Internal Curing

Improves Concrete Performance throughout its Life

By Ryan Henkensiefken, Javier Castro, Haejin Kim, Dale Bentz, and Jason Weiss

Introduction

In recent years, the technology of internal curing has been steadily progressing from laboratory studies to field application. Prominent examples of field applications include a railway transit yard in Texas [1], Texas state highway 121 [2], and bridge decks in Ohio [3] and New York. A winter 2006 *Concrete InFocus* article focused on enhancing high performance concrete through internal curing [4]. More recent studies at Purdue University [5-8] and the National Institute of Standards and Technology (NIST) [9, 10] have indicated that internal curing with pre-wetted fine lightweight aggregates positively impacts a variety of aspects of concrete performance from its fresh state throughout its life cycle, from cradle to grave. Results from these studies are summarized in this paper.

Background

When Philleo originally suggested the concept of internal curing using pre-wetted fine lightweight aggregates (LWA), his goal was to provide a means for supplying adequate curing water to the interior of high strength concrete members [11]. Without a supply of extra curing water, these mixtures at a low water-to-cementitious materials ratio (*w/cm*) will self-desiccate (i.e., run out of the water necessary for hydration), resulting in a reduction in the amount of cement that hydrates and the creation of water-vapor-filled capillary pores that results in a measurable autogenous shrinkage that may contribute to early-age cracking. For this reason, the reduction in autogenous deformation produced by internal curing was initially the major focus of research in this field [12, 13]. Internal curing provides a set of water-filled reservoirs within the concrete that supply water on demand to the hydrating cement paste from the time of mixing (i.e., for reducing plastic shrinkage and maintaining workability) until the time when moisture equilibrium is achieved between the reservoirs and the surrounding cement paste (i.e., for reducing autogenous and drying shrinkage) [14]. The individual pores in the pre-wetted LWA are typically much larger than those in a hydrating cement paste. Thus, when pores in the LWA do empty during internal curing, the self-desiccation stresses created in the process are orders of magnitude less then those exhibited in comparable concretes without internal curing. In this way, internal curing offers the possibility of effectively eliminating autogenous shrinkage and avoiding early-age cracking [6, 9, 15]. Autogenous shrinkage is one component of the overall volume change in concrete and increases in magnitude when *w/cm* is reduced.

From a practical standpoint, one question a ready mix concrete producer must address is how much pre-wetted fine LWA is necessary to provide internal curing for a specific concrete mixture. This topic was addressed in detail in a 2005 article in *Concrete International* [16], where an equation for mixture proportioning was determined by balancing the water supplied by the pre-wetted LWA with that demanded by the hydrating cement paste in the specific concrete mixture. The equation for a concrete based on an ordinary portland cement (OPC) is given by:

$$M_{LWA} = \frac{C_f * CS * \alpha_{max}}{S * \phi_{LWA}} \qquad (1)$$

where: M_{LWA} = mass of (dry) LWA needed per unit volume of concrete (kg/m^3 or lb/yd^3),
C_f = cement factor (binder content) for concrete mixture (kg/m^3 or lb/yd^3),
CS = chemical shrinkage of cement (g of water/g of cement or lb/lb),
αmax = maximum expected degree of hydration of cement,
S = degree of saturation of LWA (0-1), and
ϕLWA = absorption (desorption) capacity of LWA (kg water/kg dry LWA or lb/lb).

For an OPC concrete, typical coefficients for chemical shrinkage (*CS*) are in the range of 0.06 to 0.08 at room temperature. For *w/c* below 0.36, the maximum expected degree of hydration of the cement under saturated conditions (a_{max}) can be estimated as ((*w/c*)/0.36) and should not vary significantly with curing temperature. For *w/c* higher than 0.36, the maximum expected degree of hydration can be estimated as 1[16]. This equation has also been converted into a nomograph, available for downloading at http://concrete.nist.gov/ICnomographEnglishunits.pdf for English units or http://concrete.nist.gov/ICnomographSIunits.pdf for SI units.

Table 1. Mortar Mixture Proportions for NIST/NRMCA study [8]

Material or Property	*Control (g)*[A]	*LWA-1 (g)*	*LWA-2 (g)*[B]	*CCA-1000 (g)*	*CCA-3000 (g)*	*CCA-5000 (g)*	*CCA-1000 / LWA (g)*
Blended cement (20 % slag)	2000	2000	1000	2000	2000	2000	2000
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	696.1	379.8	569.8	625.0	466.6	664.6
Graded sand	722	613.2	320.2	341.8	356.3	238.6	545.4
20-30 sand	722	576.9	306.6	278.4	295.4	57.3	502.3
GS16 coarse sand	1406	704.9	440.1	497.7	491.8	16.2	653.1
w LWA	-	833.7	312.6	-	-	-	625.3
SSD CCA	-	-	-	1740.0	1735.8	2488.9	435
"Free" water in SSD LWA	-	160	60	-	-	-	120
"Free" water in SSD CCA	-	-	-	160	160	160	40
Fresh air content (from cup mass)	3.1 %	2.9 %	4.2 %	6.6 %	4.0 %	4.4 %	5.0 %

[A] Masses are reported in grams as these were the units employed in preparing the mortar mixtures.

[B] Note that the mixture size for LWA-2 mortar is only 50% of the other mixtures.

It is important to note that in addition to determining the necessary volume of LWA, this LWA should be well distributed throughout the concrete. As a result, fine LWA is generally preferred to coarse LWA since it will have a smaller distance between the aggregates and will therefore provide the beneficial effects of internal curing water to a greater volume of paste [11].

This paper presents results from several recent studies that demonstrate that in addition to reducing autogenous shrinkage, several other properties of concrete are beneficially impacted via internal curing. The first part of the paper summarizes a study that compares crushed returned concrete fines to LWA; the second part focuses on the influence of LWA replacement volume.

Comparing Crushed Returned Concrete Fines and Lightweight Aggregate

The first study considered the blending of crushed returned concrete fine aggregates (CCA) with fine LWA as a sustainable approach to produce mortars with reduced autogenous deformation, but equivalent strength [9]. In this joint NIST/National Ready Mixed Concrete Association (NRMCA) study, pre-wetted fine CCA * (passing a 4.75 mm sieve) with three strength levels (nominally 1000 psi, 3000 psi and 5000 psi at 28 d) were investigated as replacements for a portion of the normal weight sand in high performance mortars with a *w/cm* of 0.3 [9], utilizing the mixture proportions provided in Table 1. Aggregate characteristics are summarized in Tables 2 and 3. For this study, the high percentage of minus 200 (0.003 in or 0.075 mm) particles in the CCA fines was removed to avoid extra variances. In Table 1, "free" water was determined as that quantity of water desorbed from saturated surface-dry (SSD) conditions down to 93% RH for each internal curing agent.

Autogenous Shrinkage and Strength

Autogenous shrinkage was assessed from time of set using the corrugated tube protocol as developed by Jensen and Hansen [17]. While some reduction in measured autogenous deformation (Figure 1 and Table 4) was produced with the CCA alone as a replacement material, substantially lower mortar cube compressive strengths were also measured, as summarized in Table 5. In contrast, mixtures with a pre-wetted LWA as the replacement material exhibited a substantial reduction in autogenous shrinkage and a 10% to 20% strength increase at ages of 28 d and 56 d. However, a more economical and sustainable solution may be provided by

Table 2. Measured Particle Size Distributions after Removing Minus 200 Sieve Fraction [8]

Sieve no. (opening)	*Percent passing*			
	LWA	**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 [8]

Fine Aggregate	*Normal weight sand*	*LWA*	*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

a blend of the two materials, as exemplified by the results for the LWA-CCA 1000 blend in Tables 4 and 5. This mortar contained a blend of 43 % CCA 1000 and 57 % LWA by (dry) mass to provide the necessary internal curing water. It greatly reduced both early age and longterm autogenous shrinkage, while producing an equivalent 56 d cube strength as the control mortar with no internal curing. To ensure that the CCA 1000 material in the blend was contributing to the longterm autogenous shrinkage reduction, the LWA-2 mixture was formulated to contain the same LWA content as the CCA-1000/LWA blend. The results in Table 4 confirm that the CCA-LWA blend has a greater reduction in longterm autogenous shrinkage than the LWA-2 mixture containing an equivalent quantity of only LWA.

The Influence of LWA Replacement Level

This portion of the paper discusses a series of tests that were performed using pre-

Table 4. Autogenous Deformation Results for Mortar Mixtures [9]

	Control	*LWA-1*	*LWA-2*	*CCA-1000*	*CCA-3000*	*CCA-5000*	*CCA-1000 / LWA*
	Net Autogenous Shrinkage[A] (εmin - εmax) (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	-	78 %	75 %	53 %	27 %	59 %	79 %
8 d reduction, % of control	-	86 %	65 %	44 %	21 %	50 %	76 %
56 d reduction, % of control	-	91 %	39 %	30 %	2 %	37 %	71 %

[A] Net autogenous shrinkage has been computed as the difference between the initial maximum and the minimum deformation values achieved up to the specific age being evaluated [9, 13].

Table 5. Compressive Strength Results for Mortar Cubes Cured under Sealed Conditions [9]

	Control (psi)	*LWA-1 (psi)*	*LWA-2 (psi)*[A]	*CCA-1000 (psi)*	*CCA-3000 (psi)*	*CCA-5000 (psi)*	*CCA-1000/ LWA (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	7,91W0 (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

[A] For LWA-2 mixture, two cubes tested at each of 3 ages.

[B] Standard deviation in units of psi for testing three (or two) cubes at each age.

Table 6. Mixture Proportions for Mortars with Various Levels of LWA Replacement [5]

Material	**Mix ID (as volume fraction of LWA)**								
	0 %	3.8 %	7.3 %	11 %	14.3 %	18.3 %	23.7 %	29.3 %	33 %
Cement (kg/m^3)	728	728	728	728	728	728	728	728	728
Water (kg/m^3)	218	218	218	218	218	218	218	218	218
Fine Aggregate (kg/m^3)	1418	1319	1230	1135	1050	950	808	667	567
Dry LWA (kg/m^3)	0	60	114	172	223	283	369	455	525
Water (absorbed) provided by LWA (kg/m^3)	0	6	12	18	23	30	39	48	54

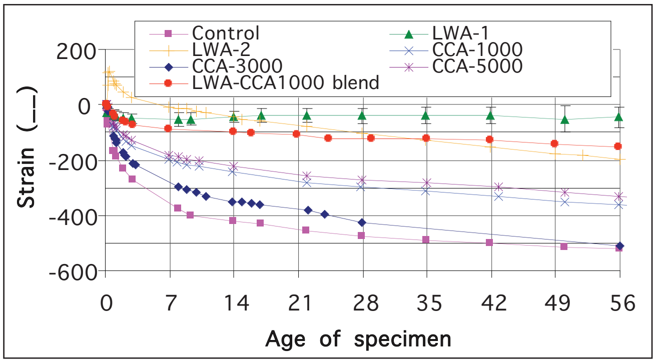


Figure 1. Autogenous deformation in microstrain ($\mu\varepsilon$) results for mortar mixtures with and without internal curing using various LWA/CCA blends. A typical standard deviation between three specimens is illustrated by the error bars on the LWA-1 data points [9].

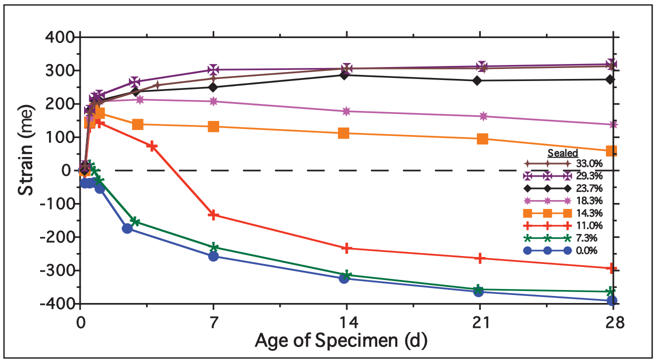


Figure 2. Autogenous shrinkage results of control and LWA mortar mixtures in sealed curing conditions at (23 ± 1) °C. The measured values shown are the average of three samples with a typical standard deviation of 20 με [6].

wetted lightweight fine aggregates with various LWA replacement levels [5, 6]. Mortars were prepared with a constant paste volume (paste volume = 45 %, aggregate volume = 55 %) and a water-to-cement ratio (*w/c*) of 0.3 using the mixture proportions provided in Table 6. An expanded shale lightweight aggregate was used as the LWA with a measured 24 h absorption of 10.5% by dry mass. The mixture labels used in this paper describe the total volume of the mortar that is composed of LWA. As such, the 0% mixture contains no LWA while the 23.7% mixture consists of 23.7% of the total volume of the mixture being lightweight aggregate (23.7 % LWA + 31.3% Sand = 55% aggregate by total volume). The 23.7% volume replacement corresponds to the amount of LWA necessary to eliminate self-desiccation as proposed in equation 1.

Sealed (Autogenous) Shrinkage

For this study, autogenous shrinkage was assessed using the corrugated tube protocol of Jensen and Hansen [17] for measurements during the first day and using ASTM C157-04 prisms (75 mm by 75 mm by 285 mm) sealed with aluminum tape after that. Since higher replacement levels of LWA result in the supply of more internal curing water, the measured autogenous shrinkage varies with the LWA replacement level. Figure 2 was obtained for the *w/c* = 0.3 mortars with volume fractions of pre-wetted LWA varying from 0% to 33% [6]. A few observations can be drawn from Figure 2. First, the addition of water-filled lightweight aggregate produced an expansion at early ages which can be very beneficial in reducing the potential for cracking. Second, the replacement level predicted by equation (1) (23.7%) produced a mortar with very little if any autogenous shrinkage at 28 d, instead exhibiting a net expansion of about 250 με. Replacement levels below that recommended by equation (1) reduce (or eliminate) autogenous shrinkage at early ages but they do not provide sufficient extra water to maintain saturation of the hydrating cement paste and reduce shrinkage in the longer term (beyond a few days). Replacement levels higher than that recommended by equation (1) also eliminated the longterm autogenous shrinkage as they supplied extra water in excess of that needed to maintain a saturated cement paste. But, as will be shown in the following section, this additional water can ameliorate the drying shrinkage performance of these mortars.

Unsealed (Drying + Autogenous) Shrinkage

Unsealed ASTM C157-04 prism specimens experience both the consumption of water by the hydration process (i.e., self-desiccation) and the loss of water to the surroundings (i.e., drying). Both of these effects will add together to cause shrinkage. Figure 3 shows the total length change for specimens that were exposed to drying after 24 h (the sealed measurements of autogenous shrinkage were used prior to this time). The control mixture shows the greatest shrinkage during the first 28 d while the samples with the largest amount of LWA addition show a slight expansion. It is interesting to note that the mixtures containing 7.3% and 11.0% LWA shrink rapidly after the initial expansion and 'catch up to' the shrinkage of the control mixture. This occurs since the water in the LWA is lost to environmental drying, as verified by mass loss measurements [5]. It can be noticed that in this case, the mixtures with the higher volumes of LWA (23.7% and 29.3%) show some shrinkage after the first few days, unlike for the comparable sealed specimens.

The specimen with the largest volume of LWA (33%) shows very little shrinkage until 3 weeks. This confirms that when the LWA provides more curing water than is needed to counteract the effects of self-desiccation, this additional water can be effectively used to replenish any water that is lost from the cement paste due to drying.

The shrinkages of the mixtures for the sealed and unsealed conditions are compared in Figure 4a at 7 d. It can be observed that in all cases the unsealed specimens (drying and autogenous shrinkage) exhibit more shrinkage than the sealed specimens (autogenous shrinkage only). It is also interesting to note that the effect of drying results in an additional 160 for nearly all the mixtures with LWA replacement levels below the critical level of 23.7%.

In addition to measuring unrestrained length change, the potential for cracking was assessed in each of these mixtures using the restrained ring test (ASTM C1581). This test consists of casting the concrete around a stiff steel ring. Sealed specimens were obtained once again using aluminum tape on the top and circumferential surfaces. The unsealed ring specimens were exposed to 50% relative humidity at 24 h and were sealed on the top surface with aluminum tape to limit moisture loss to the outer circumference only (the bottom surface was sealed by the ring's base support). As the concrete shrinks, the steel resists this shrinkage, resulting in the development of tensile residual stresses which, if high enough, can result in cracking. From Figure 4b it can be noticed that the control

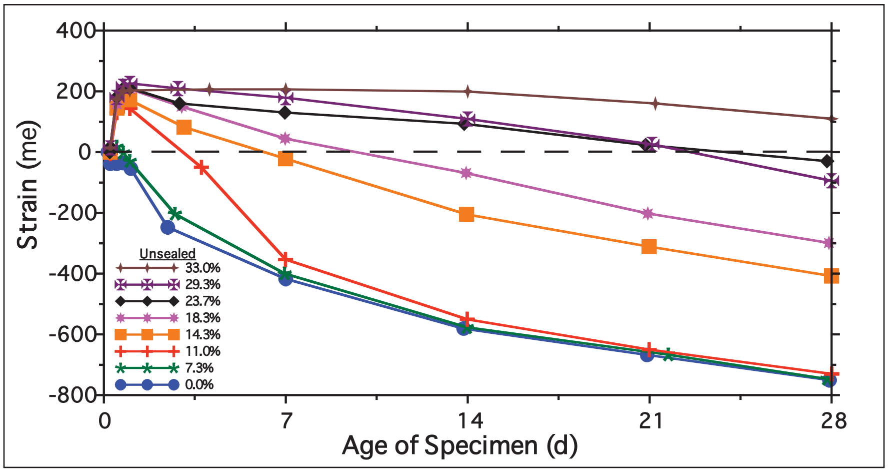


Figure 3. Shrinkage results of control and LWA mortar mixtures in unsealed curing conditions at (23 ± 1) °C, (50 ± 2) % RH [6].

mixture cracks at the earliest age. This can be explained by the fact that this mixture has the highest measured shrinkage (and likely the highest modulus of elasticity). The mixtures with low volumes of LWA do not show much improvement. This is because the water depleted during the first days due to self-desiccation combined with rapid water loss due to evaporation results in similar measured shrinkage. When a larger replacement volume of water-filled LWA was used (23.7 %), the time to cracking was delayed or cracking was completely prevented. These results indicate that, even under these harsh conditions (rapid drying and a high level of restraint), the potential for cracking can be greatly reduced if a sufficient volume of water-filled LWA is employed.

Plastic Shrinkage

In addition to its susceptibility to cracking at later ages, concrete can be susceptible to cracking around the time of placement, if the evaporation rate is high [1]. While these cracks are not generally a cause for concern in terms of the load the structure can carry, they can be unsightly and can lead to the ingress of aggressive agents that accelerate the corrosion of reinforcing steel. To evaluate their potential for plastic shrinkage cracking, samples were tested following ASTM C1579 "Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)". In addition, tests were performed to measure the settlement and evaporative weight loss from the concrete [5, 8].

Figure 5 shows the crack width distribution that was obtained for *w/c* = 0.55 concretes (average of three panels) made with different volume replacements of LWA (exposure conditions of 32 °C ± 1 °C, 25 % RH ± 3 % RH, and 15 km/h wind speed). The plastic shrinkage tests were performed on concrete mixtures with 30% by volume coarse aggregate, and 30% by volume of a mixture of normal weight fine aggregate and LWA. The examined volume fractions of LWA in these mixtures of fine aggregates for the concretes remained the same as the volume fractions of LWA from the previous study of mortars. Because the coarse aggregate was added to the system, the percentage of LWA in the total system changes, thus the naming convention for these mixtures changes. The 18.0% (percentage of concrete volume) LWA now represents the volume of LWA needed to eliminate autogenous shrinkage from equation 1. The control mixture (0.0 % LWA) shows the earliest cracking and the largest crack widths while the potential for plastic shrinkage cracking and crack widths decrease as the LWA replacement volume increases. When a sufficient volume of LWA is used (18 %), plastic shrinkage cracking was eliminated for the environmental conditions tested in this study.

It is hypothesized that plastic shrinkage cracking is reduced with internal curing as water in the LWA replenishes water lost due to evaporation as shown in Figure 6. Immediately after placement, the system is in a fluid state and the aggregate and cement particles tend to settle due to gravity forcing pore fluid (water) to the surface. This is commonly observed in practice as bleed water. During this initial period, the thin layer of bleed water covers the surface of the concrete and the water evaporates from the surface at a relatively constant rate (provided the environmental exposure conditions are constant). As a result, this is commonly referred to as the constant rate period of drying [18]. During this time, the system continues to consolidate in the vertical direction resulting in settlement of the surface.

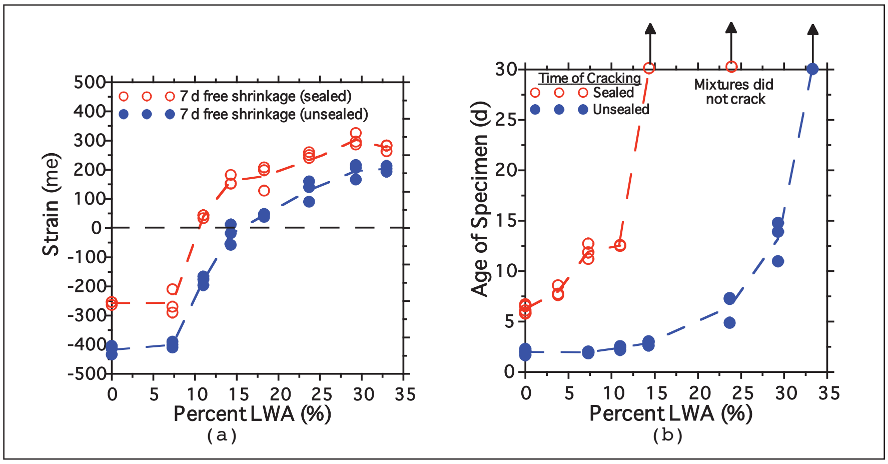


Figure 4. Comparison of control and LWA mortar mixtures for: a) unrestrained length change at 7 d under sealed and unsealed curing conditions at (23 ± 1) °C, (50 ± 2) % RH, and b) the measured age of cracking [6].

After some time, the rate of settlement dramatically reduces as the particles begin to come in contact with one another. Assuming that the rate of evaporation is relatively high, the layer of bleed water will be lost from the surface. When the water available to evaporate decreases, a slower rate of evaporation is observed, which is referred to as the falling rate period [18]. During the falling rate period, evaporation draws water from between the particles, resulting in the development of a capillary stress in the

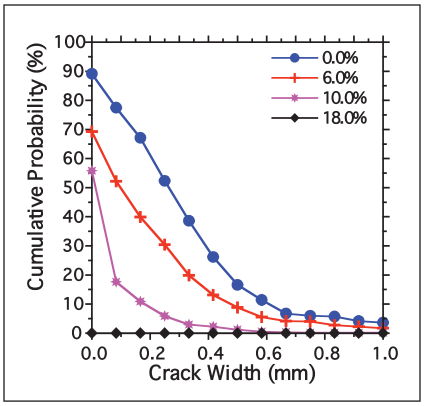


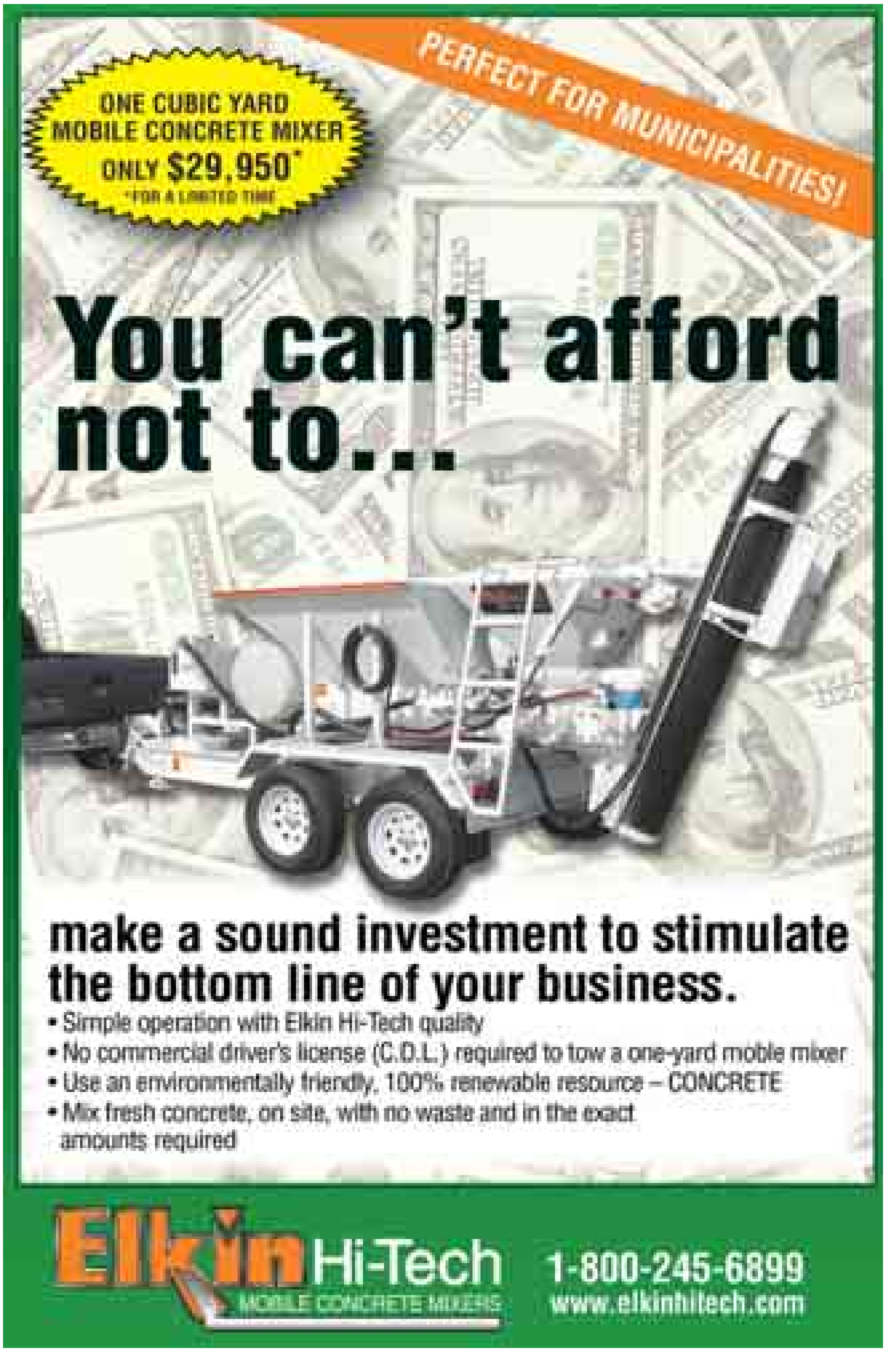
Figure 5 – Cumulative distribution of crack width occurrences in concrete with different replacement volumes of LWA [5, 8].

system that produces further consolidation and may lead to cracking. In the conventional control concrete system, the stresses will rise relatively dramatically during this period, however in the system with internal curing, water is instead first provided by the pre-wetted LWA to supply the water evaporating from the surface of the concrete. This helps to keep the capillary stress low during the falling rate period. The supply of water from the lightweight aggregate reduces the capillary stress in the system, resulting in less consolidation and a dramatically lower potential for plastic shrinkage cracking. This preferential removal of water from LWA while the surrounding cement paste remains saturated during a drying exposure of the fresh material has been verified using three-dimensional x-ray absorption microtomography measurements at NIST [8]. Conversely, in a sealed system not exposed to drying, the water remains within the LWA until it is drawn out to the surrounding cement paste by capillary forces generated during hydration [5].

While the use of water-filled LWA is beneficial in reducing the potential for plastic shrinkage cracking and reducing the width of the cracks that develop, it should noted that any water consumed in this phase will not be available later to reduce autogenous and/or drying shrinkage.

Microstructure

The additional water provided by internal curing typically not only increases the long term hydration of the cement, but also provides moisture needed for the pozzolanic and hydraulic reactions of supplementary cementitious materials (SCMs) such as silica fume, fly ash, and slag [15, 19]. Thus, internal curing generally produces a denser microstructure with fewer and smaller unhydrated cement particles (cores) and fewer and smaller capillary pores [19]. In addition to modifying the microstructure of the overall cement paste, the microstructure of the interfacial transition zones (ITZ) surrounding each aggregate will also be different for lightweight aggregates vs. normal weight aggregates. For normal weight aggregates, due to the inherent size differences between cement particles and aggregates, a "wall effect" exists, so that there is a deficiency of cement particles and a surplus of water (porosity) near the aggregate surface relative to their concentration in the bulk (non ITZ) cement paste, effectively producing a higher *w/c* within the ITZ. Furthermore, since the pores near the aggregate surface will be generally larger than those in the bulk paste, they may be the first to empty when self-desiccation is present, intensifying the porous nature of these ITZ regions [20]. Conversely, direct microstructural examinations by scanning electron microscopy (SEM) have revealed that for LWA with



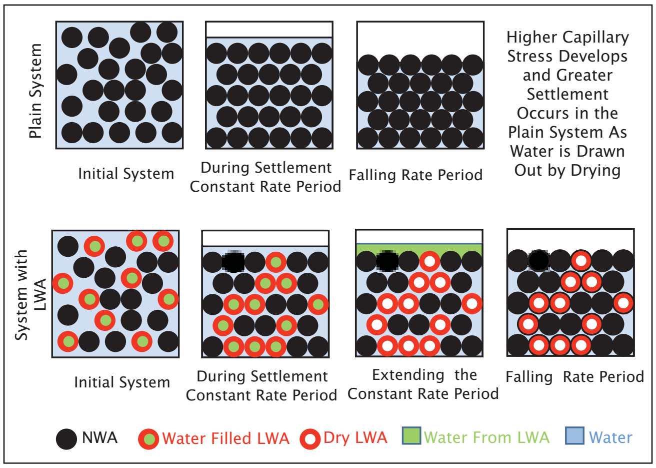


Figure 6: A conceptual illustration of the role of water-filled lightweight aggregate at the surface of a concrete exposed to drying immediately after placement.

Figure 7. Comparison of model mortars with normal weight sand particles only (left) with their surrounding ITZs and with a 50:50 blend (volume basis) of sand and LWA (right). Both the volume fraction of ITZ (grey) paste and its percolation (top to bottom) are significantly reduced by the incorporation of the LWA.

a porous outer layer, this wall effect does not exist and a nearly continuous uniform microstructure of hydration products abuts and partially penetrates the LWA [21, 22].

In a mortar or concrete, the continuity (connectivity) of the more porous ITZs often becomes an important consideration for transport and durability. Due to a reduction in the proportion of these porous ITZs when the normal weight aggregate is replaced by LWA and the potentially increased densification of the remainder of the ITZs surrounding the remaining normal weight aggregates via the internal curing, an additional effect of internal curing may be the discontinuity of the ITZ regions and the concurrent removal of a preferential pathway for the ingress of fluids and deleterious chemical species such as chloride or sulfate ions [10]. This effect is schematically illustrated in two dimensions in Figure 7 that contrasts the volume and continuity of the ITZ regions for mortars with 0% and 50% LWA by volume replacement for normal weight aggregates. Experimental results for sorptivity and chloride ion penetration in mortars with and without internal curing that support this hypothesis will be presented in the next section.

Durability

It is only recently that early-age studies on internal curing have been extended to consider longer term durability by measuring transport properties such as diffusion and sorptivity coefficients [7, 10]. One such study has focused on measuring sorptivity according to the ASTM C1585 standard test method for cylindrical specimens of pastes and mortars with and without internal curing, cured under sealed conditions in double plastic bags. As shown in Figure 8, for a given *w/c*, on a per gram of paste basis, the mortars exhibit a significantly higher 8 d sorption than their corresponding pastes. This is conjectured to be due to the more porous and connected ITZ regions that are present only in the mortars. Replacing a portion of the normal weight sand with a prewetted LWA, however, reduces the measured sorption for the mortar so that it approaches the value of the corresponding *w/c* paste. Viewed from the perspective of equivalent paste microstructures (Figure 8b), a *w/c* = 0.3 mortar behaves like it is composed of a *w/c* = 0.37 cement paste. An 11.0 % volume fraction of pre-wetted LWA reduces this equivalent paste *w/c* to 0.35, while a 23.7 % volume fraction achieves the same sorption on a per paste basis as the original *w/c* = 0.3 paste. Future efforts at Purdue will be directed toward SEM analysis of the microstructure (porosity and ITZs) of these same mortar specimens.

As part of a recent study to evaluate a new paradigm for reducing diffusion in concretes by increasing the pore solution viscosity [23], chloride ion penetration into mortars with and without internal curing has also been evaluated. In that study, after being exposed to 1 M chloride ion solutions for various periods of time, 2” by 4” (50 mm by 100 mm) *w/c* = 0.4 mortar cylinders were split down the middle. The penetration depth of the chlorides was then estimated by spraying one of the exposed cylinder faces with a 0.1 N solution of silver nitrate ($AgNO_3$). The sprayed face was then photographed and image analysis software was employed to estimate the average depth of the chloride ion penetration front. As shown in Figure 9, for specimens cured for 28 d prior to exposure to the Cl- solution, a significant reduction in penetration depth is achieved for those specimens with internal curing. Since the

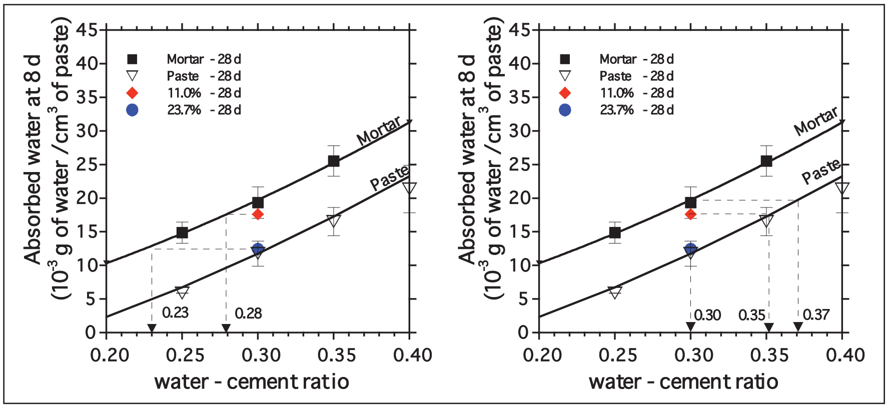


Figure 8. (a) Mortar equivalent w/c and (b) cement paste equivalent w/c, both determined from cumulated absorbed water at 8 d on samples first cured for 28 d [7]. Solid lines are provided to show a general tendency in the data.

diffusion coefficient should scale as the square of the penetration depth, the observed relative penetration depth of 85% would correspond to a diffusion coefficient for the mortar with internal curing that is about 70% of the control mortar. These results are consistent with the substantial reduction in longterm diffusion coefficients previously observed by Thomas for lightweight vs. normal weight concretes [24].

Sustainability

Sustainability has become a major focus of various industry organizations, including NRMCA and the American Concrete Institute (http://www.concretesdc.org). Internal curing has the potential to contribute to a more sustainable infrastructure in a variety of ways. As shown in the results in Tables 4 and 5, internal curing with blends of LWA and CCA may provide cost-effective sustainable materials with significant reductions in autogenous shrinkage and early-age cracking, without sacrificing strength. Internal curing not only contributes to a more efficient hydration of the cement in a concrete mixture, but also promotes enhanced performance of SCMs such as fly ash and slag, both seen as major material sources for "greener" more sustainable concretes. As demonstrated by the results of the presented studies, the use of internal curing can substantially reduce transport properties such as diffusion and sorptivity, thereby increasing the service life of concrete structures. Finally, the enhanced hydration and increased strengths provided by internal curing may allow for small but significant reductions in cement content in many concrete mixtures, thereby significantly reducing the carbon footprint of each cubic yard of concrete used throughout the world.

Summary

In summary, this paper has indicated that, while internal curing may have been originally developed to reduce autogenous shrinkage and mitigate early-age cracking in high performance concretes, its application has far-reaching consequences for the performance of concrete throughout its lifetime. By providing an on-demand source of extra water, internal curing can improve the slump retention, workability and finishability of fresh concrete [1, 2, 25], and reduce deformations and cracking due to plastic, autogenous and drying shrinkage. The increased hydration and improved ITZ microstructure provided by internal curing may increase strength while concurrently decreasing transport (and degradation). ■

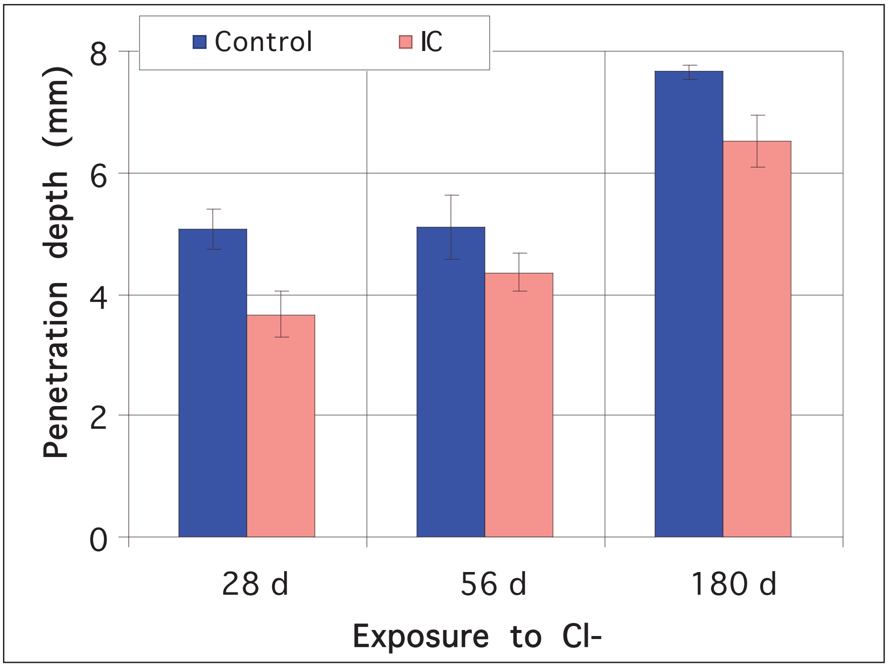


Figure 9. Depth of chloride ion penetration as assessed by spraying with $AgNO_3$ as a function of exposure time for control and internally-cured (IC) *w/c* = 0.4 mortars (both cured for 28 d prior to exposure to Cl-). Error bars indicate one standard deviation based on measurements on two replicate specimens.

** The fine CCA were available from a separate NRMCA study on reuse of crushed returned concrete as aggregate. See Obla, K., Kim, H., and Lobo, C. (2007). "Crushed Returned Concrete as Aggregates for New Concrete", NRMCA Report, Project 05-13, for further details.*

REFERENCES

1. Villareal, V.H., and Crocker, D.A., *Better Pavements through Internal Hydration*, Concrete International, Vol. 29, pp. 32-36, (2007).

2. Friggle, T., and Reeves, D., *Internal Curing of Concrete Paving: Laboratory and Field Experience, in: Internal Curing of High Performance Concrete: Laboratory and Field Experiences*, Eds. D. Bentz and B. Mohr, American Concrete Institute, Farmington Hills, MI, pp. 71-80, (2008).

3. Delatte, N., Crowl, D., Mack, E., and Cleary, J., *Evaluating High Absorptive Materials to Improve the Internal Curing of Concrete, in: Internal Curing of High Performance Concrete: Laboratory and Field Experiences,* Eds. D. Bentz and B. Mohr, American Concrete Institute, Farmington Hills, MI, pp. 91-104, (2008).

4. Roberts, J., *High Performance Concrete: Enhancement Through Internal Curing, Concrete InFocus*, Vol. Winter 2006, pp. 55-59, (2006).

5. Henkensiefken, R., "Internal Curing in Cementitious Systems Made Using Saturated Lightweight Aggregate," Purdue University, 2008,

6. Henkensiefken, R., Bentz, D.P., Nantung, T., and Weiss, J., *Volume Change and Cracking in Internally Cured Mixtures Made with Saturated Lightweight Aggregate under Sealed and Drying Conditions*, Cement and Concrete Composites, Vol. submitted, pp. (2008).

7. Henkensiefken, R., Castro, J., Bentz, D.P., Nantung, T., and Weiss, J., *Water Absorption in Internally Cured Mortar Made with Water-Filled Lightweight Aggregate*, Cement and Concrete Research, Vol. submitted, pp. (2008).

8. Henkensiefken, R., Briatka, P., Bentz, D.P., Nantung, T., and Weiss, J., *Plastic Shrinkage Cracking in Internally Cured Mixtures Made with Pre-wetted Lightweight Aggregate*, Concrete International, Vol. submitted, pp. (2009).

9. Kim, H., and Bentz, D.P., *Internal Curing with Crushed Returned Concrete Aggregates*, in: NRMCA Technology Forum: Focus on Sustainable Development, NRMCA, (2008).

10. Bentz, D.P., *Influence of Internal Curing*

Using Lightweight Aggregates on Interfacial Transition Zone Percolation and Chloride Ingress in Mortars, Cement and Concrete Composites, Vol. accepted, pp. (2008).

11. Phillleo, R.E., *Concrete Science and Reality, in: Materials Science of Concrete II*, Eds. J. Skalny and Mindess S., The American Ceramic Society, Inc., Westerville, OH, pp. 1-8, (1991).

12. *Internal Curing of Concrete*, RILEM Publications S.A.R.L., Paris, (2007)

13. *Internal Curing of High Performance Concrete: Laboratory and Field Experiences*, American Concrete Institute, Farmington Hills, MI, (2008)

14. Holm, T.A., Ooi, O.S., and Bremner, T.W., *Moisture Dynamics in Lightweight Aggregate and Concrete*, in: Theodore Bremner Symposium on High-Performance Lightweight Concrete, Eds. J.P. Ries and T.A. Holm, 167-184, (2003).

15. Bentz, D.P., *Internal Curing of High Performance Blended Cement Mortars*, ACI Materials Journal, Vol. 104, pp. 408-414, (2007).

16. Bentz, D.P., Lura, P., and Roberts, J., *Mixture Proportioning for Internal Curing, Concrete International*, Vol. 27, pp. 35-40, (2005).

17. Jensen, O.M., and Hansen, P.F., *A Dilatometer for Measuring Autogenous Deformation in Hardening Portland Cement Paste, Materials and Structures*, Vol. 28, pp. 406-409, (1995).

18. Lura, P., Pease, B., Mazzotta, G.B., Rajabipour, F., and Weiss, J., *Influence of Shrinkage-Reducing Admixtures on Development of Plastic Shrinkage Cracks, ACI Materials Journal*, Vol. 104, pp. 187-194, (2007).

19. Bentz, D.P., and Stutzman, P.E., Internal Curing and Microstructure of High Performance Mortars, in: ACI SP-256, *Internal Curing of High Performance Concrete: Laboratory and Field Experiences*, Eds. D. Bentz and B. Mohr, American Concrete Institute, Farmington Hills, MI, pp. 81-90, (2008).

20. Bentz, D.P., *Effects of Cement PSD on Porosity Percolation and Chemical Shrinkage, in: Proceedings of the 2nd International Seminar on Self-Desiccation and Its Importance in Concrete Technology*, Eds. B. Persson and G. Fagerlund, Lund University, Lund, pp. 127-134, (1999).

21. Zhang, M.H., and Gjorv, O.E., *Microstructure of the Interfacial Zone between Lightweight Aggregate and Cement Paste, Cement and Concrete Research*, Vol. 20, pp. 610-618, (1990).

22. Lo, T.Y., and Cui, H.Z., *Effect of Porous Lightweight Aggregate on Strength of Concrete*, Materials Letters, Vol. 58, pp. 916-919, (2004).

23. Bentz, D.P., Peltz, M.A., Snyder, K.A., and Davis, J.M., VERDiCT: *Viscosity Enhancers Reducing Diffusion in Concrete Technology - A New Approach to Decreasing Transport, Concrete International*, Vol. 31, pp. 31-36, (2009).

24. Thomas, M.D.A., *Chloride Diffusion in High-Performance Lightweight Aggregate Concrete*, in: Theodore Bremner Symposium on High-Performance Lightweight Concrete, Eds. J.P. Ries and T.A. Holm, 77-93, (2003).

25. Villareal, V.H., *Internal Curing - Real World Ready Mix Production and Applications: A Practical Approach to Lightweight Modified Concrete*, in: Internal Curing of High Performance Concrete: Laboratory and Field Experiences, Eds. D. Bentz and B. Mohr, American Concrete Institute, Farmington Hills, MI, pp. 45-56, (2008).