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Figure 1. A ready mixed concrete truck discharging returned concrete at the plant.

Figure 2. A crusher is used to produce CCA at the concrete plant.

Crushed, Returned Concrete as Aggregates for New Concrete

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Every year, it is estimated that 2% to 10% (an average of 5%) of the estimated 455 million cubic yards of ready mixed concrete produced in the United States is returned to the concrete plant.

The returned concrete in the truck can be handled in several different ways. A common approach is to discharge the returned concrete at a location in the concrete plant for processing (Figure 1). The hardened, discharged concrete can be subsequently crushed (Figure 2), and the coarser material can be reused as base for pavements or fill for other construction. However, it is not easy to utilize the material if it's finer than 2 inches (Figure 3). A research project was undertaken by the NRMCA Research Laboratory to study the use of crushed, returned concrete, referred to as "crushed concrete aggregate" (CCA), as a portion of the aggregate component in new concrete. The project was funded by the RMC Research & Education Foundation.

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 to 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 and other building components). CCA, on the other hand, is prepared from concrete that has never been in service and thus is likely to contain much lower levels of contamination.

The main objective of the research project was to develop technical data that will support the industry's use of CCA from returned concrete and to provide guidance on a methodology for the appropriate use of the material. Such a step can help the ready mixed concrete industry save an estimated $300 million per year in operating costs. In addition, it will reduce the amount of landfill space used by as much as 845 10-foot high football fields every year. The use of CCA also could help earn points under systems like the Leadership in Energy and Environmental Design (LEED) for certifying building projects for sustainable construction.

This short article summarizes the key findings from the 20-month study. The complete reports can be downloaded from one of the following locations:
http://www.rmc-foundation.org/newsite/index.htm or
http://www.nrmca.org/research/eng_articles.asp.

Preparation of CCA at a Ready Mixed Concrete Plant

To start with, CCA was produced at a ready mixed concrete plant. Concrete at three strength classes (1,000, 3,000 and 5,000 psi) was produced and discharged on the ground. The discharged concrete was left undisturbed for 110 days, after which the concrete was processed through a crusher to produce the CCA. The CCA was transported and stored at the NRMCA Research Laboratory for the subsequent parts of the study. Figure 4 shows the three strength classes of CCA stored in the NRMCA laboratory (gray is 1,000 psi, red is 3,000 psi and black is 5,000 psi). Typically, CCA results from returned concrete with different design strength levels that may have been through varied levels of retempering. For this research project it was considered to be important to study the effect of the initial strength of the concrete that is crushed on the performance of new concrete containing 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 article.

Characterization of CCA from Returned Concrete

Using a large-capacity sieve shaker, CCA of all three concrete grades and Pile 1 were separated into coarse (cumulative material retained on a No. 4 sieve) 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. The percentage of coarser fraction (cumulative material retained on No. 4 sieve) varied between 61% and 70% for the CCA made from the three strength grades and was 47% for the Pile 1 CCA. The properties of coarse and fine CCA were compared to that of virgin aggregates. The virgin aggregates had been used to prepare the concrete from which the CCA had been made.

Properties of Coarse CCA

Some of the properties of the coarse CCA, virgin coarse aggregate and relevant ASTM C 33 limits are provided in Table 1.

Figure 3. CCA stockpiled at the ready mixed concrete plant.

Table 1. Selected Properties of Coarse Fraction of CCA

	1000	3000	5000	Pile 1	Control	ASTM C 33
LA Abrasion, %	23.8	26.0	-	-	13.2	50
Specific Gravity	2.56	2.54	2.58	2.56	2.92	NA
Absorption, %	4.40	4.31	4.32	5.87	0.86	NA
Minus 200, %	1.13	0.65	0.32	1.66	0.37	1 – 1.5
Soundness, %	22.84	8.24	-	-	0.46	12

Table 2. Selected Properties of Fine Fraction of CCA

	1000	3000	5000	Pile 1	Control	ASTM C 33
Specific Gravity	2.17	2.25	2.27	2.11	2.61	NA
Absorption, %	11.90	10.25	10.03	16.30	0.95	NA
Minus 200, %	7.31	9.50	7.64	-	1.40	5 – 7
Soundness, %	2513	-	-	2.72	10	

Coarse CCA had higher LA abrasion loss, lower SSD-specific gravity, higher absorption and a higher percentage passing the No. 200 sieve as compared to the virgin coarse aggregate. The higher absorption and lower specific gravity of the coarse CCA are due to the lower specific gravity paste (1.43 to 1.74) adhering to the surface of the CCA. Sodium-sulfate soundness test results indicate that the coarse CCA has higher mass loss compared to the virgin coarse aggregate, suggesting poorer durability of the CCA under cycles of freezing and thawing. The implication of the sulfate-soundness test to CCA is questionable because it is not clear whether other mechanisms, such as sulfate attack of the paste phase of the CCA, might also cause a high mass loss in the test. A higher compressive strength of the returned concrete led to a coarse CCA with a greater resistance to degradation due to processing, slightly lower amount of Minus 200 fines and potentially improved resistance to degradation as indicated by the soundness test.

Properties of Fine CCA

Some of the properties of the fine CCA, virgin fine aggregate and relevant ASTM C 33 limits are provided in Table 2. Fine CCA had lower SSD-specific gravity, higher absorption and higher percent passing the No. 200 sieve as compared to the virgin fine aggregate. Soundness test results indicate that the fine CCA has higher mass loss compared to the virgin fine aggregate. A higher compressive strength of the returned concrete led to a fine CCA with a slightly higher specific gravity, slightly lower absorption and potentially improved resistance to degradation as indicated by the soundness test.

CCA and ASTM C 33 Specifications for Concrete Aggregates

Section 9.1 of ASTM C 33 states: "Coarse aggregate shall consist of gravel, crushed gravel, crushed stone, air-cooled slag, 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 1,000 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 a satisfactory service record or it's 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, and 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. 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 tests (ASTM C 666).

Figure 4. CCA of different strength classes stored at NRMCA Research Laboratory. (Red is 3,000 psi, black is 5,000 psi and gray is 1,000 psi)

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.

Experimental Study of CCA in New Concrete

Concrete tests were conducted in the NRMCA laboratory in several phases.

Phase I

In Phase I, 17 non-air-entrained concrete mixtures were cast. A control mixture was prepared with virgin coarse and fine aggregates. CCA produced from all three strength levels (1,000, 3,000 and 5,000 psi) and Pile 1 was evaluated. CCA was used in "as received" condition at 300, 600 and 900 pounds/yard^3. "As received" condition signifies that the CCA was not separated into coarse and fine size fractions. In contrast, some of the mixtures used 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. Slightly different CCA-processing techniques and mixing conditions were also evaluated. Lastly, three of the mixtures were repeated on a different day to study the effect of batch-to-batch variability. The portland cement content was maintained at 500 pounds/yard^3, and the water content adjusted to achieve a target slump of five to seven inches. The following tests were conducted: slump, ASTM C 143, air content, C 231, density, C 138, temperature, C 1064, setting time, C 403, compressive strength, C 39, elastic modulus, C 469, shrinkage, C 157, Chloride Ion Penetration and RCPT C 1202. To evaluate CCA performance in alkali silica reactivity, C 1293, four concrete mixtures were cast. A control mixture was prepared with virgin coarse and fine aggregates that had been previously determined to be non-reactive in ASR. For the ASR tests, Pile 1 CCA in "as received" condition at 600 pounds/yard^3, 3,000 psi coarse CCA with virgin fine aggregate and 3,000 psi fine CCA with virgin coarse aggregate were evaluated.

Phase I – Results and Discussions

Mixing water content of concrete containing CCA was within 5% of that recorded for the control mixture. However, concrete containing 100% coarse Pile 1 CCA had much higher mixing water content to obtain the target slump. The density of the CCA mixtures were between 1% and 6% lower than that of the control, with the extent of the reduction depending on the amount of CCA replacing the virgin aggregates. The initial and final setting times of the CCA mixtures were about 30 to 60 minutes earlier than that of the control, except for Pile 1 CCA mixtures, which had initial setting times about 1.5 to 2 hours earlier.

The 28-day compressive strength of the control mixture was 4,100 psi. The compressive strength of concrete containing CCA in the "as received" condition was about 3% to 11% lower than the control (Figure 5). Increasing the amount of CCA in a mixture led to greater strength reduction. However, this trend was not observed if the CCA had been produced from concrete with higher strengths than the new concrete. When the coarse fraction of CCA was used, strength reductions of 4% to 22% were observed. The greater strength reductions can be attributed to the greater amounts of CCA being used as compared to the "as received" condition. To summarize, the decrease in strength was not substantial, and it can be compensated for by normal mixture adjustments to achieve the desired strength. However, concrete containing 100% coarse Pile 1 CCA had about 34% less strength as compared to the control.

The 28-day static modulus of elasticity of the control mixture was about 4.7x10^6 psi. The modulus of mixtures containing CCA was between 6% and 28% lower than the control. Generally, mixtures containing lower quantities of CCA had smaller reductions. The strength of the returned concrete from which the CCA was prepared did not seem to influence the modulus of elasticity.

The 180-day length change due to drying shrinkage of the control mixture was 0.041%. The length change of concrete containing CCA was 0% to 43% higher than that of the control, with increasing numbers recorded with increasing amounts of any CCA (Figure 6). The 1,000-psi CCA led to a smaller increase in length change as compared to the 3,000-psi CCA, possibly due to the lower amount of paste present in the 1,000-psi CCA as compared to the 3,000-psi CCA. However, concrete containing 100% coarse Pile 1 CCA had twice the length change as compared to the control.

The 90-day RCPT of the control mixture was 3,618 coulombs. The RCPT of concrete containing 1,000-psi and Pile 1 CCA in the "as received" condition was between 11% and 18% lower than the control, whereas for the 3,000-psi CCA, it was between 9% and 18% higher. However, the use of 100% coarse CCA led to an all around increase (43% to 100%) in the RCP values, with the chloride ion penetrability going from moderate to high.

The expansions due to ASR of the four concrete mixtures were in the range of 0.022% to 0.032% after one year. While the three CCA mixtures had higher expansions than the control mixture, the values were still below 0.04%. By ASTM C 1293 one-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. 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.

The three concrete mixtures that were repeated on a different day showed that the batching, mixing and testing is repeatable. The different processing conditions and mixing conditions evaluated 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 freeze-thaw durability. Four air-entrained concrete mixtures were cast. Apart from the control mixture, CCA produced from the 1,000- and 3,000-psi strength classes were evaluated in "as received" condition at a replacement of 600 pounds/yard^3, and the coarse fraction of 3,000-psi CCA was used to replace virgin coarse aggregate at 100% replacement. The cement content was maintained at 564 pounds/yard^3, with w/cm of 0.45 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 six to eight inches. In addition to most of the tests conducted in Phase I, freeze-thaw durability testing was conducted according to ASTM C 666 Procedure A – Rapid Freezing and Thawing in Water. Only the results of the freeze-thaw testing are discussed in this article.

Phase II – Results and Discussions

The use of 600 pounds/yard^3 of "as received" CCA reduced the concrete's freeze-thaw durability. However, the use of 100% coarse 3,000-psi CCA did not reduce freeze-thaw durability even though it did increase surface scaling of the test specimens. The use of 3,000-psi, 100% coarse CCA to replace virgin coarse aggregate should be admissible even in concrete applications that are exposed to a freeze-thaw environment. However, concrete containing CCA in the "as received" condition should be evaluated for its freeze-thaw resistance prior to its use. 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,

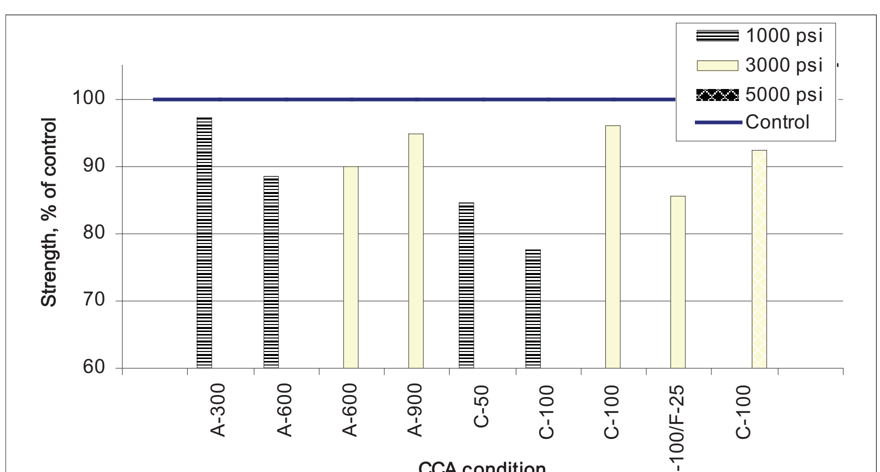

Figure 5. 28-day compressive strength performance (Control = 4,200 psi); A= "as received," C= "as coarse," F= "as fine." A-300 refers to 300 lbs/yd3 virgin aggregate by weight replaced by "as received" CCA. C-50 refers to 50% virgin coarse aggregate by volume replaced by coarse CCA. 1,000, 3,000, 5,000 psi refers to CCA strength classes.

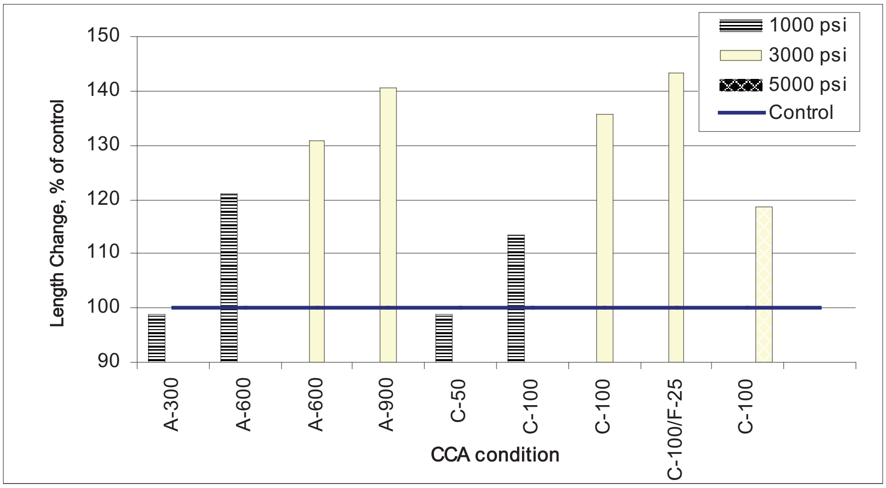

Figure 6. 180-day drying shrinkage performance (Control = 0.041%)

and it is possible that CCA made from such returned concrete may have better freeze-thaw resistance.

Other Phases – Results and Discussions

Due to space limitations, only the results are discussed here. More detailed information can be found in the report.

Since CCA consists of hydrated paste and has shown lower initial setting times, it was decided to evaluate the slump retention of CCA mixtures. Results show that 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 if the CCA is kept in a moist condition prior to batching. Slump retention of concrete is an operational issue that the concrete producer faces on a daily basis and is typically addressed by methods such as the holding back of water or the use of admixtures.

It is well known that for lightweight aggregate with high absorption, the volumetric test (ASTM C 173) is more appropriate for measuring air content. Considering the lower relative density and absorption of the CCA, there was concern whether the pressure method test (C 231) was appropriate. The air content measured by C 231 showed very close agreement with that calculated gravimetrically (ASTM C 138) over 25 mixtures. Further, aggregate correction factors of the CCA using the procedure in ASTM C 231 were very low at less than 0.40%. Therefore, it was concluded that 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 could be conducted, and if the results agree, then C 231 can continue to be used.

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. ASTM C 33 is also referenced in ASTM C 94 and AIA MasterSpec, which is the basis of specifications in most design firms. It is clear from the earlier discussions that ASTM C 33 permits the use of CCA. There should be no restriction to its use if the concrete meets the requirements of a project in most concrete applications. The design professional can choose 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 in the "as received" condition can be permitted for most applications to a limit of 10% by weight of the total aggregate. Engineers who are unsure can request additional data on service-record or test results that will do "no harm" to the concrete. In non-structural applications, provided the concrete producer does further processing, such as isolating the returned concrete >3,000 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.

The use of 20% of crushed coarse concrete aggregates in structural concrete is now a practice accepted by codes in many European countries. In light of that, for structural concrete applications, only the coarse CCA (cumulative material retained on the No. 4 sieve) should be allowed to be used at 10% by weight of total aggregate. The recommendation for structural concrete is therefore more conservative.

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.

Guidance to the Producer

A cost analysis was conducted to evaluate the economics of using CCA. Based on conservative cost assumptions and the measured 28-day strengths, the cost savings of the different CCA mixtures that would yield the same 28-day strength as the control mixture was calculated. Cost calculations suggest that the concrete producer can achieve considerable savings by using CCA from reduced use of virgin materials and reduced disposal costs. Assuming no specification restrictions, the producer can use CCA in the following incremental steps.

In the first step, the producer should limit his use of CCA to no more than 300 pounds/yard^3 (about 10% by weight of total aggregate) in "as received" condition. Negligible change in concrete performance is expected.

The second step is for the producer to separate CCA into different strength classes by diverting returned concrete to different areas at the plant. In this study, it was found that if CCA was made from returned concrete with a specified strength of 3,000 psi or higher, then it could be used at a level of 900 pounds/yard^3.

The third and 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 study, it was found that if CCA was made from returned concrete with a specified strength of 3,000 psi or higher and if the producer separated just the coarse fraction of the CCA, the producer could replace 100% of the virgin coarse aggregate, which corresponds to approximately 1,600 pounds/yard^3 of CCA.

In all three of the steps while discharging the concrete, the truck driver should take precautions in avoiding the use of water to clean the concrete truck at the location where the concrete is discharged. The cleaning of trucks should be at the washout pit.

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 basis. When high amounts of CCA are used, the producer should watch for slump-retention issues and conduct comparative measurement of air content by the pressure meter (C 231) and the volumetric method (C 173) and, if the results agree, use C 231. ■

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