



Volume change and cracking in internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed conditions

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ABSTRACT

Low water to cement ratio (w/c) concrete exhibits increased occurrences of early-age shrinkage cracking. These occurrences have spawned innovative developments in concrete mixture design that reduce the risk of cracking. One such development is internal curing, which utilizes the inclusion of saturated lightweight aggregate (SLWA). The SLWA supplies additional moisture to cement paste as it hydrates thereby counteracting the effects of self-desiccation. This paper presents results from a study that examined mortar systems with different volumes of SLWA under sealed and unsealed conditions. Specifically, the results indicate the influence of SLWA volume and type on the internal humidity, autogenous shrinkage, and restrained shrinkage cracking behavior. The performance of each system is shown to be related to the cavitation of vapor-filled space in the paste, the SLWA spacing, and the pore structure of the paste in relation to the LWA.

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1. Introduction

High-performance concrete (HPC) mixtures have been increasingly promoted for use due to potential long-term benefits in performance [1]. HPC mixtures generally have a low water-to-cement ratio (w/c) and may contain fine supplementary cementitious materials, (e.g., silica fume). While the fine pore system is beneficial for increased strength [2] and reduced fluid transport [3,4], the finer pore network can lead to increased volumetric changes in sealed systems due to self-desiccation. This volume change is problematic as it can result in cracking if the concrete is restrained from shrinking freely.

Several strategies exist to mitigate autogenous, such as the use of expansive cements [5,6], the addition of shrinkage-reducing admixtures [7–10], or the incorporation of water saturated inclusions [11–15]. The use of saturated lightweight aggregate (SLWA, known as internal curing (IC)), enables water from the SLWA to be supplied to the paste [16], thereby reducing the effects of self-desiccation. The behavior of SLWA systems is the primary focus of this study.

While several studies have shown the beneficial effects of IC on the shrinkage reduction of high-performance mixtures, few studies have investigated the role of SLWA volume fraction thoroughly [12,17]. While many studies have focused on systems with sealed

curing, a recent state-of-the-art report [18] describes how more research is needed to understand the performance when the specimens are exposed to drying. This study provides a substantial data set based on the measured performance of SLWA systems under sealed and drying curing conditions. The performance of SLWA systems is related to fundamental aspects of the pore structure of the paste, the pore structure of the SLWA, and the spacing of the SLWA.

2. A review of the fundamentals of internal curing

As previously stated, water is released from the SLWA when it is used for internal curing. As such, the IC depends on three main factors: (1) the volume of water available for IC, (2) the ability of the water to leave the SLWA when needed for IC, and (3) the distribution of the SLWA so that it is well-dispersed and its water can readily travel to all of the sections in the paste where it is needed. This section provides a brief overview of each of these topics.

2.1. Volume of water needed to alleviate shrinkage caused by self-desiccation

In order to determine the total volume of water that is needed for IC, two terms must be defined, chemical shrinkage and autogenous shrinkage.

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Chemical shrinkage, the primary cause of autogenous shrinkage and self-desiccation, is a naturally occurring process that has been known for over 100 years [19–21]. Chemical shrinkage describes the total volume reduction of the cement system occurring during hydration of cement [22], since the volume of the hydration products is less than the volume of the reactants. It has been reported that this reduction can be as much as 8–10% by volume in a mature paste [23,24]. Chemical shrinkage describes the total volume reduction of the system and is typically measured by placing cement paste in water and measuring the volume change of the cement–water system [25]. This is a key feature as water is able to permeate the paste thereby enabling the total volume change to be measured (in systems that are not influenced by the depercolation of the paste's capillary porosity) [25]. A typical chemical shrinkage result is shown in Fig. 1 for a paste with w/c of 0.30 by mass fraction (made with the same cement as used in this study). While the buoyancy measurement technique was used here [22], other procedures could be used such as the ASTM C1608 standard test method for the measurement of chemical shrinkage [26].

Autogenous shrinkage can be described as the external volume reduction of a cement paste as it hydrates [27]. Before set, the volumes of chemical shrinkage and autogenous shrinkage are the same. This occurs since the system is fluid and collapses on itself as it shrinks [22,28,29]. At the time of set, however, the volumes of chemical shrinkage and autogenous shrinkage diverge, as shown in Fig. 1 [30]. The solidification of the matrix prevents the bulk system from shrinking at the same rate as chemical shrinkage. This results in an underpressure in the fluid that eventually cavitates vapor-filled space in the pore system [31]. As hydration proceeds, these voids grow and penetrate smaller and smaller pores. The internal relative humidity can be measured in these concretes to assess the pressure that develops in the fluid.

The concept in using SLWA for IC is that the SLWA can be used as internal reservoirs that can reduce the pressure in the pore fluid by 'replenishing the vapor-filled voids,' effectively eliminating their creation within the hydrating cement paste. While strictly speaking, the volume of water that is needed is only the difference between these curves, accounting for the behavior prior to set will generally be only a minor correction and may be unnecessary for field applications. Therefore, the volume of chemical shrinkage may be approximated as the volume of water that needs to be supplied by the IC agent.

Bentz and Snyder [11] used this principle to develop a method to estimate the volume of IC water that is needed and the mass of lightweight aggregate (LWA) that is needed to hold the IC water [11,32]:

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

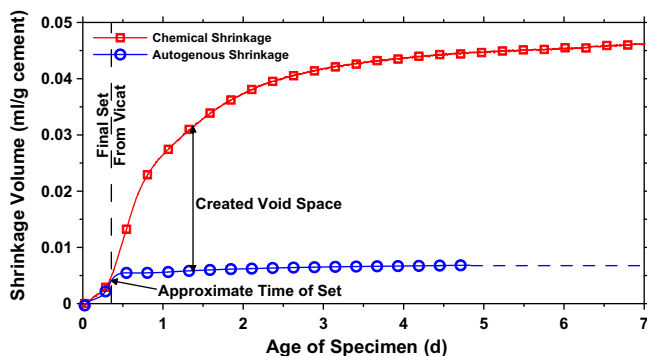


Fig. 1. Chemical shrinkage and autogenous shrinkage volumes during hydration of a paste with a w/c of 0.30 [30].

where M_{LWA} (kg/m^3) is the mass of LWA (in a dry state) that needs to be saturated to provide water to fill in the voids created by chemical shrinkage, C_f (kg/m^3) is the cement content of the mixture, CS (mL of water per g of cement) is the chemical shrinkage of the cement, $\alpha_{\max}$ (unitless) is the expected maximum degree of hydration (0–1), S (unitless) is the expected degree of saturation of the LWA (0–1) and was taken to be one in this study when the LWA was soaked for 24 h, and ϕ_{LWA} (kg of water/ kg of dry LWA) is the absorption capacity of the LWA (taken here as the 24 h absorption). An absorption period of 24 h was chosen to represent “saturated” conditions in this study since this is the absorption value which is commonly used from ASTM C128. Care must be taken when using the term “saturated” when describing LWA. Because of the pore structure of LWA, it is likely that the LWA is not in a truly saturated state. When the term “saturated” is used here, it is referring to a specific degree of saturation [33]. A more correct approach to determining ϕ_{LWA} would be to use the measured desorption capacity of the LWA from saturation down to 92% RH for example, as in an actual concrete, the LWA is initially saturated and undergoes desorption during IC [32].

2.2. Ability of water to leave the LWA

Water leaves the SLWA due to the suction (underpressure) that develops in the pore fluid within the hydrating cement paste due to chemical shrinkage and self-desiccation. The consequence of this water movement from SLWA to surrounding paste is frequently quantified in mortar as an increase in internal relative humidity and an increase in the critical pore size that remains saturated [13,30]. The basic principle for internal curing is that the largest pores will lose water first as the developed capillary stress will be minimized when pores are emptied in this order. The LWA pores are generally larger than the pores of the surrounding cement paste. The pore size distributions of hydrated cement paste at three different ages and of two different LWA were determined using mercury intrusion porosimetry (MIP), the results of which can be seen in Fig. 2. Fig. 2 demonstrates that the pores of both the LWAs used in this study are larger than the pores of the cement paste, even at early hydration ages. It should be noted that the maximum standard deviation of the MIP results for the LWA and the cement paste was 0.03 mL per gram of sample and 0.01 mL per gram of cement, respectively. Another important feature from the MIP pore size distribution is that the pores of the paste decrease in size as the specimen ages (or as hydration continues). As the pores in the paste decrease in size, the capillary pressure

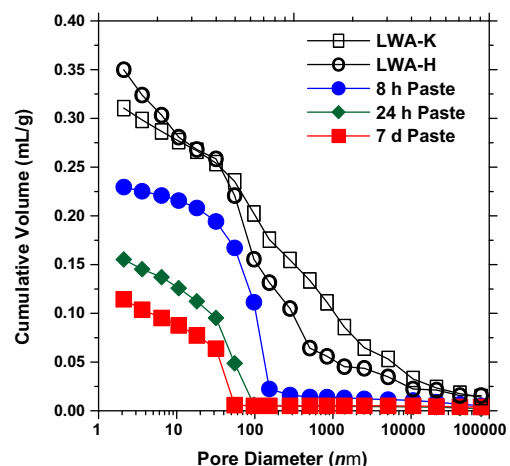


Fig. 2. Pore size distribution for cement paste with a w/c of 0.30 at three different ages and for two different LWA measured using mercury intrusion porosimetry.

that would develop upon their emptying increases, effectively increasing the driving force that pulls water out of the LWA. This implies that as the specimen ages, the hydrating paste can pull water out of successively smaller pores of the LWA. Fig. 3 illustrates desorption isotherms of two LWA (LWA-K and LWA-H). The standard deviation between duplicate samples was 0.3%. A majority of water is lost at a high relative humidity (RH > 96%) implying the pores in the LWA are large and the water is available to be lost at high relative humidities, which is preferred for internal curing. It is also important to note that the samples release almost all (99%) of their moisture when a relative humidity of 92% is reached, which implies that the water will leave the pores of the LWA if a large enough suction pressure (or a low enough internal relative humidity) exists. It should be noted that this favorable desorption behavior is not characteristic of all LWA [13].

The formation of the liquid–vapor menisci in the pores can ultimately lead to shrinkage of the three-dimensional microstructure. These menisci represent a suction pressure that developed in the fluid and is higher than the pressure in the vapor. As a result, the radius of curvature of the meniscus (critical Kelvin radius) that develops can be approximated as the size of the largest pore that is still saturated. The Young–Laplace equation can be used to relate the size of the menisci to the capillary pressure (Eq. (2)):

$$\sigma_{cap} = -\frac{2\gamma \cos(\theta)}{r} \quad (2)$$

where σ_{cap} (Pa) is the capillary pressure, γ (N/m) is the surface tension of pore fluid, θ (radians) is the liquid–solid contact angle (assumed to be zero radians), and r (m) is the radius of curvature of the meniscus or the pore size. It can be argued that the smaller meniscus radius in the low w/c mixtures corresponds to a higher capillary pressure, resulting in higher shrinkage. The capillary pressure can also be related to the internal equilibrium relative humidity as represented by Kelvin's equation (Eq. (3)):

$$\sigma_{cap} = \frac{RT \ln(RH)}{V_m} \quad (3)$$

where R is the universal gas constant (8.314 J/mol K), T (K) is the thermodynamic temperature, RH (%) is the internal relative humidity, and V_m ($\approx 18 \times 10^{-6}$ m³/mol) is the molar volume of pore solution. The capillary pressure that develops can be related to material behavior such as the shrinkage strain, ϵ_p , using a modified version of Mackenzie's formula which is described in Eq. (4) [34]:

$$\epsilon_p = \frac{S}{3} \sigma_{cap} \left(\frac{1}{K} - \frac{1}{K_s} \right) \quad (4)$$

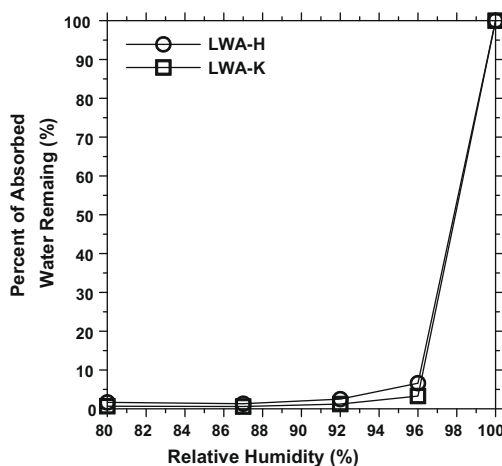


Fig. 3. Desorption isotherm of two different LWA.

where S (unitless) is the degree of saturation of the cement paste, K (Pa) is the paste's or mortar's bulk modulus, and K_s (Pa) is the modulus of the solid skeleton of the cement paste or mortar. Though Eq. (4) describes the shrinkage of the paste, the shrinkage of concrete can be described using Pickett's equation [30]. The continued consumption of water due to hydration results in the volume of vapor-filled voids progressively increasing and extending into smaller voids, corresponding to smaller radii of curvature. This results in a continuous increase in the capillary pressure, a reduction in the equilibrium relative humidity, and an increase in autogenous shrinkage.

As previously mentioned, the largest pores will empty first so that the LWA acts as a sacrificial water reservoir that can be used to replenish the pores of the paste. This concept is illustrated in Fig. 4 [12,35]. In a sealed system without LWA, pores smaller than a specific size (r_1) will remain saturated. In a LWA system, the emptying pores can be replenished from water in the LWA, provided the water is stored in a larger pore (r_2). It should be noted that this is for conceptual purposes and that the pores of the LWA may eventually empty, depending on the extent of self-desiccation/hydration. However, in that case, the size of the pores that are still saturated will be larger in the LWA system than in the system without LWA.

2.3. LWA spacing

Knowing how much water is needed for IC (Section 2.1) and knowing how much of that water will likely leave the aggregate (Section 2.2), the last issue that needs to be understood is the distribution of the SLWA throughout the microstructure. Even if a sufficient volume of water is supplied to a system, as determined from Eq. (1), if the distribution of the water (i.e., SLWA) is insufficient, the system will likely exhibit poor shrinkage performance. This has been shown by comparing the effectiveness of coarse SLWA and fine SLWA when the same volume of water is considered [36,37]. Though the volume of water may be the same, the distribution of the SLWA particles will be much different, resulting in

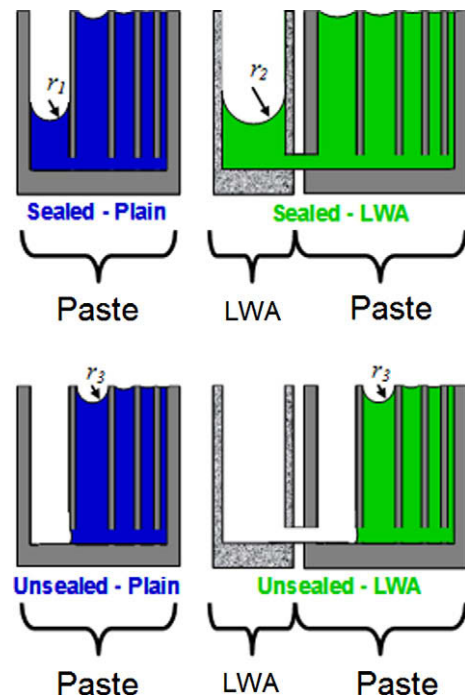


Fig. 4. Conceptual illustration of the menisci formation in sealed and unsealed specimens made of plain and SLWA concrete.

a different volume of protected paste (i.e., the volume fraction of the paste within a given distance from a SLWA particle). The coarse SLWA proved to be less effective than the fine SLWA even though they had the same volume of water because of the increased spacing between the aggregate.

The concept of protected paste volume can also be applied when different volumes of fine SLWA are considered. For a constant LWA particle size distribution, when the volume of SLWA is increased, not only is the volume of water increased, but the distribution of water is also improved, which results in a larger fraction of protected paste. The effect of different volume replacements on the protected paste volume was simulated using the hard core/soft shell model developed at the National Institute of Standards and Technology (NIST) [38–40]. The results of the simulations for the mortars investigated in this study are shown in Fig. 5. Fig. 5 describes the volume fraction of cement paste that is within a given distance from the surface of a SLWA particle. It is not intended to show that the paste is protected by internal water stored in the SLWA, since properties like absorption and desorption of the aggregate as well as paste permeability would have to be known to determine whether the water in the SLWA could reach the paste. As the volume replacements are increased, the fraction of paste within a specified proximity of a SLWA also increases. When lower replacements are incorporated in a mixture, there is a rapid increase in the fraction of paste within 1.0 mm of a SLWA particle. At low replacement volumes, if the water in the SLWA can travel

up to 1.0 mm, a majority of the paste will be protected. When higher replacement volumes are used, a larger fraction of paste is within 0.20 mm, which may be important at later ages [10]. This is because water cannot travel as far in a mature paste, and the distribution of the SLWA becomes important. This implies that if water is able to travel a large distance, a low replacement volume can protect a majority of the paste (assuming the SLWA can provide enough water). However, if the water cannot travel large distances, a higher replacement volume is needed to protect a majority of the paste.

3. Difference between the drying mechanisms in sealed and unsealed systems

3.1. Sealed system

As previously discussed, vapor-filled spaces are created in the paste due to chemical shrinkage, as shown in Fig. 6a. The creation of vapor-filled spaces results in the reduction of the internal relative humidity of a sealed sample, called self-desiccation, and could be considered similar to ‘internal drying’. In low w/c mixtures, the radius of curvature of these vapor-filled voids would be smaller than in higher w/c mixtures due to the decreased interparticle spacing, resulting in a significant shrinkage-inducing capillary tension (σ_{cap}) from Eq. (2).

3.2. External drying

For an unsealed specimen that loses moisture externally, liquid–vapor menisci also form [35]. However, in this case, they form at the surface of the concrete. This is schematically shown in Fig. 6b and c. Fig. 6b shows a hypothetical case in which only external drying occurs and self-desiccation is not included. Fig. 6c shows a more realistic picture of a cement paste that is unsealed at one surface. In this case, while external drying occurs at the exposed surface, self-desiccation develops throughout the interior of the material. This suggests that while a sealed specimen only experiences internal drying (Fig. 6a), an unsealed system would simultaneously undergo both internal and external drying (Fig. 6c).

The formation of a liquid–vapor menisci corresponds with a reduction in the internal relative humidity of cement paste. In an unsealed specimen, as moisture evaporates from the surface, the radius of the menisci continues to decrease. This causes the drying front to penetrate into smaller openings and to gradually grow from the surface towards the interior of the material. The internal relative humidity is proportional to the menisci radius and thus decreases continuously as drying progresses until the internal relative humidity of the cement paste reaches equilibrium with the

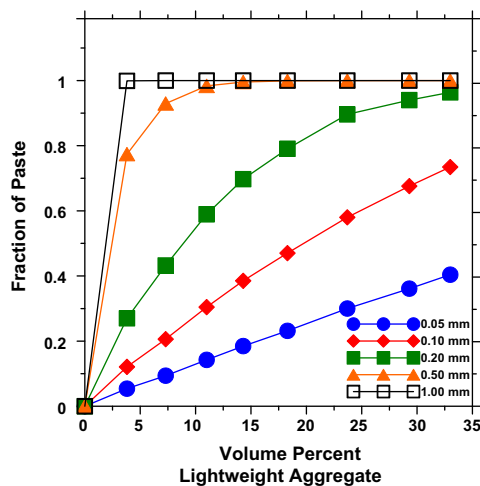


Fig. 5. Volume fraction of paste within a specified distance of a SLWA. This plot does not show whether water can reach the paste. Volume and travel distance of water need to be considered to determine this.

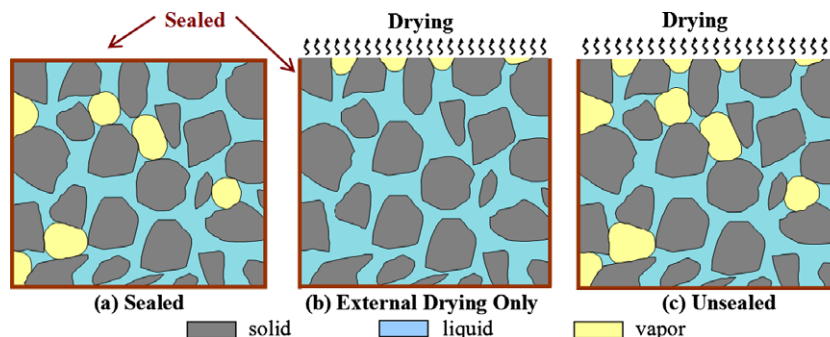


Fig. 6. Illustration of drying mechanisms in sealed and unsealed systems: (a) sealed – only internal drying, (b) only external drying, and (c) unsealed – internal plus external drying.

ambient relative humidity. Since any system will ultimately come to equilibrium with the ambient relative humidity, this will occur at an equal pore radius (r_3), as illustrated in Fig. 4. In an IC concrete however, the water must leave the LWA first, which could result in a reduction in the rate of shrinkage.

4. Materials

ASTM C150 Type I ordinary portland cement (OPC) was used, with a Blaine fineness of 370 m²/kg and an estimated Bogue composition of 56% C₃S, 16% C₂S, 12% C₃A, 7% C₄AF and a Na₂O equivalent of 0.68%, all by mass fraction.

A high-range water-reducing admixture (HRWRA) was added in varying rates depending on the volume fraction of LWA replacing normal weight sand. For LWA replacement volume fractions up to 7.3%, the HRWRA was added at a dosage of 0.44 g per 100 g of cement. For replacement volume fractions of 7.3–23.7%, the HRWRA was added at a dosage of 0.50 g per 100 g of cement. For replacement volume fractions larger than 23.7%, 0.66 g per 100 g of cement was used. Different rates of HRWRA were used to keep similar consistencies of these mixtures.

The normal weight sand used was natural river sand with a fineness modulus of 2.71 and a specific gravity of 2.58. Portions of the normal weight sand were replaced with two manufactured rotary kilned expanded shales (LWA-K and LWA-H), with a fineness modulus of 3.10 and a specific gravity of 1.56. The 24 h absorption of the normal weight sand, LWA-K and LWA-H were determined to be 1.8%, 10.5% and 5.8% by mass, respectively, according to ASTM C128-07 [26]. The desorption isotherms for the LWA can be found in Fig. 3.

4.1. Mixture proportioning

Eleven different mixtures were prepared with an effective w/c of 0.30: this included a plain mortar mixture designated as 0.0% and 10 mortar mixtures with varying amounts of sand replaced by saturated LWA, as shown in Table 1. Two types of LWA were used (LWA-K and LWA-H). The LWA-K expanded shale was used for eight of these mixtures which were designated as 3.8%k, 7.3%k, 11.0%k, 14.3%k, 18.3%k, 23.7%k, 29.3%k and 33%k. The LWA-H expanded shale was used for the remaining two mixtures designated as 23.7%h and 43%h. It is important to note that the designations are on a total volume basis. The volume of aggregate (LWA and 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). The mixture proportions for each mixture are illustrated in Fig. 7.

It should be noted that the 23.7%k and 43%h volume replacements correspond to the amount of LWA necessary to eliminate self-desiccation proposed in Eq. (1) [11,32]. The different volumes required for the two aggregates arise from the fact that the LWA-K can absorb more water (10.5%) in a similar time period as compared to the LWA-H (5.8%). For this reason, a lower volume of LWA-K was needed to provide the same volume of IC water. This

can be noticed by observing the last line in Table 1, where the additional water provided for the 23.7%k and 43%h mixtures are the same. It is also important to note that one mixture was prepared so that the replacement volume of LWA-K and LWA-H were the same (23.7%k and 23.7%h). However LWA-K absorbs more water in 24 h (10.5%) than LWA-H (5.8%), the volume of IC water for the 23.7%k was more than that for the 23.7%h. Because of the absorption difference between LWA-K and LWA-H, the volume of IC water for the 23.7%h was similar to the 14.3%k mixture, though a smaller volume of aggregate was used.

4.2. Mixing procedure

The mixing procedure used was in accordance with ASTM C192-06. The LWA was oven dried, air cooled, and then submerged in water for 24 ± 1 h prior to mixing. The volume of water used to submerge the LWA included both mixing water and the water the LWA would absorb in 24 h. The excess water (water not absorbed in 24 h) was then decanted and used as the mixing water. The sand was oven dried and cooled for 24 h before mixing.

5. Experimental methods

5.1. Measurements of unrestrained volumetric change during the first 24 h

The autogenous deformation of the mortar specimens during the first 24 h was measured using the corrugated tube protocol [22,41]. This procedure consists of placing fresh mortar (approximately 15 min after water is added to the mixture) in a corrugated polyethylene tube. The length and diameter of the tube was 400 mm and 30 mm, respectively. The shrinkage strain is measured using two LVDTs. The typical standard deviation after set between two duplicate specimens was 4 µε (microstrain). For each mixture tested, two corresponding corrugated tubes were measured. The specimens were placed in a dilatometer that was maintained at 23 ± 1 °C. The transducers were connected to a PC for automated length measurements every 5 min for the first 7 d.

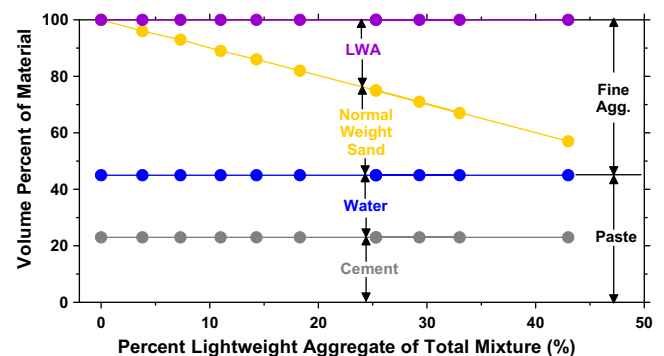


Fig. 7. Mixture proportions on a volumetric basis.

Table 1
Mixture proportions.

Material	0.0%	3.8%k	7.3%k	11.0%k	14.3%k ^a	18.3%k	23.7%k ^b	29.3%k	33.0%k	23.7%h ^a	43%h ^b
Cement (kg/m ³)	728	728	728	728	728	728	728	728	728	728	728
Water (kg/m ³)	218	218	218	218	218	218	218	218	218	218	218
Fine aggregate (kg/m ³)	1418	1319	1230	1135	1050	950	808	667	567	808	310
Dry LWA (kg/m ³)	0	60	114	172	223	285	369	455	525	369	670
Additional water provided by LWA (kg/m ³)	0	6	12	18	23	30	39	48	54	22	39

^a Denotes an equal volume of water supplied by the 14.3%k and 23.7%h mixtures.

^b Denotes an equal volume of water supplied by the 23.7%k and 43%h mixtures.

5.2. Measurements of unrestrained volumetric change and mass loss after 24 h

Free shrinkage was measured using $75\text{ mm} \times 75\text{ mm} \times 285\text{ mm}$ prisms according to ASTM C157-04 [42]. Three samples for the sealed condition and three samples for the unsealed condition were prepared. The sealed samples were encased in aluminum tape on all sides. The unsealed samples were sealed on two opposite faces so that they could be directly compared to the restrained shrinkage measurements described in the next section. The length was measured using a comparator beginning 24 h after casting. The unrestrained volumetric change from the tube protocol for the first 24 h was added to the prism measurements. The typical standard deviation for unrestrained shrinkage between triplicate specimens was $20\text{ }\mu\text{ε}$. The mass loss was recorded for both sealed and unsealed conditions. The mass loss for the sealed samples was measured to ensure a sealed state was maintained during testing. The mass loss measurements for the unsealed samples can be used to monitor the extent of drying (water loss) that has occurred. The typical standard deviation for mass loss between triplicate specimens was 0.80 g .

5.3. Measurements of restrained shrinkage

The restrained shrinkage cracking potential was measured using the restrained ring test, in accordance with ASTM C1581-04 [43,44]. Three samples of each mixture were measured. Before casting, molds were conditioned in an environmental chamber at a temperature of $23.0 \pm 0.1\text{ }^{\circ}\text{C}$. Each ring was cast in two layers with each layer being vibrated for 15 s. After casting, all samples were kept sealed for 24 h in an environmental chamber at a constant ambient temperature of $23.0 \pm 0.1\text{ }^{\circ}\text{C}$ before they were demolded. After demolding the rings, the sealed ring specimens were sealed with aluminum tape. The unsealed ring specimens were exposed to $50 \pm 0.1\%$ 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). Restrained shrinkage data was measured and collected at 5 min intervals. The typical standard deviation for restrained shrinkage between triplicate specimens was $4\text{ }\mu\text{ε}$ [45].

5.4. Internal relative humidity measurement of sealed specimens

To measure changes in the internal relative humidity of a sealed sample over time, specimens without normal weight sand were cast in plastic containers which were demolded at an age of 12 h. Approximately 10 g of the sample was crushed and placed in a glass container with a diameter of 25 mm and a length of 50 mm and sealed to prevent loss of moisture. The sealed glass container was kept in an environmental chamber at a constant temperature of $23.0 \pm 0.1\text{ }^{\circ}\text{C}$. A temperature and relative humidity meter was used to record relative humidity and temperature data inside the sealed container at 2 h intervals for 7 d. The standard deviation for relative humidity measurements was 1.1%. The sensor was calibrated using saturated salt solutions with known relative humidities in the range of 75–100% (ASTM E104-02) [46].

6. Experimental results and discussion

6.1. Effect of internal curing with different LWA volume replacements on free shrinkage

6.1.1. Sealed curing conditions

The results of free shrinkage tests performed on the plain mixture along with the mixtures containing LWA-K during the first 7 d

and first 28 d are shown in Figs. 8 and 9, respectively. When a lower replacement volume of LWA is used (7.3%k and 11.0%k), the performance is similar to that of a plain mixture [17]. When higher volume replacements are used (14.3%k, 18.3%k, 23.7%k, 29.3%k, and 33.0%k), after the initial expansion, the mixtures remain nearly volumetrically stable. The expansion in these materials during the first hours could be due to osmotic pressure or the formation of ettringite, however no experimental data exists to confirm this. Other researchers have seen similar expansions at early ages [24,29,47].

The shrinkage can be more thoroughly explained if the volume of void creation is considered as shown in Fig. 10. The volume of chemical shrinkage minus the volume of autogenous shrinkage is the approximate volume of voids created in the cement paste.

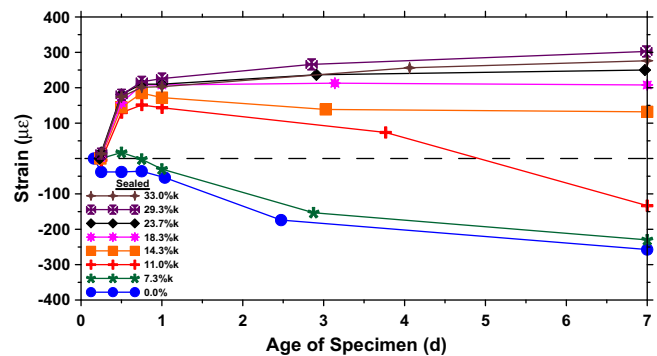


Fig. 8. Free shrinkage results of plain and LWA-K mortar mixtures in sealed curing conditions during the first 7 d.

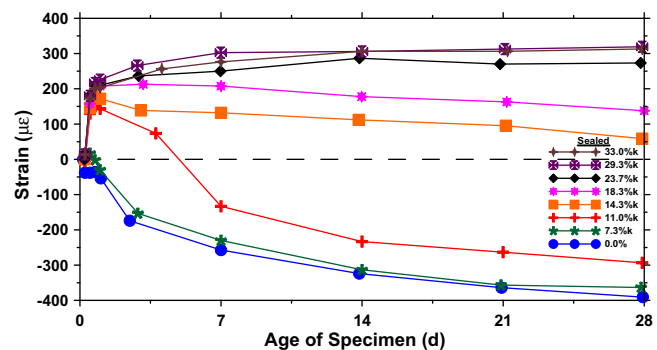


Fig. 9. Free shrinkage results of plain and LWA-K mortar mixtures in sealed curing conditions.

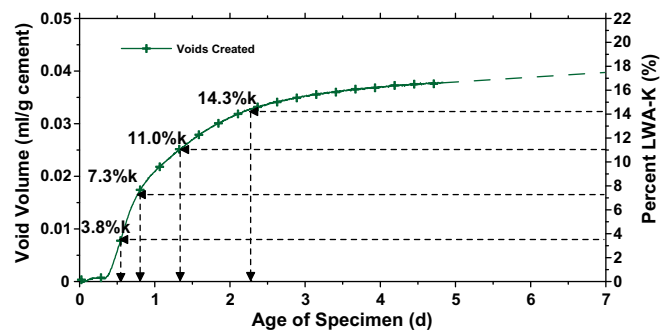


Fig. 10. Void creation in cement paste and the time when water depletes from the LWA-K as volume replacements increase. The 18.3%k, 23.7%k, 29.3%k and 33.0%k mixtures don't deplete of water before 7 d.

The volume of water supplied in the LWA can only fill in voids until all the water in the LWA is depleted. Even if voids are created, the water may not leave the LWA. This could be because the internal relative humidity is not low enough to pull the water from the LWA. When water no longer leaves the LWA, the pores of the paste will begin to empty and significant shrinkage is induced. An explanation for the similar performances of lower replacement volumes could also be explained by their having lower protected paste volume fractions (Fig. 5). This is not to say that lower replacement volumes of LWA are not beneficial. The 11.0%k mixture has a substantially lower rate of shrinkage during the first 7 d. The lower rate of shrinkage could provide enough time for sufficient strength to develop to resist cracking. Indeed, it will be demonstrated later that lower replacement volumes have beneficial effects in re-strained shrinkage.

Fig. 11 can be used to provide a better explanation for the shrinkage that occurs in the mixtures with replacement volumes lower than 18.3%k. This plot shows when the water is expected to deplete from the LWA based on Fig. 10 along with when the mixtures 'begin to shrink' as measured by the corrugated tubes and sealed prismatic specimens. What is meant by 'begin to shrink' is when the mixture first begins to shrink after its initial expansion, not when the mixture actually shows a negative (<0) value of strain in Figs. 8 and 9. From Fig. 11, the times at which the water depletes (from Fig. 10) and when shrinkage occurs in these lower replacement volume mixtures are similar, though not exactly the same. It is expected that the time at which shrinkage would begin would actually occur at a slightly earlier time since all the IC water may not be available in the actual measurements though it is assumed to completely be so in Fig. 10. The time at which water depletes (from chemical shrinkage) and the time to the beginning of shrinkage is very similar for low replacement volumes (<14.3%), however, when the volume replacement is larger, the curves diverge.

Another important feature to note is that there is not a significant benefit of using replacement volumes larger than that needed to eliminate self-desiccation (23.7%k) in the sealed case; however, in the drying case to be presented subsequently, some additional

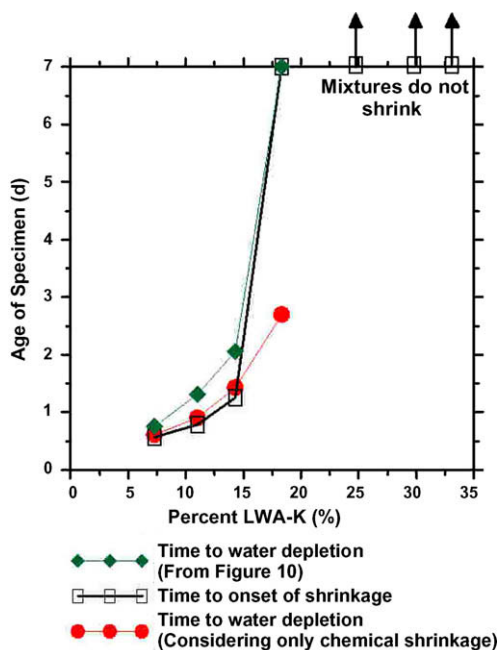


Fig. 11. Time of water depletion from the SLWA versus the time when the mixtures begin to shrink as measured by the corrugated tubes and sealed prisms.

benefits can be observed. The volume and distribution of water in the 23.7%k mixture is sufficient to eliminate self-desiccation. The additional water provided by the 29.3%k and 33.0%k mixtures would have no voids to fill in the paste and some IC water would simply remain stored in the LWA.

To better understand the effectiveness of these systems, the 7 d free shrinkage was plotted against the replacement volume of LWA-K, as shown in Fig. 12. When a lower replacement volume (7.3%k) is used, the shrinkage is very similar to that of the plain mixture. When larger replacement volumes are used, the system becomes more effective in decreasing the shrinkage.

6.1.2. Unsealed curing conditions

Fig. 13 shows the average unrestrained length change from three replicate samples of each mixture exposed to drying. The first 24 h of the unsealed specimens are the same as the sealed specimens (Fig. 8). After 24 h, the specimens were exposed to drying. As expected, the plain mixture shows the most shrinkage during the first 28 d. The 7.3%k mixture performed similar to the plain mixture. The 11.0%k mixture has a large expansion during the first day, however when the sample was exposed at 24 h, it shrinks rapidly. After 28 d of testing, the 11.0%k mixture has a similar shrinkage performance as the plain mixture. As the LWA replacement volume is increased, the shrinkage performance improves.

Fig. 12 shows the 7 d free shrinkage of the unsealed samples. Low replacement volumes proved to be ineffective in mitigating

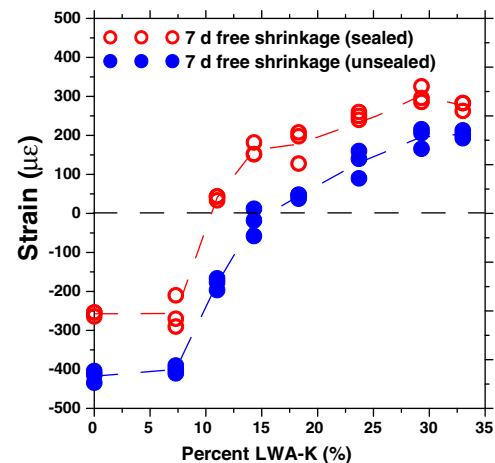


Fig. 12. Seven days free shrinkage measurements plotted as a function of the replacement volume of LWA-K (three samples are shown for each mixture).

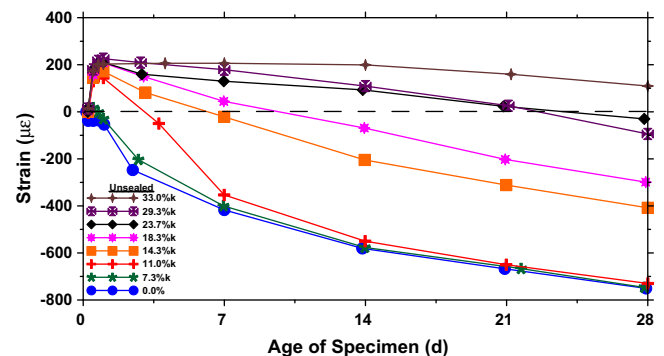


Fig. 13. Free shrinkage results of plain and LWA-K mortar mixtures in unsealed curing conditions.

shrinkage caused by the combined effects of external and internal drying. However, when the replacement volume is increased beyond a critical level, the shrinkage is decreased. When high replacement volumes are used, the benefits are similar in Fig. 12.

The mass loss of the LWA-K samples during testing can be seen in Fig. 14. The larger the replacement volume the more mass loss occurred. This general trend can be seen in Fig. 15. This is what would be expected since there is more total (mixture and IC) water which can be lost as drying progresses.

6.2. Effect of internal curing with different LWA volume replacements on restrained shrinkage

6.2.1. Sealed curing conditions

The results of the restrained shrinkage tests performed in the plain mixture along with the mixtures containing LWA-K expanded shale are shown in Fig. 16 for the sealed samples. When small volume replacements of LWA are incorporated, only a small beneficial effect can be observed. For example, the 0.0% mixture cracked on the sixth day while the mixture containing 3.8% LWA cracked at 7.5 d and the 7.3% mixture cracked at 12 d. The LWA mixtures show a decreasing residual strain at the time of cracking. This may be due to a reduced strength or elastic modulus. When larger replacement volumes are used, it can be seen that cracking can be substantially reduced. Testing of the 14.3% mixture was stopped after 19 d (with only a residual strain of $-13 \mu\epsilon$). Testing of the 23.7% mixture was stopped after 13 d and had not developed any residual strain (likely due to a slight expansion). It should be noted that the strain measured using the

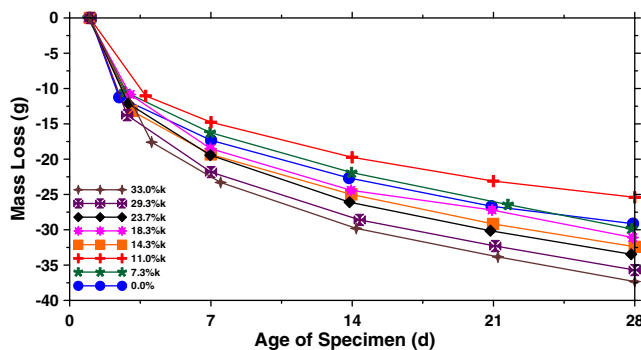


Fig. 14. Mass loss of LWA-K free shrinkage samples in unsealed curing conditions.

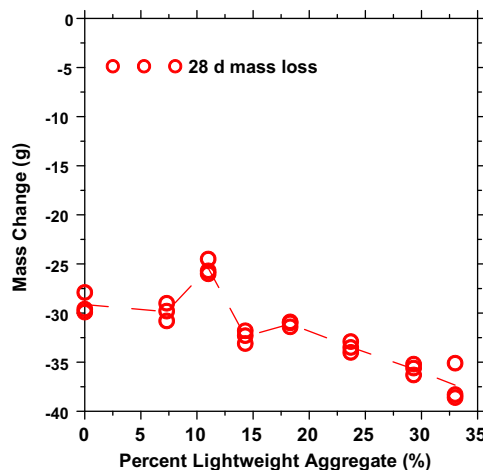


Fig. 15. Twenty eight days mass loss measurements for unsealed free shrinkage measurements plotted as a function of the replacement volume of LWA-K.

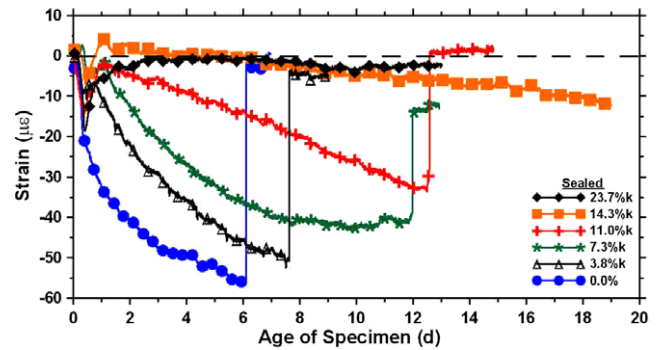


Fig. 16. Restrained shrinkage results of plain and LWA-K mortar mixtures in sealed curing conditions (in each case, a typical response is shown from the three samples tested). Sharp vertical rise in strain curve indicates occurrence of cracking in the specimen.

strain in the steel ring, however this can be approximated as the strain in the mortar [45].

The performance of the mixtures as a function of SLWA replacement volume fraction is presented in Fig. 17 for both sealed and unsealed samples. It can be seen that low SLWA volume fractions crack at an early age, however as the replacement volumes are increased to a sufficient percentage, the time to cracking is greatly extended.

6.2.2. Unsealed curing conditions

Fig. 18 shows the strain measured from the inner surface of the restrained ring. The plain mixture cracks after approximately 2 d. The times to cracking for the mixture with replacement volumes less than 14.3% were similar to that of the plain mixture, though some cracked at a lower strain. This is likely due to water depleted during the first days due to self-desiccation combined with rapid water loss due to evaporation. When a larger replacement volume was used (23.7%), the time to cracking was prolonged to approximately 8 d. With a further increase in the replacement volume (29.3%), cracking was delayed to 14 d. During the 14 d of testing, the 33.0% mixture did not crack and showed little shrinkage strain under these testing conditions.

The performance of the mixtures as a function of SLWA volume fraction is presented in Fig. 17. It can be seen that low SLWA volume fractions crack at an early age; however as the replacement

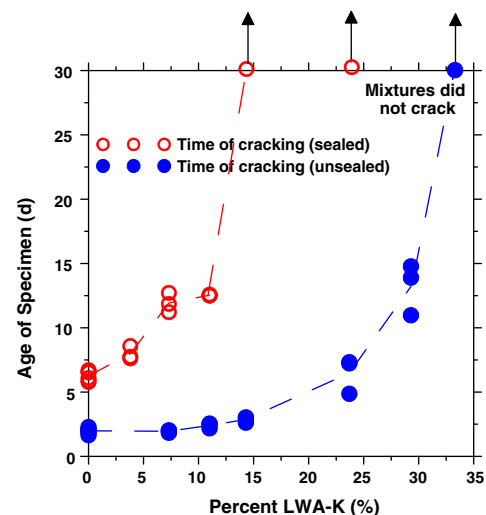


Fig. 17. Time of cracking in LWA-K mixtures plotted as a function of replacement volume (three samples are shown for each mixture).

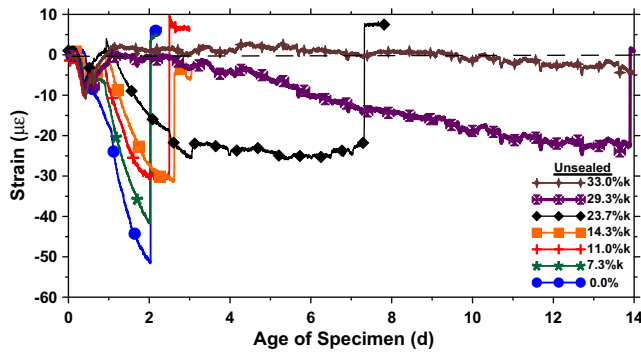


Fig. 18. Restrained shrinkage results of plain and LWA-K mortar mixtures in unsealed curing conditions (in each case, a typical response is shown from the three samples tested). Sharp vertical rise in strain curve indicates occurrence of cracking in the specimen.

volumes are increased to a sufficient percentage, the time to cracking is greatly extended or cracking is eliminated. Fig. 19 shows the strain at cracking for both the unsealed and sealed curing conditions. The strain at cracking for each mixture at low replacement volumes is the same regardless of the curing condition [48] (i.e., strain at cracking for the 11.0%k mixture is the same in both sealed and unsealed curing conditions). The mixtures for which the strains do not match are the mixtures that did not crack in sealed curing conditions. It is expected that if the strain for the sealed samples that did not crack (14.3%k and 23.7%k) were to approach the strain experienced by the unsealed samples, they would crack. It can be said that the curing condition does not have an effect on the strain at a cracking event.

6.3. Effect of internal curing with different volume replacements on internal relative humidity

Fig. 20 shows the internal relative humidity measurements for the LWA-K mixtures. While the specimens employed for measurement of internal relative humidity contained no normal weight aggregates, the cement paste to SLWA proportion was adjusted to be the same as in the corresponding mortar mixtures. As expected, when higher replacement volumes are used, the internal relative humidity remains higher. Again, this is related to the pore size that remains saturated according to Eq. (3). Because the internal relative humidity is higher (thus the pore size that is still satu-

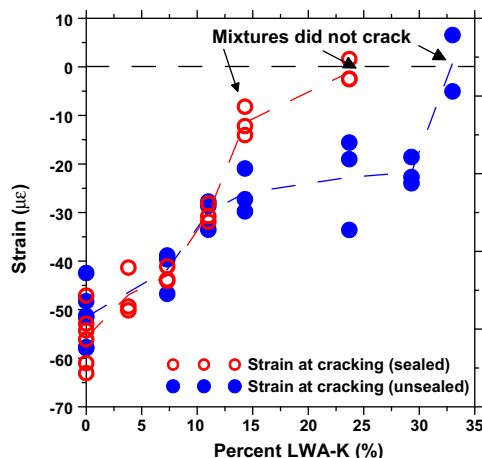


Fig. 19. Strain at cracking in LWA-K mixtures plotted as a function of replacement volume (three samples are shown for each mixture).

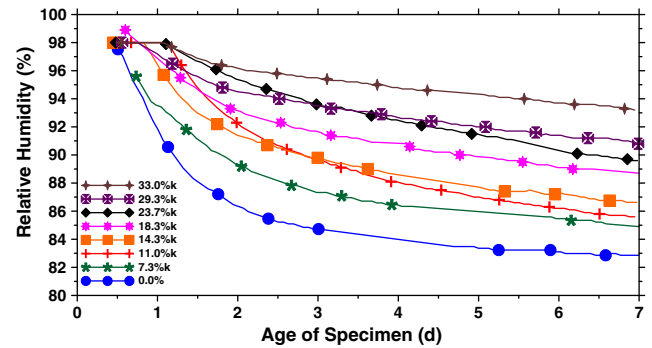


Fig. 20. Internal relative humidity measurements for the sealed LWA-K mixtures.

rated is larger), it would be expected that the shrinkage for higher replacements volumes in sealed curing conditions would be less. The radius of the meniscus for the pore (approximately the pore size still saturated) and the capillary stress are plotted as a function of the replacement volume in Fig. 21. It can be seen that a critical value exists for the replacement volume of SLWA. When high replacement volumes (29.3%k and 33.0%k) are used the pore size which remains saturated becomes larger. This can be used to explain why these mixtures perform significantly better under restrained shrinkage. The capillary stress is reduced with increasing replacement volume.

6.4. Effect of particle spacing on internal curing effectiveness

To show the importance of LWA particle size and spacing on the shrinkage performance of internal curing, a second LWA was tested. The aggregates had similar desorption properties, as seen in Fig. 3, but different absorption volume. This would imply that they would give up water in a similar manner; however the volume of water they could give up would not be the same. The LWA-K had a 24 h absorption of 10.5% while the LWA-H was much lower at approximately 5.8%. Two sets of mixtures were selected for this comparison. The first comparison provided enough water to fill in the voids created by chemical shrinkage. The LWA-K mixture was designated as 23.7%k, and the LWA-H mixture was designated as 43%h. Because the LWA-H absorbed less water, more aggregate was needed. The second comparison would have the same replacement volume of LWA. This mixture was designated as 23.7%h, to be compared against 23.7%k. It should be noted that

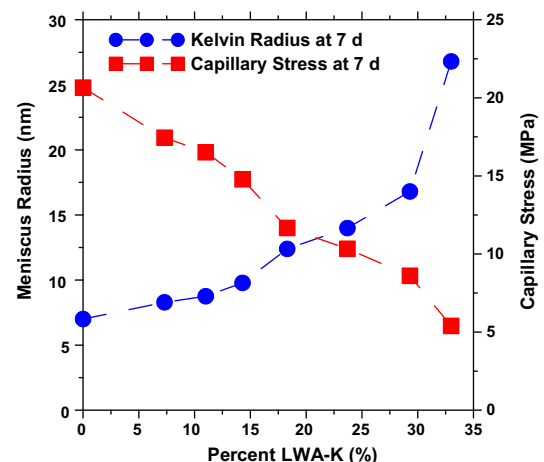


Fig. 21. Kelvin Radius and capillary stress as determined from RH measurements as a function of replacement volume of LWA-K at 7 d.

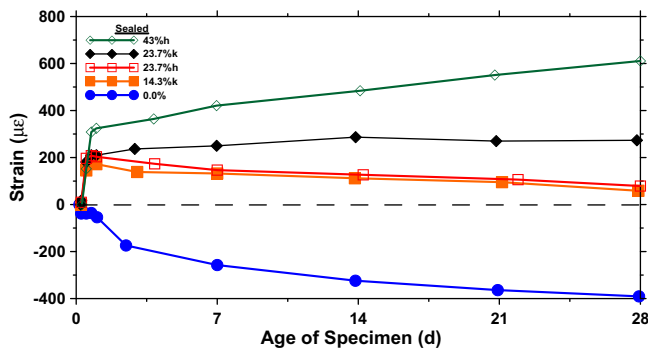


Fig. 22. Free shrinkage results of a comparison between LWA-K and LWA-H LWA in sealed curing conditions.

the 23.7%h mixture provided a similar volume of water as the 14.3%k mixture.

Fig. 22 shows the free shrinkage results for the LWA-K and LWA-H mixtures in sealed curing conditions. It can be seen that when a similar volume of water is supplied (two data sets depicted with diamonds), and when that water is better distributed in the 43%h mixture, the shrinkage performance is better. Fig. 23 shows the restrained shrinkage results for the LWA-K and LWA-H mixtures in unsealed curing conditions. When a similar replacement volume is used (23.7%k and 23.7%h), the strain develops in a similar manner, however the mixture with less water (23.7%h) cracks at an earlier age. This is what would be expected since the mixtures have similar mechanical properties; however the mixture containing LWA-H depletes of water earlier, resulting in earlier

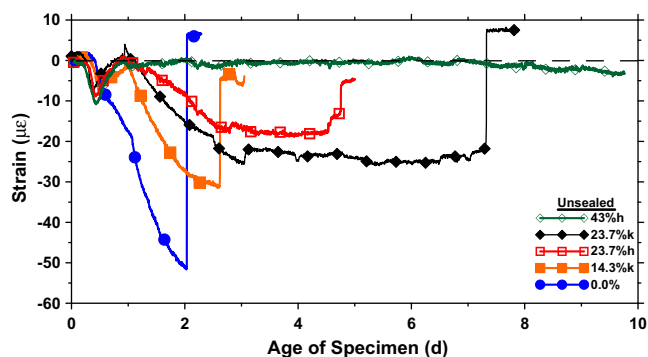


Fig. 23. Restrained shrinkage results of a comparison between LWA-K and LWA-H LWA in unsealed curing conditions.

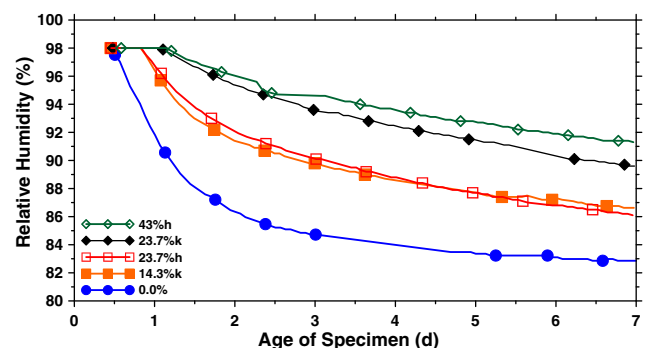


Fig. 24. Internal relative humidity results of a comparison between LWA-K and LWA-H SLWA.

cracking. When similar volumes of water (23.7%k and 43%h) are used, the mixture with more particles and thus a better particle distribution (43%h) performs better. The internal relative humidity tests for these mixtures can be found in Fig. 24. This shows that when similar volumes of water are used, the internal relative humidity is approximately equal, which would imply a similar pore radius that is still saturated.

7. Conclusions

This paper has presented a comprehensive data set that describes the behavior of sealed and unsealed mortars made with SLWA. The paper provides an understanding of what is occurring in the mixtures with different volume replacements of SLWA. The influence of boundary conditions (sealed or unsealed) on the performance of self-curing concrete is described. The inclusion of a sufficient volume of SLWA can significantly reduce self-desiccation, reduce autogenous shrinkage and delay the time of cracking. A summary of the general conclusions from the data presented in this paper are:

Sealed specimens

- Specimens with larger volume fractions of SLWA showed a greater reduction in both the rate of shrinkage and the volume of autogenous shrinkage. This can be attributed to the ability of the SLWA to supply water to the hydrating paste, which acts to reduce the effects of self-desiccation and maintains the internal relative humidity at a higher level.
- Similar free shrinkage and cracking behavior was observed between a plain mixture and mixtures with low volumes of SLWA replacement. This may be due to the fact that the SLWA particles are spaced too far apart to effectively supply water to all the paste or that the IC water supply is depleted too early in the hydration process. The time to cracking can be prolonged if a sufficiently high replacement volume of SLWA is incorporated.
- Self-desiccation results in a reduction in the internal relative humidity of a low water to cement ratio paste. Specimens with a larger replacement volume of SLWA maintained a higher internal humidity as expected.

Unsealed specimens

- The addition of SLWA showed a reduction in the total shrinkage during the first 28 d. This may be due to the initial reduction in self-desiccation and the additional water that can complete hydration and temporarily replace the water that is lost to the environment.
- A larger mass of water was lost for samples with an increasing volume of SLWA. This is consistent with these mixtures having a larger volume of total (mixture and IC) water.
- The time to cracking is prolonged for mixtures with an increasing volume of SLWA. As illustrated in this study, this is likely due to the reduced shrinkage; in addition, although not specifically examined in this study, reduced elastic modulus, increased relaxation, and increased fracture toughness of the mixtures with SLWA could also contribute to this increase in time to cracking.

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