Plastic Shrinkage Cracking in Internally Cured Mixtures

Prewetted lightweight aggregate can reduce cracking

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Depending on the weather conditions between the time of placement and the time of set, concrete can be susceptible to plastic shrinkage cracks.[1] In addition to being unsightly, these cracks can be a problem as they can lead to the ingress of deleterious substances. Several studies have shown the beneficial effects of internal curing (IC) on autogenous shrinkage and shrinkage cracking in hardened concrete.[2-4] It has also been noted that pavements and residential slabs-on-ground with IC exhibit less plastic shrinkage cracking than equivalent conventional concretes.[5]

The study presented herein provides data on settlement and plastic shrinkage cracking in mortars and concretes with different volume replacements of prewetted lightweight aggregate (LWA). While the data indicate that sufficient LWA can reduce or eliminate plastic shrinkage cracking, further work would be needed to demonstrate the proper mixture proportions that should be used for a specific application.

MECHANISMS OF PLASTIC SHRINKAGE

X-ray studies of LWA-containing mortar specimens under sealed curing conditions indicate that water begins to leave LWA only after setting.[6,7] X-ray studies of two-layer cement composites under drying conditions, however, indicate that water is removed from the layer with the coarser pore structure first, regardless of which layer is exposed to the drying environment or how the coarse pore structure is produced.[8]

In a drying environment, fresh concrete undergoes three drying phases.[9] During Phase I, sedimentation can occur as the denser cement and aggregate particles settle and water rises to the surface. This layer of bleed water is free to evaporate at a rate similar to that of bulk water.[10]

Phase II begins when the layer of bleed water evaporates and liquid-vapor menisci form at the surface and within the concrete.[11] A capillary pressure develops that is inversely proportional to the radius of curvature at a given meniscus. The pressure rearranges cement particles (consolidation), forcing more pore solution to the top surface of the concrete. The net internal pressure drop can produce further particle rearrangement (consolidation), forcing more pore solution to the top surface of the concrete. For concretes with prewetted LWA, the water will be drawn out of the LWA before it is drawn out of the paste because LWA generally contains larger pores than the paste. It would thus also be expected that a reduction in the settlement would occur as water is provided from the rigid LWA rather than from the fluid, deformable cement paste. When the pressure can no longer be reduced due to a rearrangement of the particles in the system and the drying front recedes from the surface toward the interior of the concrete, the concrete is susceptible to cracking. The transition that occurs at this point is referred to as the critical point,[10] as it represents the point in time when the concrete is most susceptible to cracking.[12,13]

During Phase III, the drying front penetrates into the interior of the concrete and the continuous liquid path between the surface and the interior is lost. Evaporation and settlement rates slow.

MIXTURES
Constituent materials

Normalweight fine aggregate (sand), LWA, and coarse aggregates used in our mixtures are described in Table 1. Mortar specimens comprised only fine aggregates (sand and LWA). All mixtures included ASTM C150 Type I portland cement with a Blaine fineness of 370 m^2/kg. The estimated Bogue phase composition for cements used in mortar mixtures was 56% C_3S, 16% C_2S, 12% C_3A, 7% C_4AF, and 0.68% Na_2O equivalent. The estimated Bogue phase composition for cements used in concrete mixtures was 50% C_3S, 16% C_2S, 12% C_3A, 7% C_4AF, and 0.68% Na_2O equivalent.

To maintain similar consistencies for mortar mixtures, a polycarboxylate-based high-range, water-reducing admixture (HRWRA) was added in varying doses, depending on the volume replacement level of the LWA. For LWA volumes up to 18.3% of the total mixture volume, the HRWRA dosage was 0.50% of the cement weight. For LWA volumes larger than 18.3%, the dosage of HRWRA was 0.66% of the cement weight. No HRWRA was used for the concrete mixtures.

Proportioning

Five mortar mixtures were prepared, each with a water-cement ratio (w/c) of 0.30. The mixtures had varying amounts of sand replaced by prewetted LWA (Table 2). The total volume of LWA and sand was maintained at 55%. It should be noted that the 23.7% LWA volume corresponds to the computed amount of LWA necessary to eliminate self-desiccation in mortar mixtures.[14,15]

Four concrete mixtures were prepared, each with an effective w/c of 0.55, including a plain mixture designated as 0.0%C and three mixtures with varying amounts of sand replaced by prewetted LWA (Table 3). The total volume of fine aggregate (LWA and sand) was maintained constant at 30% in the concretes, and the total aggregate content (coarse aggregate, LWA, and sand) was maintained at 60%.

It should be noted that the 18.0% LWA volume corresponds to the amount of LWA necessary to eliminate self-desiccation in concrete mixtures.[14,15]

EXPERIMENTAL METHODS
Evaporation

The purpose of this experiment was to determine if, when exposed to drying conditions prior to achieving set, the prewetted LWA, with its larger water-filled pores, will supply water to the nearby cement paste before the cement paste itself begins to desiccate.

Two small composite specimens were prepared to directly examine water movement during drying. A prewetted LWA particle (dry mass of about 0.2 g [0.007 oz]) was carefully placed in the bottom of a plastic drinking straw and covered with a 4 mm (0.16 in.) thick layer of Type II/V cement paste with a w/c of 0.35. The bottom surface of the LWA was sealed with putty so that drying could only occur at the top (cement paste) surface. Two control specimens (straws containing cement paste only) were also prepared. Specimens were placed in the exposure chamber (23°C [73°F], 40% relative humidity) of an X-ray microtomography unit, and three-dimensional (3D) scans were conducted at periodic intervals over the course of 24 hours as they were drying. X-ray absorptions were directly measured in the two-dimensional (2D) images obtained from the 3D reconstruction process (refer to Reference 20 for a discussion of 3D scans).

Settlement

Mortar specimens were prepared for settlement tests. LWA was oven dried, air cooled, and then submerged in water for 24 hours prior to mixing. The volume of water used to submerge the LWA included both mixing water and the water that the LWA was expected to absorb when immersed for 24 hours.[16] (The water not absorbed in 24 hours was then decanted and used as the mixing water.) The mixing of the mortar was done in accordance with ASTM C305-06, with a modification to the order in which the materials were added. The LWA was added to a prewetted mixing bowl followed by the sand. The aggregate mixture was mixed for 30 seconds, the cement was added, and the mixture was mixed for another 30 seconds. The water (premixed with HWRWA) was then added. The mixture was mixed at slow speed (about 140 revolutions per minute [rpm]) for

TABLE 1:
AGGREGATE CHARACTERISTICS

Type	Description	Fineness modulus	Apparent specific gravity	24-hour absorption
Coarse	9.5 mm (3/8 in.) MSA	NA	2.58 (SSD)	2.3*
Sand	River sand	2.71	2.58 (SSD)	1.8†
LWA	Rotary-kiln-expanded shale	3.10	1.56 (Dry)	10.5†

*Per ASTM C127-04.
†Per ASTM C128-07a.

TABLE 2:
MIXTURE PROPORTIONS FOR MORTAR MIXTURES

Material	0.0%M	11.0%M	18.3%M	23.7%M	33.0%M
Cement, kg/m³	728	728	728	728	728
Water, kg/m³	218	218	218	218	218
Sand, kg/m³	1418	1135	950	808	567
Dry LWA, kg/m³	0	172	285	369	515
Additional water provided by LWA, kg/m³	0	18	30	39	54

Note: 1 kg/m³ = 1.686 lb/yd³.

30 seconds and medium speed (about 285 rpm) for an additional 30 seconds. Mixing was stopped for 90 seconds, after which mixing resumed on medium speed for 60 seconds. Duplicate samples were cast in 75 x 100 mm (3 x 4 in.) cylinders in two layers, each of which was vibrated for 15 seconds. Ten minutes after the addition of the water to the mixing bowl, the samples were placed in an environmental chamber at 23.0°C ± 0.1°C (73.4°F ± 0.2°F) and a relative humidity of 50% ± 0.1%.

Settlement was measured at 1 minute intervals for the first 6 hours. Measurements were made using a proximity sensor to monitor the movement of a laser beam reflected off the surface of the mortar at a small angle. For more complete descriptions of similar apparatus, refer to Reference 17.

Plastic shrinkage cracking

Plastic shrinkage tests were performed in accordance with ASTM C1579-06. The coarse aggregate and sand were oven dried and cooled for 24 hours before mixing. The LWA was prepared in the same manner as the LWA for the settlement test. The coarse aggregate, sand, and lightweight aggregate were placed into a prewetted mixing bowl and mixed for 30 seconds. Cement was added, and the decanted water was slowly poured into the dry mixture. The concrete was mixed for 3 minutes, allowed to rest for 2 minutes, and mixed an additional 3 minutes.

The concrete was placed in molds (Fig. 1[18]), screeded, and finished with a trowel. Twenty-five minutes after the addition of water, specimens were placed in an environmental chamber with a temperature of 36°C ± 3°C (97°F ± 5°F), relative humidity of 30% ± 5%, and wind velocity of 24 km/h ± 2 km/h (14.7 mph ± 1.2 mph). The fans were turned off after 6 hours, and the specimens were exposed to the chamber temperature and humidity for an additional 18 hours.

The specimens were taken out of the environmental chamber after 24 ± 2 hours and photographed from a consistent height. Images were subsequently analyzed for cracks and crack widths using image analysis software.[19]

EXPERIMENTAL RESULTS AND DISCUSSION
Evaporation

Figure 2 provides a summary of the X-ray absorption results obtained for the cement paste specimens with and without an underlying prewetted LWA. An increase in the relative intensity is indicative of an increase in density, whereas a decrease indicates a decrease in density, assumed in this experiment to be caused by the loss of water to the environment. Prior to 2 hours, the LWA covered by paste loses intensity while the cement paste gains intensity. This indicates a slight consumption of water from the LWA by the cement paste to maintain saturated conditions as chemical shrinkage occurs (Fig. 2(a)).[20] Beyond 2 hours, the LWA continues to lose water while the cement paste starts to lose water to the drying environment

(Fig. 2(b)). However, the degree of saturation (density) of the cement paste in this specimen remains significantly higher than that achieved in the specimens with only cement paste.

These results indicate that under drying exposure conditions—both prior to and after setting—significant water is transferred from the LWA to the nearby cement paste and, ultimately, to the environment via evaporation. The water supplied by the LWA during this time maintains a greater degree of saturation of the cement paste, which should have a significant impact on both the settlement and propensity for cracking of the specimens.

Settlement

Figure 3 shows the settlement results for the mortar samples over a 6-hour period. The 0.0%M mixture shows considerably more settlement than the mixtures with LWA. It is also interesting to note that as the volume replacement of LWA is increased, the settlement decreases. This is consistent with our hypothesis that reduction in capillary stresses due to the release of water from the rigid but porous LWA results in less overall settlement of the mortar.

TABLE 3:
Mixture proportions for concrete mixtures

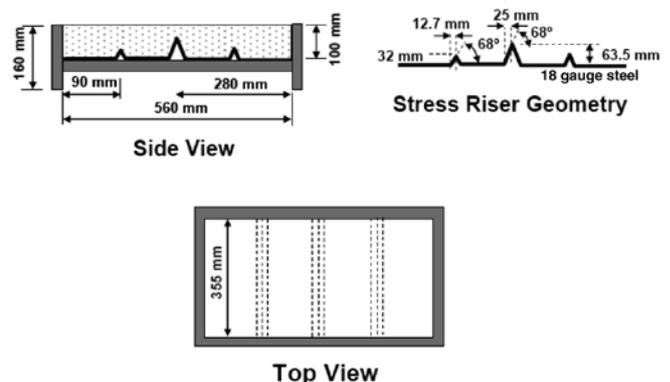| Material	0.0%C	6.0%C	10.0%C	18.0%C
Cement, kg/m³	461	461	461	461
Water, kg/m³	254	254	254	254
Sand, kg/m³	774	619	518	309
Coarse aggregate, kg/m³	825	825	825	825
Dry LWA, kg/m³	0	94	154	281
Additional water provided by LWA, kg/m³	0	9.8	16.2	29.5

Note: 1 kg/m³ = 1.686 lb/yd³

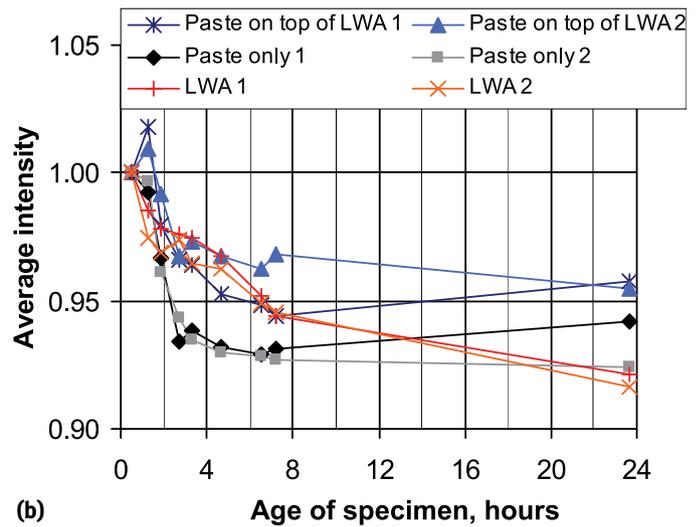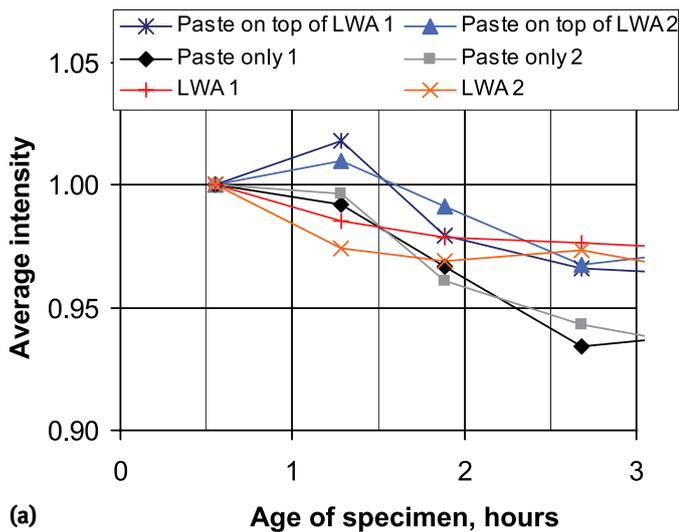Fig. 1: Geometry of specimens used for concrete plastic shrinkage investigation (25.4 mm = 1 in.)[18]

Fig. 2: Relative intensity of X-ray absorption versus time for drying cement pastes with and without LWA for: (a) first 3 hours; and (b) for 24 hours of drying. Results for two replicate specimens are shown to provide indication of measurement variability
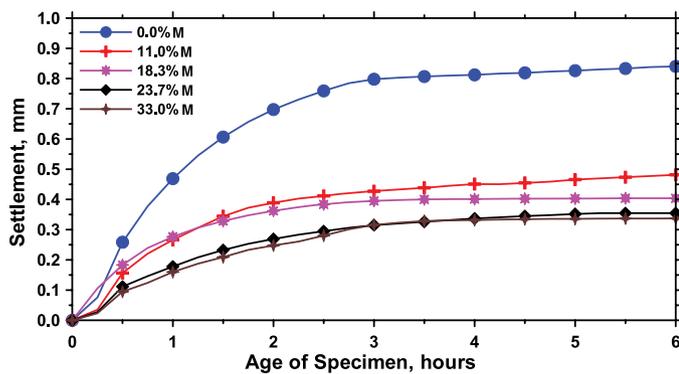

Fig. 3: Settlement results for mortars made with different replacement volumes of LWA. Maximum standard deviation was 0.09 mm (25.4 mm = 1 in.)
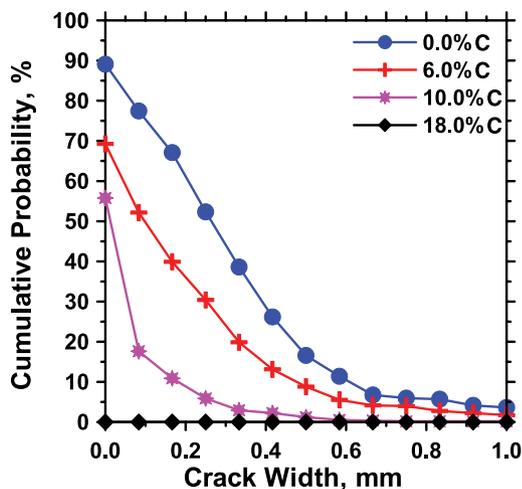

Fig. 4: Cumulative distribution of crack width occurrences in concretes with different replacement volumes of LWA (25.4 mm = 1 in.)

Plastic shrinkage

Figure 4 shows the cumulative probability distribution of crack widths occurring in concrete mixtures made with different volume replacements of LWA. The curves shown in Fig. 4 are the average crack measurements of three panels and, for each curve, the *y*-intercept represents the probability of observing a crack within the sampled grid mask.[19] The 0.0%C mixture shows the largest crack widths. The probability of plastic shrinkage cracks forming decreases as the LWA replacement volume increases. When a sufficient volume of LWA is used (18.0%C), plastic shrinkage cracking was eliminated for the conditions investigated in this study. Figure 5 shows the probability of crack widths smaller than 0.0 mm (0.0 in.)—effectively, no cracking—and 0.2 mm (0.008 in.) as the volume replacement of LWA is increased. The 0.0 curve shows that cracking can be eliminated if a high enough replacement volume of LWA is used. By providing additional water that can replace the water that is evaporating from the surface of the concrete, the LWA can reduce or eliminate plastic shrinkage cracking. It should be noted, however, that if this water from the LWA is used to eliminate plastic shrinkage cracking, it will not be available later to reduce the shrinkage and cracking caused by self-desiccation and drying.

From the results of the crack width analyses, the crack reducing ratio (CRR) can be calculated according to Eq. (1),[18] allowing the reduction in plastic shrinkage cracking to be calculated as a single value.

$$CCR = \left[1 - \frac{\text{Average Crack Width of Modified Concrete}}{\text{Average Crack Width of Reference Concrete}} \right] 100\% \qquad (1)$$
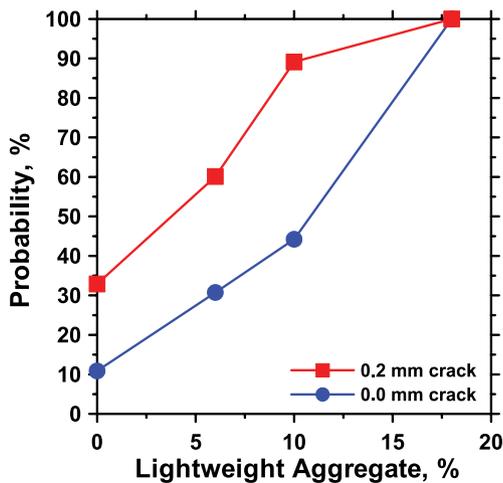
Fig. 5: Probability of crack widths being smaller than 0.0 mm (0.0 in.) and 0.2 mm (0.008 in.) for concretes with different LWA replacement volumes

Table 4 shows the average crack width and CRR for the three LWA mixtures tested. The average crack width is reduced as the LWA replacement volume is increased, leading to significant increases in the CRR.

VERIFIED BENEFITS

The replacement of sand with prewetted LWA can provide a significant reduction in settlement and plastic shrinkage cracking of mortars and concretes. If a sufficient volume of prewetted LWA is provided, plastic shrinkage cracking can be reduced or eliminated under the exposure conditions employed in this study. The water movement from the LWA to the nearby cement paste, both prior to and after setting, has been verified using X-ray absorption measurements. The supply of water by the rigid but porous LWA reduces the settlement accompanying evaporation and the magnitude of the capillary stresses that are developed during drying as the water-filled pores in the LWA are generally larger than those in the hydrating cement paste. It should be noted that if self-desiccation is also a concern, the mixture needs to be properly proportioned to include enough water stored in the LWA to alleviate both of these problems.

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

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