Plastic Shrinkage Cracking in Internally Cured Mixtures Made with Pre-wetted Lightweight Aggregate

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Abstract

The incorporation of pre-wetted lightweight aggregates (LWA) in concrete has been used to reduce shrinkage cracking associated with self-desiccation in the hardened state. Little research, however, exists to show the influence of internal curing on the formation of plastic shrinkage cracks. The paper presents a background on the formation of plastic shrinkage cracks and presents results from a study that examined mortar and concrete systems with pre-wetted LWA. Specifically, the results indicate that the incorporation of pre-wetted LWA can reduce settlement and formation of plastic shrinkage cracks. It is shown that water will preferentially leave the LWA during early-age drying, thus resulting in a system where the cement paste remains more saturated and less likely to crack.

Keywords: Evaporation, Internal Curing, Plastic Shrinkage, Lightweight Aggregates, Settlement, Shrinkage Cracking, X-ray Absorption.

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1. Introduction

Concrete can be susceptible to plastic shrinkage cracks depending on the weather conditions between the time of placement to the time of set [1]. Though these cracks may be unsightly, a larger problem exists as they may lead to the ingress of deleterious materials. Pre-wetted lightweight aggregate (LWA) for use in concrete has been increasingly promoted for its benefit of reducing shrinkage cracking caused by self-desiccation. While several studies have shown the beneficial effects of internal curing (IC) on autogenous shrinkage and shrinkage cracking in hardened concrete [2-4], few, if any, studies have investigated the influence of IC on the formation of plastic shrinkage cracking, although it has been noted that field concretes with IC exhibit less plastic shrinkage cracking than their conventional concretes without IC counterparts [5].

This study provides measurements of settlement and plastic shrinkage cracking in mortars and concretes with different volume replacements of LWA. The results indicate that if a sufficient volume of LWA is added to concrete, plastic shrinkage cracking can be reduced or eliminated.

2. Mechanisms of plastic shrinkage

The formation of plastic shrinkage cracks can be described by the three drying phases that concrete undergoes [6]. Fresh concrete may undergo sedimentation with the denser cement and aggregate particles settling due to gravitational forces and water rising to the top surface of the concrete. This water is known as bleed water. This layer of bleed water that covers the concrete surface is free to evaporate during the first drying phase. The initial evaporation rate from such a concrete surface is from the layer of bleed water that forms and is similar to the evaporation of bulk water [7]. This region of evaporation is generally referred to as the first drying region (i.e., phase (I)).

Once the layer of bleed water evaporates, liquid-vapor menisci form at the surface and within the concrete [8]. The formation of the liquid-vapor menisci results in capillary pressure. This is commonly referred to as the second drying phase (phase (II)). The Young-Laplace equation can be used to relate the radius of the menisci to the capillary pressure (Equation 1):

$$\sigma_{cap} = -\frac{2\gamma\cos(\theta)}{r} \qquad \text{Equation 1}$$

where: σ_{cap} (Pa or psi) is the capillary pressure, γ (N/m or lb/inch) is the surface tension of the pore fluid, θ (radians) is the liquid-solid contact angle (assumed in this work to be 0 radians), and r (m or inch) is the radius of curvature of the meniscus. The capillary pressure that develops may produce further particle rearrangement (i.e., consolidation) with more pore solution is forced to the top surface of the concrete. With greater capillary pressure, more pore solution (water) will be expelled to the surface. For concretes with internal curing using pre-wetted LWA, it is hypothesized that during this stage, water will be preferentially first drawn out of the LWA (because it generally contains larger pores than the cement paste), similar to the manner in which water is imbibed from the LWA by the hydrating cement paste at a later age. During this phase, it would thus be expected that a reduction in the settlement would occur as water is provided from the rigid LWA as opposed to the fluid, deformable cement paste. When the capillary pressure is no longer able to compress the system and the drying front recedes from the surface towards 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 [7]. The critical point represents the point in time when the concrete is most susceptible to cracking [9]. Further details on the formation of plastic shrinkage cracks can be found in the literature [10].

In the final drying phase, phase (III), the evaporation and settlement slow down as the drying front penetrates into the interior of the concrete and the continuous liquid path between the surface and the interior is lost.

3. Constituent Materials

The coarse aggregate used was pea gravel with an apparent specific gravity of 2.58 and a 9.5 mm (3/8 inch) maximum size aggregate. The normal weight fine aggregate used was natural river sand with a fineness modulus of 2.71 and an apparent specific gravity of 2.58. Portions of the normal weight sand were replaced with the same volume of a manufactured rotary kilned expanded shale with a fineness modulus of 3.10 and a specific gravity of 1.56. The 24-h absorption of the coarse aggregate was determined to be 2.3 % in accordance to ASTM C127-04 [11]. The 24 h absorption of the normal weight sand and LWA were determined to be 1.8 % and 10.5 %, respectively, in accordance to ASTM C128-07 [12].

For the mortar mixtures, ASTM C150 Type I ordinary portland cement (OPC) was used, with a Blaine fineness of 370 m^2/kg and an estimated Bogue composition of 56 % C_3S, 16 % C_2S, 12 % C_3A, 7 % C_4AF and a Na_2O equivalent of 0.68 %. It should be noted that for the concrete mixtures, a different cement was used that also meets ASTM C150 (Type I OPC) requirements, with a Blaine fineness of 370 m^2/kg and an estimated Bogue phase composition of 50 % C_3S, 16 % C_2S, 12 % C_3A, 7 % C_4AF and 0.68 % Na_2O equivalent.

A polycarboxylate-based high-range water-reducing admixture (HRWRA) was added to the mortar mixtures in varying rates depending on the volume replacement level of the LWA. For LWA replacement volumes up to 18.3 %, the HRWRA was added at a rate of 0.50 g per 100 g of cement (0.50 lb per 100 lb of cement). For replacement volumes larger than 23.7 %, 0.66 g of HRWRA per 100 g of cement (0.66 lb of HRWRA per 100 lb of cement) was used. Different rates of HRWRA were used to maintain similar consistencies for these mixtures. No HRWRA was used for the concrete mixtures.

3.1. Mixture proportioning

3.1.1. Mortar mixture proportions

Five different mixtures were prepared with a water-to-cement ratio (*w/c*) of 0.30. This included a plain mortar mixture designated as 0.0 %m and four mortar mixtures with varying amounts of sand replaced by pre-wetted LWA, as shown in Table 1. The LWA expanded shale was used for the mixtures designated as 11.0 %m, 18.3 %m, 23.7 %m, and 33.0 %m. It is important to note that the designations are on a total volume basis. The volume of aggregate (LWA and natural sand) was maintained constant at 55 % since only the sand was replaced with LWA. The number in the designation represents the total volume of the mixture occupied by the LWA (in percent) and the letter "m" indicates that it was a mortar. It should be noted that the 23.7 %m volume replacement corresponds to the computed amount of LWA necessary to eliminate self-desiccation [13, 14].

3.1.2. Concrete mixture proportions

Four different mixtures were prepared with an effective *w/c* of 0.55: this included a plain concrete mixture designated as 0.0 %c and three concrete mixtures with varying amounts of sand replaced by pre-wetted LWA, as shown in Table 2. The LWA expanded shale was used for these mixtures designated as 6.0 %c, 10.0 %c, and 18.0 %c. It is important to note that the designations are on a total volume basis. The volume of fine aggregate (LWA and sand) was maintained constant at 30 % in these concretes, since only the sand was replaced with LWA. The total aggregate content (coarse aggregate, LWA and sand) for these mixtures was maintained constant at 60 % by volume. The number in the designation represents the total volume of the mixture occupied by the LWA (in percent) and the letter "c" represents that it was concrete. It should be noted that for the concrete mixtures, the 18.0 %c volume replacement corresponds to the amount of LWA necessary to eliminate self-desiccation [13, 14].

4. Experimental methods

4.1. Evaporation

The purpose of this experiment was to validate the hypothesis that when exposed to drying conditions prior to achieving set, the pre-wetted LWA with its larger water-filled pores will first supply water to the nearby cement paste, prior to the cement paste itself beginning to desiccate. Previous x-ray studies under sealed conditions have indicated that water begins to leave the LWA only after set is achieved [15, 16]. Conversely, under drying conditions, it has been previously observed in two-layer cement paste composites that water is preferentially removed first from a cement paste layer with a coarser pore structure regardless of which layer is exposed to the drying environment, whether that coarser pore structure is produced by a higher *w/c* for a single cement or via the utilization of a coarser cement at a constant *w/c* [17].

In a separate experiment, two replicate small single aggregate-cement paste composite specimens were prepared to directly examine water movement during drying. Individual pre-wetted LWA (dry mass of about 0.2 g or 0.007 oz) were carefully placed in the bottom of a 7 mm (0.28 in) inner diameter plastic drinking straw and covered with a 4 mm (0.16 in) thick layer of *w/c* = 0.35 Type II/V cement paste. The bottom surfaces of the specimens were sealed with putty so that drying only occurred at the top (cement paste) surfaces of the specimens. This is illustrated in Figure 1. Two control specimens with cement paste only were prepared for comparison purposes. These specimens were placed in the exposure chamber (23 ºC or 73 ºF, 40 % RH) of an x-ray microtomography unit and three-dimensional scans were conducted at periodic intervals during the course of 24 h as they were drying. X-ray absorptions were directly measured in the two-dimensional images obtained from the three-dimensional reconstruction process.

4.2. Settlement

The LWA was oven dried, air cooled, and then submerged in water for 24 h prior to mixing. The volume of water used to submerge the LWA included both mixing water and the water that the LWA would absorb in 24 h when it is immersed in water [18]. The excess water (water not absorbed in 24 h) was then decanted and used as the mixing water. The mixing of the mortar was done in accordance with ASTM C305 [19], with a modification in the order in which the materials were added. The LWA was added to the pre-wetted bowl, to which the normal weight fine aggregate was added. The aggregate mixture was mixed for 30 s. The cement was added and the mixture was mixed for another 30 s. The water (pre-mixed with HWRWA) was added. The mixture was mixed at slow speed (≈ 140 rpm) for 30 s and then on medium speed (≈ 285 rpm) for an additional 30 s. Mixing was stopped for 90 s, after which mixing resumed on medium speed for 60 s. Duplicate samples were cast in 75 mm × 100 mm (3 in x 4 in, depth × diameter) cylinders in two layers, each of which was vibrated for 15 s. The samples were placed in an environmental chamber at 23.0 ˚C ± 0.1 ˚C (73.4 ºF ± 0.2 ºF) and a relative humidity of 50 % ± 0.1 %, 10 min after the addition of the water to the mixing bowl.

Settlement was measured using a laser setup [20, 21], with an accuracy of 0.001 mm (4×10^{-5} in), at an interval of 1 min for the first 6 h. The lasers were situated above the specimens and the laser beam was reflected from the surface of the specimen. The shift of the laser beam reflected from specimen's surface (while the laser projects a laser beam toward the specimen at a small angle) can be used to indicate the consolidation of the sample. This concept is illustrated in Figure 2. The experimental setup was similar to previous work by Lura et al. [7, 20, 21].

4.3. Plastic Shrinkage Cracking

The plastic shrinkage tests were performed in accordance with ASTM C1579-06 [22]. The LWA was prepared exactly like the LWA for the settlement test. The coarse aggregate and normal weight sand were oven dried and cooled for 24 h before mixing. The coarse aggregate, normal weight sand and lightweight aggregate were placed into the pre-wetted mixing bowl and mixed for 30 s. After this period, cement was added and the decanted water was slowly poured into the dry mixture. The concrete was mixed for 3 min followed by a 2 min rest and finished by 3 min of mixing.

The concrete was cast into plastic shrinkage molds, shown in Figure 3, screeded and finished with a trowel. The samples were put into an environmental chamber 25 min after the addition of water, where they were exposed to the following ambient conditions: temperature of 36 ˚C ± 3 ˚C (97 ºF ± 5 ºF), relative humidity of 30 % ± 10 % and wind velocity of 24 km/h ± 2 km/h (14.7 mph ± 1.2 mph). The fans were turned off after 6 h and for the remaining 18 h the specimens were exposed to the chamber environment without significant air circulation.

The specimens were taken out of the environmental chamber after 24 h ± 2 h, and pictures were taken of their surfaces. The pictures were always taken from the same height of 184 mm (7.2 in). Subsequently, pictures were analyzed for cracks and crack widths using image analysis software that enables approximately 300 measurements for each specimen, thereby providing statistically valid information about cracks widths and their variability [23].

5. Experimental results and discussion

5.1. Evaporation

Figure 4 provides a summary of the x-ray absorption results obtained for the cement paste specimens with and without an underlying pre-wetted LWA, along with the results for the LWA covered by paste. Because the x-ray generator was turned on and off between the periodic measurements, all results were normalized to the first absorption readings obtained for the putty used to seal the bottom of the specimen, assuming a perfect seal and that the putty doesn't absorb water. In Figure 4, an increase in the relative intensity is indicative of an increase in density, while a decrease indicates a decrease in density, assumed in this experiment to be caused by the loss of water to the environment. Contrasting the results for the cement pastes over an LWA vs. those of the cement paste by itself, several differences are noted. At very early ages prior to 2 h, in Figure 4a, while the LWA covered by paste is losing significant water, the intensity of the cement paste on top of it is actually increasing, indicating a slight imbibition of water by the cement paste from the LWA to maintain saturated conditions as chemical shrinkage occurs [24]. Beyond 2 h, in Figure 4b, the LWA continues to lose water and its covering layer of cement paste also starts to lose water to the drying environment. However, the degree of saturation (density) of the cement paste in this specimen remains significantly higher than that achieved in a specimen of only cement paste, also exposed directly to drying.

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 allows the maintenance of 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, as will be verified directly in the sections that follow.

5.2. Settlement

Figure 5 shows the settlement results for the mortar samples over a 6 h 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 likely because as capillary stresses increase during phase (II), water is released by the LWA to reduce the capillary stress thereby reducing further consolidation, as supported by the x-ray absorption results in Figure 4. The reduction in the capillary stress due to the release of water from the rigid but porous LWA results in less overall settlement of the mortar.

5.3. Plastic Shrinkage

Figure 6 shows the cumulative probability distribution of crack widths occurring in concrete mixtures made with different volume replacements of LWA. The curves shown in Figure 6 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 [23]. 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 7 shows the probability of crack widths being 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. By observing the 0.0 curve, corresponding to no cracking or at least to cracks that can not be detected using the experimental setup, it can be seen that cracking can be eliminated if a high enough replacement volume of LWA is used. Plastic shrinkage cracking can be reduced or eliminated because the LWA provides additional water that can replace the water that is being evaporated from the surface of the concrete. It should be noted however, that if this water from the LWA is used to eliminate plastic shrinkage cracking, it will not be later available to reduce the shrinkage and cracking caused by self-desiccation and drying.

From the results of the crack width analysis, the crack reducing ratio (CRR) can be calculated according to Equation 2 [22]. The crack reducing ratio equates the reduction in plastic shrinkage cracking to a single value.

$$CRR = \left[1 - \frac{\begin{array}{c}\text{Average Crack Width}\\ \text{of Modified Concrete}\end{array}}{\begin{array}{c}\text{Average Crack Width}\\ \text{of Reference Concrete}\end{array}} \right] \times 100\% \qquad \text{Equation 2}$$

Table 3 shows the average crack width and the CRR for the three LWA mixtures tested. The average crack width is reduced as the LWA replacement volume is increased. The plastic shrinkage cracking is reduced as shown by the significant increases in the CRR.

6. Conclusions

It has been demonstrated that the replacement of normal weight sand with pre-wetted LWA can provide a significant reduction in settlement and plastic shrinkage cracking of mortars and concretes. If a sufficient volume of pre-wetted 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 also reduces the magnitude of the capillary stresses that are developed during drying since the water-filled pores in the LWA are generally larger than those in the hydrating cement paste. It should be noted that the water from the LWA employed to reduce plastic shrinkage cracking is unavailable to alleviate the later problems associated with self-desiccation and drying.

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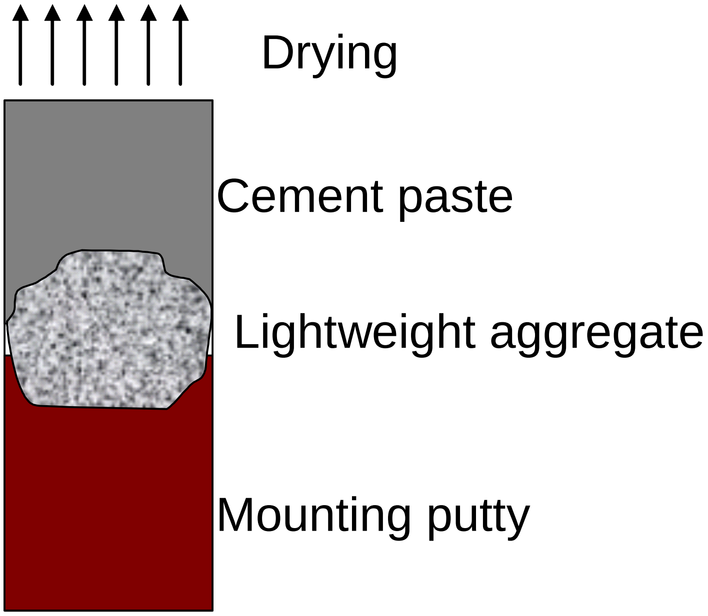

Figure 1 – Experimental setup for the evaporation study conducted using x-ray microtomography.

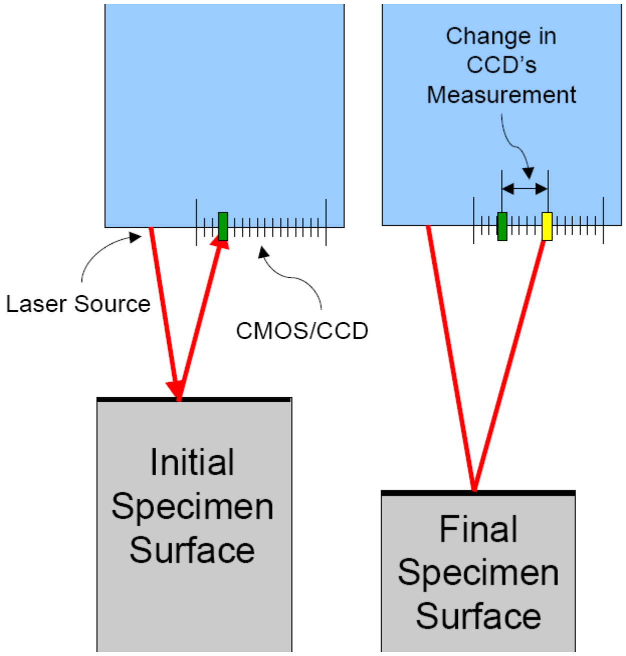

Figure 2 – Laser setup for mortar settlement test [20].

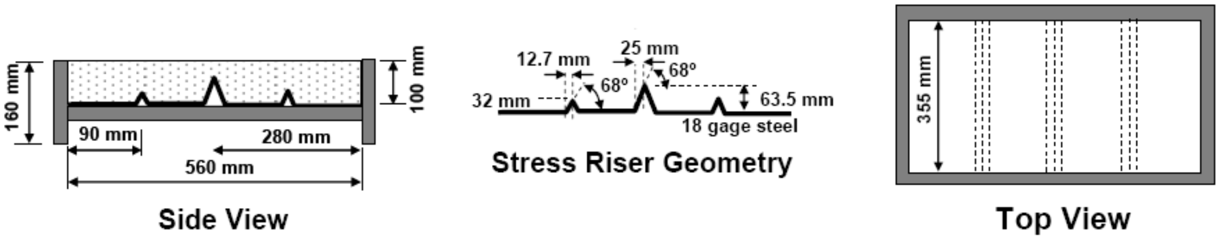

Figure 3 – Geometry of the specimens used for concrete plastic shrinkage investigation (25.4 mm = 1 in) [6].

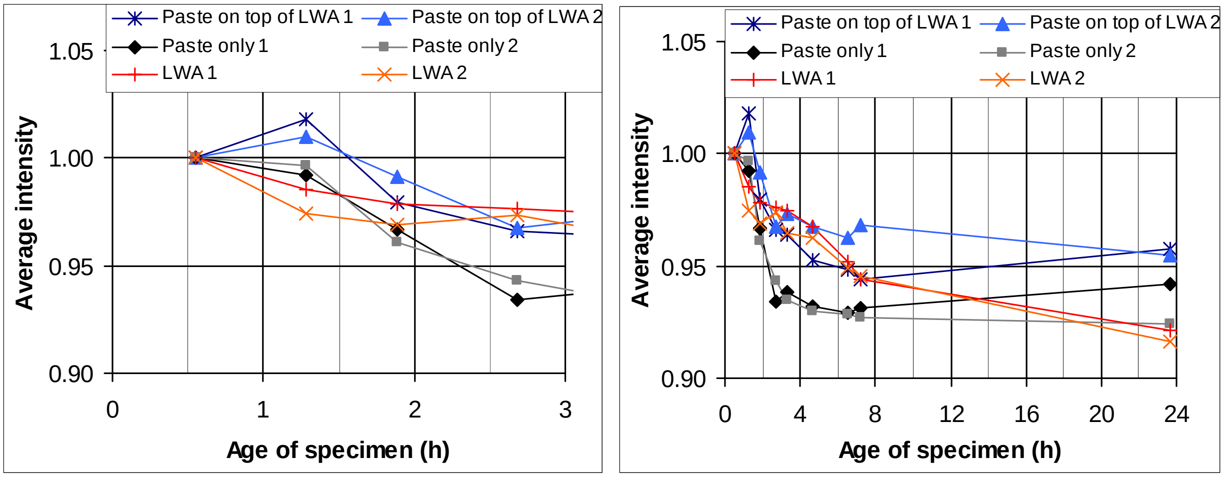

Figure 4 – Relative intensity of x-ray absorption vs. time for drying cement pastes with and without LWA for a) first 3 h and b) for 24 h of drying. Results for two replicate specimens are shown to provide an indication of measurement variability.

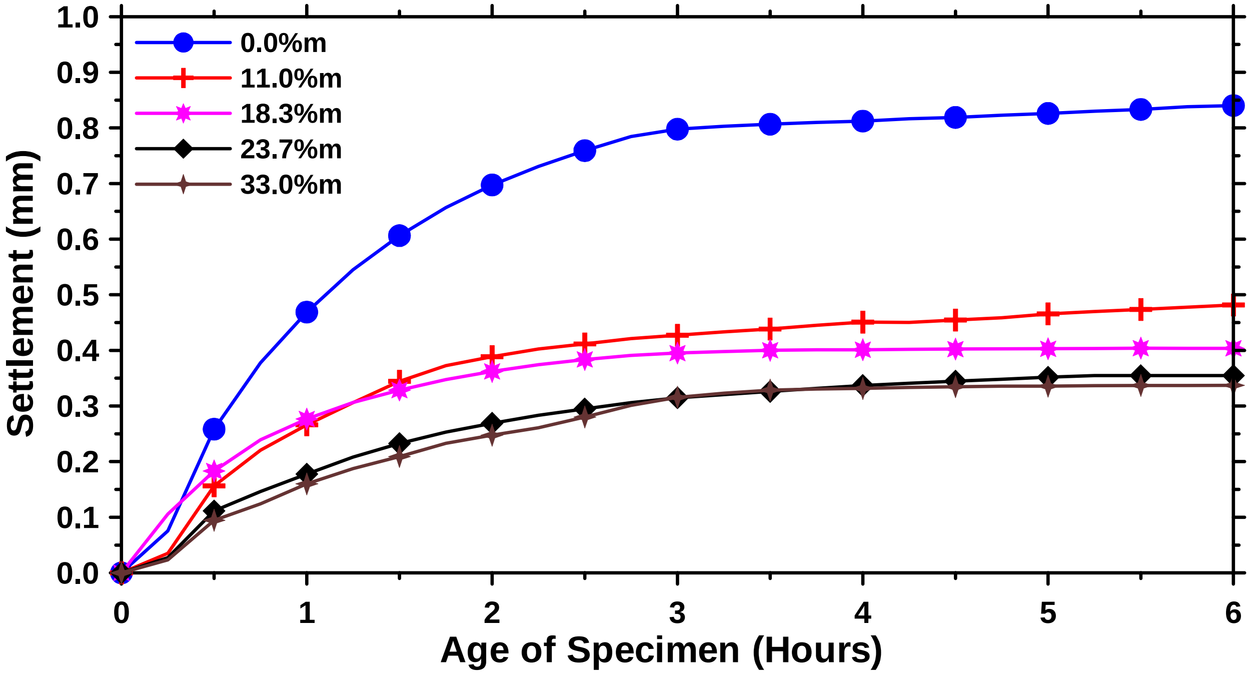

Figure 5 – Settlement results for mortars made with different replacement volumes of LWA. The maximum standard deviation was 0.09 mm. (25.4 mm = 1 in).

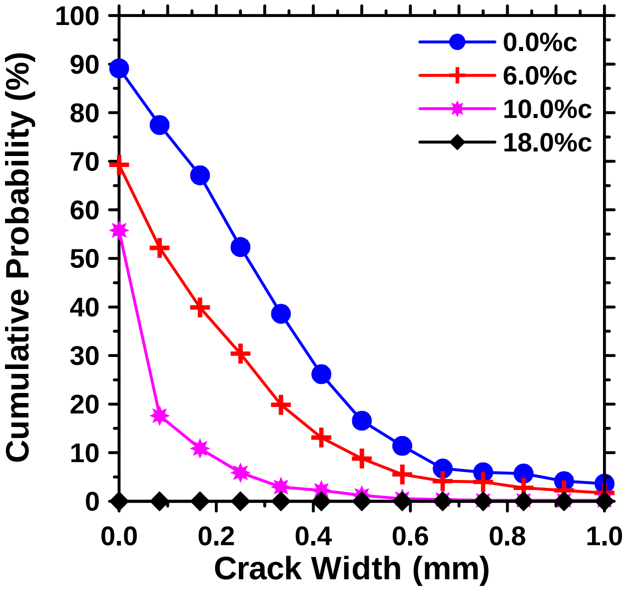

Figure 6 – Cumulative distribution of crack width occurrences in concretes with different replacement volumes of LWA (25.4 mm = 1 in).

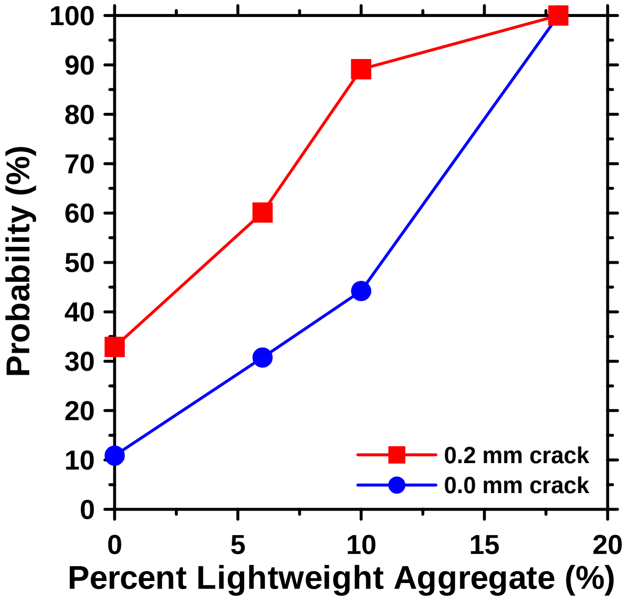

Figure 7 – Probability of cracks widths being smaller than 0.0 mm (0.0 in) and 0.2 mm (0.008 in) for concretes with different LWA replacement volumes.

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Table 1 – Mixture proportions for mortar mixtures

Material	0.0%m	11.0%m	18.3%m	23.7%m	33.0%m
Cement (kg/m^3)^A	728	728	728	728	728
Water (kg/m^3)	218	218	218	218	218
Fine Aggregate (kg/m^3)	1418	1135	950	808	567
Dry LWA (kg/m^3)	0	172	285	369	515
Additional Water Provided by LWA (kg/m^3)	0	18	30	39	54

^{A}1 kg/m^3 = 1.686 lb/yd^3

Table 2 – Mixture proportions for concrete mixtures

Material	0.0%c	6.0%c	10.0%c	18.0%c
Cement (kg/m^3)^A	461	461	461	461
Water (kg/m^3)	254	254	254	254
Fine Aggregate (kg/m^3)	774	619	518	309
Coarse Aggregate (kg/m^3)	825	825	825	825
Dry LWA (kg/m^3)	0	94	154	281
Additional Water Provided by LWA (kg/m^3)	0	9.8	16.2	29.5

^{A}1 kg/m^3 = 1.686 lb/yd^3

Table 3 – Crack reducing ratios for concretes made with different LWA replacement volumes

Volume of LWA	Avg. Cr. W. (mm)	Avg. Cr. W. (in)	CRR (%)
0.0%c	0.49	0.019	0
6.0%c	0.20	0.008	65
10.0%c	0.05	0.002	89
18.0%c	0.00	0.000	100