	**Percent Passing**
1-1/2"	100
3/4"	55 - 90
No. 4	25 - 50
No. 50	5 - 20
No. 200	3 - 10

Added “for DGA” to distinguish from RCA for PCC.

901.10.02 Recycled Concrete Aggregate (RCA) for DGA

The Contractor may produce DGA from recycled concrete aggregate that conforms to the gradation and plasticity requirements specified in 901.10.01 and to the following:

1. **Composition.** Ensure that the composition, as determined according to NJDOT A-3, conforms to the requirements specified in Table 901.10.02-1.

Table 901.10.02-1 Composition Requirements for RCA

Aggregate Property	Minimum Percent	Maximum Percent
Concrete[1]	90	
HMA		10
Brick, cinder block, schist, concrete washout, and other friable material		4
Reactive material		0
Wood		0.1

[1] To meet the minimum requirement for concrete, the Contractor may add broken stone, vitreous china, or crushed gravel. Use broken stone conforming to 901.03.01 or crushed gravel conforming to 901.03.02, except that it need not be washed

2. **Percentage of Wear.** Ensure that the loss does not exceed 50 percent when tested according to AASHTO T 96.

3. **Reporting of Recycled Materials Usage.** Report the tonnage of concrete aggregate being recycled to the Solid Waste Management District of origin, according to N.J.A.C 7:26A.

903.03 CONCRETE

903.03.01 Composition

NO CHANGES WERE PROPOSED TO THIS SECTION

903.03.02 Mix Design and Verification

NO CHANGES WERE PROPOSED TO THIS SECTION

903.03.03 Mixing for Central-Plant and Transit Mixing

NO CHANGES WERE PROPOSED TO THIS SECTION

903.03.04 Mixing on the Project

NO CHANGES WERE PROPOSED TO THIS SECTION

903.03.06 Tables

Table 903.03.06-1 Requirements for Roadway Concrete Items

			Percent Air Entrainment for Coarse Aggregate[1]	
	Concrete Class	Slump[1] (inch)	No. 57 & No. 67	No. 8
Cast-in-Place Items				
Surface Course, Base Course	B	2 ± 1	6.0 ± 1.5	7.0 ± 1.5
Inlets, Manholes, Headwalls, Sidewalks, Driveways, Islands	B	3 ± 1	6.0 ± 1.5	7.0±1.5
Slope Gutters, Vertical Curb, Sloping Curb, Barrier Curb, Concrete	B	4 ± 1	6.0 ± 1.5	7.0 ± 1.5

Islands				
Foundations for: Inlets, Manholes and Electrical Items	B	3 ± 1	7.5 max	8.5 max
Signs	B	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Footings for: Fence Post, Beam Guide Rail Terminals, and Anchorages	B	3 ± 1	7.5 max	8.5 max
Culverts	A	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Monuments	A	3 ± 1	7.5 max	8.5 max
Slope Protection	B	2 ± 1	6.0 ± 1.5	7.0 ± 1.5
Pipe Bedding, Thrust Blocks, Pipe Plugs, Encasements, Saddles	B	3 ± 1	7.5 max	8.5 max
Precast Items				
Culverts	P	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Inlets, Manholes, Junction Boxes, Headwalls, Reinforced Concrete End Sections	B	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Concrete Barrier Curb	B	3 ± 1	7.0 ± 2.0	8.0 ± 2.0
Slip-Form Items				
Surface Course, Base Course	B	1-1/2 ± 1	6.0 ± 1.5	7.0 ± 1.5

[1] When using a Type F or G admixture, change the requirements for Slump and Air Content for the given concrete item as follows:

[1.1] Slump: 6 ± 2 inches

[1.2] Air Content: Increase both the target value and tolerance percentages by 0.5.

Table 903.03.06-2 Requirements for Structural Concrete Items

	Concrete Class	Slump[1] (inches)	Percent Air Entrainment for Coarse Aggregate[1]	
			No. 57 & No. 67	No. 8
Cast-in-Place Items				
Bridge Approach	A	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Footings, Piles	B	3 ± 1	7.5 max	8.5 max
Abutments, Wing Walls, Pier Shafts, Retaining Walls	B	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Drilled Shafts[2]	A	7 ± 1[2]	–	7.5 ± 1.5
Concrete Barrier Curb, Bridge	B	4 ± 1	7.0 ± 2.0	8.0 ± 2.0
Pier Columns and Pier Caps, Arch Spans, Culverts	A	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Decks, Sidewalks, Curbs, Parapets, Concrete Patch	A	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Seal (Tremie) Concrete	S	7 ± 2	7.5 max	8.5 max
Prestressed Items				
Beams	P, P-1,& P-2	2 ± 1	5.0 ± 1.5	5.0 ± 1.5
Piles	P	2 ± 1	6.0 ± 1.5	7.0 ± 1.5
Precast Items				
Piles	B	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Culverts, Parapet	P	3 ± 1	6.0 ± 1.5	7.0 ± 1.5
Modular Bin Units, MSE Wall Panels, Leveling Pads	P	2 ± 1	6.0 ± 1.5	7.0 ± 1.5
Slip-Form Items				
Parapet	A	1 ± 1/2	6.0 ± 1.5	7.0 ± 1.5

[1] When using a Type F or G admixture, change the requirements for Slump and Air Content for the given concrete item as follows:

[1.1] Slump: 6 ± 2 inches

[1.2] Air Content: increase both the target value and tolerance percentages by 0.5.

[2] For drilled shaft concrete, use Type F or G admixture to achieve the required slump. If concrete in the drilled shaft is placed under a drilling fluid, the required slump is changed to 8±1.

Table 903.03.06-3 Mix Design Requirements						
	Class A	**Class B**	**Class S**	**Class P**	**Class P-1**	**Class P-2**
Class Design Strength[2] (28 days, psi)	4600	3700	2000	5500	6000	6500
Verification Strength[2] (28 days, psi)	5400	4500	–	6000	6500	7000
Maximum Water-Cement Ratio[3] (lb/lb)	0.443	0.488	0.577	0.400	0.400	0.400
Minimum Cement Content (lb/cy)	611	564	658	[1]	[1]	[1]

[1] According to *PCI MNL-116.*

[2] Record all concrete test results to the nearest 10 psi.

[3] When a Type F or G water-reducing, high range admixture is used as specified in Table 903.03.06-1 and Table 903.03.06-2, reduce the maximum water-cement ratio by 0.043 for all classes of concrete except for Classes P, P-1 and P-2.

Table 903.03.06-4 Lot Sizes, Sampling Rates, and Retest Limits						
	Class A	**Class B**	**Class S**	**Class P**	**Class P-1**	**Class P-2**
Lot Size[1,2] (maximum)	**Day's Production**			**Day's Production of a Single Steam Bed**		

Pay-Adjustment Items						
Initial Sampling Rate[3, 4]	5/Lot	5/Lot	–	5/Lot	5/Lot	5/Lot
Retest Sampling Rate[5] (minimum)	5/Lot	5/Lot	–	5/ Unit or Load Test		
Non-Pay-Adjustment Items						
Initial Sampling Rate [3, 4]	3/Lot	2/Lot	1/Lot	5/Lot	5/Lot	5/Lot
Retest Limit (psi)	4400	3600	2000	5400	5900	6400
Retest Sampling Rate[5]	5/Lot	5/Lot	5/Lot	5/Lot	5/Lot	5/Lot

[1] The lot sizes are maximums. The ME may subdivide a lot into 2 or more smaller lots. When a subdivision is made, the specified sampling rate applies to each of the smaller lots.

[2] The ME will not include more than 1 class of concrete in a lot.

[3] An initial sample is defined as 2 cylinders taken from a concrete sample.

[4] The ME will sample at the specified sampling rates except that no more than 1 test per truckload or batch of concrete will be required (except for air and slump tests when retempering). The ME may accept nonstructural concrete lots consisting of 20 cubic yards or less without strength tests.

[5] A retest sample is defined as 1 core.

903.06 SELF-CONSOLIDATING CONCRETE (SCC)

903.06.01 SCC for Drilled Shafts

A. **Composition.** Produce SCC conforming to the composition requirements specified in 903.03.01, except use a Type F admixture and a viscosity modifying admixture (VMA). Use Type F and VMA admixtures, as specified in 903.02.02 and 903.02.04, at a dosage to produce a flowable concrete that does not require vibration for consolidation. Proportion the aggregates so that the fine aggregate is less than 50 percent by weight of the total aggregate.

B. **Mix Design and Verification.** Design the mix as specified in 903.03.02 to conform to the strength requirements, water-cement ratio, and cement content for a Class A concrete and the requirements specified in Table 903.06.01-1.

Table 903.06.01-1 Requirements for SCC for Drilled Shafts		
Property	**Test Method**	**Requirement**
Air Content		
Coarse Aggregate No. 57	AASHTO T 152	6.5 ± 2.0 percent
Coarse Aggregate No. 67		6.5 ± 2.0 percent
Coarse Aggregate No. 8		7.5 ± 2.0 percent
Slump Flow	NJDOT C-4	21 ± 3 inches
Visual Stability Index		
Plastic Concrete	NJDOT C-4	1 maximum
Hardened Concrete	NJDOT C-5	1 maximum

Perform mix design verification as specified in 903.03.02. For the verification batch, ensure that the air content is in the top half of the allowable range and the slump flow is between 21 and 24 inches. Perform air content, slump flow, and visual stability index (plastic concrete) testing on the verification batch. Make concrete cylinders for compression testing as specified in 903.03.02 and make 2 additional 4 × 8-inch cylinders for evaluation of the visual stability index of the hardened concrete. Saw the additional cylinders length-wise according to NJDOT C-5. The ME will perform the compressive strength testing and the visual evaluation to assign a visual stability index in order to approve the mix.

C. **Verification of Pumpability.** Verify pumpability at least 10 days before pouring the SCC concrete in the drilled shaft. Demonstrate the pumpability of the SCC to the ME by pumping a trial batch through the pump proposed for placing the SCC into the drilled shaft. Use the proposed methods for mixing the concrete including any anticipated time delays. The ME will test the SCC before and after pumping to verify that the SCC meets the requirements of Table 903.06.01-1 after pumping.

D. **Mixing.** Mix SCC as specified in 903.03.03.

E. **Control and Acceptance Testing.** Perform quality control testing as specified in 903.03.05.

The ME will perform acceptance testing as specified in 903.03.05 for a non-pay adjustment Class A concrete, except that the provisions for slump testing are replaced with requirements for slump flow testing and visual stability index on the plastic concrete. The ME will perform the slump flow testing and the visual stability index according to NJDOT C-4, at the sampling rate specified for slump testing of Class A concrete. The ME will perform visual stability index on the hardened concrete according to NJDOT C-5 at a rate of at least 1 per day. If the visual stability index on the hardened concrete does not conform to the criteria in Table 903.06.01-1, the ME will require redesign of the mix.

In the performance of quality control or acceptance testing, fill cylinder molds, slump flow cones, and air buckets in one lift. Do not vibrate, rod, or tap to consolidate the SCC.

903.06.02 SCC For Precast Concrete

A. **Composition.** Produce SCC conforming to the composition requirements specified in 903.03.01, except use a Type F admixture or a combination of a Type F and a viscosity modifying admixture (VMA). Use Type F and VMA admixtures, as specified in 903.02.02 and 903.02.04, at a dosage to produce a flowable concrete that does not require vibration for consolidation. Proportion the aggregates so that the fine aggregate is less than 50 percent by weight of the total aggregate.

B. **Mix Design and Verification.** Design the mix, as specified in 903.03.02 or 903.05.02, to conform to the strength, water-cement ratio, cement content, and air content requirements for the specified class of concrete for the item that is being cast. In addition, ensure that the SCC conforms to the requirements specified in Table 903.06.02-1.

Table 903.06.02-1 Requirements for SCC for Precast Concrete

Property	Test Method	Requirement
Slump Flow	NJDOT C-4	24 to 28 inches
Visual Stability Index		
Plastic Concrete	NJDOT C-4	1 maximum
Hardened Concrete	NJDOT C-5	1 maximum

Perform mix design verification as specified in 903.03.02 or 903.05.02. For the verification batch, ensure that the air content is in the top half of the allowable range and the slump flow is between 26 and 28 inches. Perform air content, slump flow, and visual stability index (plastic concrete) testing on the verification batch. Make concrete cylinders for compression testing as specified in 903.03.02 or 903.05.02 and make 2 additional 4 × 8 inch cylinders for visual stability index on the hardened concrete. Saw the additional cylinders length-wise according to NJDOT C-5. The ME will perform the compressive strength testing and the visual evaluation to assign a visual stability index in order to approve the mix.

C. **Mixing.** Mix SCC as specified in 903.03.03.

D. **Control and Acceptance Testing.** Perform quality control testing as specified in 903.03.05.

The ME will perform acceptance testing as specified in 903.03.05 for specified class of concrete for the item, except that the provisions for slump testing are replaced with requirements for slump flow testing and visual stability index on the plastic concrete. The ME will perform the slump flow testing and the visual stability index according to NJDOT C-4, at the sampling rate specified for slump testing for the specified class of concrete. The ME will perform visual stability index on the hardened concrete according to NJDOT C-5 at a rate of at least one per day. If the visual stability index on the hardened concrete does not conform to the criteria specified in Table 903.06.02-1, the ME will require redesign of the mix.

In the performance of quality control or acceptance testing, without remixing the sample, fill cylinder molds, slump flow cones, and air buckets in one lift. Do not vibrate, rod, or tap to consolidate the SCC.

New specification section.

Allowing use for most roadway items but not for surface course and not for structural concrete. Also allows for these items to be precast.

903.11 Recycled Aggregate Concrete (RAC)

903.11.01 Recycled Aggregate Concrete for Roadway Items

A. **Composition.** RAC may be produced for roadway items identified in Table 903.03.06-1 with the exception of surface course and base course concrete. Produce RAC conforming to the composition requirements specified in 903.03.01 and the requirements of Table 903.03.06-1. These items may be precast with SCC following 903.06.02. Coarse aggregates used must conform to 901.06 and may be a 100 percent recycled concrete coarse aggregate or a blend of recycled concrete aggregates and washed gravel or crushed stone. Recycled concrete fine aggregates are not permitted.

Unless the original aggregate source in RCA is known, mix designs must assume mitigation of alkali-silica reactivity. Fly ash, slag, or low alkali cement must be used to control-alkali-silica reactivity. If fly ash is added to control alkali-silica reactivity, use at least 15 percent fly ash by weight of the total cementitious material. If AASHTO T 303 testing results in an expansion greater than 0.40 percent, use at least 20 percent fly ash. If slag is used to control alkali-silica reactivity, use at least 25 percent slag by weight of the total cementitious material. If low alkali cement is used to control alkali-silica reactivity, use cement with equivalent alkali of less than 0.60 percent.

B. **Mix Design and Verification.** Design the mix, as specified in 903.03.02 or 903.06.02, to conform to the strength, water-cement ratio, cement content, and air content requirements for the specified class of concrete for the item that is being cast.

C. **Mixing.** Mix RAC as specified in 903.03.03.

Forcing mitigation of ASR if source aggregate is not known.

Control and Acceptance Testing. **Perform quality control testing as specified in 903.03.05.**

Appendix c – Recommended Specification for Measurement of Residual Mortar Content of Recycled Concrete Aggregates

NJDOT A-7 – RESIDUAL MORTAR CONTENT OF RECYCLED CONCRETE AGGREGATES

A. Scope. This test method is used to determine the percent of mortar adhered to coarse aggregates produced through the crushing of hydraulic cement concrete. This test method is suitable for use on No. 67, No. 57, or equivalent sized coarse aggregate.

B. Apparatus. Use the following apparatus:

1. A drying oven capable of reaching and maintaining temperatures of 105 ^{o}C.
2. A #4 sieve conforming to AASHTO M 92.
3. A 3000g capacity balance with resolution of 0.1g conforming to AASHTO M 231.
4. A freezer capable of cooling the samples to -18 ^{o}C ±3 ^{o}C in a period of 16 hrs and maintaining the temperature with a full sample load.

C. Procedure. Perform the following steps:

1. Representative 2000 g samples of the RCA are obtained through an appropriate process;

2. The samples are dried for 24 h at 105 °C, weighed, and then the oven-dried aggregate samples are immersed for 24 h in a 26 percent (by weight) sodium sulphate solution;

3. RCA samples, still in their sodium sulphate solution, are then subjected to five daily cycles of freezing and thawing, i.e. overnight (~ 16 h) at -17 °C and 8 h in an oven at 80 °C.

4. After the last freezing and thawing cycle, the solution is drained from the sample and the aggregates washed with tap water over a No. 4 (4.75 mm) sieve.

5. The aggregates retained on the #4 sieve are then placed in an oven for 24 h at 105 °C, and their oven-dried mass measured.

D. Calculations.

The residual mortar content (RMC) is obtained using

$$RMC = \left[\frac{W_{RCA} - W_{OVA}}{W_{RCA}}\right] x100$$

Where W_{RCA} is the oven dried weight of the original sample and W_{OVA} is the oven dried weight of the material retained on the #4 sieve after testing.

E. Report. Report the residual mortar content as the average of three samples to the nearest 0.1 percent.