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Crushed Returned Concrete as Aggregates for New Concrete

Final Report

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Introduction

Every year, it is estimated that 2% to 10% (average of 5%) of the estimated 455 million cubic yards of ready mixed concrete produced in the USA (est. 2006) is returned to the concrete plant. The returned concrete in the truck can be used in the following manner:

1. If it is a small quantity of returned concrete, fresh material can be batched on top. Hydration stabilizing admixtures might be involved in this process.
2. Returned concrete can be processed through a reclaimer system to reuse or dispose the separated ingredients, including the process water with a hydration stabilizing admixture as needed.
3. Returned concrete can be used for site paving and production of other products, such as concrete blocks, either for resale or disposal.
4. Returned concrete can be discharged at a location in the concrete plant for processing. The hardened discharged concrete can be subsequently crushed for reuse as base for pavements or fill for other construction. The separation of the crushed material can produce different products for use. In general, the finer crushed product is difficult to manage and dispose. This could be material finer than 2 inches and associated fines that provide a significant challenge for the ready mixed concrete producer to dispose of.

Option 1 is probably done on a small scale and is not always practicable because of restrictions by concrete specifications. Option 2 is limited to larger volume plants in metropolitan areas and requires a significant capital investment, followed by attention to proper practice. Option 3 is limited by several factors – there is only so much area in a plant that can be paved and the volume of block production depends on local market conditions and opportunities.

Option 4 has significant potential in the USA and it is reasonable to assume that this can be used to manage about 60% of all returned concrete. With some assumptions, one can estimate that the quantity of crushed returned concrete material generated by the ready mixed concrete industry is on the order of 30 millions tons/year with most of it likely being diverted to landfills. If all of this material can be beneficially used in concrete as aggregates at an estimated cost of $10/ton (cost of virgin aggregates plus reduced cost of land filling) it would represent the recuperation of a total cost impact in the range of $300 million/year for the ready mixed concrete industry's bottom line. Additionally, this will significantly benefit sustainable building initiatives by enhancing the considerable benefits provided by the use of concrete as a construction material. This research project addresses the use of crushed returned concrete, referred to in this report as Crushed Concrete Aggregate (CCA), as a portion of the aggregate component in new concrete.

Demolishing old concrete structures, crushing the concrete and using the crushed materials as aggregates is not new and has been researched to some extent. This material is generally referred as Recycled Concrete Aggregates (RCA). However, RCA is different from CCA as construction debris tends to have a high level of contamination (rebar, oils, deicing salts, etc.). CCA on the other hand is prepared from concrete that has never been in service and thus likely to contain much lower levels of contamination. *It is the contention of the principal investigators in this research study that published research on reuse of CCA is not extensive.*

The main objective of this research study is to develop technical data that will support the use of CCA from returned concrete by the industry and to provide guidance on a methodology for appropriate use of the material. The technical data developed can be used to support revisions to current industry standards and permit the use of returned concrete as crushed aggregates. Such a step can help the ready mixed concrete industry to save an estimated $300 million/year in operating costs. In addition, it will reduce landfill space by as much 845 – 10-feet high football fields every year.

Literature Review

Since much of the published literature is on the use of crushed concrete from existing concrete structures, this literature review is intended as a summary of these studies, but will pertain to the use of crushed concrete aggregate (CCA) as well.

Properties of Recycled Concrete Aggregates

Recycled concrete aggregates (RCA) have higher water absorption rates than virgin aggregates. Higher absorption rates are indicative of higher volume fractions of old cement mortar adhering to the virgin aggregate particles in the original concrete[1-3]. ASTM C 33, *Specification for Concrete Aggregates*, includes a requirement of an abrasion loss (by ASTM C 535) of less than 50% for aggregates used in concrete construction and less than 40% for crushed stone used in pavements[4]. According to the ACI 555 Committee Report[4], all RCA except that made from the poorest quality recycled concrete, can be expected to meet these abrasion loss requirements. The abrasion property of the aggregates controls the abrasion resistance of the concrete, a property that is important for warehouse floors, and concrete pavements. The relative density of RCA is 5%-10% lower than that of virgin aggregates (VA)[5]. This is because of bricks in demolished construction waste[6] and/or the lower density of the cement mortar that remains adhered to the aggregates[4,6,7].

Effects of RCA on Fresh Concrete Properties

Studies have shown that as RCA content in concrete mixtures increases, their workability decreases. One study found that in order to produce similar workability as VA concrete 5% more mixing water was required when using just the coarse fraction of recycled concrete aggregates (coarse RCA) and up to 15% more mixing water when using both the coarse and fine fractions of RCA[8-11]. Issues of workability are largely tied to the inclusion of recycled fines in RCA. For that reason, it is recommended that fine recycled concrete aggregate (FRCA) levels remain at or below 30% of total fine aggregate content[12]. Entrapped air contents of non-air entrained concrete containing RCA were up to 0.6% higher and varied more than air contents of non-air entrained control mixtures[4]. The density (unit weight) of concrete made using RCA were found to be within 85%-95% of the VA concrete[4]. Finishability of concrete containing RCA is generally adversely affected[5].

Effects of RCA on Hardened Concrete Properties

Compressive strength of concrete containing RCA is dependent upon the strength of the original concrete from which the RCA was made. Concrete's compressive strength gradually decreases as the amount of FRCA increases. The reduction is reported to be between 5% and 24% when just coarse RCA was used and between 15%-40% when all of the RCA (including the fine fraction) was used. Strength reduction becomes more significant when the FRCA content surpasses 60% of the total fine aggregate[13]. RCA concrete has around the same or 10% less flexural strength than concrete containing VA[4]. However, some studies have found that with the incorporation of FRCA the reduction in flexural strength can be as much as 10%-40%[5].

A research program[15] that evaluated the influence of RCA on concrete durability with testing such as chloride conductivity, oxygen permeability and water sorptivity concluded that concrete durability became adversely affected with increases in the quantities of RCA and, as expected, the durability improved with the age of curing. This phenomenon was explained by the fact that cracks and fissures created in RCA during processing render the aggregate susceptible to ease of permeation, diffusion and absorption of fluids. Interestingly, the use of RCA resulted in a reduction in the leaching of calcium ions from the concrete[16].

Creep of concrete is proportional to the content of paste or mortar in it. To that end, it is understandable that RCA undergoes increased creep because it can contain about 70% more paste volume than concrete made with virgin aggregate, with the exact amount dependent upon the amount of RCA replacing the VA, and paste volume in the RCA and the new concrete[15]. Researchers have observed creep to be 30%-60% greater in concrete manufactured using RCA compared to concrete with VA[5]. Like creep, increased shrinkage rates are also related to increases in cement paste contents[17]. One study found that while RCA shrinkage rates are still dependent on the amount of recycled aggregates used, the 1 year values are comparable to that of concrete containing VA[13]. Other studies have shown more differentiation in drying shrinkage values. One study showed that concrete made with RCA resulted in 70%-100% greater shrinkage. The same study also reported that concrete made using coarse RCA along with natural sand increased shrinkage by only 20%-50%[4].

The measure carbonation depth, mostly below 5 mm, increases with the amount of recycled aggregate content[13]. However, the carbonation rate when using RCA made from carbonated concrete were 65% higher than control groups[4]. One study indicated higher rate of corrosion when RCA is used in concrete. This effect can be mitigated by reducing the w/c ratio[4]. In ASTM C 1202, which tests chloride-ion penetration, concrete using RCA could be regarded as having moderate resistance if the FRCA is below 60%[13].

Concrete containing RCA can have good freeze/thaw resistance provided the concrete is adequately air entrained[12]. However, in one of the studies where no air entrainment was used it was shown to be less resistant to cycles of freezing and thawing than concrete made with VA[7]. The study suggested that RCA can contribute to concrete's freeze-thaw damage by expelling water into surrounding cement paste during the freezing process. Furthermore, if it has unsound particles, they would be deteriorated by the repeated freezing/thawing action[7].

Effects on Mixture Proportioning and Production

At the mixture design stage it can be assumed that the w/c for a required compressive strength will be the same for concrete containing RCA as that for conventional concrete when coarse RCA is used with natural sand[4]. The optimum ratio of fine to coarse aggregate is the same for concrete containing RCA as it is for concrete made with VA. Minnesota DOT limits the allowable amount of FRCA to 25% or 30% of total fine aggregate. Many aspects of production of concrete containing RCA are similar to that of conventional concrete; however, extra care must be taken and the following differences are noted[4].

- To off-set the high water absorption it is required to presoak RCA.
- Removing materials smaller than No. 8 sieve (approx 2 mm) prior to production will improve concrete performance (some recommend eliminating the use of FRCA).
- Trial mixtures are mandatory to evaluate the effects on water demand, slump and slump loss, strength, etc.

One study reported that dry mixing of RCA before adding other concrete mixture constituents resulted in higher compressive strength, tensile strength, and modulus of elasticity. It was theorized that during the dry mixing the shape of the RCA is improved; old mortar on the surface of the RCA's particles is removed; and lastly, fine particles of old cement are released, thus contributing to cement hydration[8]. However, this procedure is impractical to be used at a ready mixed concrete plant. Another study suggested a new mixing technique which they termed as the Two Stage Mixing Approach (TSMA) which was shown to enhance compressive strength and other properties. In the first stage only half of the required water is added to the concrete mixture. By adding only half the water, a thick layer of cement slurry is created on the surface, which then permeates the porous, old cement mortar, filling cracks and voids. The mixing process is completed in the second stage by adding the remaining water to the mixture, creating a strengthened interfacial zone, which ultimately leads to improved performance[1]. The applicability of this in conventional production of ready mixed concrete is also questionable.

FHWA Experience with RCA

In the US, transportation agencies, including the Federal Highway Administration (FHWA), have evaluated the reuse of crushed concrete from construction demolition, such as concrete pavements that have completed their service life. Old concrete pavements are broken up, the aggregates separated as coarse and fine aggregates, and reused in the construction of new concrete pavements. The product is also crushed in place to serve as a base material. The RCA is typically reused as a pavement base layer. Very few roadway projects have used the material as an aggregate component in the concrete pavement layer due to concerns of the quality of concrete for this application. An FHWA report[10,18,19] mentions that as many as 38 state DOTs are recycling crushed concrete as aggregate base and 12 state DOTs are recycling concrete as aggregate for portland cement concrete (PCC). Even though 12 states surveyed have reported use of RCA in PCC, it is not known how much it is being used. Further, the use is limited to paving, i.e. non-structural concrete.

Experimental Study

With the exception of Task 1, this research program was conducted at the NRMCA Research Laboratory. The experimental program is divided into five tasks.

Task 1. Preparation of CCA at a Ready Mixed Concrete Plant

The CCA was prepared at Virginia Concrete's Edsall plant. Three different concrete mixtures with target 28 day strengths of nominal 1000 psi, 3000 psi and 5000 psi were produced at the ready mixed concrete plant on January 20, 2006. All mixtures were non-air entrained; portland cement only mixtures contained a small dosage of a Type A water reducer. A small amount of integral color was added to each concrete mixture to allow for identification of the different grades. The concrete was discharged on the ground using a normal process for discharging returned concrete. The concrete mixtures were tested for slump, air content, temperature, density (unit weight), and compressive strengths at various ages. The compressive strength cylinders were subjected to two curing conditions: lab moist curing; field curing near the location where the concrete had been discharged. It was felt that the latter strengths were more representative of the concrete that was crushed to make CCA.

The mixture proportions and test results are provided in Table 1. The volume of paste divided by the volume of total aggregate varies from 31% to 43% with increasing values obtained for the higher strength concrete mixtures due to the higher cement content. Paste volume refers to the volume of cement, water and air used in the concrete mixture. CCA produced by crushing this concrete will have high absorption, lower strength and durability because it contains paste. The paste specific gravity varied between 1.43 and 1.74 with increasing values obtained for the higher strength concrete mixtures due to the higher cement contents. This would suggest that CCA, particularly the finer fraction of CCA, will tend to have lower specific gravity due to the high paste content in that fraction. The actual 56 day field cured strengths of the different classes were averaged at 1320 psi, 3630 psi, and 6480 psi. However, the different classes of CCA will continue to be referred to as 1000 psi, 3000 psi, and 5000 psi primarily for ease of notation. The discharged concrete was left undisturbed for 110 days, after which the concrete was processed through a crusher to produce the CCA. Figure 1 shows a picture of the crusher used to make the CCA. The CCA was transported and stored at the NRMCA Research Laboratory for the subsequent parts of the study. Figure 2 shows the CCA stored in the laboratory. The grey CCA is made from the 1000 psi concrete, the red CCA from 3000 psi concrete, and the black CCA from 5000 psi concrete.

Three different strength classes of CCA were included in this study to evaluate the effects of this factor on the properties of the resulting concrete. Typically, CCA results from returned concrete with different design strength levels that may have been through varied levels of retempering. It is important to study the effect of initial strength of the concrete that is crushed on the performance of new concrete containing CCA. Furthermore, it was felt that if a noticeable difference in performance existed then recommendations could be developed so that the producer can make attempts to separate CCA based on the strength levels of the returned concrete. This could help toward more efficient utilization of CCA.

In addition to the CCA prepared in a controlled manner specifically for this study, CCA generated and stockpiled at the concrete producer’s yard from normal practice was also evaluated. There was no control on the concrete discharged to produce this CCA. This CCA is referred to as Pile 1 in this report. This evaluation provides a means of comparing the portions of the study using the controlled CCA to that generated from normal practice. As might be expected in typical operations, the characteristics of the returned concrete from which the CCA in Pile 1 are unknown, which is one factor that cannot be quantified in this portion of the study. The ready mixed concrete producer is interested to know how much of this material can be used to still produce concrete with acceptable performance.

Task 2. Characterization of CCA from Returned Concrete

Using a large capacity sieve shaker shown in Figure 3 CCA of all three concrete grades and Pile 1 were separated into coarse and fine fractions. Aggregate tests required by ASTM C 33, *Specification for Concrete Aggregates*, were conducted. Other quality tests typically performed on concrete aggregates were conducted as well. These tests are essential to understand the performance of CCA in concrete and are discussed in the section under Testing.

Task 3. Experimental Study of CCA in New Concrete – Phase I
Several non-air entrained concrete mixtures were prepared with CCA and tested on the following criteria:

1. Control mixture using virgin coarse and fine aggregates.
2. Use CCA in "as received" state at different replacement levels for virgin aggregate.
3. Use coarse fraction of CCA (to replace virgin coarse aggregate) and a portion of the fine fraction of the CCA to replace virgin fine aggregate at different replacement levels.

Task 4. Effect of CCA on Freeze-Thaw Resistance of Concrete – Phase II
Phase II of the study was conducted primarily to evaluate the effect of CCA on air entrainment dosage, and freeze-thaw durability. Several air entrained concrete mixtures were prepared with CCA and tested under ASTM C 666.

Task 5. Slump Retention Study – Phase III
An important aspect is the slump retention capabilities of concrete mixtures considering delivery time and ambient conditions. This portion of the study evaluated the slump retention or slump loss characteristics of limited conditions with the use of CCA.

More details are discussed in the section under Testing.

Materials

The following materials were used in the study. Lot number references are for cataloging purposes at the NRMCA Research Laboratory.

- ASTM Type I Portland Cement, Lot # 8056
- ASTM C 260 tall oil air entraining admixture, Lot # 7941
- ASTM C 494 Type F naphthalene sulfonate high range water reducing admixture, Lot # 7975
- ASTM C 33 Virgin natural sand, Lot # 8044
- ASTM C 33 Virgin crushed trap rock sand, Lot # 8058 (used only for ASR tests)
- ASTM C 33 No. 57 Virgin crushed trap rock coarse aggregate, Lot # 8043
- Crushed concrete aggregate (1000 psi gray), Lot # 8049
- Crushed concrete aggregate (3000 psi red), Lot # 8047
- Crushed concrete aggregate (5000 psi black), Lot # 8048
- Crushed concrete aggregate (Pile 1), Lot # 8059

The aggregate characterization details are provided in the section under Testing.

Aggregate Testing Results and Discussions

Using a large capacity sieve shaker shown in Figure 3 CCA was separated into coarse and fine fractions on the 4.75-mm (No. 4) sieve. The percentage of the coarse fraction (by volume and by mass) in each CCA is shown in Table 2. It can be seen that coarse fraction (by volume) is 61% for the 1000 psi CCA, and about 70% for the other two CCAs made for this project. In comparison, Pile 1 CCA gave a very low coarse fraction of 47%. Two possible reasons for this were surmised upon discussing this with the concrete producer: 1. It is likely that the returned concrete in the normal practice had higher water content due to retempering prior to discharge. 2. It is likely that the returned concrete was disturbed and arranged in rows (but not crushed into CCA) the next day. Both of these steps can make the resulting CCA weaker and help explain the lower amount of Coarse CCA in Pile 1.

Once the CCA was separated into coarse and fine CCA with the help of a large sieve shaker, the Coarse fraction (which was in 4 different sieve sizes) was recombined in a 3.5 cu. ft. concrete mixer for about 15 minutes to make it homogeneous. This portion was used for all the aggregate tests for the "Coarse Fraction" whereas all the material passing the No. 4 (4.75 mm) sieve was used for the aggregate tests for the "Fine Fraction". The following aggregate tests were conducted:

- ASTM C127-04 Specific Gravity, Absorption of Coarse Aggregate, 3 samples
- ASTM C128-04a Specific Gravity, and Absorption of Fine Aggregate, 3 samples
- ASTM C136-05 Sieve Analysis of Fine and Coarse Aggregates, 3 samples
- ASTM C117-04 Materials Finer than 75-µm (No. 200) Sieve, 3 samples
- ASTM C29/C29M-97(2003) Unit Weight and Voids in Aggregate, 3 samples
- ASTM C131-03 LA Abrasion, 3 samples
- ASTM C40-04 Organic Impurities in Fine Aggregates for Concrete, 3 samples
- ASTM C1252-03 Uncompacted Void Content of Fine Aggregate, 3 samples
- ASTM C88-05 Sodium Sulfate Soundness, 2 samples
- ASTM D2419-02 Sand Equivalent Value of Soils and Fine Aggregate, 3 samples

While the control aggregates and the 1000 psi and 3000 psi CCA were tested for all properties the 5000 psi and Pile 1 CCA were tested only for those properties that are essential for establishing concrete mixture proportions.

All aggregate test results are provided in Tables 3, 4, and 5.

The sieve analysis of the coarse and fine fractions of the different CCAs are reported in Table 3. Based on the sieve analysis, the nominal maximum size of the virgin coarse aggregate and Coarse CCA is 1-inch, except for the 5000 psi Coarse CCA which is at 1 ½ inches. The fineness modulus of the control coarse aggregate and all Coarse CCA except the 5000 psi Coarse CCA is about 7.0. The 5000 psi Coarse CCA is 7.28 indicating that it has less fines. It is believed that the processing of the coarse CCA (15 minute blending in a 3.5 cu. ft. concrete mixer) removes a part of the mortar adhering to the coarse CCA resulting in the generation of some minus No. 4 material. This is confirmed because the greater the initial strength of the returned concrete the lower the measured amount of minus No. 4 material thus confirming that the stronger material does not break down so easily. The amounts of minus No. 4 material in each of the coarse CCA were 12% for the 1000 psi; 9% for the 3000 psi; 3% for the 5000 psi; 14% for the Pile 1.

Coarse CCA Test Results and Discussions

Table 4 summarizes the measured properties of the different types of coarse CCA as well as the virgin coarse aggregate.

Coarse CCA had higher LA abrasion loss as compared to the virgin coarse aggregate (about 25% vs. 13%). However, these values are still lower than the 50% loss limit in ASTM C 33.

The SSD specific gravity of Coarse CCA is lower as compared to the virgin coarse aggregate (about 2.55 compared to 2.92). The absorption of Coarse CCA is higher than the virgin coarse aggregate (4.3% to 5.9% compared to 0.9%). Pile 1 had higher absorption (5.9%) than that of the controlled coarse CCA (about 4.3%). The higher absorption and lower specific gravity of the coarse CCA as compared to the virgin coarse aggregate is due to the lower specific gravity paste (1.43 to 1.74 of CCA prepared by Table 1) adhering to the surface of the CCA. Further, it is possible that Pile 1 CCA had been prepared with returned concrete that had been air entrained or had much higher paste volume and this might explain the higher absorption of Pile 1 as compared to the other CCA.

The percent passing the No. 200 sieve for the coarse CCA was generally higher than that for the virgin coarse aggregate (0.32% to 1.66% compared to 0.38%) but is still lower than the 1.5% limit in ASTM C 33. The lowest value (0.32%) was for the 5000 psi coarse CCA and the highest value (1.66%) was for the Pile 1 CCA.

The dry rodded unit weight of the coarse CCA was slightly lower as compared to the control coarse aggregate (89.3 to 97.1 lb/ft^3 compared to 105.6 lb/ft^3). This is due to the lower specific gravity of the CCA.

Sodium sulfate soundness test results indicate that the Coarse CCA has higher mass loss compared to the virgin coarse aggregate (8.24% to 22.84% compared to 0.46%). The 3000 psi CCA had a lower mass loss (8.24%) than the 1000 psi CCA and met the performance requirement of ASTM C 33 which is 12%. The sulfate soundness test is conducted to evaluate the weathering potential of concrete aggregate and is often correlated to the durability of the aggregate under cycles of freezing and thawing. The implication of the sulfate soundness test to CCA is questionable because it is not clear whether the same mechanism is relevant or if other mechanisms such as sulfate attack might also result in a high mass loss in the test.

A higher compressive strength of the returned concrete does lead to a coarse CCA with a lower percentage of finer particles (minus No. 4 fraction), lower amount of Minus 200 fines, and potentially improved resistance to degradation as indicated by the LA Abrasion and soundness tests.

Fine CCA Test Results and Discussions

Table 5 summarizes the measured properties of the different types of Fine CCA as well as the virgin fine aggregate. There was no indication of organic impurities for the Fine CCA and the virgin fine aggregate.

The SSD specific gravity of fine CCA is lower compared to the virgin fine aggregate (2.11 to 2.27 compared to 2.61). The specific gravity of the fine CCA increased with increasing strength of the returned concrete. The absorption of fine CCA is much higher compared to the virgin fine aggregate (10.0% to 16.3% compared to 0.95%). The absorption of the fine fraction from Pile 1 was 16.3%. The absorption of the fine CCA decreased with increasing strength of the returned concrete. The higher absorption and lower specific gravity of the Fine CCA as compared to the virgin fine aggregate is due to the lower specific gravity paste (1.43 to 1.74 of CCA prepared by Table 1) adhering to the surface of the CCA. It should be noted here that it is difficult to achieve the saturated surface dry condition of fine CCA and that will impact the specific gravity and absorption results.

The percent passing the No. 200 sieve for the fine CCA was higher than that for the virgin fine aggregate (7.3% to 9.5% compared to 1.3%). These are above the 5% or 7% limit in ASTM C 33 for manufactured sand. The fineness modulus of the Fine CCA were about the same as compared to the virgin fine aggregate (about 2.75) except that the 5000 psi fine CCA had a much higher fineness modulus (3.05).

The sand equivalency of the fine CCA was lower compared to the virgin fine aggregate (56% to 63% compared to 87%). Sand equivalency is an indication of the relative proportions of detrimental fine dust or clay-like materials in fine aggregate; thus indicating that the fine CCA had a higher percentage of fines.

The uncompacted voids content of the fine CCA as measured by the ASTM C 1252, standard graded sample (Test Method A) were slightly lower as compared to the virgin aggregate (37% to 40% vs 42%). Generally lower voids contents indicate a more rounded and/or smooth-textured aggregate particles. However, the difference between the CCA and virgin aggregate in this case is not very significant.

Soundness test results indicate that the fine CCA has higher mass loss compared to the virgin fine aggregate. Both the fine CCA's tested exceeded the 10% limit for sodium sulfate soundness in ASTM C 33.

A higher compressive strength of the returned concrete does lead to a fine CCA with higher fineness modulus, higher specific gravity, lower absorption, and potentially improved resistance to degradation as indicated by the soundness test.

Phase I

Mixing Concrete

A revolving drum mixer with a 2.5 cu. ft. mixing capacity was used to mix the concrete batches. Concrete batch size was kept at 1.5 cu. ft. All concrete mixtures except Mixture 16 were mixed in accordance with ASTM C 192 with the CCA being batched along with virgin aggregate.

Mixture 16 was mixed similar to the "Two Stage Mixing" approach discussed in the literature review[1,31] to evaluate the claim in that study of improved concrete performance. For Mixture 16, the coarse aggregate, CCA, and the fine aggregate were placed with 60% of mix water. This was mixed for about 60 seconds. The mixer was stopped and cement added and then mixed for 2 minutes. This was followed by a rest period of 3 minutes after which the rest of the water was added and concrete mixed for another 2 minutes.

Concrete Testing

Concrete tests were, for the most part, conducted in accordance with ASTM standards. Non-standardized tests and deviations from ASTM standards (if any) are noted when applicable. The NRMCA Research Laboratory participates in proficiency sample testing of the Cement and Concrete Reference Laboratory (CCRL), is inspected biannually for conformance to the requirements of ASTM C 1077 and maintains its accreditation under the AASHTO Laboratory Accreditation Program.

Fresh Concrete Tests

All concrete batches were tested for slump, ASTM C 143, air content, C 231, density, C 138 and temperature, C 1064.

Setting time was measured by the thermal method, currently being by considered by ASTM. Setting time test by penetration resistance as per ASTM C 403 were also performed for some mixtures for comparisons. For the setting time of concrete by the thermal method, a representative sample of fresh concrete was placed in a container approximately to the depth of 6 in. After consolidating the concrete by rodding, the sides of the container was tapped gently to level the surface of the concrete. The container was then placed into an insulating cavity in which a thermocouple was embedded at the bottom to monitor the temperature change of the concrete specimen as a function of time. For selected mixtures the sieved mortar for the setting time test (ASTM C 403) was transferred to a 70ºF, 50% relative humidity room where they were stored and penetration resistance measured until the concrete attained final set.

Hardened Concrete Tests

Compressive strength tests for concrete mixtures were conducted in accordance with ASTM C 39 at an age of 7, 28, and 90 days. Specimen size used was 4 x 8 inch cylindrical specimens. Test specimens were transferred to the 100% humidity room as soon as they were made, demolded at 24 hours and cured until the test age. Neoprene caps in accordance with ASTM C 1231 of 70 durometer hardness were used to cap the test specimens. Strength test results reported are the average of 2 test cylinders tested at the same age.

Length change of concrete due to drying shrinkage was tested by ASTM C 157. Prismatic specimens 3 x 3 x 11 inches with embedded studs were used to measure the length change, using a gage length of 10 inches between the insides of the studs. The test specimens were moist cured for 7 days and were then stored at 70 ºF with a relative humidity of 50%. Length change measurements were obtained at various periods of air drying as indicated in the reported results. The length change reported is the average of 2 specimens. These measurements were terminated after 180 days of drying.

The elastic modulus of concrete was tested by ASTM C 469 at an age of 28 days. Two 4 x 8-inch cylindrical specimens were prepared for the C 469 test. Test specimens were transferred to the 100% humidity room as soon as they were made, demolded at 24 hours and cured until the test age. The results reported for modulus of elasticity are the average of 2 test cylinders tested at the same age.

The rapid indication of chloride ion penetrability, also referred to as the Rapid Chloride Permeability (RCP) test, was conducted in accordance with ASTM C 1202. Two 4 x 8-inch cylindrical specimens were prepared for the C 1202 test. Test specimens were transferred to the 100% humidity room as soon as they were made, demolded at 24 hours and cured until the test age. The top 2-inch portion of the test specimen as cast was used for the test. The charge passed result reported is the average of two specimens tested at the same age of 90 days.

In addition to the test program discussed here ASTM C 1293 ASR testing was conducted on 4 different concrete mixtures to evaluate whether CCA affects expansions due to alkali silica reactivity. These mixtures were prepared independently according to ASTM C 1293 requirements and the test is completed after 1 year.

Mixture Proportions

A total of seventeen concrete mixtures were prepared. The experimental variables, mixture proportions, adjusted for yield, and test results are provided in Table 6. All mixtures were non-air entrained and the water content was adjusted to achieve a target slump of 5-7 inches. The cement content was maintained at 500 lb/yd^3 for all mixtures.

Mixture 1 is the control mixture whose proportions were determined according to ACI 211 using virgin coarse and fine aggregate.

Mixtures 2-6 use CCA in “as received” state at different replacement levels for virgin aggregate. “As received” condition signifies that the CCA was not separated and recombined. Representative samples of CCA were obtained from the CCA stock pile. The CCA aggregate replaced a portion of virgin aggregate in the concrete mixture. The replacement was done by weight on the coarse virgin aggregate based on the size distribution of the CCA determined in the preliminary separation. CCA was used as a third aggregate and its absolute volume was calculated from the measured specific gravity. Finally, the quantity of virgin fine aggregate was adjusted to achieve the target yield.

Mixtures 7-10, and 12 use coarse fraction of CCA (to replace virgin coarse aggregate) with virgin fine aggregate. Mixture 11 uses coarse fraction of CCA (to replace virgin coarse aggregate) and a portion of the fine fraction of the CCA to replace virgin fine aggregate. For these mixtures the replacement of virgin aggregate by CCA was based on a volume basis.

Mixtures 7-11 and Mixture 12 differed in the way by which the Coarse CCA was prepared.
For Mixtures 7-11 the Coarse CCA was prepared exactly as discussed earlier. Since the Coarse CCA contained some material passing No. 4 sieve as shown in Table 3 the material was again sieved over a No. 4 sieve and only the material retained on No. 4 sieve was used as Coarse CCA.

For Mixture 12 the CCA in an "as received" condition was first sieved through the smaller Tylab sieve shaker. This helped to separate the CCA into various size fractions. The size fractions coarser than the No. 4 sieve were discharged onto the floor and mixed well with the aid of a shovel to prepare a homogenous coarse CCA fraction. This processing did not break up the CCA as was observed in the other form of processing.

The concrete mixtures were designed to evaluate the following conditions:

- Mixture 1 was the control mixture with virgin aggregates. This mixture proportions were established to achieve an average strength of 4000 psi.
- Mixture 2 and 3 used 1000 psi CCA in "as received" state at replacement levels of 300 lbs/yd^3 and 600 lbs/yd^3 for virgin aggregate, respectively.
- Mixture 4 and 6 used 3000 psi CCA in "as received" state at replacement levels of 600 lbs/yd^3 and 900 lbs/yd^3 for virgin aggregate, respectively.
- Mixture 5 used Pile 1 CCA in "as received" state at replacement level of 600 lbs/yd^3 for virgin aggregate.
- Mixture 7 and 8 used the coarse fraction of 1000 psi CCA to replace virgin coarse aggregate at different replacement of 50%, and 100%, respectively.
- Mixture 9 and 10 used the coarse fraction of 3000 psi CCA, 5000 psi CCA, respectively to replace virgin coarse aggregate at 100% replacement.
- Mixture 11 used the coarse fraction of 3000 psi CCA and the fine fraction of 3000 psi CCA to replace virgin coarse and fine aggregates at replacement of 100% and 25%, respectively.
- Mixture 12 used the coarse fraction of Pile1 CCA to replace virgin coarse aggregate at 100% replacement.
- Mixture 13, 14, and 17 were replicates of Mixture 1, 4, and 12 conducted on a different day to establish the batch-to-batch repeatability of the study.
- Mixture 15 is a repetition of Mixture 9 except that preparation of the coarse fraction of the CCA was similar to that of Mixture 12 in order to study how processing of the CCA prior to its use can affect its performance in concrete.
- Mixture 16 is a repetition of Mixture 4 except using a modified batching sequence for the CCA as discussed in the Mixing Concrete section.

For alkali silica reactivity (ASR) testing four conditions were evaluated:

- Mixture A was a control mixture containing virgin aggregates. The aggregates were virgin crushed trap rock stone and virgin crushed trap rock sand that have been previously determined to be non-reactive in ASR.

- Mixture B used Pile 1 CCA in "as received" state at replacement of 600 lbs/yd^3 for virgin aggregate.
- Mixture C used the coarse fraction of 3000 psi CCA to replace virgin coarse aggregate at 100% replacement.
- Mixture D used the fine fraction of 3000 psi CCA to replace virgin fine aggregate at 100% replacement.

The other material and mixture proportion details were according to ASTM C 1293. The 4 mixtures were cast, cured and tested separately according to ASTM C 1293.

Discussion of Test Results – Phase I

Fresh Concrete Properties

The slump for all the mixtures ranged between 5 to 7 inches. Only Mixture 12 had a lower slump of 3.75 inches. The temperature of the concrete mixture was maintained between 74°F and 78°F. The resultant mixing water content of these mixes is reported in Table 6. The mixing water content calculation is not accurate as the CCA moisture in some mixtures was lower than SSD moisture. Further, for aggregates with high absorptions there is always some error in the absorption and moisture content determination.

The mixing water content for the control mixture was 287 lbs/yd^3. When CCA was used in "as received" condition (Mixture 2-6) the mixing water content did not vary very much from that of the control mixture. For Mixtures 7-11 which used different proportions of coarse and fine fractions of CCA to replace the virgin coarse and fine aggregates the water content appears to be lower. However, some of these mixtures (notably #7, #8, #10) had CCA moistures at lower levels than absorption (between 1.38% and 1.78%) which could induce some errors in the mixing water calculations. For Mixture 12 (Pile 1 CCA) the mixing water content was about 34 lbs/yd^3 higher when 100% coarse CCA was used. When this mixture was repeated (Mixture 17) it still yielded a high water content suggesting that it was not a batching error. The high mixing water content for this mixture could be due to the increased fines in the Pile 1 CCA.

The air content, measured by C 231, of the control mixture was 2.5%. Most of the CCA mixtures had similar air contents; however, it was noticeable that as the CCA amount, more particularly the fine CCA amount, increased the entrapped air contents tended to be higher. This effect is most noticeable in Mixtures 11 and 12. The density of the control mixture was 152.1 lb/ft^3. Concrete containing CCA is expected to have lower density due to the lower density of the CCA, higher water demand, and higher entrapped air content. The greater the amount of CCA the more these effects matter and therefore the density will decrease. When small amounts of CCA was used in "as received" condition (Mixtures 2-6) then the concrete density were similar to control – decreased by about 1% to 2%. However, when CCA was used in greater quantities (Mixtures 7-11) the decrease in density was higher – about 6%. Mixture 12 had about 9% lower density which is mainly due to its much higher water content, higher entrapped air and the lower density of the Pile 1 Coarse CCA.

The initial and final setting times of the Control mixture as determined by the thermal method is 4:14 hrs and 7 hrs respectively. The setting times of the CCA mixtures by and large were similar to control in the range of 30 minutes. However, for Mixture 9 the setting times were accelerated by more than 1 hour. The initial setting times measured by ASTM C 403 for the control mixture had initial and final setting times of 4:43 hrs and 6:32 hrs, respectively. The C 403 setting times of the CCA mixtures generally tend to be lower than that of the control mixture by about 45 minutes to 1 hour. However the mixtures containing the Pile 1 aggregates had much lower initial setting times – about 1.5 hours lower.

Compressive Strength

Compressive strength of the control mixture (Mixture 1) was 3080 psi at 7 days, and 4100 psi at 28 days. Compressive strength of mixtures containing CCA were generally lower than the control, between 3% and 22% lower, at 28 days. In general, as the quantity of CCA in the mixture was reduced, the reduction in strength was less. Further, the higher the strength of the returned concrete from which the CCA was prepared the lower the strength reduction. It was anticipated that when the strength of the returned concrete when crushed and used was equal to or higher than the strength of the new concrete then the CCA is unlikely to adversely affect the strength of the new concrete. In this study the returned concrete used to manufacture the 3000 psi CCA had a 56 day strength of about 3500 psi which is in the range of the design strength for the series of mixtures in this study. Therefore, it was anticipated that the 3000 psi and 5000 psi CCA are unlikely to impact the strength very much as opposed to the 1000 psi CCA. In the discussions below, the 28 day compressive strengths of the mixtures containing CCA have been compared to that of the control mixture.

- For the mixtures containing 1000 psi CCA the strength was 3% (110 psi) lower when 300 lb/yd^3 was used (Mixture 2) while it was 11% (470 psi) lower when 600 lb/yd^3 was used (Mixture 3).
- For the mixtures containing 3000 psi CCA the strength was 10% (410 psi) lower when 600 lb/yd^3 was used (Mixture 4) while it was 5% (210 psi) lower when 900 lb/yd^3 was used (Mixture 6). Interestingly the higher amount of 3000 psi CCA actually yielded slightly higher strengths. This is possibly explained by the discussions earlier where we stated that if the strength of the returned concrete was higher than the strength of the new concrete then the use of that CCA is unlikely to affect the strength very much.
- For the mixture containing Pile 1 CCA the strength was 17% (690 psi) lower when 600 lb/yd^3 was used (Mixture 5).
- For the mixtures containing 1000 psi CCA the strength was 15% (630 psi) lower when 50% coarse CCA was used (Mixture 7) while it was 22% (920 psi) lower when 100% coarse CCA was used (Mixture 8).
- For the mixtures containing 3000 psi CCA the strength was 4% (170 psi) lower when 100% coarse CCA was used (Mixture 9) while it was 14% (590 psi) lower when 100% coarse CCA and 25% fine CCA was used (Mixture 11).
- For the mixture containing 5000 psi CCA the strength was 8% (310 psi) lower when 100% coarse CCA was used (Mixture 10).
- For the mixture containing Pile 1 CCA the strength was 34% (1410 psi) lower when 100% coarse CCA was used (Mixture 12). The low strength for this mixture could be due to high water demand and high w/c of this mixture.

When 90 day compressive strength results are analyzed, the following additional conclusions can be drawn:

1. As compared to the control mixture compressive strength of mixtures containing CCA was between 2% higher and 23% lower.
2. The higher the strength of the concrete from which the CCA was made, the higher the resulting concrete strength. This was evident when 100% coarse CCA test results were compared.
3. The higher amount of 3000 psi CCA (Mixture 6 vs. Mixture 4) yielded higher 90 day strengths thus confirming the observations made based on the 28 day strength test results.
4. Mixture containing Pile 1 CCA at 600 lbs had comparable strengths to the mixture containing 3000 psi CCA at 600 lbs. However, when 100% coarse Pile 1 CCA was used the strengths were 33% lower than that of the control mixture.

Static Modulus of Elasticity

The static modulus of elasticity of the control mixture (Mixture 1) was 4.7 x 10^6 psi at 28 days. The modulus of elasticity of mixtures containing CCA was generally lower than the control, between 6% and 28% lower at 28 days. Generally mixtures containing lower quantities of CCA in the mixture had smaller reductions in the modulus of elasticity. Strength of the returned concrete from which the CCA was prepared did not seem to influence the modulus. However, Mixture 9 (100% coarse 3000 psi CCA) had lower modulus as compared to Mixture 8 (100% coarse 1000 psi CCA). Mixture 11 (100% coarse 3000 psi CCA plus 25% fine 3000 psi CCA) had lower modulus than Mixture 8 even though it had higher strengths. The explanation is probably as follows: Table 1 suggests that even though the strength of the returned concrete mixtures varied a great deal it is probably unlikely that the modulus varied very much. This is because of the much higher paste contents (8% to 12% more paste volume) of the higher strength mixtures as compared to the lower strength mixture. It is well known that a coarse aggregate such as trap rock has a much higher elastic modulus as compared to the paste.

Drying Shrinkage

Drying shrinkage test results following 180 days of air drying indicate that increasing amounts of any CCA leads to increasing length change as compared to the control mixture. However, the 1000 psi CCA led to smaller increase in length change as compared to the 3000 psi CCA. This could be because of the lower amount of paste present in the 1000 psi CCA as compared to the 3000 psi CCA (Table 1). For example 600 lbs of 1000 psi CCA is expected to contribute 19% more paste than the Control mixture. In contrast, 900 lbs of 3000 psi CCA is expected to contribute 36% more paste than the Control mixture. The 5000 psi CCA led to lower increase in length change (similar to the 1000 psi CCA mixture) inspite of its higher total paste content. This could be due to the lower fine material larger than the No. 200 sieve present in the 5000 psi CCA. However, it should be noted that even the 3000 psi CCA led only to about 40% increase in length change over the control mixture. Pile 1 CCA when used at 600 lbs/yd^3 led to a very slight increase in length change. However, when it was used at 100% Coarse CCA the length change levels doubled!

Chloride Ion Penetrability

The use of small amounts of CCA (300 lbs, 600 lbs) does not change the RCP values as compared to the control mixture. The use of the 1000 psi CCA at 300 lbs, and 600 lbs and Pile 1 CCA at 600 lbs led to slightly lower RCP values whereas the use of 3000 psi CCA led to slightly higher RCP values. However, the use of 100% coarse CCA led to an all around increase in the RCP values with the chloride ion penetrability going from moderate to high. The 1000 psi CCA, and the 5000 psi CCA had lower increases in RCP values as compared to the 3000 psi CCA and Pile 1 CCA mixtures.

Alkali Silica Reactivity

Alkali silica reactivity (ASR) test results in accordance with ASTM C 1293 are summarized in Table 7. The expansions of the 4 concrete mixtures are in the range of 0.022% to 0.032% after 1 year. While the three CCA mixtures had higher expansions than the control mixture, the values were still below 0.04%. By ASTM C 1293 1 year expansions below 0.04% are indicative of aggregate that can be classified as non-reactive due to alkali-silica reaction. These results are not surprising because the concrete from which the CCA was made contained aggregates that were not susceptible to ASR. So addition of CCA might be increasing the alkali level in the system due to the additional cementitious paste. So a virgin aggregate that may be on the borderline in terms of ASTM C 1293 expansion may lead to a CCA that fails the C 1293 expansion limit if used to make new concrete in combination with the virgin aggregate. However, if the virgin aggregate expansions are significantly low as in this case (0.022%) then the CCA clearly can be tested to be non-reactive. Since the use of fly ash or slag is common in most ready mixed concrete operations, this will provide additional protection against deleterious ASR and can be tested if critical to the proposed application.

Repeatability

Mixture 13, 14, and 17 were replicates of Mixture 1, 4 and 12 conducted on a different day to establish the batch-to-batch repeatability of the study. A quick look at the water content, air content, density, strength (28, 90 days), elastic modulus (28 days), shrinkage (180 days), and RCP (90 days) shows that the mixtures are repeatable as the properties did not vary by more than the standard precision levels associated with the different test methods.

Effect of Processing Variations

Mixture 15 was conducted to evaluate how difference in preparation of the coarse CCA affected concrete performance. In order to draw conclusions, it is best to compare the performance of Mixture 15 with that of Mixture 9 both of which are identical but for the difference in preparation of the coarse CCA. It can be observed that the water demand for this mixture was slightly higher (by 5 lbs/yd^3) and the slump was lower by 1-inch. No significant difference was observed in air content, density, compressive strength (90 days), and shrinkage (180 days). RCP (90 days) test results were about 15% lower.

Mixture 16 was conducted to see how the effect of concrete mixing sequence would affect the concrete performance. In order to draw conclusions, it is best to compare the performance of Mixture 16 with that of Mixture 4 both of which are identical but for the difference in concrete mixing. No significant difference was observed in water content, air content, density, strength (28, 90 days), and RCP (90 days). Length change (180 days) values were about 20% lower. It appears that the modified mixing sequence did not provide any benefit relative to concrete properties.

Phase II

Phase II of the study was conducted primarily to evaluate the effect of CCA on air entrainment dosage, and freeze-thaw durability. Since concrete containing CCA has higher paste (10% to 80%), at a given total air content it was felt that the freeze-thaw resistance of concrete containing CCA may be lower than that of concrete containing virgin aggregate.

Materials, Mixing, Mixture Proportions, and Testing

The same materials were used as in Phase I. In addition, an ASTM C 494 Type F High range water reducer (HRWR) and an ASTM C 260 air entraining admixture were used.

Mixing was similar to Phase I with the following changes. Air entraining admixture was added on top of the fine aggregate followed by the addition of the mixing water. HRWR was added only after the concrete had been mixed for about 2 minutes and a slump of about ½-in. had been ascertained visually. The use of HRWR meant that the concrete was mixed for an additional 2 minutes over the 3-3-2 mixing cycle per ASTM C 192.

A total of four concrete mixtures were cast. The experimental variables, yield adjusted mixture proportions and test results are provided in Table 6. The cement content was maintained at 564 lb/yd^3 for all mixtures. All mixtures were air entrained to achieve a design air content of 6% ± 1.5%. HRWR dosage was adjusted to achieve a target slump of 6 to 8 inches.

The concrete mixtures were designed to evaluate the following conditions:

- Mixture II-1 was control mixture with virgin aggregates.
- Mixture II-2 used 1000 psi CCA in "as received" state at a replacement of 600 lbs/yd^3 for virgin aggregate.
- Mixture II-3 used 3000 psi CCA in "as received" state at a replacement of 600 lbs/yd^3 for virgin aggregate.
- Mixture II-4 used the coarse fraction of 3000 psi CCA to replace virgin coarse aggregate at 100% replacement.

All concrete batches were tested for slump, ASTM C 143, air content, C 231, density, C 138 and temperature, ASTM C 1064. Compressive strength (ASTM C 39), drying shrinkage (ASTM C 157), and RCP tests (C 1202) for concrete mixtures were conducted in accordance with ASTM standards. Other details such as specimen size, curing conditions are similar to Phase I.

Freeze-thaw durability testing was conducted according to ASTM C 666 Procedure A – Rapid Freezing and Thawing in Water. Specimen dimensions were identical to that of the drying shrinkage test (C 157) specimens. Specimens were introduced into the freeze-thaw chamber after 56 days of moist curing. Two specimens were tested for each mixture. Dynamic modulus of elasticity, length change, and mass change were recorded periodically until the specimens had been subjected to 300 freeze-thaw cycles.

Discussion of Test Results - Phase II

The slump for all the mixtures ranged between 6 to 7.5 inches. The temperature of the concrete mixture was maintained between 69°F and 70°F. HRWR dosages for the control mixture (II-1) and coarse CCA mixture (II-4) are similar. HRWR dosages for the mixtures which used CCA in the "as received" condition was 17% and 58% higher with the higher dosage required for the 3000 psi CCA.

The air content, measured by C 231, varied between 4.8% and 8.5%. For similar air contents as the control mixture it was estimated that slightly higher air entraining admixture dosages (20% to 30%) will be required when the CCA is used in the "as received" condition (Mixtures II-2, II-3). However, when coarse CCA was used (Mixture II-4) no increase in air entraining admixture dosage was required. The density of the control mixture was 148.9 lb/ft^3. Concrete containing CCA is expected to have lower density due to the lower density of the CCA. When small amounts of CCA was used in "as received" condition (Mixtures II-2, II-3) concrete density decreased by about 1% to 2% as compared to the control mixture. However, when CCA was used in greater quantities (Mixtures II-4) the decrease in density was higher – about 9%. A portion of that lower density is attributed to the higher air content of Mixture II-4.

Compared to the control mixture, the use of 3000 psi CCA at 600 lb/yd^3 did not lead to any strength reductions while the use of 1000 psi CCA at 600 lb/yd^3 led to about 10% strength reduction. The use of coarse 3000 psi CCA (Mixture II-4) led to about 16% strength reductions although half of that could be attributed to the much higher air content. The use of CCA led to increased length change due to drying shrinkage. After 180 days of drying the average length change values increased by 15% to 51% with the higher values reported when 100% Coarse CCA was used. The 90 day RCP values suggested that all four concrete mixtures had moderate chloride ion penetrability with the 100% Coarse CCA mixture having the highest RCP values.

Observations on the ASTM C 666 test results after freeze-thaw cycles:

1. Control Mixture – Both specimens had a durability factor in excess of 90% (average 92%), average mass loss of 0.52% and negligible length change. No visible signs of deterioration could be noted apart from some minor surface scaling (Figure 4).
2. 1000 psi CCA at 600 lb/yd^3 – Both specimens failed, i.e. their relative dynamic modulus of elasticity went below 60% in less than 300 cycles. Specimen 1 failed in 107 cycles whereas Specimen 2 failed in 190 cycles. Average mass loss was only 0.18% and average length change was 0.14%. It was obvious that the specimens had cracked up significantly particularly near the ends (Figure 5).
3. 3000 psi CCA at 600 lb/yd^3 – Both specimens failed, i.e. their relative dynamic modulus of elasticity went below 60% in less than 300 cycles. Specimen 1 failed in 243 cycles where as Specimen 2 failed in 300 cycles. Average mass loss was only 0.73% and average length change was 0.03%. No visible signs of deterioration however could be noted (Figure 6).

4. 3000 psi CCA at 100% Coarse CCA – Both specimens had a durability factor in excess of 88% (average 89%), average mass loss of 1.23% and negligible length change. The higher mass loss was due to noticeable amount of surface scaling that was observed (Figure 7).

Both concrete mixtures containing 600 lb/yd^3 of CCA in the "as received" condition had poorer freeze-thaw durability. The mixture containing 3000 psi 100% coarse CCA had good freeze-thaw durability. These results seem to be consistent with the aggregate sulfate soundness (ASTM C 88) test results, which is normally an indicator test for freeze-thaw durability of aggregate. In that test 3000 psi coarse CCA passed the sulfate soundness test where as both the 1000 psi and 3000 psi fine CCA failed the sulfate soundness test. This suggests that the inclusion of fine CCA which occurs in the "as received" condition may lead to poorer freeze-thaw performance. However, it should be noted that both the concrete mixtures containing CCA in the "as received" condition had lower measured air contents (about 1 to 2%) where as the mixture containing 3000 psi 100% coarse CCA had higher air content (about 2%) as compared to the control mixture. This was not done on purpose but this may be suggesting that CCA mixture needs to have higher air contents to have similar freeze-thaw performance as control mixtures. A different but related point is that the original concrete from which the CCA was prepared was non-air entrained. Most likely in a freeze-thaw environment the original concrete is likely to have air entrainment and it is possible that CCA made from such returned concrete may have better freeze-thaw resistance.

Based on the freeze-thaw test results it would appear that the use of 3000 psi 100% coarse CCA should be acceptable even in concrete applications that are exposed to freeze-thaw environment. However, concrete containing CCA in the "as received" condition must be further evaluated for its freeze-thaw resistance if that is critical to the application. Evaluation might be based on determination of service records of test sections (if such exist), or freeze-thaw testing in accordance with ASTM C 666. ASTM C 666, Procedure A, used in this study is a very severe test and appropriate for concrete flatwork that will be continuously moist in service with anticipated use of deicing chemicals. Exterior members that are not continuously moist in service, such as vertical members, will not be subject to this very severe exposure and may not require the level of caution expressed in this report.

Phase III

An important aspect is the slump retention capabilities of concrete mixtures considering delivery time and ambient conditions. This portion of the study evaluated the slump retention or slump loss characteristics of limited conditions with the use of CCA. The same materials were used as in Phase I. Mixing was similar to Phase I.

A total of four concrete mixtures were cast. The batch size was 0.7 ft^3. The experimental variables, yield adjusted mixture proportions and test results are provided in Table 9. The cement content was maintained at 550 lb/yd^3 for all mixtures. Water content was adjusted to achieve a target slump of 6 to 8 inches.

The concrete mixtures were designed to evaluate the following conditions:

- Mixture SL-1 was the control mixture with virgin aggregates.

- Mixture SL-2 used 1000 psi CCA in "as received" state at a replacement of 300 lbs/yd^3 for virgin aggregate. The CCA was kept moist prior to batching.
- Mixture SL-3 used the coarse fraction of 3000 psi CCA to replace virgin coarse aggregate at 100% replacement. The CCA was kept moist prior to batching.
- Mixture SL-4 used the coarse fraction of 3000 psi CCA to replace virgin coarse aggregate at 100% replacement. The CCA was batched in a dry condition. The total moisture measured was 0.61% while the absorption was 4.31%. This condition was included to evaluate the effect of using CCA in a dry condition on the slump retention.

All concrete batches were tested for slump, ASTM C 143, air content, C 231, density, C 138 and temperature, ASTM C 1064.

The slump retention study was conducted as follows:
Concrete batches were mixed to target an initial slump (Slump 1) of 6 to 7.5 inches. After the initial mixing, a portion of the concrete was discharged from the mixer and tested for slump (Slump 1), unit weight, air content, and temperature. Two 4x8 concrete cylinders were cast from this portion to be tested after 14 days of moist curing according to ASTM C 39.

After the initial sample of concrete, the mixer was set at an agitating speed (4 revolutions per minute as opposed to the normal mixing speed of 19 revolutions per minute) for about 30 minutes. Following this the mixer was set at the normal mixing speed for 2 minutes after which a concrete sample was obtained and the concrete slump measured (Slump 2). The difference in the slump at 30 minutes and the initial slump is the slump loss as a percentage of the initial slump reported in Table 9. After this step, additional water was added to the remaining concrete followed by mixing for 2 minutes to obtain close to the initial slump. The concrete was discharged from the mixer and the slump of the concrete was tested (Slump 3). This was intended to simulate what occurs in actual practice where water might be added at the job site to increase slump to required or specified levels. Two 4 x 8-inch concrete cylinders were cast to be tested after 14 days of moist curing. The resulting strength on retempering the concrete after 30 minutes represents the impact of slump loss of concrete over a typical delivery period as a result of jobsite addition of water to obtain the required slump for placing concrete.

Discussion of Test Results - Phase III

The original slump (Slump 1) for all the mixtures ranged between 6.5 to 7.5 inches. The temperature of the concrete mixture was maintained between 73°F and 75°F. The air content, measured by C 231, varied between 2.5% and 3.2% and the density varied between 142.5 lb/ft^3 and 151.7 lb/ft^3. The slump loss of the control mixture SL-1 over the 30 minute period was 12%. The highest slump loss of 43% was observed for Mixture SL-2 which contained CCA in the "as received" state and batched in a moist condition. The slump loss for Mixture SL-3 which contained the coarse 3000 psi CCA at 100% was in the same range as that of the control mixture. The slump loss for Mixture SL-4 in which the coarse 3000 psi CCA was used in the dry state was higher at 33%. Based on these results, it is recommended that CCA stockpiles should be sprinkled prior to batching to avoid significant slump loss, especially if larger quantities are used. Even with maintaining CCA in a moist condition, significant slump loss was observed with the "as received" 1000 psi CCA, presumably due to the increased quantity of fines. Slump retention of concrete is an operational issue that the concrete producer faces on a daily basis and should evaluate whether the level is excessive for the conditions and the market he is furnishing to. This will determine the appropriate methods, such as holdback of water or the use of admixtures, to address this and still obtain the required slump and strength at the point of discharge on a project. In this study simulating a 30 minute delivery time with 75°F concrete, the addition of 12 to 18 lb/yd^3 of water was adequate to bring the slump back to required or specified levels. This extra water addition resulted in a negligible loss in strength measured at 14 days. Mixture SL-2 which had the largest slump loss resulted in a strength reduction due to water addition of approximately 500 psi or 12% of the strength following initial mixing.

Appropriate Test to Measure Air Content of Concrete Containing CCA

In this project, the air content of concrete containing CCA was determined using the ASTM C 231 Type B pressure meter. Considering the lower relative density and absorption of the CCA, there was concern whether the pressure method for measuring air content was appropriate. The pressure method measures entrained air in the concrete and that of pores in aggregates not saturated with water. For this reason, the method includes an aggregate correction factor that is subtracted from the measured air content to obtain the air content in the paste fraction of the concrete. With natural aggregates with a high absorption (higher aggregate correction factor) or for lightweight aggregate the volumetric method, ASTM C 173, is more applicable for measuring the air content in fresh concrete as it measures only the air contained in the mortar and is not affected by the air that may be present inside porous aggregate particles. ASTM C 231 does not state any limit for the aggregate correction factor for which the method would not be applicable. Coarse CCA has a relative density exceeding 2.50 with absorption of about 4% and it is assumed that ASTM C 231 could be used to measure the air content of containing just the coarse fraction of CCA. Fine CCA has a relative density in the range of 2.20 and so when CCA is used in the “as received” condition the resultant relative density of the aggregate is about 2.3 with absorption of about 6%.

The measured air content by the C 231 and the gravimetric air content calculated by ASTM C 138 are compared in Table 10 for all the concrete mixtures prepared in this study. The air content determined by the gravimetric approach should be accurate as long as the batch weights, material’s relative density and C 138 measurements are accurate. Gravimetric air contents also are not affected by the air that may be present inside porous aggregate particles. So, in the absence of the C 173 tests they serve as a good check for the accuracy of the air content as measured by the pressure meter. Table 10 indicates that with the exception of two mixtures the air contents measured by the pressure meter correlate to within 1% of that determined by the gravimetric method. In particular, the four air entrained Stage II mixtures which are reflected by the prefix II, the correlation is extremely good with the maximum difference being 0.34%. Further, the aggregate correction factors have been measured for aggregate proportions used in several of these mixtures and listed in Table 11. The virgin aggregate had very low aggregate correction factor, about 0.10%. The CCA also had very low values, less than 0.40%. Light weight aggregates generally show much higher aggregate correction factors. From these evaluations, it appears that the pressure meter test is appropriate to measure the air content of concrete containing CCA. If the choice of method is a concern, one might chose to run ASTM C 231 and C 173 in parallel for concrete using CCA. If the results compare well, air content measurements can be made by C 231.

Guidance to the Producer

One purpose of this study is to provide guidance to ready mixed concrete producers on options for use of crushed returned concrete as aggregate in concrete. There should be a balance between operational considerations and quality of concrete produced and associated economics for a specific plant or market area.

The questions that the ready mixed concrete producer should consider: Should the returned concrete be separated by strength classes? Should there be a process set up to separate crushed material into fine and coarse fractions or use the material as processed? What classes of concrete or market segments will the CCA be used in? These decisions will depend on factors at the specific plant and location – quantity of returned concrete, availability of space, availability of processing equipment, market served by the plant and alternative options for managing returned concrete.

To evaluate the economics of using CCA some assumptions are made here:

- The 28 day compressive strength is assumed to be the controlling factor relative to a control mixture with virgin aggregate.
- To increase concrete strength by 200 psi will cost approximately $\$1/yd^3$ in material costs – use of admixtures and/or additional cement.
- Cost savings from the use of CCA can be due to two reasons – cost of virgin aggregates being replaced and cost savings from transportation and disposal fees of returned concrete.
- The cost of producing the CCA will involve some cost such as the use of a crusher and associated energy costs.
- It is assumed the net cost savings to the producer is at $8/ton of CCA used.
- An additional cost will be applicable if the producer chooses to separate the CCA into coarse and fine fractions. This cost is assumed to be $2/ton.

Based on the cost assumptions and the measured 28 day strengths of the different mixtures, the cost savings of the different CCA mixtures that would yield the same 28 day strength as the control is calculated and reported in Table 6, below the reported strengths. From that the following scenarios are possible:

1. If the CCA is not separated by strength classes it is generally of no consequence to concrete performance if the use of CCA is limited to a level of 300 lbs per cubic yard (about 10% by weight of the total aggregate quantity). This assumes that the CCA would be of the lowest strength grade – i.e. 1000 psi CCA. In this scenario, the cost savings to the producer is in the range of $\$0.66/yd^3$. If the quantity is increased to a level of 600 lbs/cubic yard the cost savings disappear due to reduced compressive strength and the need to make mixture adjustments to compensate for that.
2. If CCA is not separated by strength classes but is separated into coarse and finer fraction the optimum option is to replace 100% virgin coarse aggregate with coarse CCA. This will provide a cost savings of $0.31 per cubic yard, which is less than the first scenario. This also assumes that the coarse CCA is at the lowest strength grade evaluated in this study at 1000 psi.
3. If CCA is separated by strength classes the quantity of “as received” CCA can be increased to 900 lbs per cubic yard, assuming that strength classes exceeding 3000 psi will be used for

producing CCA. This will require training drivers to divert returned concrete of classes of concrete exceeding 3000 psi to an assigned area and ensuring that excessive water is not used to wash out concrete in this section. After discharging returned concrete, the trucks can be washed out in the appropriate wash-out pit system. The concrete might be crushed after about 14 days, i.e. after the returned material has achieved a minimum strength level. The savings estimated for this scenario is in the range of \$2.52/yd^3 by using 900 lbs of CCA in "as received" condition to replace virgin coarse and fine aggregate. There will still be lower grade returned concrete that will have to be managed.

4. If the CCA was separated by strength classes and additionally separated into coarse and finer fraction, based on the results of this study, up to 100% coarse CCA can be used to replace virgin coarse aggregate. It is assumed that strength classes exceeding 3000 psi will be used for producing CCA. By taking all the precautions mentioned in Scenario #3 the estimated cost savings to the producer is in the range of \$3.98 per cubic yard. Disposal of fine CCA will still need to be managed. It might be an option to use the fine CCA in a limited manner for some applications, such as for flowable fill.

The appropriate option for the ready mixed concrete producer is strongly dependant on the local costs for processing and disposal of returned concrete. If the disposal costs are higher than assumed above, a net cost savings for using CCA can be as high as \$18/ton. Using this number, the estimated cost savings to the producer will be in the range of \$3.00, \$8.50, \$6.98, and \$12.03/yd^3 for the above 4 scenarios, respectively. At this point, it becomes more cost effective for the producer to consider separating the CCA into the coarse and fine fractions before trying to separate them into different strength classes. In some instances where the concrete specifications require maximum w/cm and/or minimum cementitious content, etc., the strengths attained by the producer will be much higher than the specified strength. In such situations the producer need not attempt to adjust for the reduced strength of the CCA mixtures which means that the cost savings due to the use of CCA will be even higher that that suggested here.

In all of these considerations only strength is given priority. Even though appropriate mixture adjustments can be made to account for lower strengths due to the use of CCA other performance criteria such as shrinkage, modulus, durability, etc., may also need to be evaluated if these are pertinent for the applications for which the concrete is furnished. Other concrete mixture adjustments may be required so that the concrete meets the performance criteria if the producer chooses to use CCA for these types of projects. Using CCA to ensure achieving other performance criteria may or may not entail higher costs. For example, if some durability aspect of concrete containing CCA is reduced then it can be adjusted by the increased use of supplementary cementitious materials that may not result in any cost increase. However, if shrinkage is much higher, mixture adjustment options may result in increasing the material costs. Under any case the producer should test the concrete containing CCA for all performance properties so that it can be assured that the concrete meets the performance criteria for that application.

The following steps or options are recommended for the concrete producer interested in using CCA in concrete:

Step 1

To start with, it is recommended that the producer limit their use of CCA to no more than 300 lbs/yd^3 in an "as received" condition. The producer should evaluate the effect of this on his concrete mixtures to verify that it works with his materials and processes. No attempt need to be made in trying to separate the returned concrete into strength classes or into coarse and fine fractions. In this project as compared to the control mixture the use of 1000 psi CCA at 300 lbs/yd^3 led to negligible change in water demand, setting time, density, shrinkage, 6% lower elastic modulus, and 15% lower RCP values.

Step 2

The next step is for the producer to separate CCA into different strength classes by diverting returned concrete to different areas at the plant. In most instances this step should prove cost effective compared to trying to separate the CCA into coarse and finer fractions. Nevertheless the producer can attempt to do an experimental study like that presented here to test the performance of the CCA that is produced in his plant. Based on their performance and cost structure the producer can take the appropriate decision of whether to separate the returned concrete into different strength classes or separate the CCA into coarse and finer fractions. At a minimum, lower grade concrete that has been retempered with large quantities of water should be diverted away from the crushing process. In this example, it was found that the producer can attempt to have all the CCA with a specified strength of 3000 psi or higher to be discharged into a area designated for processing CCA. While discharging the concrete, the truck driver should take precautions in avoiding use of water to clean the concrete truck. One option is to discharge the concrete and wash out the truck at the wash out pit. Another operational issue would be to leave the discharged concrete undisturbed for a period of at least 14 days. With appropriate testing and evaluation, it is anticipated that CCA made from this stockpile could be used at a level of 900 lbs/yd^3. In this project as compared to the control mixture the use of 3000 psi CCA at 900 lbs/yd^3 led to negligible change in water demand, about 30-60 minutes lower initial setting times, 3% lower density, 8% lower modulus, 41% higher shrinkage, 21% higher RCP values, and most likely poorer freeze-thaw durability.

Step 3

The final step will be for the producer to separate CCA into different strength classes and additionally separate the CCA into coarse and fine fractions. In this scenario, the producer can divert all returned concrete with a specified strength of 3000 psi or higher to be discharged into a designated area to produce CCA. The producer can use 100% of the coarser fraction of this CCA to replace virgin coarse aggregate. This is approximately 1600 lbs/yd^3 of CCA. In this project, the use of 100% Coarse 3000 psi CCA led to negligible change in water demand, about 60 minutes lower setting times, 6% lower density, 25% lower modulus, 36% higher shrinkage, 77% higher RCP values, acceptable freeze-thaw durability but increased scaling. The fine fraction of CCA can be used in limited quantities or for some applications like flowable fill. Another consideration with this option is the available market for higher strength coarse CCA for use as fill material as this might prove to be a profitable use for the concrete producer.

In all situations, the producer should conduct a laboratory and field study and develop performance data on strength and other criteria such as shrinkage, durability, etc., for the CCA mixtures. Concrete containing CCA should not be used in applications where such concrete will not be able to meet other performance criteria such as shrinkage, creep, modulus, permeability, freeze-thaw durability, etc., unless it can be documented that concrete containing CCA meets all the required performance criteria in such applications. The CCA stockpile should be kept moist by the use of sprinklers as the CCA should ideally be maintained at a level greater than the saturated surface dry condition. It is also recommended that CCA characterization studies such as absorption, and relative density (specific gravity) should be conducted on a weekly basis.

CCA and Sustainable Development

As mentioned earlier it is estimated the beneficial use of CCA can reduce landfill space by as much as 845 – 10' high football fields every year. Nowadays, there is a significant interest in sustainable development. The use of CCA in concrete significantly contributes to concepts incorporated in sustainable construction initiatives. The use of CCA as concrete aggregate results in the recycling of a post-industrial waste material that would otherwise be diverted to landfill and also conserves the use of and energy associated with the mining of virgin natural aggregates, which are in limited supply. The use of CCA in conjunction with the use of fly ash, slag or silica fume and recycled water considerably increases the volume percentage of recycled content in a concrete mixture.

In the US, the US Green Building Council (USGBC) through its Leadership in Energy and Environmental Design (LEED) Green Building Rating System fosters sustainable construction of buildings. Other sustainable development initiatives, such as the Green Highway Initiative, Green Globes and those adopted by local jurisdictions are also in place. Under the USGBC, building projects are awarded Silver, Gold, or Platinum certification depending on the number of credits they achieve. The use of CCA could help attain LEED Credit points under the Construction Waste Management under Materials and Resources (MR-C2). The wording could be as follows[40] – "Three percent by volume of all concrete for this project was returned to the ready mixed concrete production facilities used for this project. Of that amount, 100% was diverted from landfills by crushing the returned concrete and reusing that as crushed concrete aggregate in concrete furnished for the project". In addition, if CCA is purchased similar to fly ash and slag it could qualify for the recycled materials credit as well[40].

Experience in Europe and US

European countries have generally been more advanced in terms of sustainable development, particularly related to the use of recycled concrete aggregate (RCA not just CCA) in concrete. In 2004, there was an International RILEM Conference on the Use of Recycled Materials in Buildings and Structures" in Barcelona. A final report on the use of Recycled Materials by RILEM Technical Committee 198-URM[41] has also been published. The report concludes that the use of 20 % of crushed concrete aggregates in structural concrete is now an extended practice in many European countries. Only concrete aggregates ≥ 4 mm (according to ASTM C 125 coarse aggregates are generally >4.75 mm in size) are used. When only crushed concrete aggregate ≥ 4 mm is used and it amounts to not more than about 20 % of the natural aggregate, the mechanical properties remain the same. At higher percentages it is necessary to check through experiments the changes in the mechanical and durability related properties, as well as shrinkage and creep. The fraction ≤ 4 mm generally contains a too high percentage of fines ≤ 0.063 mm (approximately equivalent to minus No. 200) and this adversely affects workability, shrinkage and creep.

In the USA, Congress, through transportation infrastructure appropriations, has supported the Recycled Materials Resource Center (RMRC) at the University of New Hampshire to perform research and outreach to reduce barriers to recycling in a highway environment[42]. The RMRC has done stellar work aimed at promoting the use of RCA in concrete. They have conducted research, numerous surveys and developed the "Standard Specification for Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Portland Cement Concrete"[43].

CCA and ASTM C 33 Specification for Concrete Aggregates

Section 9.1 of ASTM C 33 states "Coarse aggregate shall consist of gravel, crushed gravel, crushed stone, air-cooled slag, or crushed hydraulic-cement concrete or a combination thereof, conforming to the requirements of this specification." In this study, aggregate test results indicate that the coarse CCA meets ASTM C 33 specifications except in the case of 1000 psi coarse CCA, which did not meet the soundness test results. ASTM C 33 does include a provision (Section 11.3 in the 2003 version) that permits the use of an aggregate that does not meet one or more of its criteria if there is satisfactory service record or proven to have relevant concrete properties for the intended application.

Section 5.1 of ASTM C 33-03 states "Fine aggregate shall consist of natural sand, manufactured sand, or a combination thereof." ASTM C 125 defines manufactured sand as "fine aggregate produced by crushing rock, gravel, iron-blast furnace slag, or hydraulic-cement concrete." In this study, aggregate test results indicate that fine CCA meets C 33 specifications with two exceptions: 1. Material finer than the No. 200 sieve is slightly higher than the 5% to 7% limit allowed; 2. Soundness test limits are exceeded. ASTM C 33 Section 6.3 permits the use of an aggregate that does not comply with the grading limits with the documentation of service record or performance tests. Soundness limits might only be pertinent to exterior concrete subject to freezing and thawing cycles and the use of fine CCA use might be appropriate for other applications. If the application will be exposed to a freeze-thaw environment, Section 8.3 states that even if the soundness test results are not met the fine aggregate shall be regarded as meeting the requirements if the supplier demonstrates it gives satisfactory results in concrete subjected to freezing and thawing test (ASTM C 666).

ASTM C 33 requires the testing of aggregates for clay lumps and friable particles, coal/lignite, and chert. These tests were not conducted in this study. Before using CCA the producer should consider conducting all the tests that document compliance with ASTM C 33 or other requirements of the project specification.

Guidance to the Engineer

The ACI 318 Building Code for Structural Concrete (Section 3.3.1) and ACI 301 Reference Specification for Structural Concrete require that concrete aggregates shall conform to ASTM C 33. This specification is also referenced in ASTM C 94 and in AIA MasterSpec that is the basis of master specifications in most design firms. It is clear from the above discussions that CCA meets ASTM C 33. This should permit the use of CCA in most concrete applications unless the design professional chooses a more conservative approach in limiting its use to non-structural or less critical applications related to loads or durability.

Based on the results of this study, it seems that the use of CCA can be permitted for most applications to a limit of 10% by weight of the total aggregate. Engineers who feel uncomfortable with this can request additional data on service record or test results that will do “no harm” to the concrete. The concrete produced should still meet all the performance requirements for that application.

In light of the European experience, for structural concrete applications coarse CCA should be allowed to be used at 10% by weight of total aggregate.

In non-structural applications provided the concrete producer does further processing such as isolating the returned concrete>3000 psi, the producer could be allowed to use CCA in the “as received” condition up to 30% by weight of total aggregate. In non-structural applications, if the concrete producer just used the coarse fraction of the CCA the producer could be allowed to replace all of the virgin coarse aggregate with coarse fraction of CCA.

In all of the above situations the concrete produced should still meet all the performance requirements for that application. For increased acceptance of CCA, it is suggested that the ASTM C 94 Standard Specification for Ready Mixed Concrete include a recommended provision that crushed concrete aggregate can be used to a limit of 10% of the total aggregate weight.

Summary

The main findings in this research study can be summarized as follows:

1. Use of CCA significantly benefits sustainable development by reducing the necessity of landfilling returned concrete and conserves the use of increasingly scarce good quality virgin aggregate. Use of CCA can also potentially help reduce $300 Million in annual operator costs by the US ready mixed concrete industry.
2. A detailed literature search and bibliography on the effect of recycled concrete aggregate on concrete performance has been conducted as part of this study. Most of the literature is related to the use of crushed concrete from existing structures and not of crushed concrete from returned concrete which was the main focus of this project.
3. Compared to virgin aggregate, CCA has lower specific gravity, higher absorption, higher percentage of minus 200 fines, and lower aggregate weathering potential as measured by the sulfate soundness test. Both the coarse and fine fraction of CCA meet most of the ASTM C 33 requirements for aggregates. However, not all CCA (particularly the finer fraction of CCA) meet the percentage of minus 200 fines, and sulfate soundness test. ASTM C 33 permits the use of CCA in concrete.
4. Mixing water content of concrete containing CCA was not substantially different from that of concrete containing virgin aggregates. However, concrete containing 100% coarse Pile 1 CCA, representing crushed concrete from a concrete plant with no control, had much higher mixing water content.
5. The compressive strength and elastic modulus of concrete containing CCA is lower than that of the control concrete. However, the decrease in strength is not substantial and the strength drop

can be compensated for by normal mixture adjustments to achieve the desired strength. However, concrete containing 100% coarse Pile 1 CCA had significantly lower strengths.

6. The three concrete mixtures that were repeated on a different day showed that the batching, mixing and testing is repeatable.
7. The addition of CCA tends to increase the average length change due to drying shrinkage slightly. The use of large amounts of Coarse CCA increased the RCP values.
8. The use of 600 lbs/yd^3 of "as received" CCA reduced the concrete's freeze-thaw durability. However, the use of 100% coarse 3000 psi CCA did not reduce freeze-thaw durability even though it did increase surface scaling of the test specimens. The use of 3000 psi 100% coarse CCA to replace virgin coarse aggregate should be admissible even in concrete applications that are exposed to freeze-thaw environment. However, concrete containing CCA in the "as received" condition should be evaluated for its freeze-thaw resistance prior to its use.
9. If CCA is used in the "as received" condition, slump loss due to the fine fraction of the CCA tends to be an issue. When coarse CCA is used slump loss is negligible particularly if the CCA is kept in a moist condition prior to batching.
10. The pressure meter (C 231) is adequate to measure the air content of concrete containing CCA accurately. If deemed necessary comparative testing with C 231 and C 173 can be conducted and if the results agree then C 231 can be continued to be used.
11. The use of 20 % of crushed coarse concrete aggregates in structural concrete is now a practice accepted by Codes in many European countries.
12. Based on the results of this study, the use of "as received" CCA up to 10% by weight of the total aggregate should be permitted in most concrete applications. The concrete produced should still meet all the performance requirements for that application. In light of the European experience, for structural concrete applications coarse CCA should be allowed to be used at 10% by weight of total aggregate. Greater amounts of CCA could be allowed in non-structural applications provided the concrete producer does the processing requirements (using >3000 psi returned concrete to make CCA or just using the coarse fraction of CCA for example). For increased acceptance of CCA it is suggested that the ASTM C 94 Standard Specification for Ready Mixed Concrete include these provisions.
13. Cost calculations suggest that the concrete producer can achieve considerable savings by using CCA from reduced use of virgin materials and reduced disposal costs. The concrete producer should test the concrete containing CCA for a wide range of properties that are important for the application. If CCA will be used the producer should adopt quality control measures while producing the CCA. The CCA pile should be kept moist as the CCA should ideally be maintained at a level greater than the saturated surface dry condition. CCA characterization studies such as absorption, and relative density (specific gravity) are recommended on a weekly frequency.

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Table 1. Mixture proportions and Test results of Concrete from which CCA was Prepared

	1000 psi	3000 psi	5000 psi
Material, lb/yd^3			
Cement	282	423	600
Fine aggregate	1625	1645	1453
Coarse aggregate (No. 57)	1800	1800	1850
Water	267	283	283
Type A Water Reducer (oz/cwt.)	3	3	3
Vol. of Paste (incl. air) / Vol. of Aggregate, %	31	39	43
Specific Gravity of Paste (calculated)	1.43	1.45	1.74
Fresh Concrete Properties			
Slump, in.	5.25	4.5	4.75
Air, %	1.7	4.2	2
Temperature, °F	75	74	76
Density, lb/ft^3	147.4	146.6	151.7
Hardened Concrete Properties			
Compressive Strength, psi (Lab cure)			
7 days	810	2,290	4,950
28 days	1,330	3,200	6,800
56 days	1,640	3,390	7,410
Compressive Strength, psi (Field cure)			
7 days	610	1,990	4,160
28 days	890	2,530	5,260
56 days	1,320	3,630	6,480
117 days	1,320	3,800	7,630

All strengths are average of 2 cylinders. Concrete was crushed at 110 days and CCA prepared

Table 2. Percent of plus No. 4 materials in each case

CCA Coarse Aggregate	1000psi gray (%)	3000psi red (%)	5000psi black (%)	Pile1 (%)
By Mass	66.6	73.5	72.6	53.6
By Volume	61.2	70.0	68.8	46.5

Table 3. Properties of Aggregate Used in Study

Sieve Size	Percent Passing									
	Coarse Aggregate					Fine Aggregate				
	Control No.57	1000 psi Gray	3000 psi Red	5000 psi Black	Pile 1	Control Sand	1000 psi Gray	3000 psi Red	5000 psi Black	Pile 1
2 1/2	100	100	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100	100	100
1 1/2	100	100	100	100	100	100	100	100	100	100
1	99	95	90	83	88	100	100	100	100	100
3/4	87	78	75	64	68	100	100	100	100	100
1/2	48	45	50	36	40	100	100	100	100	100
3/8	17	28	34	21	27	100	100	100	100	100
No. 4	2	12	9	3	14	99	100	100	100	100
No. 8	0	0	0	0	0	83	80	81	72	83
No. 16	0	0	0	0	0	69	63	63	52	67
No. 30	0	0	0	0	0	51	47	45	37	48
No. 50	0	0	0	0	0	19	25	25	22	24
No. 100	0	0	0	0	0	4	12	14	12	11
No. 200	0	0	0	0	0	2	7	9	8	7
FM	6.95	6.87	6.92	7.28	7.03	2.75	2.73	2.71	3.05	2.67

1000 psi-gray, and 3000 psi-red sieve analysis were average of three samples whereas the rest were average of two samples.

Table 4. Coarse Aggregate Characterization Test results

Coarse Aggregate	**1000 psi Gray**	**3000 psi Red**	**5000 psi Black**	**Pile 1**	**Control No. 57**
LA Abrasion	23.6	26.4			13.1
(%)	24.5	25.9			13.4
ASTM C131	23.4	25.8			
Average	**23.8**	**26.0**			**13.2**
Specific Gravity	2.56	2.54	2.57	2.56	2.91
(SSD)	2.55	2.55	2.59	2.55	2.92
ASTM C127	2.56	2.52	2.59		
Average	**2.56**	**2.54**	**2.58**	**2.56**	**2.92**
Absorption	4.43	4.30	4.45	5.61	0.86
(%)	4.45	4.19	4.20	6.13	0.86
	4.32	4.44	4.30		
Average	**4.40**	**4.31**	**4.32**	**5.87**	**0.86**
Minus 200	1.01	0.64	0.28	1.86	0.39
(%)	1.14	0.62	0.36	1.46	0.36
ASTM C117	1.22	0.70			
Average	**1.13**	**0.65**	**0.32**	**1.66**	**0.37**
Fineness Modulus	6.86	6.94	7.32	6.93	6.99
ASTM C136	6.89	6.86	7.25	7.12	6.92
	6.86	6.95			
Average	**6.87**	**6.92**	**7.28**	**7.03**	**6.95**
Dry Rodded Unit Weight	97.5	89.3	93.7		105.4
(pcf)	96.7	89.5	93.3		105.8
ASTM C29	97.1	89.3	93.7		105.6
Average	**97.1**	**89.3**	**93.6**		**105.6**
Soundness	21.37	6.54			0.51
(%)	24.31	9.93			0.41
ASTM C88					
Average	**22.84**	**8.24**			**0.46**

Table 5. Fine Aggregate Characterization Test results

Fine Aggregate	1000 psi Gray	3000 psi Red	5000 psi Black	NA Pile1	Control Sand
Organic Impurity	1	1			1
ASTM C40	1	1			1
	1	1			
Average	**1**	**1**			**1**
Specific Gravity	2.15	2.23	2.26	2.09	2.61
(SSD)	2.16	2.27	2.26	2.14	2.61
ASTM C128	2.21	2.26	2.29		
Average	**2.17**	**2.25**	**2.27**	**2.11**	**2.61**
Absorption	11.52	10.44	9.94	17.03	0.98
(%)	12.06	10.06	10.33	15.56	0.92
	12.13	10.24	9.81		
Average	**11.90**	**10.25**	**10.03**	**16.30**	**0.95**
Minus 200	7.04	9.31	7.73		1.51
(%)	7.33	9.67	7.56		1.29
ASTM C117	7.57	9.52			
Average	**7.31**	**9.50**	**7.64**		**1.40**
Fineness Modulus	2.74	2.74	3.03	2.69	2.74
ASTM C136	2.73	2.69	3.07	2.65	2.76
	2.72	2.69			
Average	**2.73**	**2.71**	**3.05**	**2.67**	**2.75**
Sand Equivalency	54.8	61.4			85.4
(%)	53.2	62.1			87.0
ASTM D2419	57.6	61.8			
Average	**56.0**	**63.0**			**87.0**
Uncompacted Void	37.0	40.1			41.7
Contents (%)	36.9	40.4			41.7
ASTM C1252	37.1	40.3			
Average	**37.0**	**40.3**			**41.7**
Soundness	32.23	16.46			2.72
(%)	30.15	16.09			2.71
ASTM C88					
Average	**31.19**	**16.28**			**2.72**

Table 6. Details of Stage I Mixtures

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
CCA Type	0	1000	1000	3000	Pile1	3000	1000	1000	3000	5000	3000	Pile1	0	3000	3000	3000	Pile1
CCA, lbs/yd^3	0	300	600	600	600	900	NA	NA	NA	NA	NA	NA	0	600	NA	600	NA
CCA, coarse, %	0	NA	NA	NA	NA	NA	50	100	100	100	100	100	0	NA	100	NA	100
CCA, fine, %	0	NA	NA	NA	NA	NA	0	0	0	0	25	0	0	NA	0	NA	0
Calculated Batch Quantities, lb/yd^3																	
Cement	495	503	495	498	494	496	497	498	493	490	498	471	490	496	502	498	480
Virgin Coarse	1921	1750	1524	1491	1599	1266	964	0	0	0	0	0	1900	1485	0	1498	0
CCA (as recd.)	0	302	594	597	593	892	-	-	-	-	-	-	0	595	0	600	-
Coarse CCA	-	-	-	-	-	-	817	1637	1610	1628	1627	1529	0	0	1637	0	1560
Virgin Fine	1373	1192	1051	1109	949	970	1378	1380	1405	1396	1036	1317	1370	1119	1395	1127	1331
Fine CCA	0	0	0	0	0	0	0	0	0	0	273	0	0	0	0	0	0
Mixing Water	287	280	292	288	287	292	274	258	289	277	294	321	284	287	294	290	329
Fresh Concrete Properties																	
Slump, in.	6	6	6.5*	6	5	6*	6.25	6	6	6	7	3.75	6.25	6.5	5	7	6.25
Air, %	2.5	2.1	2.4	2.1	2.3	2.7	2.8	3.1	2.8	3	3.5	3.8	3.2	2.5	2.2	1.8	3
Density, lb/ft^3	152.1	150.9	148.9	149.7	148.5	147.7	147.7	142.9	143.7	143.5	142.1	138.5	150.9	149.7	144.9	150.9	140.9
Temperature, ^{0}F	75	75	76	77	75	75	75	74	75	74	73	74	77	78	72	73	68
Initial Set Time**	4:14	4:03	4:04	3:52	3:48	3:44	3:42	4:01	3:00	-	4:11	4:00	4:02	3:52	-	-	-
Final Set Time**	7:00	6:44	5:54	6:30	4:41	5:52	6:32	6:16	6:24	-	5:42	4:51	6:46	6:25	-	-	-
Initial Set Time***	-	-	-	-	3:09	-	4:34	3:54	3:58	-	3:45	3:16	4:43	4:05	-	-	-
Final Set Time***	-	-	-	-	4:41	-	6:19	5:40	5:45	-	5:29	4:37	6:32	5:44	-	-	-
Hardened Concrete Properties																	
Compressive Strength, psi																	
7 days	3080	2910	2410	2800	2590	2800	2640	2460	2730	2740	2520	2140	2980	2610	-	-	-
28 days	4100	3990	3630	3690	3410	3890	3470	3180	3930	3790	3510	2690	3930	3760		3900	2840
90 days	4740	4670	3790	4450	4530	4720	4330	3630	4270	4810	4110	3190	5350	4570	4220	4390	3360
28 d, % control	100	97.3	88.5	90	83.2	94.9	84.6	77.6	95.9	92.4	85.6	65.6	95.9	91.7	85.1	95.1	67.4
Cost Saving, \$/yd^3		0.66	0.03	0.34	-1.08	2.52	-0.7	0.31	3.98	3.33	2.75	-2.47					
Elastic Modulus (E_c), x10^6 psi																	
28 days	4.69	4.42	3.91	4.09	4.20	4.29	4.42	3.87	3.5	3.87	3.36	3.28	4.69	4.39	-	-	-
28 d, % control	100	94.2	83.4	87.2	89.6	91.5	94.2	82.5	74.6	82.5	71.6	69.9	100	93.6	-	-	-
Length Change (Drying Shrinkage), %																	
28 days	0.012	0.013	0.021	0.022	0.022	0.026	0.017	0.020	0.029	0.021	0.029	0.044	0.025	0.026	0.028	0.021	0.019
90 days	0.031	0.035	0.042	0.043	0.040	0.048	0.033	0.040	0.049	0.041	0.051	0.072	0.042	0.049	0.047	0.036	0.051
6 months	0.036	0.040	0.049	0.053	0.047	0.057	0.040	0.046	0.055	0.048	0.058	0.083	0.045	0.051	0.051	0.041	0.061
180 d, % control	88.9	98.8	121.0	130.9	116.0	140.7	98.8	113.6	135.8	118.5	143.2	204.9	111.1	125.9	125.9	101.2	150.6
RCP, Coulombs																	
90 days	3618	2970	2984	3936	3232	4276	5402	5187	6248	4729	7231	6201	3424	3316	5036	3683	6033

* slump sheared slightly, ** Thermal Method, *** ASTM C 403

Table 7. ASTM C 1293 Test Result

Mix No.	Description	ASTM C1293 Expansion %, Age – 12 months
A	No.57 Virgin Coarse (Lot 8043) + Virgin Crushed Fine (Lot 8058)	0.022
B	No.57 Virgin Coarse + 600 lbs/yd^3 Pile1 CCA + Virgin Crushed Fine	0.027
C	Coarse fraction of 3000 psi CCA + Virgin Crushed Fine	0.032
D	No.57 Virgin Coarse + Fine fraction of 3000 psi CCA	0.028

Table 8. Details of Stage II Mixtures

	II-1	II-2	II-3	II-4
CCA Type	0	1000	3000	3000
CCA, lbs/yd^3	0	600	600	NA
CCA, coarse, %	0	NA	NA	100
Calculated Batch Quantities, lb/yd^3				
Cement	566	575	570	550
Virgin Coarse Agg. (No. 57)	1945	1570	1514	0
CCA (as received)	0	612	607	-
Coarse fraction of CCA	-	-	-	1591
Virgin Fine Aggregate	1225	906	957	1190
Mixing Water	255	260	259	248
AE admixture – oz/cwt	0.4	0.4	0.5	0.5
Type F admixture – oz/cwt	10	11.7	15.8	10
Fresh Concrete Properties				
Slump, in.	7.50	7.00	6.25	6.00
Air, %	6.4	4.8	5.6	8.5
Density, lb/ft^3	148.9	147.7	146.9	135.5
Temperature, ^{0}F	70	69	70	69
Hardened Concrete Properties				
Compressive Strength, psi				
7 days	3980	3650	4090	3530
28 days	5100	4510	5030	4290
90 days	6040	5280	6120	5030
28 d, % of control	100	88.4	98.6	84.1
Length Change (Drying Shrinkage), %				
28 days	0.020	0.028	0.025	0.038
90 days	0.034	0.046	0.043	0.058
6 months	0.041	0.050	0.047	0.062
180 d, % of control	100	122.0	114.6	151.2
RCP, Coulombs				
90 d @ moist cure	2261	3044	2510	3821
Freeze and Thaw after 300 cycles				
Durability Factor, %	92	13[*]	9	89
Length Change, %	-0.01	0.14	0.03	-0.01
Mass Loss, %	0.52	0.18	0.73	1.23

[*] Test was terminated at 226 F/T cycles due to the specimen failure.

Table 9. Details of Mixtures designed to Study Slump Retention

	SL-1	SL-2	SL-3	SL-4
CCA Type	0	1000	3000	3000
CCA, lbs/yd^3	0	300	NA	NA
CCA, coarse, %	0	NA	100	100
CCA, fine, %	0	NA	NA	NA
Calculated Batch Quantities, lb/yd^3				
Cement	541	545	542	544
Virgin Coarse Agg. (No. 57)	1808	1723	0	0
CCA (as received)	0	297	-	-
Coarse fraction of CCA	-	-	1609	1613
Virgin Fine Aggregate	1314	1189	1317	1320
Mixing Water	303	294	296	287
Fresh Concrete Properties				
Slump, in.	6.50	7.00	7.25	6.75
Density, lb/ft^3	151.7	151.7	142.5	142.5
Air, %	2.7	2.5	3.2	3
Temperature, ^{0}F	74	73	75	73
Slump Retention Study				
Slump, inch				
Slump1	6.50	7.00	7.25	6.75
Slump2	5.75	4.00	6.00	4.50
Slump3	6.00	7.00	6.50	7.50
Slump loss, % of slump1	11.5%	42.9%	17.2%	33.3%
Water Adjustment, lbs/yd^3				
Slump2 → Slump3	13.9	17.2	12.0	16.8
Hardened Concrete Properties				
Compressive Strength at 14 days, psi				
Sampled with Slump1	4340	4340	4100	3870
Sampled with Slump3	4240	3840	4020	3960

Mixture SL-4 was identical to Mixture SL-3 except that the CCA was in a dry condition as opposed to a moist condition for Mixture SL-3

Table 10. Air Test Results - Pressure Meter Air (C 231) vs. Gravimetric Air (C 138)

Mix ID	Air (C 231) %	Air (C 138) %	Diff. of C231 %
1	2.50	2.70	-0.20
2	2.10	2.76	-0.66
3	2.40	2.51	-0.11
4	2.10	2.28	-0.18
5	2.30	2.63	-0.33
6	2.70	2.39	0.31
7	2.80	3.18	-0.38
8	3.10	3.98	-0.88
9	2.80	2.10	0.70
10	3.00	3.34	-0.34
11	3.50	1.80	1.70
12	3.80	4.49	-0.69
13	3.20	3.49	-0.29
14	2.50	2.31	0.19
15	2.20	1.18	1.02
16	1.80	1.50	0.30
17	3.00	2.79	0.21
II-1	6.40	6.19	0.21
II-2	4.80	4.61	0.19
II-3	5.60	5.32	0.28
II-4	8.50	8.84	-0.34
SL-1	2.70	2.53	0.17
SL-2	2.50	1.90	0.60
SL-3	3.20	2.74	0.46
SL-4	3.00	3.10	-0.10

Table 11. Aggregate Correction Factor Test Results

Mix No.	Description	ACF[+] #1	ACF[+] #2
1	No.57 Virgin Coarse + Virgin Fine	0.10	0.10
2	No.57 Virgin Coarse + 300 lbs/yd^3 1000 psi CCA + Virgin Fine	0.15	0.15
3	No.57 Virgin Coarse + 600 lbs/yd^3 1000 psi CCA + Virgin Fine	0.20	0.20
4	No.57 Virgin Coarse + 600 lbs/yd^3 Pile1 CCA + Virgin Fine	0.30	0.30
5	No.57 Virgin Coarse + 900 lbs/yd^3 3000 psi CCA + Virgin Fine	0.30	0.30
6	No.57 Virgin Coarse + 50% Coarse fraction of 1000 psi CCA + Virgin Fine	0.18	0.20
7	Coarse fraction of 3000 psi CCA + Virgin Fine	0.30	0.40
8	No.57 Virgin Coarse + 600 lbs/yd^3 1000 psi CCA[*] + Virgin Fine	0.30	0.30

[+] ACF = Aggregate Correction Factor,

[*] 1000 psi CCA was oven dried for 1 hour

Figure 1. Crusher Used to Produce CCA at the Concrete Plant

Figure 2. CCA Stored at NRMCA Research Laboratory (Red=3000 psi, Black=5000 psi, Gray=1000 psi)

Figure 3. Large Capacity Sieve Shaker

Figure 4. Control Mixture After 300 Freeze-thaw Cycles

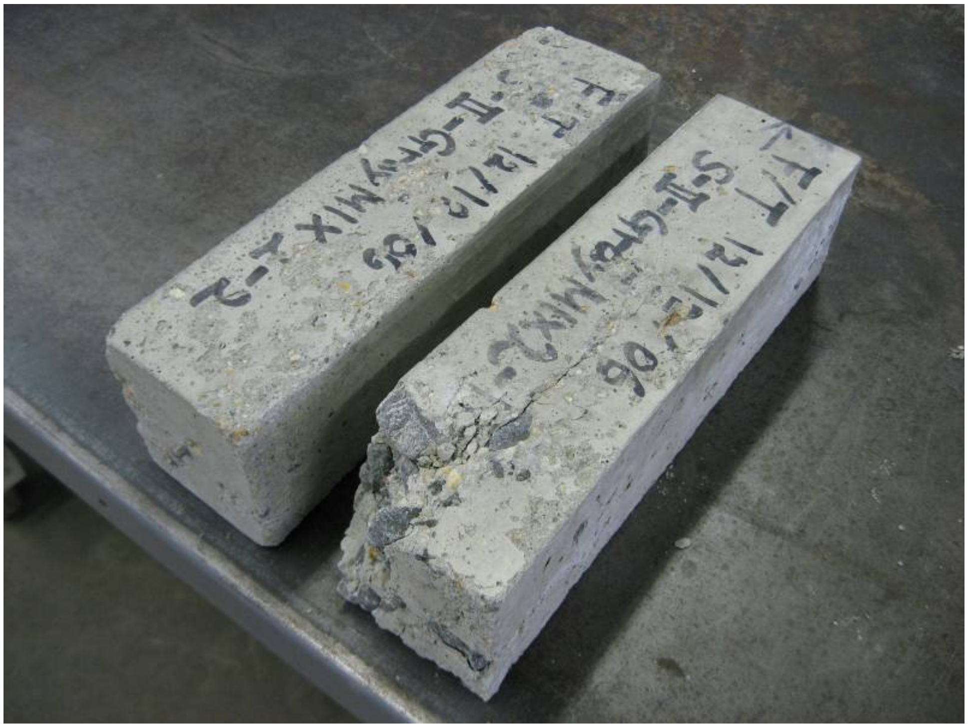

Figure 5. 1000 psi CCA at 600 lb/yd^3 Mixture After 300 Freeze-thaw Cycles

Figure 6. 3000 psi CCA at 600 lb/yd^3 Mixture After 300 Freeze-thaw Cycles

Figure 7. 3000 psi CCA at 100% Coarse Mixture After 300 Freeze-thaw Cycles