Effect of Fine Lightweight Aggregate on Curling Behavior of Concrete Beams

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Abstract

Addition of saturated lightweight aggregate fines to concrete have demonstrated the ability to enhance hydration, reduce autogeneous shrinkage and permeability, and increase strength. However, no study has yet been conducted on the impact of employing saturated lightweight aggregates in concrete mixtures to reduce concrete moisture curling under external drying conditions. In this study, a set of paving mixtures was cast with and without saturated fine lightweight aggregates. Saturated fine lightweight aggregates were found to reduce the moisture curling of a concrete specimen up to 50% when compared to an identical mixture without fine lightweight aggregates. As the curing duration increased, the moisture curling deformations were also higher albeit with a higher concrete strength. Overall, the addition of saturated fine lightweight aggregates had a substantial and beneficial impact on the moisture curling of concrete slabs.

Keywords: internal curing; moisture curling; lightweight aggregates

Introduction

Concrete slab curling deformations are driven by transient temperature and moisture gradients. At early-ages these temperature and moisture gradients can lead to irreversible curling deformations and strains in the slab, which is sometimes referred to as built-in curling (Beckemeyer et al. 2002; Hansen et al. 2006; Rao and Roesler 2005; Wells et al. 2006). Restrained curling strain gradients produce material tensile stress, which may increase the probability of early- or longer-term slab cracking. Temperature curling is dependent on the local climate and the concrete's thermal and surface properties. Moisture curling is driven primarily by external drying environment adjacent to the free surfaces and internal pore structure. As water is lost to the environment and/or as self-desiccation occurs, the internal suction pressures cause the cement hydration products around the pore to contract (Pickett 1956), leading to high internal material strains. However, maintaining a high level of pore saturation will keep these induced strains at a minimum. While external moist curing can maintain surface pore saturation levels and is considered a necessary component of developing a high quality material (ACI International 2001), other techniques exist to ensure that the pores remain saturated.

Maintaining high levels of pore saturation away from the exposed surface can be achieved through the use of a highly absorptive saturated aggregate in a process commonly known as internal curing. The aggregate for this purpose is usually an expanded version of a mined natural rock such as slate or shale (Bentz and Weiss 2011). While the aggregate can be

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nearly any size and gradation, fine lightweight aggregates (FLWA) are most commonly employed. In addition to the internal curing properties, FLWA do not typically lower the compressive strength and modulus as much as the coarse portion (Lo et al. 2007).

Relatively long moist curing durations have been noted as a preferred method for ensuring adequate strength development in most concrete applications (ACI International 2001). While it is true that longer moist curing durations increase strength and improve surface properties such as hardness and permeability, the effect on the curling behavior of slab systems can be detrimental, as it has been generally noted that longer curing durations can increase slab curling deflections (Farny 2001; Suprenant 2002). For industrial floor design, it has been recommended to moist cure for a duration of three to seven days and then begin a slow drying process (Farny 2001). Since surface durability is an important factor, industrial floors need some moist curing but also a slow drying process to reduce the effect of the moisture gradient. Similarly, recent literature has shown that when the moist curing duration is significantly long, between seven and 14 days, large deformations can develop within the concrete specimen upon external drying (Hajibabaee and Ley 2014; Ley et al. 2012a, 2013; Perenchio 1997).

Research Significance

Past research has shown the benefits of adding FLWA to concrete mixtures with water-to-cementitious (w/cm) ratios less than 0.40 to reduce autogenous shrinkage. With the exception of one study (Espinoza-Hijazin and Lopez 2011), the effect of adding FLWA to concrete mixtures with w/cm ratios greater than 0.40 has received insufficient attention. Furthermore, very little research has been done to quantify the curling behavior of concrete mixtures containing FLWA. This study aims to examine the potential for FLWA to have a beneficial effect on the curling of concrete pavements.

Experimental Design

In order to measure concrete moisture curling accurately and continuously in a laboratory setting, a long, slender beam geometry was chosen. The final dimensions of the beam were 1.4m by 0.15m by 0.08m which is similar in geometry to previous beam curling studies (Hiller et al. 2003; Ley et al. 2012b; Wei and Hansen 2011). This beam length ensured that the curling deflections had significant magnitudes to be detected with linear variable differential transducers (LVDTs). After exiting the curing room, all sides of the beams but the finished surface were sealed with aluminum foil. This was done to produce a one-dimensional drying gradient similar to one that would be produced in the field. The curling magnitude was measured using three LVDTs: one at each end of the beam and one at the center of the beam. An unrestrained beam setup was chosen to minimize the effects of early age creep, restraint, and deformations from the foundation layer. The beam was placed on its side, relative to the drying surface, as seen in Figure 1. To prevent friction and binding on the supporting surface, the beams were placed on a bed of glass ball bearings to provide a near frictionless surface. The beams were placed into an environmental chamber maintained at a constant temperature, 25^{o}C ± 0.3^{o}C, and a constant relative humidity (RH), 47% RH ± 5% RH.

Figure 1. Beam curling setup with mounted LVDTs.

The volumetrics were kept constant for each concrete mix design throughout the study (Table 1). All mixtures had a w/cm of 0.42. An air-entrainment admixture was used to achieve a target air content of 6%. The coarse and intermediate aggregates were both dolomite while the fine aggregate was a natural sand. The saturated fine lightweight aggregate was an expanded shale that had a 24 hour absorption value of 14%. When added to the concrete mixtures, the moisture content of the lightweight varied between 15% and 18% with the additional water accounted for during batching. Each mixture had two replicate beams along with three free drying shrinkage prisms. Free drying shrinkage measurements generally followed ASTM C157 (2012) with the specimens having a 75mm square cross section and a gauge length of 254mm. The only deviation from ASTM C157 (2012) was the curing duration, as this was dictated by the experimental layout.

Table 1. Concrete mixture designs used for this study (values in kg/m^3).

Mix	PC	CCFA	CA	IA	FA	FLWA	Water	Cure [days]
F0	287	72	938	268	420	96	150	0.00
V0	287	72	938	268	575	0	150	0.00
F3	287	72	938	268	420	96	150	3.25
V3	287	72	938	268	575	0	150	3.25
F6	287	72	938	268	420	96	150	6.50
V6	287	72	938	268	575	0	150	6.50

The abbreviations PC, CCFA, CA, IA and FA represent the Type I Portland cement, class C fly ash, coarse aggregate, intermediate aggregate, and fine natural sand aggregate portions, respectively.

All cast specimens were initially covered with plastic for 24 hours in the ambient laboratory temperature condition of 23ºC ± 2ºC. The moist curing duration listed in Table 1 refers to the additional time the de-molded specimens were kept in the 100% moist curing room prior to testing. The free drying shrinkage and fracture specimens experienced the same moist curing duration as the curling beam specimens. Once the beams were placed into the drying chamber, the curling measurements were recorded automatically every 60 seconds for a minimum of 28 days. At each point in time, the three LVDT measurements were fitted to a circle to obtain the radius of curvature. Given three points in Cartesian space, (x_1, y_1), (x_2, y_2), and (x_3, y_3), the radius and center point of the circle passing through the three points is found by solving Eq. (1) which is the equation of an arbitrarily placed circle where (x_c, y_c) is the coordinate of the center of the circle, (x, y) is an arbitrary point along the circumference of the circle, and *r* is the radius. The general equation can be substituted into the determinant solution of a circle, Eq. (2), with Eqs. (3) - (5) now defining the center coordinate of the circle and the radius from the minor determinants, M_{ij}.

$$(x-x_c)^2+(y-y_c)^2=r^2 \tag{1}$$

$$\begin{vmatrix} x^2+y^2 & x & y & 1 \\ x_1^2+y_1^2 & x_1 & y_1 & 1 \\ x_2^2+y_2^2 & x_2 & y_2 & 1 \\ x_3^2+y_3^2 & x_3 & y_3 & 1 \end{vmatrix}=0 \tag{2}$$

$$x_c=\frac{M_{12}}{2M_{11}} \tag{3}$$

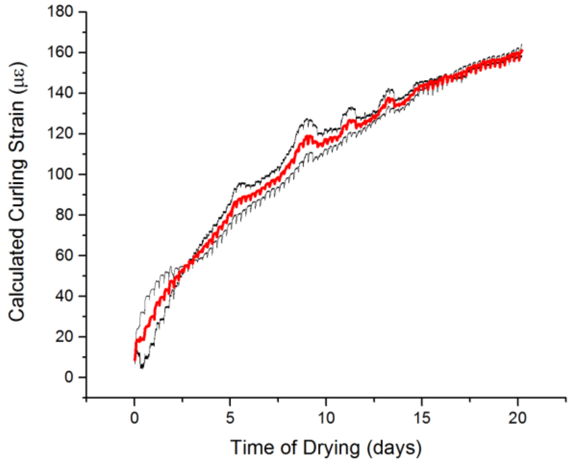
$$y_c=\frac{-M_{13}}{2M_{11}} \tag{4}$$

$$r^2=x_c^2+y_c^2+\frac{M_{14}}{M_{11}} \tag{5}$$

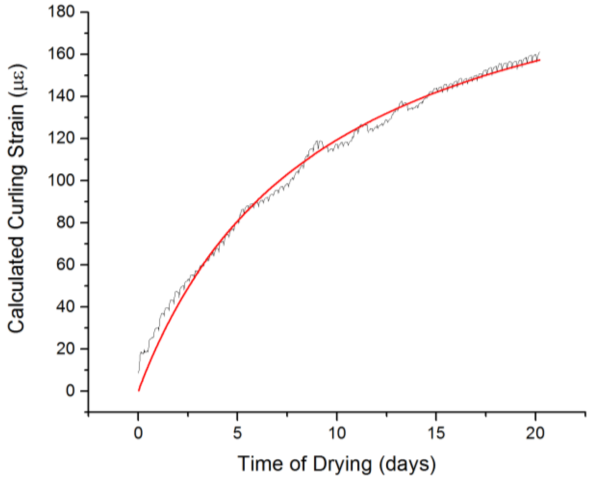
The unrestrained curling deflection value was calculated using Eq. (6) where *s* is the arc length of the beam assumed to be the length of the undeformed beam and *r* is the radius of curvature calculated from Eq. (5). This method to calculate the unrestrained curling deflection accounts for any rigid body translation or rotation of the beam during the measurement period.

$$\delta=r\left(1-\cos\left(\frac{s}{2r}\right)\right) \tag{6}$$

Each unrestrained curling deflection value was converted into a strain value, ε, from the beam curvature in Eq. (7) where h is the height of the beam (80mm), L is the length of the beam (1400mm), and δ is the calculated unrestrained beam deflection. Each mixture produced two time dependent strain curves, which were averaged and then fitted with a hyperbolic equation, Eq. (8), as shown in Figure 2. The fit produces the model coefficients A and B which are a function of time, t. In general, the standard error of the averaging and fitting process was 30 με.



(a)



(b)

Figure 2. Average (red thick line) of two replicate beams curling data (a) and the hyperbolic fit (red line) of the average (b).

$$\varepsilon = \frac{8\delta\left(\frac{h}{2}\right)}{L^2} \tag{7}$$

$$\varepsilon = \frac{At}{B+t} \tag{8}$$

Results

The study was formulated to determine the sensitivity of the presence of FLWA and moist curing duration on unrestrained moisture curling and free shrinkage. The introduction of FLWA into the concrete mixture with no moist curing produced the most drastic reduction in curling magnitude within the first 28 days of drying (Figure 3). At longer drying ages (i.e., greater than 14 days) without additional moist curing, there is a 50% reduction in curling when FLWA replaces 27% of the natural sand aggregate volumetrically in the concrete mixture. The additional water from the FLWA maintains a higher saturation level in the surface region compared to the virgin mixture and this effectively reduces the curling strain. Because the surface porosity is similar, the relative rates of curling are somewhat similar with both mixtures reaching half of their ultimate curling after approximately 5.5 days of drying.

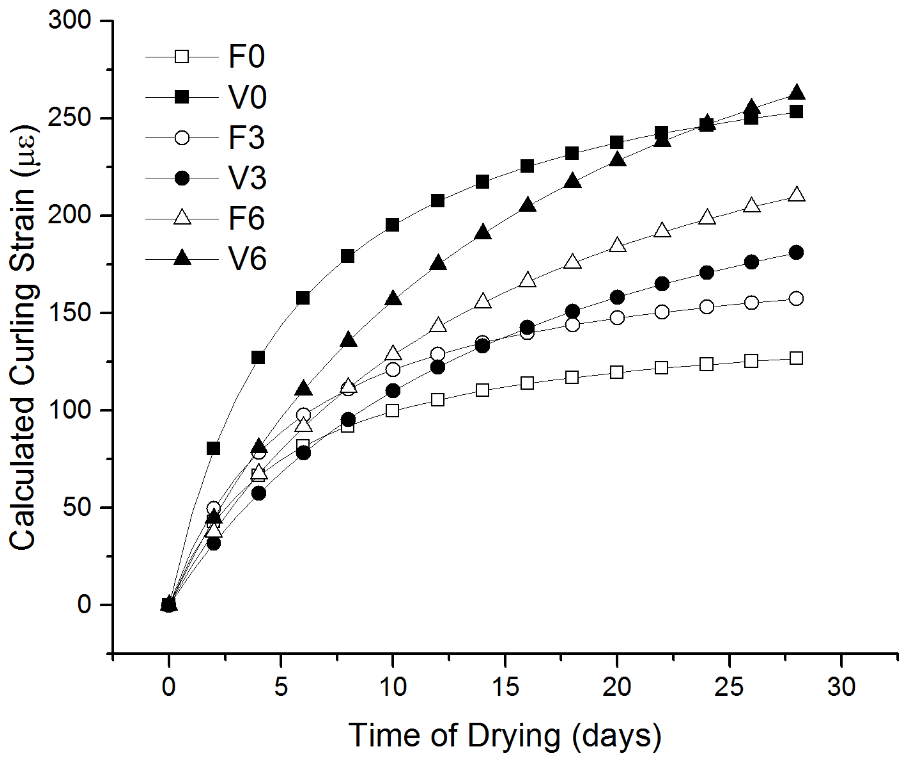


Figure 3. Averaged and fitted beam curling data for all mixtures tested.

With longer curing duration (6.5 days), the curling and free drying shrinkage strains were ultimately the greatest at later drying times. Since both the virgin and FLWA mixtures had 6.5 days of external moist curing, the near surface porosity for both sets is expected to have similar pore size distributions. Thus initially, the two mixtures have similar curling and free drying shrinkage magnitudes (Figure 4). However, as the smaller pores near the surface begin to empty, the FLWA-modified mixture is able to maintain a high saturation level because of the release of water held by the saturated FLWA. This reduces the curling rate as only the largest, non-strain generating pores are able to continue drying. The virgin mixture continues to empty smaller pores at later drying times generating 30% higher ultimate strains with respect to the FLWA modified mixture. The free drying shrinkage trends similarly follow the curling behavior. As the curing duration is increased, the free drying shrinkage strain increases because of the more refined pore structure at the surface.

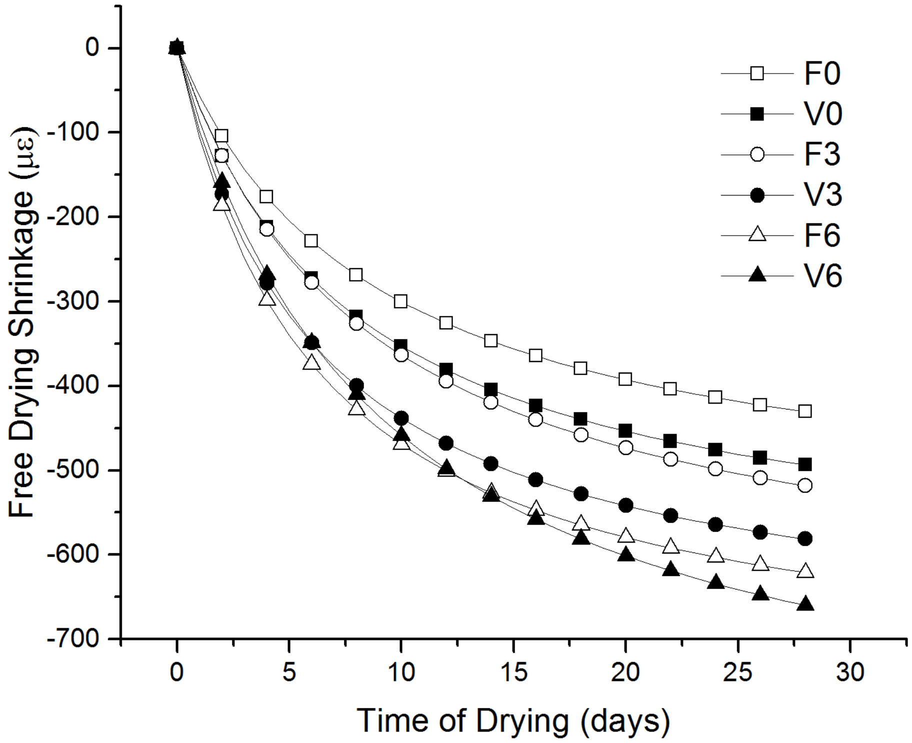


Figure 4. Free drying shrinkage measurements for all mixtures.

These responses showing that the longer moist curing durations have higher curling values was expected based on previous published work (Hajibabaee and Ley 2014; Ley et al. 2012a, 2013; Perenchio 1997). Specifically, it was seen that there was an 80% reduction in curling at 28 days between equivalent specimens that had no moist curing and 3 days of moist curing (Ley et al. 2012a).The curling differences from this study are much less severe but follow the same general trends. The reasons for the differences are that the beams in (Ley et al. 2012a) began drying 5 hours from casting and had a tined surface which greatly increased the drying surface area. Furthermore, the drying chamber was more aggressive at 40% RH. From the experimental data, current model predictions, and literature, any moist curing to concrete specimens will result in an increase in unrestrained curling. First, this may not necessarily be a problem if it does not lead to cracking or performance issues such as roughness or joint damage. Although, inadequate moist curing could lead to other premature failures unrelated to curling such as surface cracking, low abrasion resistance, high surface porosity/permeability, and reduced surface durability in concrete slabs. For example, in aggressive environments where large amounts of de-icing salts are used, minimal curing of concrete pavement may lead to significant surface scaling and other surface durability distresses.

To characterize the effect of curing duration and the possibility of further hydration with the inclusion of FLWA, the fracture properties of the mixtures was measured. The disk-shaped compact tension (DCT) geometry was used for the testing and followed the procedure and analysis outlined in (Amirkhanian et al. 2016). Specifically, the critical stress intensity factor, K_{IC}, and total fracture energy, G_F, were calculated for each mixture in this study (Figure 5 andFigure **6**). The critical stress intensity factor describes the stress at which a crack will form in the material. The total fracture energy describes the amount of energy required to fully separate the two faces along a crack path in the material.

The first set of specimens were tested immediately at the end of the curing regime. The results indicate that for the specimens at the start of drying, the virgin mixtures have either the same or higher K_{IC} values compared to the FLWA mixtures at all moist curing durations. This was somewhat expected due to the low strength of the FLWA aggregates and the slight negative effect they have on modulus. At these early ages, the benefits of increased hydration from the inclusion of FLWA are not readily observable. The total fracture energy of the specimens at the start of drying displays a slightly different trend. It appears that for mixtures with some amount of moist curing, the FLWA modified mixtures have slightly higher fracture energies. This is likely due to the slightly better bond between the FLWA and cement matrix and denser interfacial transition zone around the aggregates (Elsharief et al. 2005).

The same mixtures were then tested after 28 days of drying. The FLWA modified mixtures saw the largest gains in fracture resistance during this drying phase. On average, the K_{IC} values for the FLWA modified mixtures increased 66% from the start of drying compared to only an average increase of 35% for the virgin mixtures. This strongly suggests the FLWA is furthering the hydration of the mixtures even under drying conditions. The fracture energy results suggest that little benefit is seen from the increased hydration as evident from the near level values for all mixtures after 28 days of drying.

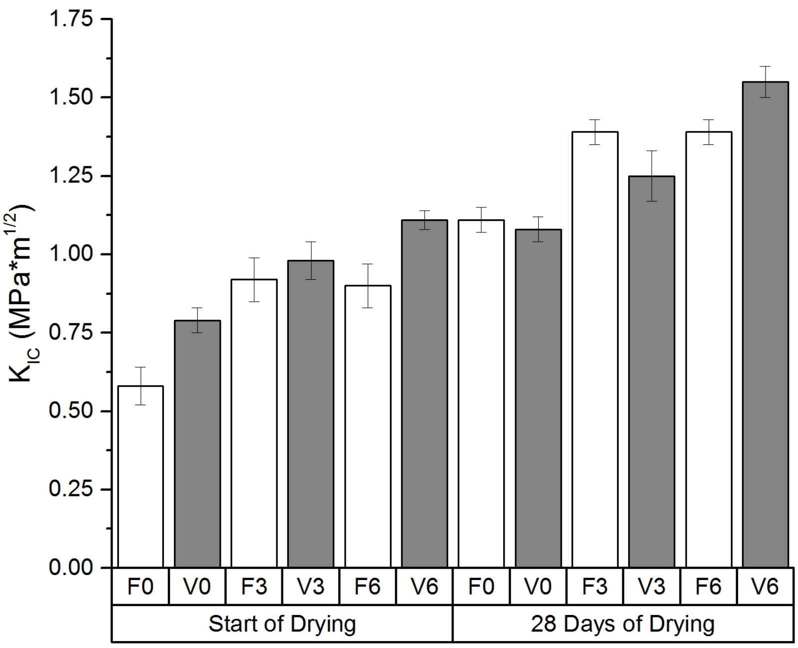


Figure 5: Critical stress intensity factors for all mixtures at the start of drying and 28 days after the start of drying.

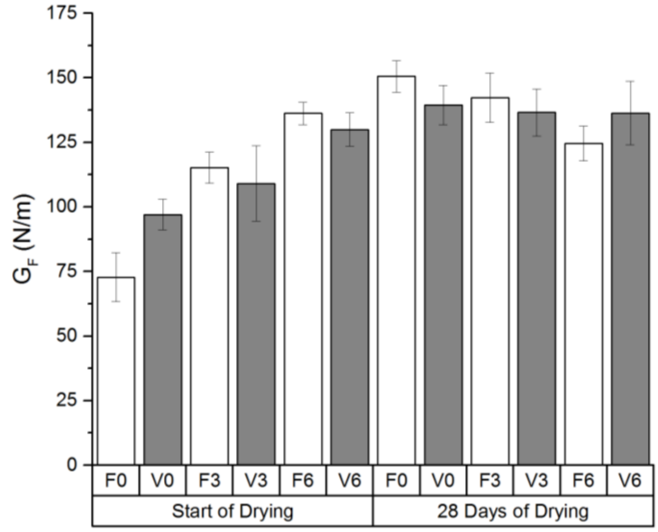


Figure 6: Total fracture energy for all mixtures at the start of drying and 28 days after the start of drying.

Conclusions

The addition of FLWA had a profound and beneficial impact to the beam curling behavior of the mixtures tested. It was found that the addition of FLWA reduced the magnitude of beam curling from drying by up to 50% for mixtures with no moist curing. It was also found that the duration of moist curing had a significant effect on the magnitude of curling, which confirms findings by other researchers. Mixtures that are moist cured for longer periods of time have higher curling magnitudes than those moist cured for shorter periods. The pore refinement that is generated with longer curing durations, while beneficial in terms of strength and permeability, causes higher strains to develop upon drying. This effect was demonstrated for mixtures with and without FLWA. Free drying shrinkage measurements seemed to correlate well to the behavior of the curling in terms of order of significance.

Fracture testing revealed that initially the FLWA modified mixtures will have a slightly lower fracture resistance. However, upon drying, the water from the FLWA continues the hydration process and an average increase of 66% is seen in the fracture resistance compared to only 35% in virgin mixtures. The total fracture energy data suggests that at early ages, the FLWA has some benefit though upon drying the differences become statistically insignificant.

The addition of FLWA to concrete pavement mixtures should be examined in more detail to determine if the curling reductions seen in the unrestrained beams is applicable to full scale slabs. If FLWA can reduce the curling response of concrete slabs, it will be extremely beneficial for industrial floor slabs requiring high degrees of planeness as well as highway pavements to reduce roughness.

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