

Internal Curing with Crushed Returned Concrete Aggregates for High Performance Concrete

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ABSTRACT

High performance concrete (HPC) requires a low water-to-cementitious materials mass ratio (w/cm), often with the inclusion of supplemental cementitious materials such as silica fume in the mixture, thus necessitating the use of a superplasticizer. Because of the low w/cm and rapid reaction at early ages, proper curing from the earliest time possible is very essential in HPC. Internal curing has been developed and demonstrated to substantially reduce autogenous shrinkage and minimize early-age cracking of HPC. In 1991, Philleo suggested this new concept of “water-entrained” concrete with the addition of saturated lightweight fine aggregates (LWAS) as a remedy to provide an internal source of water to offset the chemical shrinkage that occurs during hydration of the paste. This article explores the use of less expensive crushed returned concrete aggregate (CCA) as an internal curing material. In this investigation, CCAs in the 1000 psi (6.9 MPa), 3000 psi (20.7 MPa) and 5000 psi (34.5 MPa) strength range were prepared for evaluation as internal curing agents. The best performing CCA was then selected and further tested in combination with LWAS. Test results showed a significant reduction in net autogenous shrinkage (79 % and 70 % reduction of the control at the ages of 1 d and 56 d, respectively) found with the CCA/LWAS blended mixture, while the compressive strength reduction was negligible (6 % and 0 % reduction of the control at the ages of 28 d and 56 d, respectively).

Keywords: Building technology; crushed returned concrete aggregate; internal curing; lightweight aggregate; recycling; sustainability.

INTRODUCTION

It is estimated that every year between 2 % and 10 % of the 460 million cubic yards of ready-mixed concrete produced in the USA is returned to the concrete plant (Obla et al. 2007). The returned concrete is used in several ways, such as adding on top of fresh material, processing the returned concrete through a reclaimer system that separates ingredients for further usage, producing other products such as concrete blocks, or discharging the returned concrete at the concrete plant for later crushing and reuse as a subbase material in road construction or other applications. According to a report by the National Ready Mixed Concrete Association (Obla et al. 2007) the amount of crushed

material produced by the ready-mixed concrete industry is on the order of 30 million tons per year, with most of it currently being diverted to landfills. It is the authors' contention that recycling crushed returned concrete aggregate (CCA) is critical to a sustainable economy. The crushed returned concrete aggregate has useful aggregate properties because it is free of any contamination. Thus, CCA is distinguished from other recycled concrete aggregates that come out of existing structures with possibly high contamination from many years exposure during the structures' service lives.

CCA has potential as an internal curing agent due to its high absorption capacity and low cost. The practice of internal curing has been developed and demonstrated to substantially reduce autogenous shrinkage and minimize early-age cracking of high performance concrete (HPC). Philleo suggested the concept of "water-entrained" concrete (Philleo 1991), with the addition of saturated lightweight fine aggregates (LWAS) as a remedy that provides an internal source of water to offset the chemical shrinkage that occurs during hydration of the cementitious paste. However, LWAS may not always be cost effective, which brings attention to exploring CCA that can be more cost effective and yet may provide similar engineering properties, such as internal curing and strength. For this investigation, CCAs in the 1000 psi^A (6.9 MPa), 3000 psi (20.7 MPa), and 5000 psi (34.5 MPa) strength range were prepared for evaluation as internal curing agents. The best CCA for internal curing was selected and further tested in combination with LWAS.

EXPERIMENTAL

Materials Characterization

For this laboratory study, a blended cement containing about 20 % by mass ground granulated blast furnace slag was obtained from a cement manufacturer. The cement's chemical and physical characteristics are included in Table 1. The CCA was prepared at Virginia Concrete's Edsall plant.^B The concrete mixtures with target 28 day strengths of about 1000 psi (6.9 MPa), 3000 psi (20.7 MPa), and 5000 psi (34.5 MPa) were produced at the ready-mixed concrete plant with gray, red, and black pigments for identification purposes. All mixtures were non air-entrained Portland cement mixtures with no supplemental cementitious materials and containing only a small dosage of a Type A water reducer. The discharged concrete was left undisturbed for 110 days and then was crushed to make CCA. The grey CCA was made from the *1000 psi* concrete (hereafter called CCA-1000), the red CCA from *3000 psi* concrete (CCA-3000), and the black CCA from *5000 psi* concrete (CCA-5000). Subsequently, each CCA was separated into coarse and fine fractions using an ASTM C33 No. 4 (4.75 mm) sieve (ASTM International 2003). Then, the CCA fines were sampled and tested for their material characteristics according to relevant ASTM standards with the test results shown in

^A It is standard NIST practice to use SI units. Because the U.S. construction industry uses inch-lb units on a daily basis, inch-lb units are the primary units presented in this paper except where common practice dictates otherwise, with SI equivalents provided in parentheses.

^B Certain commercial products are identified in this paper to specify the materials used and procedures employed. In no case does such identification imply endorsement by the National Institute of Standards and Technology, nor does it indicate that the products are necessarily the best available for the purpose.

Tables 2 and 3. For the purposes of this study the high percentage of minus 200 (0.003 in or 0.075 mm) particles in the CCA fines were removed to avoid extra variances. It is observed that the CCA fines have a higher absorption capacity (relative to typical normal weight aggregates with absorptions in the range of 0 % to 2 % by mass) and a lower specific gravity as shown in Table 3, due to the mortar fraction that is combined with the virgin low absorption coarse aggregate.

Table 1. Characteristics and Compositions of Slag Blended Cement

Characteristic	
Blending agent	Slag (GGBFS*)
Mass fraction	20 %
Blended cement specific gravity	3.16 ± 0.01
CaO (mass basis)	58.8 %
SiO ₂	22.6 %
Al ₂ O ₃	5.8 %
Fe ₂ O ₃	2.4 %
MgO	4.5 %
SO ₃	2.7 %
Loss on ignition	1.5 %
Equivalent alkalies	0.6 %

* GGBFS = ground granulated blast furnace slag

Table 2. Measured Particle Size Distributions after Removing Minus 200 Sieve Fraction

Sieve no. (opening)	Percent passing			
	LWAS	CCA-1000	CCA-3000	CCA-5000
4 (4.75 mm)	98.6	99.6	99.1	97.0
8 (2.36 mm)	70.1	71.6	69.9	58.6
16 (1.18 mm)	44.7	58.3	55.0	42.8
30 (0.6 mm)	29.6	37.7	35.2	26.3
50 (0.3 mm)	20.4	5.5	11.7	9.4
100 (0.15 mm)	14.5	1.0	0.0	2.6
Pan	0.0	0.0	0.0	0.0

Table 3. Fine Aggregate Properties

Fine Aggregate	Normal weight sand	LWAS	CCA-1000	CCA-3000	CCA-5000
Specific Gravity (SSD)	2.61	1.80	2.15	2.23	2.15
Absorption (mass %)	Negligible	23.8	16.0	12.4	12.0
Minus 200 sieve (mass %)	0.57	Not meas.	7.31	9.50	7.64
Fineness Modulus	Not meas.	3.2	2.73	2.71	3.05

The LWAS, an expanded shale, was obtained from a lightweight aggregate manufacturer. It has a saturated-surface-dried (SSD) specific gravity of 1.80 and a total absorption capacity of 23.8 % by mass. The measured particle size distributions of all internal curing materials (after removing the minus 200 particles from the CCA materials) are provided in Table 2.

Internal Curing Agent Desorption Characteristics

A desorption isotherm indicates the moisture content of a material during drying from saturation down to 0 % RH. Desorption isotherms for the four internal curing agents (ICAs) were measured according to the general procedures provided in ASTM C1498 (ASTM International 2004), using saturated salt solutions (slurries) of potassium sulfate, potassium nitrate, and potassium chloride. The measured desorption isotherms shown in Figure 1 indicate that the CCA fines have a lower absorption capacity than the LWAS (also shown in Table 3), indicating that a higher volume fraction may be required to provide equivalent internal curing.

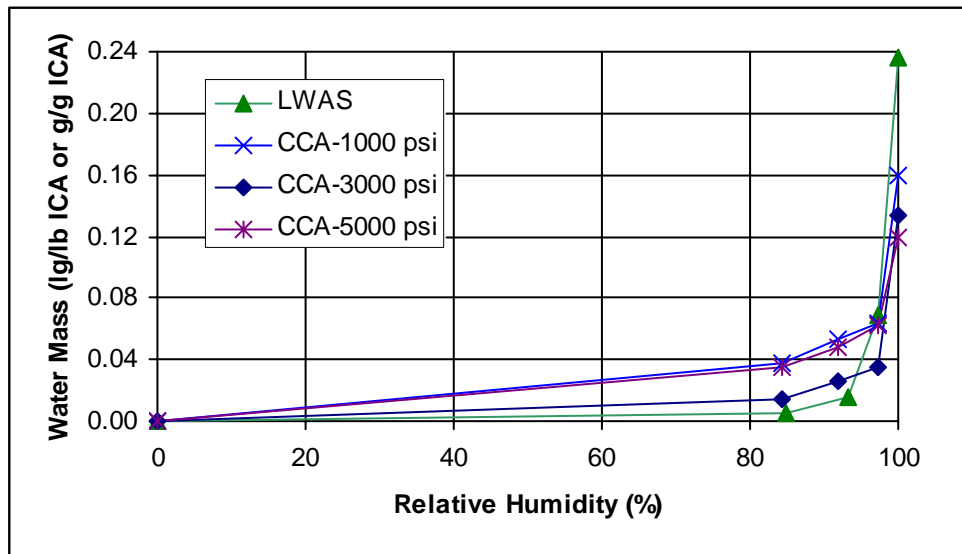
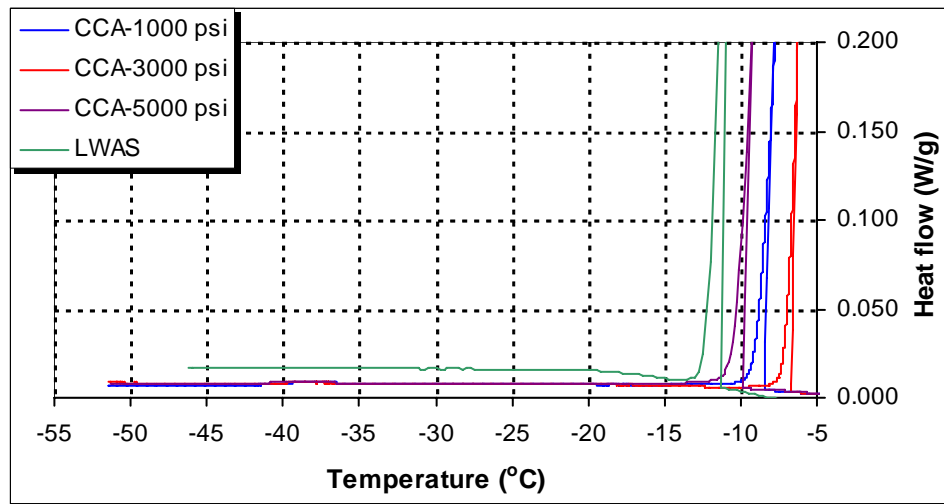


Figure 1. Desorption Isotherms for the CCAs and LWAS.

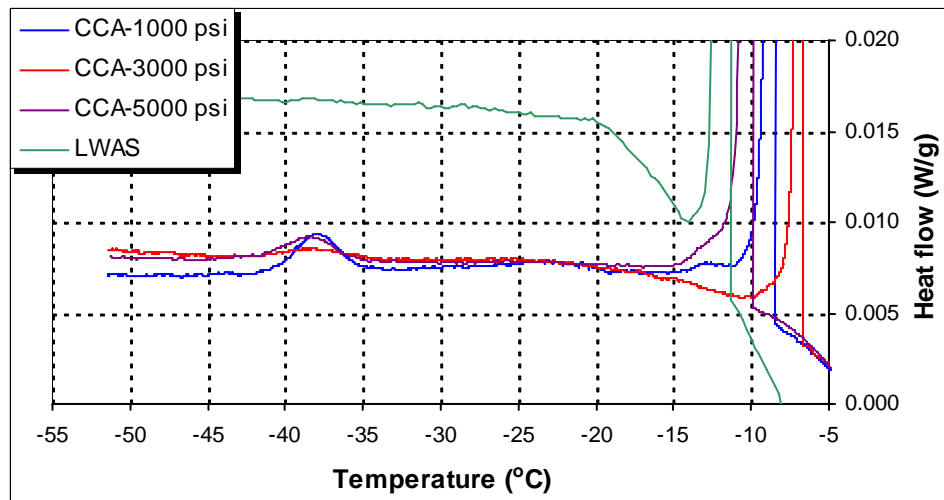
The maximum potential water available for internal curing is assumed to be that amount desorbed from saturated conditions down to an RH of about 93 % (Bentz et al. 2005). Not only does the LWAS have a higher total absorption capacity, it also releases a greater fraction of this total water during desorption to this RH. Some of the water in the CCA is contained in the hydrated cement paste portion of these fines and will not be desorbed until much lower RH values are achieved (typically around 50 % RH or less). Thus, the CCA fines retain a higher fraction of their water at 93 % RH, a potential detriment to their internal curing effectiveness. The desorption isotherms for the CCA-1000 and CCA-5000 are quite similar for RHs of 97% and lower, while that of the CCA-3000 material is significantly lower.

Low Temperature Calorimetry (LTC)

To examine the sizes of the pores in each internal curing agent, low temperature calorimetry (LTC) scans were conducted (Bentz 2007, Snyder and Bentz 2004, Bentz 2006). The LTC scans for the various raw materials are presented in Figure 2. Aggregate particles were first saturated in distilled water and then sampled to obtain an individual representative aggregate. The relevant aggregate (particle) was surface dried and placed in the differential scanning calorimeter (DSC) for the LTC scan. In the DSC, as the temperature is lowered, water freezes in pores with successively smaller and smaller entryway diameters. Thus, LTC is much like a mercury intrusion experiment, but doesn't require drying of the material (Snyder and Bentz 2004, Bentz 2006). The results in Figure 2(a) suggest that the various CCA fines have a slightly larger pore size than the LWAS as indicated by their higher freezing points. The results are rescaled in Figure 2(b)



(a)



(b)

Figure 2. Low Temperature Calorimetry Scans for the CCAs and LWAS.

Data is presented in SI units as they are the ones conventionally employed in DSC measurements.

For temperature conversion, $^{\circ}\text{F} = (1.8 ^{\circ}\text{C} + 32)$; for heat flow, $1 \text{ W/g} = 1548 \text{ BTU}/(\text{h}\cdot\text{lb})$.

to indicate that the hydrated cement paste present in the CCAs is detectable as producing a peak near -40 °C, as has been observed previously (Snyder and Bentz 2004, Bentz 2006) for hydrated cement paste specimens. Based on the size of this lower temperature peak, for the three CCA particles examined, the CCA-3000 appears to contain less hydrated paste than the other two materials. This could, however, just be a matter of sampling and variability amongst the individual CCA particles selected for LTC analysis.

Mixtures Proportions

Seven mortar mixtures were prepared, including a control mortar mixture with no internal curing agent, three mortar mixtures with the various CCA fine materials, a mortar mixture with a CCA/LWAS blend, and two mortar mixtures with LWAS alone, to examine the performance of these internal curing agents with respect to their influence on autogenous deformation and compressive strength. The sieve size distributions of each CCA and the LWAS were determined (see Table 2) so that a similar size distribution of the normal weight sand (a blend of four sands to achieve high performance) could be replaced. Mortars were proportioned with a constant volume of (blended) cement paste and a water-to-cementitious materials mass ratio (w/cm) of 0.3, and for the mortars with internal curing, generally, an extra 0.08 mass units of “free” water per mass unit of cementitious binder (w/cm basis, “free” water determined as that desorbed from SSD conditions down to 93 % RH for each internal curing agent) were added via the various individual internal curing agents (blends). Thus, different replacement levels (mass fractions) of LWAS and CCAs were required to provide equivalent quantities of additional “free” water in each respective mixture. Mortar mixture proportions and fresh air contents are summarized in Table 4. The CCA-1000 exhibited a significantly higher air content than the other six mixtures. The LWAS-2 mixture was formulated to contain the same LWAS content as the CCA/LWAS blend so that the contribution of the CCA to

Table 4. Mortar Mixture Proportions.

Material or Property	Control	LWAS-1	LWAS-2	CCA-1000	CCA-3000	CCA-5000	CCA-1000/ LWAS
	(g) ^A	(g)	(g) ^B	(g)	(g)	(g)	(g)
Blended cement	2000.0	2000.0	1000.0	2000.0	2000.0	2000.0	2000.0
Water	584.6	584.6	292.3	584.6	584.6	584.6	584.6
Type A admixture	25.6	25.6	12.8	25.6	25.6	25.6	25.6
F95 fine sand	950.0	696.1	379.8	569.8	625.0	466.6	664.6
Graded sand	722.0	613.2	320.2	341.8	356.3	238.6	545.4
20-30 sand	722.0	576.9	306.6	278.4	295.4	57.3	502.3
GS16 coarse sand	1406.0	704.9	440.1	497.7	491.8	16.2	653.1
SSD LWA	-	833.7	312.6	-	-	-	625.3
SSD CCA	-	-	-	1740.0	1735.8	2488.9	435.0
“Free” water in SSD LWA	-	160.0	60.0	-	-	-	120.0
“Free” water in SSD CCA	-	-	-	160.0	160.0	160.0	40.0
Fresh air content	3.1 %	2.9 %	4.2 %	6.6 %	4.0 %	4.4 %	5.0 %

^AMasses are reported in grams as these were the units employed in preparing the mortar mixtures. For mass conversion, 1 g = 0.0022 lb.

^BNote that the mixture size for LWAS-2 mortar is only 50 % of that of the other mixtures due to blended cement supply limitations.

the blend's properties could be more fairly evaluated.

Measurements

Mortar cubes were prepared according to ASTM C109 procedures (ASTM International 2007) and cured under sealed conditions; corrugated tube autogenous deformation specimens were also prepared for evaluation using the equipment developed by Jensen and Hansen (Jensen and Hansen 1995). Curing and autogenous deformation measurements were conducted at 77 °F (25 °C). The procedure is currently being standardized in ASTM subcommittee C09.68; in the draft standard, the single laboratory precision is listed as 30 microstrains for mortar specimens.

RESULTS AND DISCUSSION

Compressive Strength Results

The mortar cube compressive strengths for the CCA-1000, CCA-3000, and CCA-5000 mixtures are about 63 %, 81 %, and 65 %, respectively of the control mortar strength at an age of 28 d, whereas the strengths for the LWAS-1, LWAS-2, and CCA/LWAS mixtures are 109 %, 116 %, and 94 %, respectively of the control mortar strength at an age of 28 d, as shown in Table 5. Similar trends of the strength gain for all mortar mixtures are observed at 56 d as shown in Figure 3. Three factors are likely contributing to the reduced strengths in the CCA mortars. First, the replacement of sand by low strength CCA fines should naturally produce a strength reduction. Second, during mixing, by contrasting the flow/workability/bleeding characteristics of the seven mixtures, it was apparent that a portion of the water contained in the CCA particles was readily released into the mortar mixture, effectively increasing its true w/cm , which will also result in a strength reduction. Third, the generally higher air content in the CCA mortar mixtures will further reduce the strength.

It is also noted that the strength of the CCA-3000 mixture was superior to that of the CCA-1000 and CCA-5000 mixtures. The similarity of the CCA-1000 and CCA-5000 mixtures with respect to strength may seem surprising given the inherent large strength difference between the two raw materials, but one must keep in mind that to potentially supply the same quantity of internal curing water (desorption from SSD down to 93 % RH), a much larger volumetric substitution of the CCA-5000 was necessary due to its lower desorption capacity, as indicated in Figure 1 and Table 4. Thus, the higher inherent strength of the CCA-5000 aggregate was offset by its larger volumetric content in the mortar, ultimately producing lower compressive strengths.

Autogenous Deformation Results

Autogenous deformation results are presented in Figure 4. As shown in the figure, the autogenous shrinkage of the control mortar observed during 56 days is almost eliminated by the addition of the larger quantity of LWAS-1 and reduced significantly by the CCA/LWAS blend, while some minor improvements are observed with the CCA-1000 and CCA-5000 mixtures. Because it provided a similar reduction in autogenous shrinkage to the CCA-5000 material, but at a lower replacement level (Table 4), the CCA-1000 material was selected for preparing the CCA/LWAS blend. In

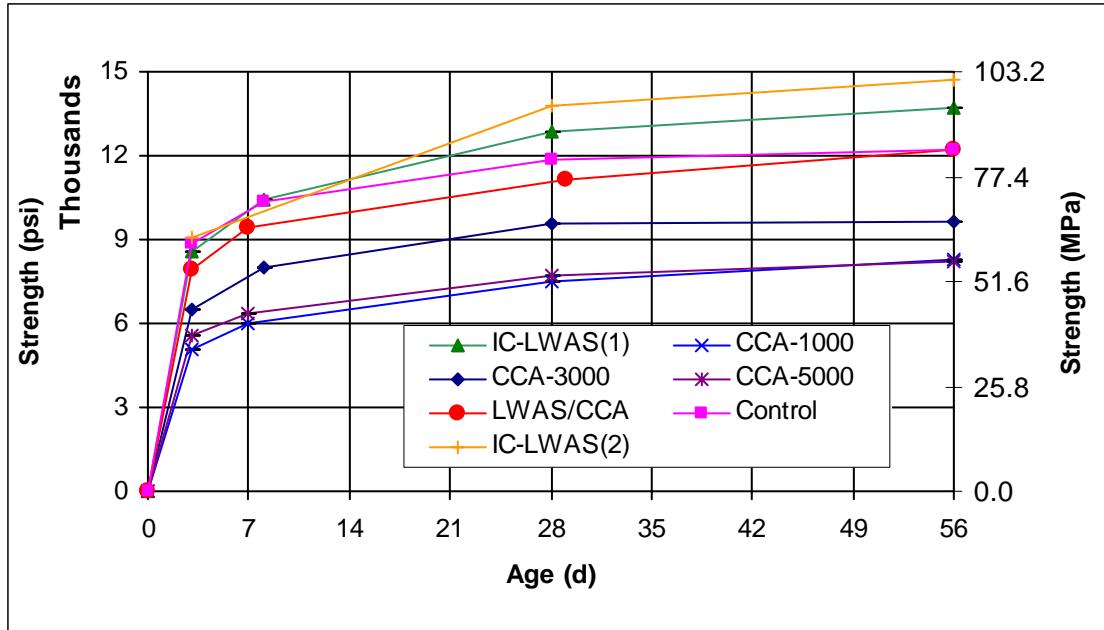


Figure 3. Compressive Strength Results for the 7 Mortar Mixtures

Table 5. Compressive Strength Results

	Control	LWAS-1	LWAS-2	CCA-1000	CCA-3000	CCA-5000	CCA-1000/LWAS
	(psi)	(psi)	(psi) ^A	(psi)	(psi)	(psi)	(psi)
3 d	8,830 (125) ^B 60.9 MPa	8,580 (602) 59.2 MPa	9,070 (27) 62.5 MPa	5,110 (35) 35.2 MPa	6,500 (90) 44.8 MPa	5,570 (44) 38.4 MPa	7,910 (271) 54.5 MPa
7 d	---	---	---	6,030 (131) 41.6 MPa	---	6,370 (259) 43.9 MPa	9,390 (151) 64.8 MPa
8 d	10,380 (285) 71.5 MPa	10,400 (327) 71.7 MPa	---	---	7,970 (88) 55.0 MPa	---	---
28 d	11,860 (458) 81.8 MPa	12,870 (566) 88.8 MPa	13,790 (464) 95.0 MPa	7,490 (136) 51.6 MPa	9,600 (442) 66.2 MPa	7,730 (82) 53.3 MPa	11,110 (281) 76.6 MPa
56 d	12,230 (820) 84.3 MPa	13,730 (148) 94.7 MPa	14,660 (57) 101.4 MPa	8,280 (123) 57.1 MPa	9,640 (924) 66.5 MPa	8,230 (454) 56.8 MPa	12,230 (1160) 84.3 MPa
28 d, % control	100	109	116	63	81	65	94
56 d, % control	100	112	120	68	79	67	100

^AFor LWAS-2 mixture, two cubes tested at each of 3 ages, due to cement supply limitations.

^BStandard deviation in testing three (or two) cubes at each age.

contrast to the other two CCA mixtures, the CCA-3000 material basically produced an autogenous deformation response that was quite similar to that of the control mortar.

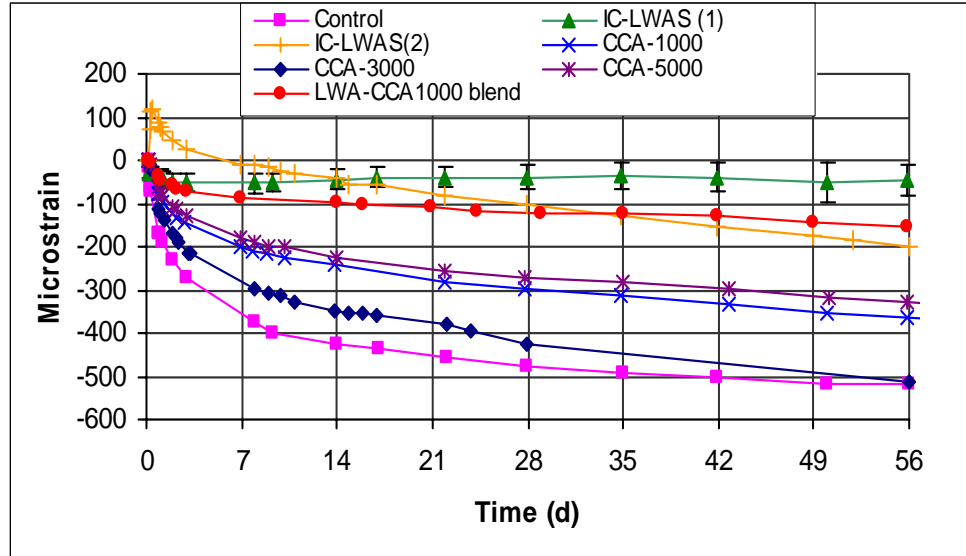


Figure 4. Autogenous Deformation Results for the 7 Mortar Mixtures.

A typical standard deviation between three specimens is illustrated by the error bars on the IC-LWAS(1) curve.

Table 6. Autogenous Deformation Results

	Control	LWAS-1	LWAS-2	CCA-1000	CCA-3000	CCA-5000	CCA/LWAS
Net Autogenous Shrinkage ($\epsilon_{\min} - \epsilon_{\max}$) (Microstrain)							
1 d	-167	-37	-41	-79	-122	-69	-35
8 d	-376	-53	-131	-209	-297	-189	-89
28 d	-476	-39	-220	-298	-425	-274	-121
56 d	-519	-45	-318	-363	-511	-329	-153
1 d reduction, % of control	-	77.8 %	75.4 %	52.7 %	27.0 %	58.7 %	79.0 %
8 d reduction, % of control	-	85.9 %	65.2 %	44.4 %	21.0 %	49.7 %	76.3 %
56 d reduction, % of control	-	91.3 %	38.8 %	30.1 %	1.5 %	36.6 %	70.5 %

As summarized in Table 6, for the first day, the net autogenous shrinkage reductions for the CCA-1000, CCA-3000, CCA-5000, LWAS-1, LWAS-2, and CCA/LWAS blend each relative to the control were 52.7 %, 27 %, 58.7 %, 77.8 %, 75.4 %, and 79.0 %, respectively, whereas the corresponding net autogenous shrinkage reductions after 8 d were 44.4 %, 21.0 %, 49.7 %, 85.9 %, 65.2 %, and 76.3 %, respectively. In Table 6, for each mortar mixture, net autogenous shrinkage has been computed as the difference between the initial maximum (measured expansion value or zero when immediate shrinkage is observed) and the minimum (deformation value) achieved up to the specific age being evaluated, ($\epsilon_{\min} - \epsilon_{\max}$), according to the approach recently advocated by Cusson (Cusson 2008). Autogenous shrinkage reductions have then been computed relative to the measured net autogenous shrinkage of the control mortar. Clearly, the autogenous shrinkage reduction is most effective when using the LWAS or the CCA/LWAS blend as the internal curing agents. Cusson has further hypothesized that shrinkage reduction effectiveness (at 7 d) should be proportional to the volume of additional internal curing water provided by the mixture (Cusson 2008). This theory can be examined using the two mixtures with LWAS investigated in this study.

Specifically, one finds that the measured 8 d effectiveness for the LWAS-2 mortar of 65.2 % compares quite favorably with that predicted from the measured effectiveness of the LWAS-1 mortar $(85.9 \%) \cdot (0.06/0.08) = 64.4 \%$, where 0.06 and 0.08 represent the fractional free internal curing water contents of the LWAS-2 and LWAS-1 mixtures (grams of water per gram of cement), respectively. For a later age of 56 d, however, the measured effectiveness of 38.8 % for the LWAS-2 mortar is significantly less than that of $(91.3 \%) \cdot (0.06/0.08) = 68.5 \%$ predicted by the theory, as beyond 8 d, the LWAS-2 mortar is apparently providing little if any further internal curing water to prevent autogenous deformation. This is well illustrated by the measured autogenous deformation for the LWAS-2 mortar of -187 microstrains that is produced between 8 d and 56 d, as compared to a shrinkage of -143 microstrains produced by the control mortar and an expansion of 8 microstrains produced by the LWAS-1 mortar during the same time period.

Another indication of the effectiveness of the various internal curing agents investigated in this study is provided by examining the trends in their shrinkage reduction vs. time, as provided in Table 6. While this value decreases dramatically from 1 d to 56 d for all three of the CCA internal curing agents when used by themselves (indicating a decreasing supply of the needed internal curing water), for the LWAS-1 mortar, it is seen to consistently increase from 1 d through 8 d to 56 d, suggesting that at this higher addition level of 0.08 mass units of internal curing water per mass unit of cement, the LWAS is continuously providing needed curing water throughout the first 56 d of sealed curing. As the cement paste hydrates, the sizes of its water-filled capillary pores are continuously reduced, increasing the “suction” potential that is pulling the internal curing water from the LWA sand and perhaps contributing to the increased effectiveness at later ages. For the LWAS-2 mortar with only 0.06 units of internal curing water, the shrinkage reduction value decreases after 1 d, suggesting that much of the needed supply of internal curing water has been depleted by 8 d. For the CCA/LWAS mortar, this decrease, while present, is not as dramatic, suggesting that at least some part of the additional water present in the CCA portion of the blend is contributing to effective internal curing at later ages. Of course, the fact that the effectiveness of the CCA/LWAS blend at later ages is significantly less than that of the LWAS-1, with an identical “free” water addition, indicates that a significant fraction of the “free” water in the CCA is not functioning effectively for internal curing.

To summarize, while the CCA fines have a relatively large absorption capacity (Table 3), it appears that much of their “free water” is not available as internal curing water. As mentioned earlier, some of their water is easily released during mixing and likely only serves to increase the w/cm of the mixture. Another portion of it is contained in the very small pores of the hydrated cement paste portions of the CCA particles (see LTC scans in Figure 2) and will not be released at $RH > 90 \%$, as is necessary for internal curing. The remainder, however, is available for internal curing and contributes to the limited reductions in autogenous shrinkage for the three CCA mortars, as observed in Figure 4 and Table 6, and also to the reduction achieved by the CCA/LWAS mortar relative to that of the LWAS-2 mortar.

The results presented here indicate that the optimum utilization of CCA fines will likely occur in a blend with a high performance LWAS. Because the CCA fines have a detrimental influence on strength and provide a reduced effectiveness for internal curing, such blends will likely consist of a minority of the CCA material (i.e., less than 50 %) blended with a majority of LWAS (> 50 %). Trial mixtures will be required to optimize the blending and performance for each specific concrete mixture and to verify adequate performance with respect to other properties (Obla et al. 2007). Even so, when considering the cost of CCA relative to LWAS, the potential cost savings for these mixtures are significant and the utilization of the CCA fines in new concrete can provide a sustainable solution to the problems associated with their conventional disposal (in landfills, etc.).

CONCLUSIONS

Utilization of crushed recycled concrete aggregates as internal curing agents results in a limited reduction in autogenous shrinkage of high performance mortar mixtures while reducing mortar cube compressive strengths. By blending the CCA with an appropriate lightweight aggregate sand, a substantial reduction in autogenous shrinkage will be achieved, with minimal reduction in long term compressive strength. The mortars based on LWAS substitutions alone provided the highest compressive strengths and the greatest reductions in autogenous shrinkage. But, blending the CCA with the LWAS may provide the optimum mixture in terms of material costs and sustainable development.

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