INTERNAL CURING - FROM THE LABORATORY TO IMPLEMENTATION

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ABSTRACT

Internal curing is a topic that has been receiving a lot of attention in the concrete industry recently. This method of curing typically involves the use of pre-wetted lightweight aggregate as an internal source of curing water. Many studies exist showing the benefits associated with internal curing such as a reduction in shrinkage cracking, water absorption, and plastic shrinkage crack formation. While these benefits have been shown in the laboratory, the benefits still need to make their way into the field. This paper discusses the laboratory benefits and discusses how to move internal curing to field implementation.

KEYWORDS: Autogeneous Shrinkage, Internal Curing, Lightweight Aggregate, Mixture Proportioning, Plastic Shrinkage, Sorptivity, Restrained Shrinkage

INTRODUCTION

A Review of the Fundamentals of Internal Curing

To understand how internal curing works, one must consider the driving mechanism, chemical shrinkage. Chemical shrinkage is a process in which the products of a reaction occupy a smaller volume than the reactants [1, 2]. Chemical shrinkage describes the volume reduction that occurs during hydration due to the chemical reaction. Before set, this volume change is not an issue, because as chemical shrinkage occurs, the concrete is still fluid and the particles can re-arrange (or consolidate) to fill in the space created by chemical shrinkage. After set however, the rigid nature of concrete does not allow the particles to re-arrange (or consolidate) resulting in the creation of vapor-filled voids in the concrete [3].

Internal curing works by supplying water from the pre-wetted lightweight aggregate (LWA) to fill in the voids created by chemical shrinkage [4, 5]. Internal curing has been shown in the laboratory to be quite effective as a mitigation strategy for self-desiccation and autogenous shrinkage [6, 7]. More recent findings have also shown that in addition to reducing shrinkage, internal curing can reduce shrinkage cracking [8], reduce plastic shrinkage cracking [9] and reduce water absorption [10]. This paper will review the effects of internal curing that have been shown to be beneficial in the laboratory, and discuss steps to move internal curing from the laboratory to practical field applications.

INTERNAL CURING IN THE LABORATORY

Pre-wetted lightweight aggregate used as an internal curing agent is not a new innovation. Its concept has been proven in the laboratory [4, 11] and the benefits have been realized in the field [12, 13]. This portion of the paper will review the beneficial effects of internal curing that have been realized in the laboratory.

Reduction of Shrinkage and Shrinkage Cracking

One of the major benefits of internal curing is the reduction in autogenous shrinkage [14]. In a recent study [8], it was shown that a properly proportioned volume of lightweight aggregate could be used to reduce the unrestrained and restrained shrinkage of mortars in both sealed and unsealed curing conditions. Unrestrained shrinkage data shown in Figure 1 are for mortars with a varying percentage of the sand replaced with pre-wetted lightweight aggregate. The percentage shown in the figure legend indicates the proportion of sand replaced with lightweight aggregate. The unrestrained shrinkage was measured by the corrugated tube method [15] for the first 24 hours and the ASTM C 157 method after 24 hours. The mortars had a water to cement ratio (w/c) of 0.30 with a fine aggregate content of 55%. Due to space limits in this paper, the mixture proportions and measuring techniques were not included, but can be found elsewhere [16]. The samples used to obtain the data in Figure 1 were sealed on all sides during testing. From Figure 1, it can be seen that when a sufficient volume of LWA is incorporated into this specific mixture, the unrestrained shrinkage can be reduced and even eliminated, with several of the specimens exhibiting a sustained expansion.

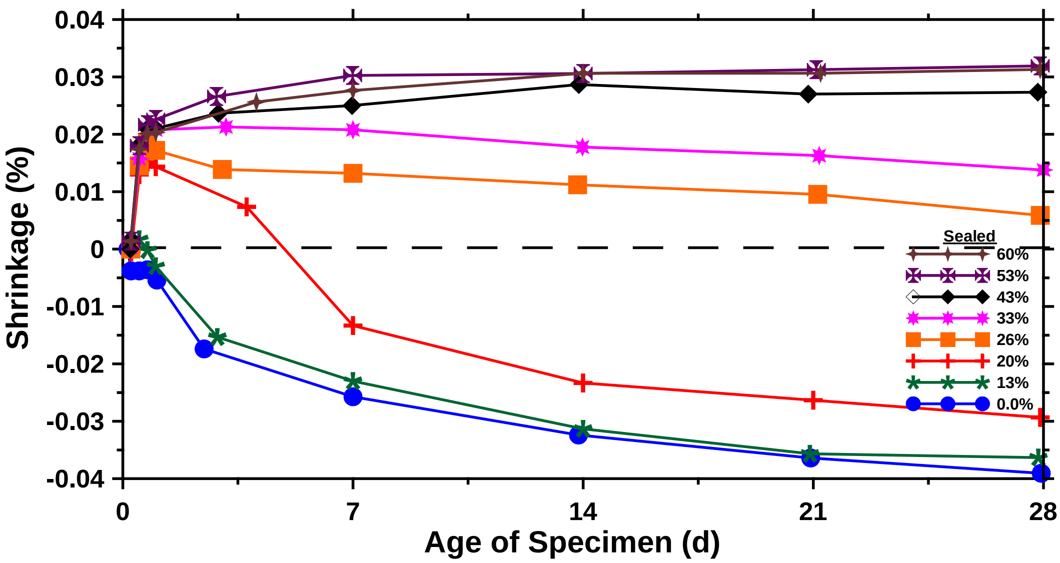

Figure 1 – Unrestrained shrinkage of mortars made with different volumes of sand replaced by pre-wetted LWA in sealed conditions.

Since very little concrete placed in the field can be considered to be in a completely sealed condition, some drying aspect needs to be considered. Figure 2 shows the unrestrained shrinkage of the same mixtures under drying conditions in 50% relative humidity (RH). It is easily seen that the shrinkage increases significantly (double in some cases) when the samples are exposed to drying. This is an important observation which indicates that the curing conditions must be considered when proportioning concrete with pre-wetted lightweight aggregate for internal curing.

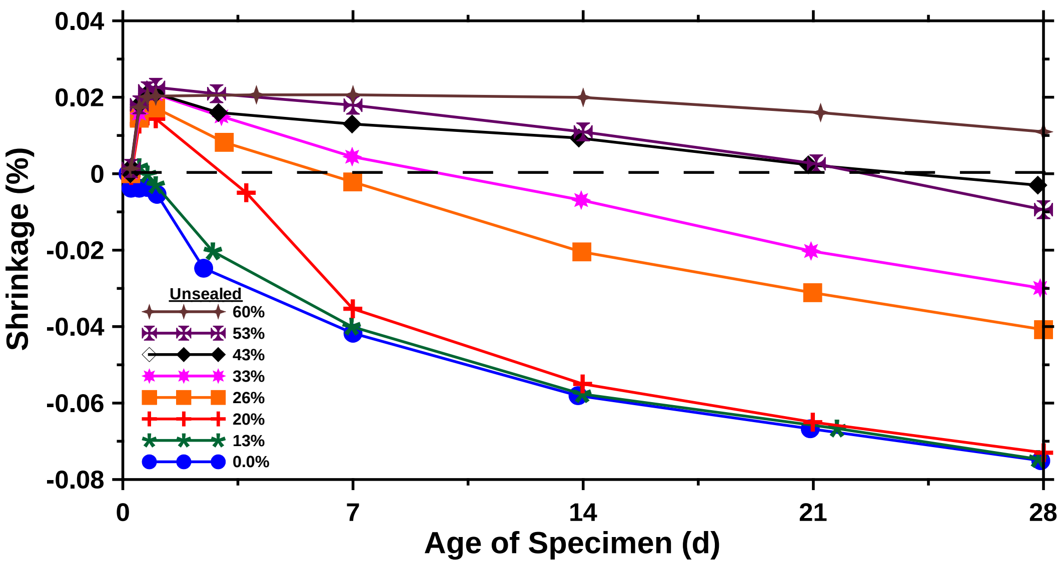

Figure 2 – Unrestrained shrinkage of mortars made with different volumes of sand replaced by pre-wetted LWA in unsealed conditions.

One of the main reasons engineers and researchers are interested in the behavior of concrete with pre-wetted lightweight aggregate is because of the reduction in shrinkage cracking. The cracking behaviors of these mixtures were also monitored using ASTM C 1581. These mixtures were exposed to 50% relative humidity 24 hours after casting.

Figure 3 shows restrained shrinkage results of these mixtures in an unsealed (50% RH) condition. Cracking of a mixture is indicated by the sharp vertical increase in the data set. It can be seen that if an insufficient volume of pre-wetted LWA is incorporated (<43% replacement of sand in these mixtures), the mortar cracks for these curing conditions. It takes a sufficient dosage of pre-wetted LWA (>43% in these mixtures and curing conditions) to increase the cracking resistance of the mixture enough to delay or avoid shrinkage cracking. This is not to say that 43% is the threshold for mixture proportioning; aspects such as curing conditions, aggregate grading, paste properties, and aggregate properties need to be considered. Therefore when developing a specification for internal curing, the unrestrained (free) shrinkage should not be the only consideration; the cracking potential from restrained shrinkage should also be considered. For example, many agencies specify a low shrinkage concrete (typically < 0.04%), but from Figure 2, it can be seen that the 26% replacement mixture has a low shrinkage, but it cracks at approximately the same age as the 0.0% mixture under these curing conditions. Not only is it important to look at the free (unrestrained) shrinkage of the concrete, one must also look at the cracking behavior when determining a sufficient volume replacement of sand with pre-wetted LWA.

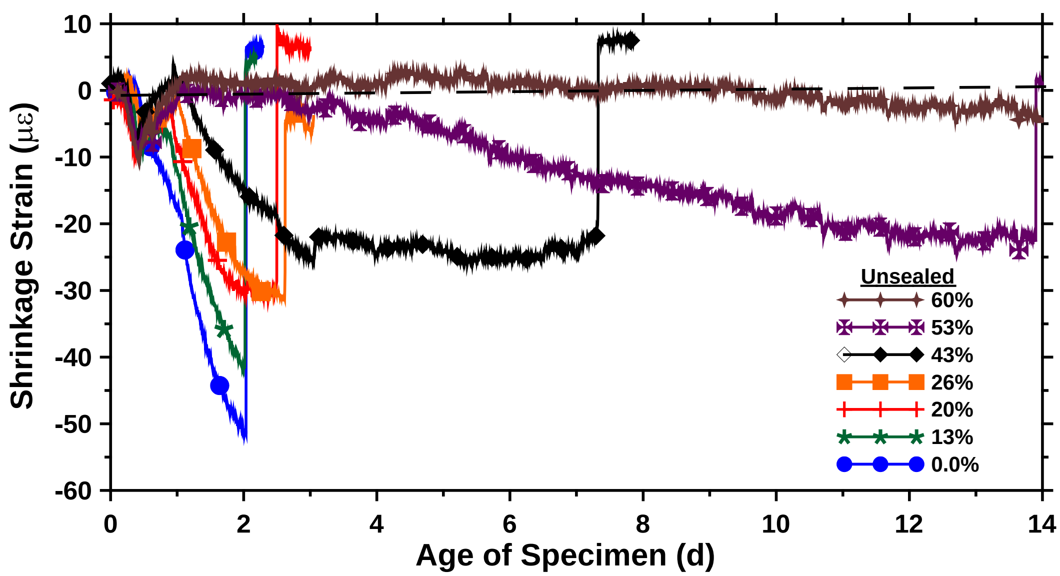

Figure 3 – Restrained shrinkage of mortars made with different volumes of sand replaced by pre-wetted LWA in unsealed conditions.

Reduction of Plastic Shrinkage Cracks

Another benefit of internal curing, is that the incorporation of pre-wetted lightweight aggregate has been shown to reduce the formation of plastic shrinkage cracks [9]. Not only are plastic shrinkage cracks unsightly, but they may lead to an increased ingress of water and deleterious substances such as chlorides or sulfates.

Figure 4 shows the probability of formation of plastic shrinkage cracks of varying widths for concrete mixtures where a portion of the sand was replaced with fine pre-wetted lightweight aggregate. The testing was performed in accordance with ASTM C 1579. The concrete mixtures had a w/c of 0.55 with 30% of the total volume being coarse aggregate and 30% being fine aggregate. The samples were exposed to 97 ºF ± 5 ºF, relative humidity of 30% ± 10% and wind velocity of 14.7 mph ± 1.2 mph. From Figure 4 it can be seen that when pre-wetted LWA is incorporated, the frequency and size of plastic shrinkage cracks is reduced. If a sufficient volume of sand is replaced with pre-wetted LWA (>43%) plastic shrinkage cracks were eliminated. This concept brings up an interesting point. If mixtures were proportioned only for shrinkage after set, they would likely have an insufficient volume of LWA. This is because the water can be drawn out of the LWA before set, if the environmental conditions are harsh enough (high temperature, low humidity, and/or high winds). If plastic shrinkage cracking is a concern, mixtures with internal curing should have an increased dosage of pre-wetted lightweight aggregate since it has been shown that internal curing is beneficial in reducing plastic shrinkage cracking.

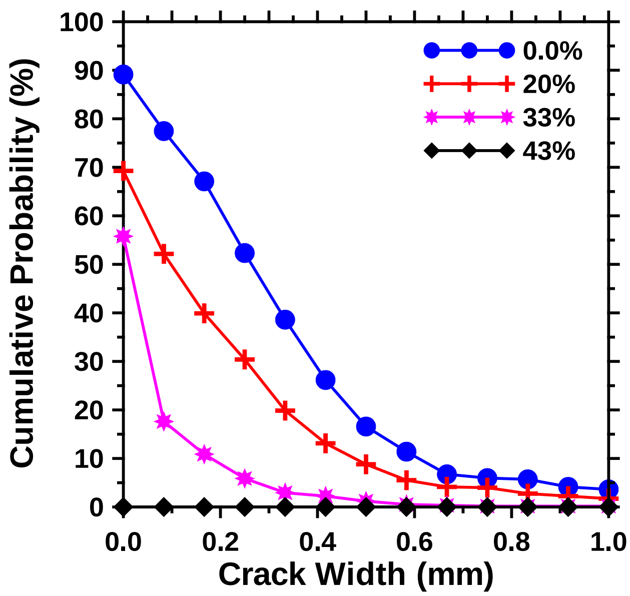

Figure 4 – Formation of plastic shrinkage cracks in concretes made with different volumes of sand replaced by pre-wetted LWA.

Reduction in Water Absorption (Sorptivity)

A benefit that has only recently been realized is that mortar mixtures with pre-wetted lightweight aggregate have reduced absorption of water in hardened concrete [10]. In a recent study, in which mixtures tested used the same proportions as the specimens used for unrestrained and restrained shrinkage measurements mentioned earlier, the water absorption in hardened concrete was monitored. Figure 5 shows that when sand is replaced with pre-wetted lightweight aggregate, the water absorption is reduced. It can be seen that at different replacement levels of pre-wetted LWA, the mortar behaves like a mortar with a lower w/c mortar.

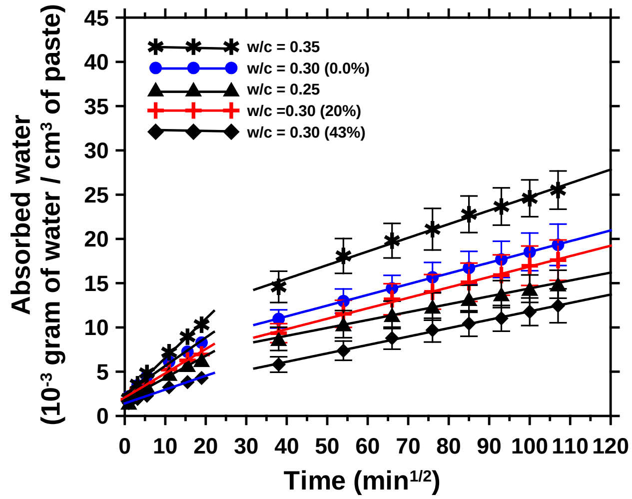

Figure 5 – Water absorption of mortars after curing for 28 days with different w/c and with different volumes of sand replaced with pre-wetted LWA.

This concept can be more easily seen in Figure 6, where it can be seen that if 20% of the sand in a mortar with a w/c of 0.30 were replaced with pre-wetted LWA, the mortar would exhibit an absorption similar to a mortar with a w/c of 0.28. If 43% of the sand were replaced, the equivalent w/c would be 0.23. Proportioning methods for internal curing should also be designed to address water absorption if this is a desired benefit.

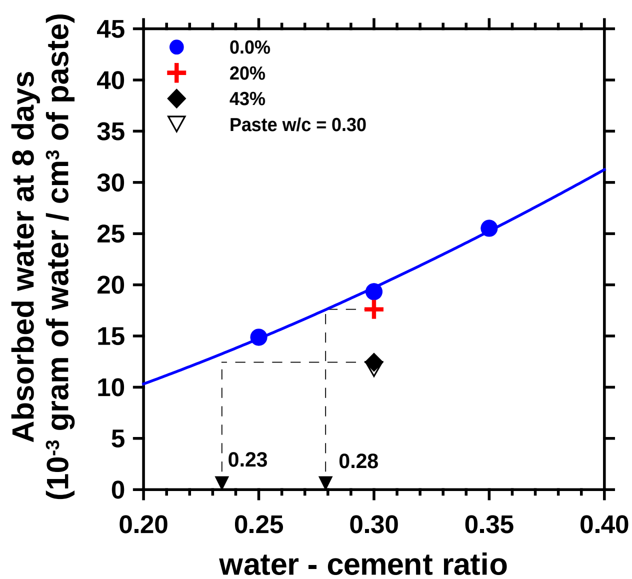

Figure 6 – Equivalent w/c of mortars after curing for 28 days when a portion of the sand is replaced with pre-wetted LWA.

NEED TO MOVE INTERNAL CURING TO PRACTICAL FIELD APPLICATIONS

It is apparent that many beneficial effects exist for concrete mixtures made with pre-wetted lightweight aggregate. But many of these benefits have only been realized in a small-scale laboratory setting. In order for this technology to move to full-scale field applications, a few details still must be worked out.

Improved Proportioning Method

The major challenge associated with internal curing is how to properly select the correct amount of pre-wetted lightweight aggregate to add into a mixture. Several methods exist for this, from a one-size-fits-all straight replacement of normal weight aggregate with LWA, to more scientific approaches of determining the amount of LWA needed to fill in the vapor-filled spaces created by chemical shrinkage.

The one size fits all proportioning method should be avoided since it can be seen from the laboratory results that different LWA replacement volumes can have significantly different impacts on performance. This is especially true when different aggregates are used. Mixture proportioning using a more scientific and performance based approach is recommended, so this method of proportioning will be discussed in further detail here.

A method of mixture proportioning for internal curing was developed by determining the required amount of LWA necessary to provide water to fill in the voids created by chemical shrinkage [17, 18]. The equation developed to express this relationship is shown below in Eq. (1):

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{\max}}{S \times \phi_{LWA}} \qquad \text{Eq. (1)}$$

where: M_{LWA} (kg/m^3) is the mass of LWA (in a dry state) that needs to be pre-wetted 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 to 1), S (unitless) is the expected degree of saturation of the LWA (0 to 1), and Φ_{LWA} (kg of water/kg of dry LWA) is the absorption capacity of the LWA (it is better to take Φ_{LWA} as the desorption of the LWA as later stated by the authors).

This equation is a good first approximation of the volume of dry LWA needed to supply water to fill the volume that is created by chemical shrinkage and would likely work for most internal curing applications. However, while this equation does not address other aspects of internal curing, it was never intended to. Several other aspects should be considered when more advanced applications for internal curing are needed, and the proportioning method should reflect this. For example, Eq. (1) may provide more than enough water for high w/c mixtures since not all the chemical shrinkage volume may need to be filled. As a result, the benefits of internal curing may be reduced with an excessive volume of LWA [19].

Bentz et al. have stated that this equation does not consider the use of supplementary cementitious materials (SCM) [17]. Many concretes have at least one SCM incorporated into the mixture design. The shrinkage behavior of concrete with SCM is much different than that of a straight Portland cement mixture. For example, the CS term for ordinary Portland cement is approximately 0.07 ml/g cement, for slag it is approximately 0.18 ml/g slag, fly ash (type F) is approximately 0.12 ml/g fly ash [20], and silica fume is approximately 0.22 ml/g silica fume. It can be seen that if a pozzolan or slag is incorporated into the mixture, much more pre-wetted LWA would need to be added. For the mixtures tested in the laboratory, the 43% mixture was the amount of pre-wetted LWA needed according to Eq. (1), which was sufficient in most cases; however this 43% could fall far short of the necessary amount if any type of SCM were added, especially in higher volumes.

A more in depth analysis needs to be made when pozzolans are used in a concrete mixture where internal curing is intended to be used. Not only is the volume of chemical shrinkage important, but the rate of reaction also needs to be considered. The rate of reaction of most fly ash (particularly F ash) are slower than that of cement, so the volume of chemical shrinkage created at early ages may not be a large concern. Silica fume however reacts quickly at early ages and it has a large chemical shrinkage, so the shrinkage problem can be worse in this case. Also, pozzolans require the cement to hydrate to form calcium hydroxide with which the pozzolans will react to form calcium-silicate-hydrates. It is possible to have too much pozzolan to where not all of it will react thus the total potential chemical shrinkage volume is not occurring. If this is the case, the excess volume of pozzolan that does not react does not need to be accounted for when determining a sufficient amount of pre-wetted LWA.

The environmental conditions in which the concrete will be placed and cured should be considered. If the concrete will be placed in a disadvantaged condition where plastic shrinkage or rapid drying could be a problem, more pre-wetted LWA could be incorporated to account for this. The reader should be reminded that when the samples from the shrinkage study were exposed to drying, the shrinkage in some cases doubled (Figure 2). If the concrete is going to be exposed to disadvantaged conditions when it is still plastic, the water will be pulled from the LWA to replace bleed water that evaporates. If this amount of water (or LWA) is not accounted for, the mixture may be under-proportioned and the internal curing benefits may not be realized.

Proper determination of moisture in LWA

One significant difficulty when working with LWA is determining the proper amount of water that is available for internal curing. Many experts are focused on the absorption capacity, however the more appropriate approach for determining the available water for internal curing would be to determine the desorption (the amount of water lost at a specified humidity). This can be easily done by placing a sample of pre-wetted LWA in a sealed container with a saturated salt solution of potassium nitrate at room temperature. This saturated salt solution at room temperature (73 °F) yields a relative humidity of approximately 94%. The weight change of the sample could be monitored until it reached equilibrium, and this amount of water could be assumed to be the water available for internal curing. It should be noted that a LWA with good internal curing potential would release a majority of its absorbed water (>90%) at this humidity. If the total water absorption value is used, it is likely that a portion of the water will remain in the LWA since the pore pressure that develops in the cement paste may not be large enough to draw all of the absorbed water out of the LWA.

Another drawback to the absorption principle is that no test method exists to determine the absorption of LWA. ASTM C 128 is typically used, however the standard test explicitly states that the test method is not intended for lightweight aggregate. Table 1 shows the absorption of several aggregates measured using different techniques [16]. It can be seen that by using different techniques, the absorption of the same aggregate could have a measured difference by as much as 15%. By using the desorption principle, the uncertainty of the amount of water available can be reduced.

Table 1 – Absorption of different aggregates (including LWA) using different measuring techniques

Method	LWA-K		LWA-H	CRCA	Sand
	24 h	Vacuum	24 h	24 h	24 h
C128 Cone Method	10.5%	15.0%	5.8%	9.8%	1.8%
C128 Provisional Cone Method	9.4%	14.3%	4.6%	8.8%	1.7%
C128 Paper Towel Method	20.8%	24.9%	15.7%	17.5%	1.9%
Absorption Rate Method	5.0%	N/A	1.0%	1.1%	0.8%
Cobalt Chloride Method	11.0%	-	-	-	-
Pycometer Method	7.9%	N/A	5.7%	3.1%	1.0%

Coarse Aggregate vs. Fine Aggregate

Strictly speaking, Eq. (1) can be used to determine the volume of LWA needed to provide internal curing. However, this volume may be provided using a fine or a coarse LWA or a blend of the two. Therefore, which type of LWA would be the better choice? It has been shown [8] that fine LWA is a better choice since the particles are better distributed throughout the concrete.

The hard-core/soft-shell model developed at NIST (http://ciks.cbt.nist.gov/lwagg.html) [21] was used to determine the volume of paste which is within 2 mm of a LWA particle. A distance of 2 mm was chosen because it has been shown to be the approximate distance water can travel in low w/c mixtures at early ages [22]. Sixteen different mixtures were modeled. Eleven of the mixtures had a coarse aggregate which could be classified as an ASTM C 33 #57 aggregate, and sands with a fineness modulus (FM) ranging from 2.15 to 3.45. The remaining six mixtures had sand with a FM of 2.7 and different coarse aggregates were used. Figure 7 shows the volume of protected paste of concrete when 30% of the aggregate (either coarse or fine respectively) is replaced by pre-wetted lightweight aggregate. It can be easily seen that if 30% of the coarse aggregate is replaced, the LWA will protect no more than 50% of the paste. This is to say that if coarse aggregate is used, only 50% of the paste would be protected by the internal curing water assuming the water can migrate up to 2 mm.

Figure 7 also shows the protected paste volume of the same ASTM C 33 fine aggregate with different FM. If the LWA used for internal curing had a lower fineness modulus (finer sand), nearly all the paste would be within 2 mm of a LWA particle. When a coarser LWA (higher fine modulus) is used, less paste is protected. Any LWA with a fineness modulus greater than 3.2 would protect less than 90% of the paste. If a LWA with a FM greater than 3.2 were used, the volume of the LWA may have to be increased to ensure that all the paste was protected. Again this is assuming that the water will migrate 2 mm from the LWA particles. This was shown to be the case in low w/c mixtures; however if a higher w/c were used, the water could likely be able to migrate a greater distance. Figure 7 is not intended to show a threshold for material selection for internal curing. It is not the intention of the authors to suggest LWA with a FM greater than 3.2 should not be used or will not work, just that the particle distribution should be considered when proportioning and material selection.

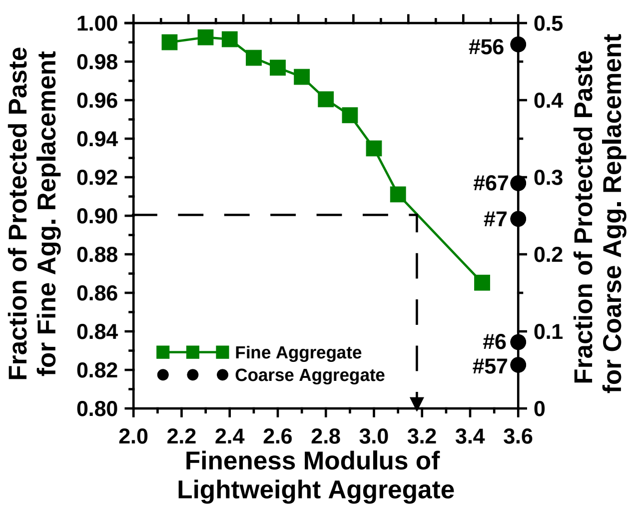

Figure 7 – Volume of protected paste of concrete where 30% of the aggregate is replaced with different coarse aggregate and sands with different fineness modulus.

OTHER CONSIDERATIONS FOR PRODUCTION

One major complaint from the ready-mix producers about using lightweight aggregate is that it can be a difficult material to work with. Proper saturation must be maintained in order to ensure that lightweight concrete will pump. This task can be accomplished by setting up a sprinkler system, a saturation pit, a pug mill or by vacuum saturating the aggregate. While fine LWA is preferred over coarse LWA for internal curing, the fine LWA is much more cohesive when it is wet. Therefore, it may be difficult to handle in a batch plant since it may stick or make a bridge over the gate. One option is to use an auger-screw gate on the hopper instead of the typical clam-gate. Another option is to batch the material as-received and determine how much water would be absorbed before set.

This option raises many concerns. The first and maybe the most important is that if the assumed amount of water the LWA would absorb is wrong, the w/c of the final product would be wrong resulting in much different properties than intended. This also raises a potential issue if the concrete were to be pumped. The amount of water that would be forced into the LWA during pumping would need to be determined in advance. This could be determined as the vacuum absorption from Table 1. If this is determined to be the best option, care must be taken when reporting properties. Since the LWA would be absorbing water until set, the slump test may not indicate the normal slump. Since extra water would be placed in the mixture for absorption, this water would increase the concrete slump and appear “wetter” than it would be if the LWA were pre-soaked, so a correction may have to be added to this test. These aspects are currently being investigated [23].

CONCLUSIONS

This paper is not intended to provide a complete consideration of all the effects of internal curing, but to identify issues that need to be investigated. In this paper, studies showing the beneficial effects of internal curing were reviewed. It can be easily shown in the laboratory how internal curing can be beneficial. These benefits include but are not limited to:

- Reduction in the unrestrained shrinkage that occurs in both sealed and unsealed curing conditions if sufficient volume of pre-wetted LWA is incorporated,
- Shrinkage cracking can be delayed or prevented in both sealed and unsealed curing conditions if a sufficient volume of LWA is added,
- Plastic shrinkage cracking can be reduced or eliminated if a sufficient volume of LWA is added,
- The incorporation of LWA can reduce the water absorption which could yield a more durable concrete.

To take full advantage of internal curing and to fully realize these benefits in the field, several aspects still need to be developed further:

- Mixture proportioning methods have focused on the autogenous shrinkage caused by the chemical shrinkage of cement. Although this may be a sufficient consideration in many internal curing applications, it has been shown that this is not the only consideration,
- More research is needed to adapt internal curing to higher w/c mixtures were issues other than autogenous shrinkage are a concern. Other issues may include plastic shrinkage cracking and water absorption,
- Aggregate desorption needs to be considered instead of aggregate absorption. With this, a proper method or database for easily determining this value should be established,

- Although the volume of LWA is an important consideration, aggregate size and grading must also be considered when proportioning,
- Issues must be addressed regarding use of pre-wetted LWA fines in a batch plant. One option is to batch the materials dry, but a good method for determining the amount of water absorbed (and subsequently desorbed) would need to be developed. A modification to the slump test would also likely need to be developed to account for the extra water that would be added to account for water that will be absorbed by the LWA, especially during pumping.

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