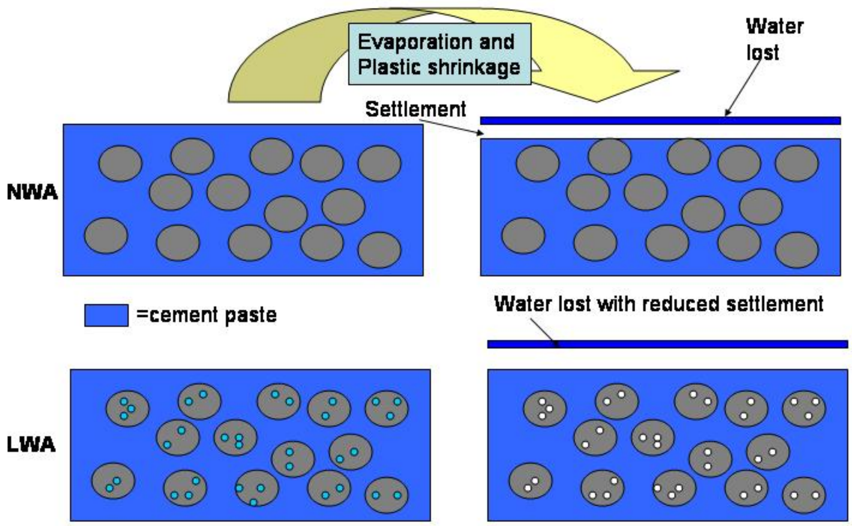
NISTIR 7765

Internal Curing: A 2010 State-of-the-Art Review



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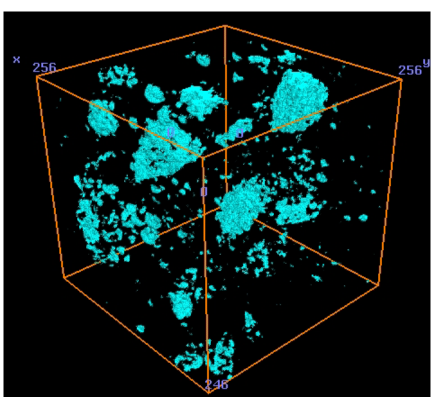

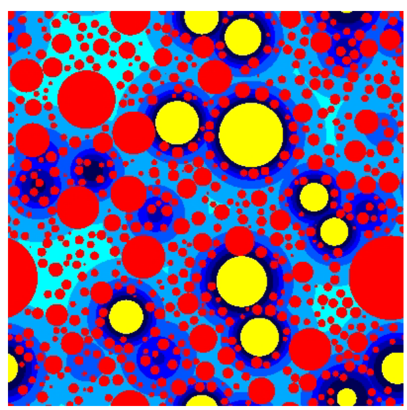

National Institute of
Standards and Technology
U.S. Department of Commerce

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Abstract

The American Concrete Institute in 2010 defined internal curing as "supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation" (American Concrete Institute, 2010). While internal curing has been inadvertently included in many lightweight concretes produced within the past 100 years, it is only within the first decade of the 21st century that this technology has been intentionally incorporated into concrete mixtures at the proportioning stage, using a variety of materials including pre-wetted lightweight aggregates, pre-wetted crushed returned concrete fines, superabsorbent polymers, and pre-wetted wood fibers. This report provides a state-of-the-art review of the subject of internal curing, first addressing its history and theory, and then proceeding to summarize published guidance on implementing internal curing in practice and published research on its influence on the performance properties of concrete. The ongoing exploration of extensions of the internal curing concept that employ the internal reservoirs to contain materials other than water are reviewed. Finally, the critical issue of sustainability is addressed. An extensive internal curing bibliography that is also available over the Internet is included in an appendix. The report is mainly focused on the utilization of pre-wetted lightweight aggregates as the internal reservoirs due to this being the current established practice within the U.S.

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1 Introduction

In the 21st century, internal curing has emerged as a new technology that holds promise for producing concrete with increased resistance to early-age cracking and enhanced durability. Since concrete service life is a key component of providing a sustainable infrastructure, internal curing can provide a positive contribution to increasing the sustainability of our nation's infrastructure. In 2010, the American Concrete Institute (ACI) defined internal curing in its ACI Terminology Guide as "supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation (American Concrete Institute, 2010)." This definition succinctly identifies the two major objectives of internal curing, maximizing hydration and minimizing self-desiccation (and its accompanying stresses that may produce early-age cracking). The two major objectives of the present report are to provide a 2010 perspective on the state-of-the-art and the state-of-the-practice of internal curing and to comment on emerging developments and future extensions of the internal curing concept.

In 2002, Hoff prepared a detailed review of the state-of-the-art of internal curing as of that time (Hoff, 2002). Five years later, RILEM committee ICC – Internal Curing of Concrete published its state-of-the-art review in book form (RILEM, 2007). That same year, a session at the ACI fall convention in Puerto Rico was dedicated to "Internal Curing of High Performance Concretes: Laboratory and Field Experiences," from which an ACI-SP was published in CD form (American Concrete Institute, 2008). The present report will extend these efforts by covering the salient features of internal curing for both the researcher and the practitioner from its inception through 2010.

2 Internal Curing in the Past

Because lightweight concretes have commonly, if inadvertently, included internal curing, it is beneficial to begin with a brief review of the history of lightweight concrete. Lightweight concrete using natural lightweight aggregate dates back to Roman times, with one of the most prominent examples being the Pantheon in Rome (Bremner & Ries, 2009). The dome of the Pantheon was constructed using a lightweight concrete with natural vesicular aggregates, where the density of the concrete was reduced as its height within the dome increased (Bremner & Ries, 2009).

Artificial or manmade lightweight aggregates (LWAs) owe their development and acceptance in the U.S. to Stephen J. Hayde, who received a patent for a firing process to produce lightweight aggregates from clay, shale, and slate rocks in 1918 (Bremner & Ries, 2009). During World War I, Hayde allowed the U.S. government to use his patent at no cost in the production of lightweight aggregates for concrete ships (Bremner & Ries, 2009). Concrete ship production continued into World War II, with many of these concrete ships still floating to this day. While these ships and several bridge structures that provided fifty years or more of service are a testimony to the generally high durability of lightweight concrete (Holm, Bremner, & Newman, 1984), any contribution of internal curing to this performance remained unclaimed until many years later.

The first published recognition of the internal curing potential of lightweight aggregates was likely that of Paul Klieger in 1957, who wrote "Lightweight aggregates absorb considerable water during mixing which apparently can transfer to the paste during hydration (Klieger, 1957)." It is appropriate that the title of Klieger's paper included the phrase "high strength concrete", as it was the search for proper curing and an avoidance of self-desiccation in high strength concrete that prompted renowned concrete technologist Robert Philleo to write these prophetic words in 1991, "Either the basic nature of Portland cement must be changed so that self-desiccation is reduced, or *a way must be found to get curing water into the interior of high-strength structural members.* The latter is possible through the use of saturated lightweight aggregate. However, people striving for high strengths are not eager to use lightweight aggregate. *A partial replacement of fine aggregate with saturated lightweight fines might offer a promising solution*. (Philleo, 1991)" (italics added for emphasis). This concept is illustrated schematically in Figure 1 where external curing water is only able to penetrate several mm into low water to cement ratio concrete, whereas internal curing enables the water to be distributed more equally across the cross section. By the mid-1990s, a variety of research groups in Germany (Weber & Reinhardt, 1995), the Netherlands (van Breugel & de Vries, 1998), and Israel (Bentur, Igarishi, & Kovler, 1999) had followed through on Philleo's concept by actively investigating internal curing via the use of pre-wetted lightweight aggregates. In the years soon after that, other materials that could function as internal water reservoirs, such as superabsorbent polymers (SAP) (Jensen & Hansen, 2001) (Jensen & Hansen, 2002) and pre-wetted wood fibers (Mohr, Premenko, Nanko, & Kurtis, 2005) were also investigated. As with many new technologies, the path from research to practice has been a slow one, but as of 2010, hundreds of thousands of cubic meters of concrete containing pre-wetted LWA for internal curing have been successfully placed throughout the U.S. (Villareal, 2008).

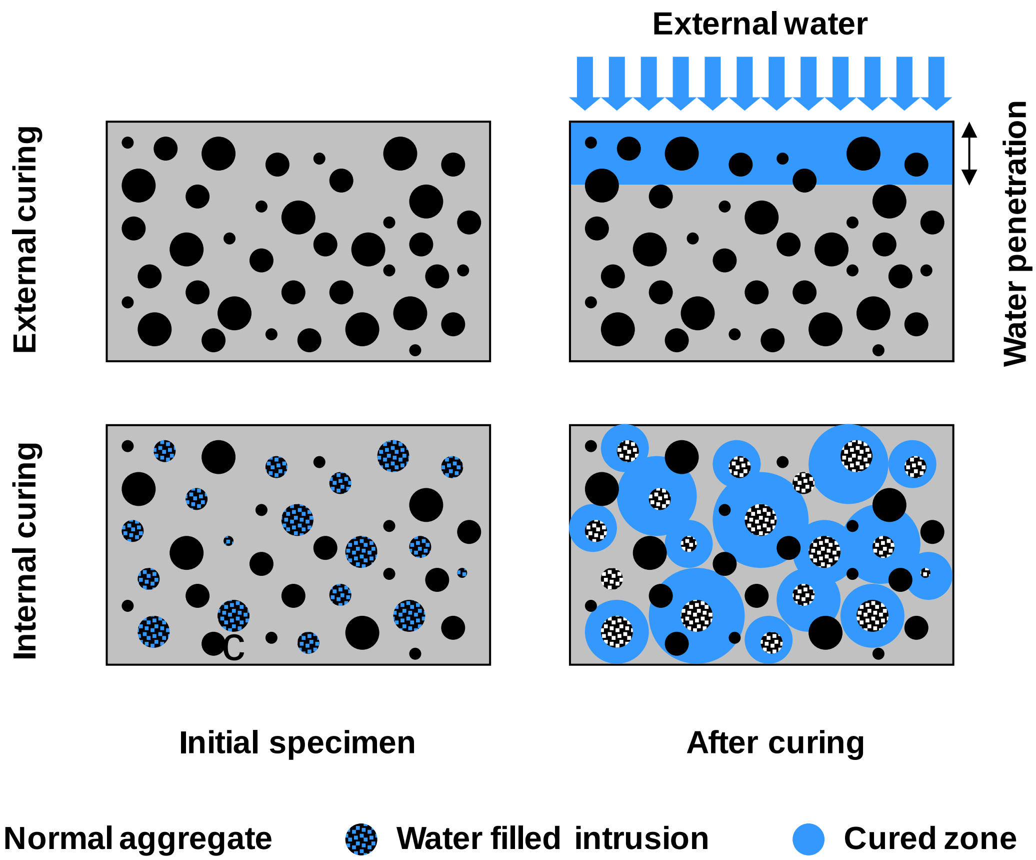


Figure 1: Illustration of the difference between external and internal curing. The water-filled inclusions should be distributed uniformly and spaced close enough to provide coverage for the entire paste system. (Castro, De la Varga, Golias, & Weiss, 2010).

3 Internal Curing in Theory

The need for internal curing emanates directly from the basic nature of cement hydration reactions. As a mixture of cement and water reacts to form crystalline and gel hydration products, the water incorporated into these hydration products generally occupies less space than water in its bulk form. Thus, the hydration (and pozzolanic) reactions are accompanied by a net chemical shrinkage as the products occupy less space than the reactants. As an example, equation (1) shows a generally accepted reaction stoichiometry for the hydration of tricalcium silicate, the major component of Portland cement (cement oxide notation is employed where C=CaO, S=SiO_2, and H=H_2O):

$$\begin{array}{llll} C_3S & +5.3H & \rightarrow & C_{1.7}SH_4 + 1.3\,CH \\ 71.1 & 95.8 & & 107.8 \quad\quad 43 \end{array} \tag{1}$$

When the molar volumes (Bentz, 1997) shown below the reaction are considered, one can calculate that the hydration of tricalcium silicate involves a net reduction of 9.6 % on a volume basis or about 0.07 mL/g C_3S (7 % on a mass of water needed to mass of C_3S basis).

Prior to setting, this chemical shrinkage will produce an equivalent physical shrinkage of the three-dimensional microstructure (Barcelo, Boivin, Rigaud, Acker, Clavaud, & Boulay, 1999) (Sant, et al., 2009). However, after a cement paste sets and develops a finite resistance to deformation, the chemical shrinkage, in the absence of an additional source of water, will produce a self-desiccation, as partially-filled pores will be created within the microstructure (Lura, Couch, Jensen, & Weiss, 2009). The pore solution menisci remaining in partially filled pores will create a measurable capillary pressure, directly proportional to the surface tension of the pore solution and inversely proportional to the size of the largest partially filled pore. Equation (2) shows Young's equation (Alberty & Daniels, 1980) that describes this relationship:

$$\sigma=(-2\gamma cos\theta)/r \tag{2}$$

where σ is the capillary pressure or stress, γ is the surface tension of the pore solution, θ is the contact angle, and r is the pore radius. From equation (2), it is clear that two viable paths to reducing the magnitude of these capillary stresses are to reduce the surface tension of the pore solution by using a shrinkage-reducing admixture (Shah, Weiss, & Yang, 1998) (Bentz, Geiker, & Hansen, 2001), or to increase the size of the pores being emptied, by providing sacrificial reservoirs of water in larger scale pores within the microstructure (i.e., internal curing). When these sacrificial larger pores are not present, the capillary stresses will rapidly increase over time, as smaller and smaller pores within the hydrating cement paste empty, even as the continuing hydration further reduces the size of the remaining water-filled capillary pores.

This capillary pressure will concurrently produce a measurable shrinkage of the microstructure that can be estimated using a modified version of MacKenzie's equation (Mackenzie, 1950) (Bentz, Garboczi, & Quenard, 1998):

$$\varepsilon=(\sigma S/3)[(1/K)-(1/K_s)] \quad (3)$$

where ε is the measured linear strain, K is the bulk modulus of the porous material, K_s is the modulus of its solid backbone, and S is the level of saturation in the pore space (0 to 1). When these autogenous stresses and strains become substantial enough, they may contribute to, or by themselves cause, early-age cracking that will compromise the intended design and service life of a concrete structure by providing open pathways for the ingress of deleterious species.

As self-desiccation occurs and σ increases, there will be a concurrent reduction in the internal relative humidity of the hydrating cement paste, as indicated by the Kelvin equation (Alberty & Daniels, 1980):

$$\sigma=[\mathrm{R}T ln(RH)]/V_m \quad (4)$$

where R is the universal gas constant, T is absolute temperature, RH is relative humidity, and V_m is the molar volume of the pore solution. Equation (4) implies that the need for internal curing, as well as the efficiency of a particular internal curing system, can be quantified by measuring the internal relative humidity of a hydrating cement-based system. When equation (4) is combined with equation (2), a relationship between relative humidity and the size of the pores being emptied is established (Figure 2).

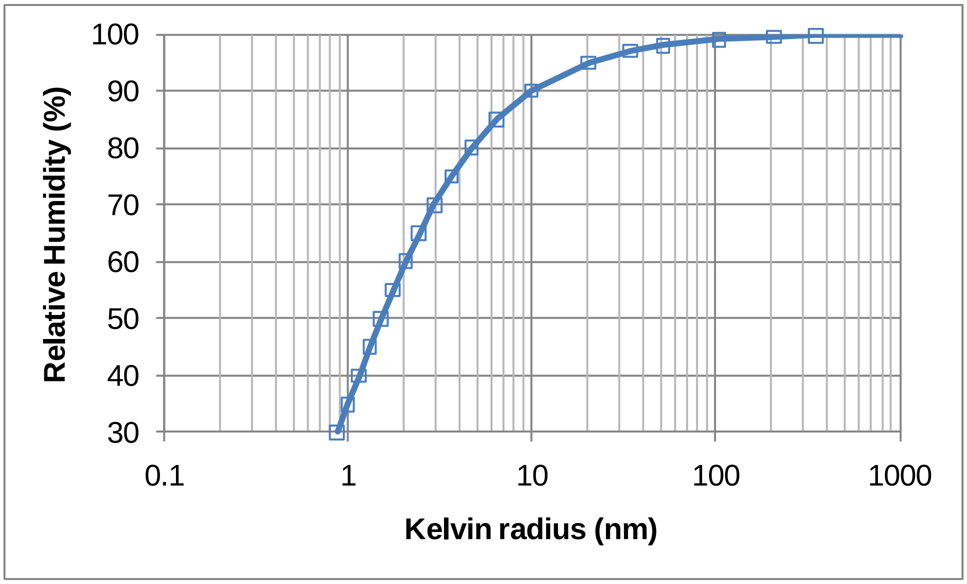


Figure 2. Relationship between relative humidity and the radius of emptying pores according to equations (2) and (4).

Based on the above analysis, the objective of internal curing is to provide a source of readily-available additional water so that the capillary porosity of the hydrating cement paste remains saturated, thus minimizing the autogenous stresses and strains. This additional water will also promote a maximization of the hydration of the cement and pozzolans in the mixture, potentially contributing to increased strengths and reduced transport coefficients. Conventionally, some of this additional water has been provided by external curing techniques such as ponding, fogging, misting, and the application of wet burlap. However, in the higher-performance concretes that are now being used, the capillary porosity becomes disconnected during the first few days of hydration (Powers, Copeland, & Mann, 1959), such that this external water may only penetrate a few mm into the concrete from the curing-applied surfaces (Bentz, 2002), while the interior of the concrete undergoes substantial self-desiccation. The goal of internal curing is to provide additional water in the proper amount and with a proper spatial distribution so that the entire three-dimensional microstructure of hydrating cement paste remains saturated and autogenous stress free.

4 Internal Curing in Practice: Proportioning

4.1 Mixture Proportioning with Internal Curing

Mixture proportioning with internal curing provides the necessary additional water to prolong the time during which saturated conditions are maintained within the hydrating cement paste. The maintenance of these saturated conditions will both contribute to an increase in the achieved degree of reaction of the cement and any pozzolans, and also minimize the development of autogenous stresses and strains that contribute to early-age cracking. Three key questions to consider in this design process are thus: 1) How much internal curing water (or what amount of internal reservoirs) is necessary for a given set of mixture proportions, 2) How far from the surfaces of the internal reservoirs into the surrounding cement paste can the needed water readily travel, and 3) How are the internal reservoirs spatially distributed within the three-dimensional structure of the mortar or concrete specimen? These questions will be addressed in the present and two following subsections of this report.

Assuming that water is not lost to the surrounding environment via evaporation, etc., the answer to the first question is found in a quantitative analysis of the mixture proportions and their expected chemical shrinkage, along with the absorption capacity, desorption isotherm, and saturation state of the internal reservoirs. Simply by equating the water **demand** of the hydrating mixture to the **supply** that is readily available from the internal reservoirs, an equation for the mass (or volume) of required internal reservoirs can be developed; equation (5) provides this relationship and shows the solution obtained for the required mass of dry LWA, M_{LWA}, being employed as the internal reservoirs (Bentz & Snyder, 1999) (Bentz, Lura, & Roberts, 2005):

$$C_f*CS*\alpha_{max}=S*\Phi_{LWA}*M_{LWA}$$
$$M_{LWA}=(C_f*CS*\alpha_{max})/(S*\Phi_{LWA}). \quad (5)$$

In the top form of the equation, the left-hand side represents the water demand of the concrete mixture and is composed of the cement (or binder) factor of the concrete mixture, C_f, the chemical shrinkage of the binder at 100 % reaction, CS, and the expected maximum degree of reaction for the binder, α_{max}, ranging from 0 to 1. The right-hand side represents the water being supplied by a mass, M_{LWA}, of the internal reservoirs, based on their saturation level relative to a quantified 'pre-wetted' condition, S, and the measured sorption capacity of the internal reservoirs, Φ_{LWA}, when in this pre-wetted condition.

In a pure Portland cement system, for a water-to-cement mass ratio (*w/c*) of 0.36 or greater, the expected maximum degree of hydration can be set to 1. For a lower *w/c*, it can be approximated by (*w/c*)/0.36 (Bentz, Lura, & Roberts, 2005). When a binary or ternary blend is employed as the binder, the numerator can be replaced by a summation of the individual water demands for each of the binder components (*i*=1, 2, 3 for cement, fly ash, and slag, for example), as:

$$Water\_demand = \sum_i C_f^i * CS^i * \alpha^i_{max} \quad (6)$$

While a typical chemical shrinkage for Portland cement is on the order of 0.07 mL/g cement, the values for fly ash and slag can be 2 and 3 times greater, respectively (Bentz, 2007). For silica fume, it may be as much as 0.22 mL/g (Jensen, 1993). For any binder of interest, the chemical shrinkage of a paste specimen can be measured using the ASTM C1608 standard test method (ASTM International, 2007). An example of measured chemical shrinkage for a *w/c*=0.30 ordinary portland cement paste is presented in Figure 3.

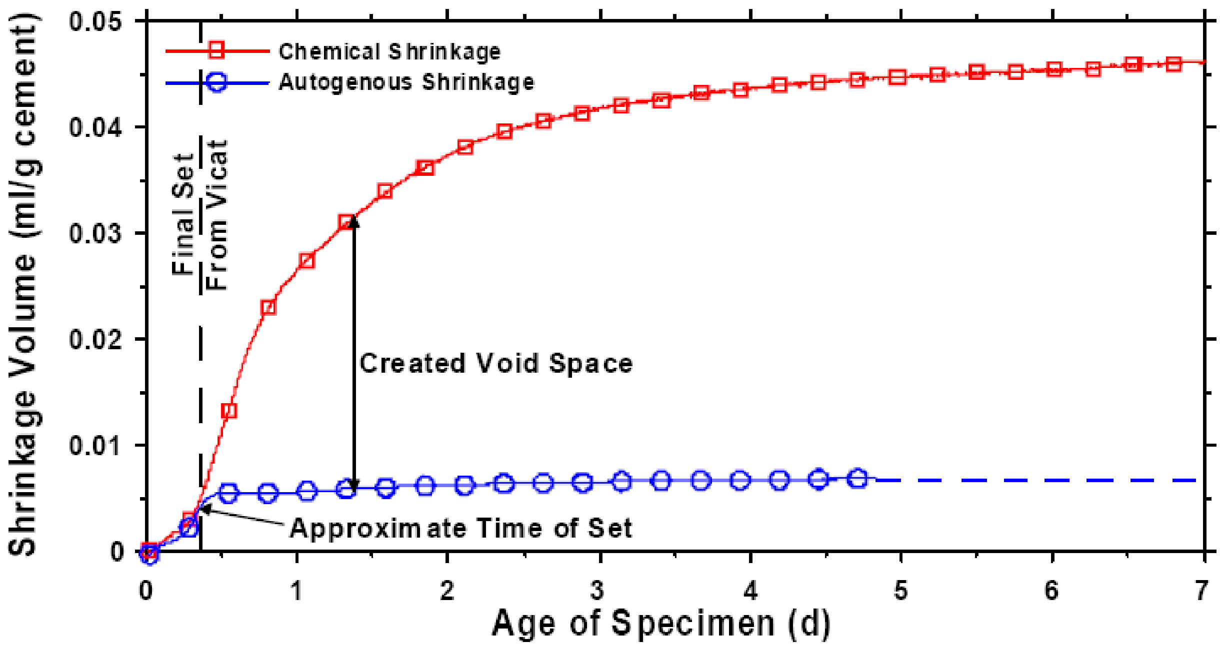


Figure 3. An illustration of chemical and autogenous shrinkage in a paste with *w/c*=0.30 during the first 7 d of hydration at 23 °C (Henkensiefken, Bentz, Nantung, & Weiss, 2009).

Considering the sorption capacity of the internal reservoirs, Φ_{LWA} would best be quantified as the measured desorption of the LWA from a pre-wetted condition down to a relative humidity in the range of 93 % to 97 % (Bentz, Lura, & Roberts, 2005). This would assure that the water in the LWA can be readily released at high relative humidities, thus minimizing the self-desiccation of the concrete. The relative humidities of 93 % and 97 % have been selected because they may be achieved by employing saturated solutions (slurries) of the salts potassium nitrate (KNO_3) and potassium sulfate (K_2SO_4), respectively (Greenspan, 1977). Because of the complexities of and lack of standard test methods for accurately determining the sorption characteristics of LWAs, this topic will be explored in more detail in the subsection on LWA characterization to follow. This same approach could be employed when using crushed returned concrete aggregates as the internal curing reservoirs (Kim & Bentz, 2008); for SAP, typically the numerator of equation (5) could be computed to determine the water demand of the mixture and the dosage of SAP then determined based on knowledge of the SAP's swelling (absorption) characteristics in pore solution (Jensen & Hansen, 2001).

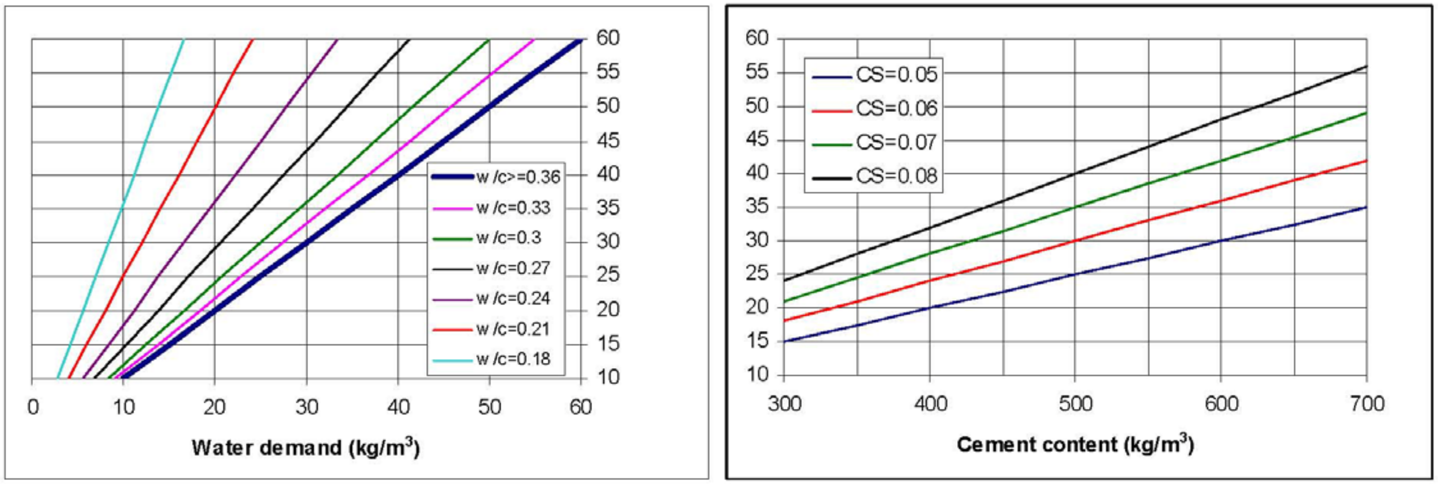
Once equation (5) is utilized to compute the needed quantity of LWA, the final replacement of normal weight aggregates (NWAs) by LWAs should be performed on a volume basis, due to their significant differences in density (Bentz, Lura, & Roberts, 2005). Generally, the size distribution of NWAs being replaced should be selected so that the combined overall gradation is conducive for quality concrete. In some cases, this would best be achieved by having the NWA being replaced and the LWA of similar gradations. In other cases, the LWA gradation has been specifically selected to compensate for deficiencies in the NWA gradation, which otherwise produced an essentially gap-graded mixture (Villarreal & Crocker, 2007).

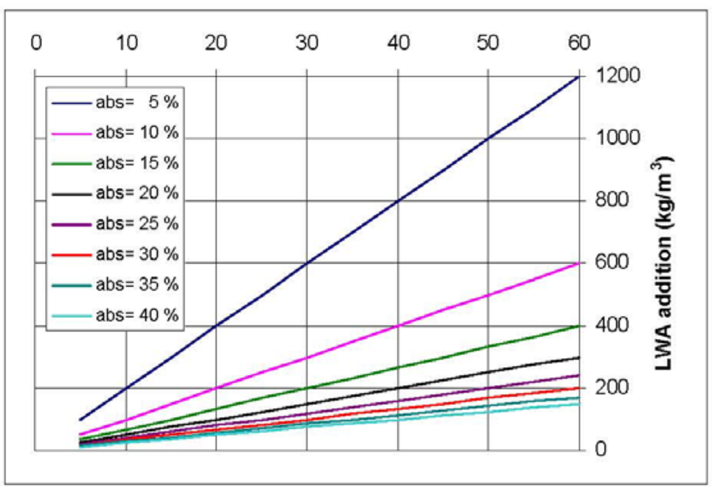
Nomographs for implementing the mixture proportioning strategy of equation (5) have also been developed. Both SI and English units versions are available at the NIST internal curing web site, http://concrete.nist.gov/internalcuring.html, and are reproduced in Figure 4 and Figure 5, respectively. When it is expected that water will be lost to the environment during the mixing, transport, placing, and curing of a concrete mixture, equation (5) will underestimate the additional water requirements of the mixture and a modification will be needed to include an estimate of the evaporated water in these additional water requirements (Radlinska, Rajabipour, Bucher, Henkensiefken, Sant, & Weiss, 2008) (Golias, 2010).

One final issue to address concerning mixture proportioning for internal curing is the potential for either 'undercuring' or 'overcuring.' The former can occur when the water provided by internal curing is less than that recommended by equation (5) and only maintains saturated conditions for some finite period of time, when some of the internal curing water is removed by surface evaporation, or when the internal curing water is not sufficiently well-distributed throughout the three-dimensional microstructure. The latter may potentially occur when water ponding or wet burlap is used to provide external curing to a concrete proportioned with internal curing. Figure 6 illustrates a potential outcome of undercuring, as the water initially provided by the internal curing substantially reduces the pore sizes within the hydrating cement paste due to a more complete hydration, which in turn leads to a greater RH reduction and higher internal stress generation when these pores begin to empty. While this increased RH reduction has been observed in at least one set of experiments (Cusson & Hoogeveen, 2008), the impact on early-age cracking may be minimal, due to the simultaneous enhanced strength development of the specimen with the (undersupplied) internal curing.

When a concrete is proportioned for internal curing according to equation (5), all of the requisite additional water is included in the internal reservoirs. If additional water is provided at the surface of the concrete, a portion of the water in the internal reservoirs may remain in place as opposed to migrating to the hydrating cement paste. If such a specimen were exposed to freezing conditions before this water has had a chance to move out of the internal reservoirs, its durability might be compromised. When internal curing is proportioned for a concrete mixture following the approach of equation (5), external curing is best utilized to seal up the exterior surfaces so that the internal curing water will remain within the concrete to serve its intended purposes.

MIXTURE PROPORTIONING WITH INTERNAL CURING

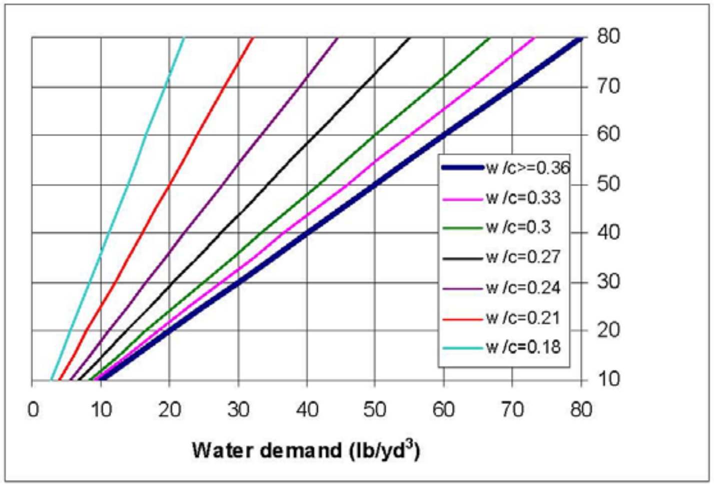


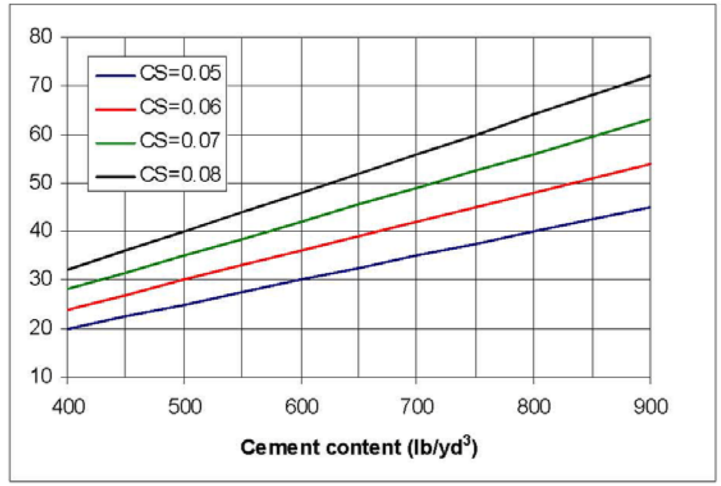


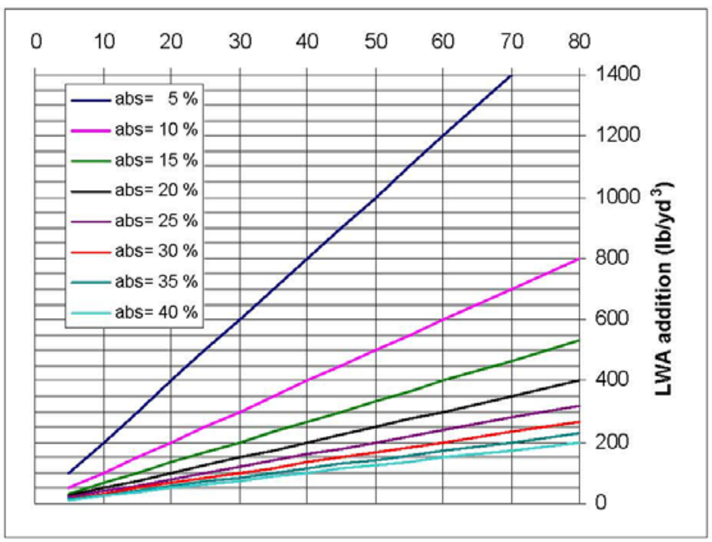
Starting with the cement content in the graph on the upper right, find the chemical shrinkage of the mixture (a good default value is 0.07). Proceed to the value on the y-axis and starting with this same value in the graph on the upper left, find the line for the mixture's w/c ratio. (Note that there is a single (thick) line for all w/c ratios greater than or equal to 0.36 as for these w/c ratio values, it is assumed that complete hydration of the cement powder can be achieved.) Proceed to the value on the x-axis and starting with this same value in the graph on the lower left, find the line for the absorption (dry mass of aggregate basis) of the lightweight aggregate. Finally, proceed to the value on the y-axis to obtain the recommended level of lightweight aggregate (dry mass basis) to be added to the concrete mixture. This replacement should then be conducted on a volumetric basis, replacing an equal volume of normal weight aggregates with pre-wetted (SSD) lightweight aggregates.

Figure 4. Mixture proportioning nomograph in SI units.

MIXTURE PROPORTIONING WITH INTERNAL CURING







Starting with the cement content in the graph on the upper right, find the chemical shrinkage of the mixture (a good default value is 0.07). Proceed to the value on the y-axis and starting with this same value in the graph on the upper left, find the line for the mixture's w/c ratio. (Note that there is a single (thick) line for all w/c ratios greater than or equal to 0.36 as for these w/c ratio values, it is assumed that complete hydration of the cement powder can be achieved.) Proceed to the value on the x-axis and starting with this same value in the graph on the lower left, find the line for the absorption (dry mass of aggregate basis) of the lightweight aggregate. Finally, proceed to the value on the y-axis to obtain the recommended level of lightweight aggregate (dry mass basis) to be added to the concrete mixture. This replacement should then be conducted on a volumetric basis, replacing an equal volume of normal weight aggregates with pre-wetted (SSD) lightweight aggregates.

Figure 5. Mixture proportioning nomograph in English units.

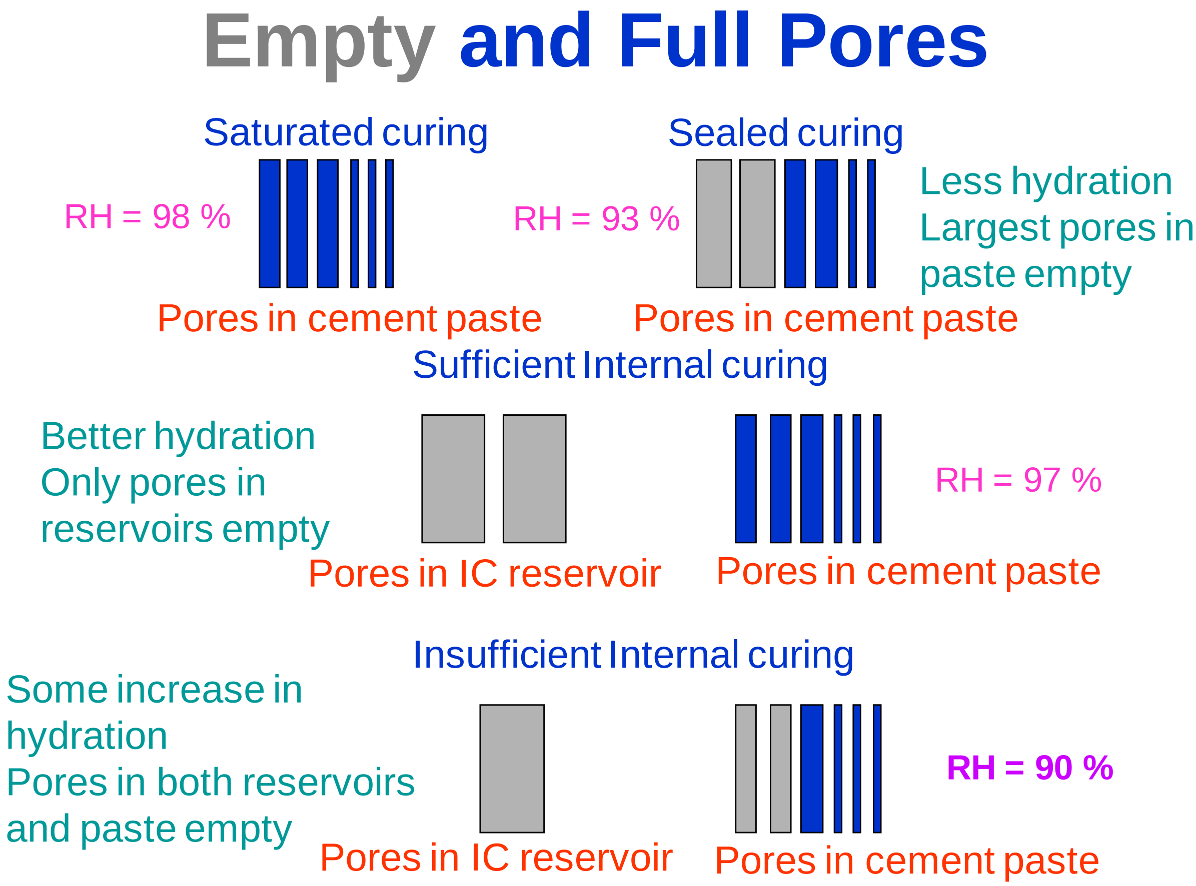


Figure 6. Illustration of potential for undercuring with internal curing. Blue indicates water-filled pores within the internal curing reservoir or hydrating cement paste, while grey indicates empty pores.

4.2 LWA Characterization for Internal Curing

For LWA to function successfully as an internal curing reservoir, the pores containing the water must be larger than those in the surrounding cement paste, so that water will preferentially move from the LWA to the hydrating cement. Previously, X-ray absorption studies of cement-based materials have indicated that during drying, water will preferentially move from coarser pores to finer ones, regardless of whether the coarser pores are present due to an increased *w/c* for a single cement or due to a coarser cement at a constant *w/c* (Bentz, Hansen, Madsen, Vallee, & Griesel, 2001). In the case of internal curing, the coarser pores are present due to the intentional incorporation of internal water reservoirs during the mixture proportioning. This ability of the LWA to release water at high relative humidities can also be quantified by measuring the absorption/desorption properties of the LWA particles. Thus, while it is clear that the absorption/desorption properties of LWA are critical to its successful performance as an internal curing reservoir, a standard test method for evaluating these properties does not currently exist.

In practice, ASTM C127-07 (Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate) and ASTM C128-07 (Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate) are commonly employed, although both test methods explicitly state in their respective Scope sections, "This test method is not intended to be used for lightweight aggregates." Both standards present test methods to produce a sample of an aggregate that is in so-called "Saturated Surface Dry (SSD)" conditions, a state that is much more easily achieved and reproduced for (low absorption) NWAs than for their higher absorption LWA counterparts. While ASTM C128 uses the 'cone method' to determine the moisture content, alternative tests using cobalt chloride or a 'paper towel method' can provide similar information without the complexities associated with the angular nature of the particles (Castro, Henkensiefken, Nantung, Bentz, & Weiss, 2010). Additionally, the absorption of many LWAs will continue at an ever decreasing rate over the course of many days, so that absorption properties must be clarified with a time descriptor, such as reporting the 24 h absorption capacity of a specific LWA (Figure 7). For determining the desorption properties of a pre-wetted LWA, ASTM C1498-04a (Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials) provides valuable guidance and a general purpose methodology based on saturated salt solutions, in the absence of a more specific standardized test method for LWAs (ASTM International, 2004).

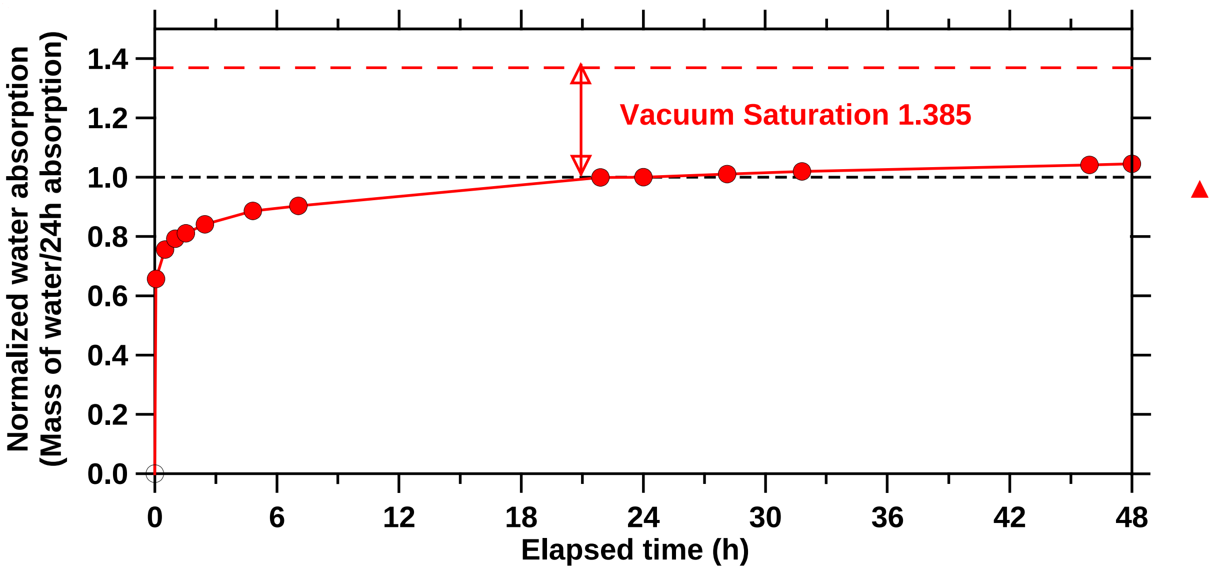


Figure 7. Typical time-dependent water absorption of LWA (Castro, Keiser, Golias, & Weiss, 2011).

For a wide variety of readily available expanded shales, clays, and slates, testing from an oven dry state produces a relative absorption (S) that scales with time (t) according to equation (7), where A is typically a value between 0.07 and 0.13 for times of up to 48 h (Castro, Keiser, Golias, & Weiss, 2011).

$$S = t^A \tag{7}$$

Table 1 shows typical 24 h absorption values for a variety of LWAs from North America. It can be noticed that absorption varies between 6 % and 31 %. Despite the limitations mentioned here, it is clear from equation (5) that the amount of LWA required for internal curing is inversely proportional to its absorption (or desorption) capacity. Thus, to provide the same amount of additional water for internal curing, LWA with a desorption capacity of 30 % will require only 1/3 of the mass of LWA required for LWA with a capacity of 10 %. This assumes, however, that both LWAs provide an adequate spatial distribution of particles to rapidly provide water to a majority of the surrounding hydrating cement paste, as will be discussed in subsequent sections. When internal curing has been selected for a concrete mixture, the judicious selection of a specific LWA for internal curing can produce a considerable cost savings for the ready-mix concrete producer.

Table 1. Desorption Behavior of Expanded Shale (4-12), Clay (1-3), and Slate (13 and 14) Aggregates Available in North America (Castro, Keiser, Golias, & Weiss, 2011).

		Relative Humidity (%)					
LWA #	**24-hr absorption(%)**	**99.9***	**99.6***	**98.9***	**98****	**96****	**94****
1	15.30	~	~	~	0.20	0.14	0.11
2	30.50	0.70	0.69	0.61	0.17	0.10	0.06
3	17.70	0.87	0.70	0.52	0.24	0.16	0.12
4	17.50	0.91	0.61	0.45	0.20	0.12	0.09
5	14.10	0.61	0.48	0.50	0.08	0.04	0.03
6	10.00	~	~	~	0.11	0.06	0.04
7	15.60	0.78	0.54	0.48	0.17	0.08	0.05
8	15.00	0.69	0.57	0.61	0.18	0.08	0.06
9	15.70	0.63	0.44	0.39	0.10	0.06	0.04
10	19.50	0.87	0.68	0.48	0.29	0.20	0.15
11	18.10	0.93	0.68	0.47	0.29	0.21	0.17
12	18.50	0.94	0.77	0.54	0.28	0.19	0.14
13	12.20	0.91	0.50	0.36	0.14	0.07	0.05
14	6.00	0.93	0.52	0.38	0.10	0.06	0.04

* Determined from the Pressure Plate Method over a Range of Aggregate Sizes
** Determined from Dynamic Vapor Desporption (Castro 2011)

While several studies have used saturated salt solutions to control the relative humidity over pre-wetted LWAs to examine their mass loss or desorption (Bentz, Lura, & Roberts, 2005) (Radlinska, Rajabipour, Bucher, Henkensiefken, Sant, & Weiss, 2008), Castro et al. (Castro, Keiser, Golias, & Weiss, 2011) employed dynamic vapor desorption in which the sample was placed in a high resolution balance in an air stream within a carefully controlled relative humidity environment, to measure its desorption isotherm. These measurements indicated that approximately 90 % of the 24-h absorbed water is readily released at high relative humidities (> 93 %) from nearly all of the examined LWAs currently produced in the U.S. This is not true, however, for all porous materials as shown in Figure 8. While the ideal aggregate shows a release of approximately 90 % of its water, the less than ideal aggregate shows a release of only 60 % to 70 %. As a result, an approximately 25 % increase in the volume of the less than ideal aggregate would be required for equivalent internal curing performance. While the dynamic desorption approach provides data below 98 % relative humidity, alternative methods may be applied at higher relative humidities. Pour-Ghaz et al. (Pour-Ghaz, Castro, Kladivko, & Weiss, 2010) used a pressure plate method suggested by Johansson (Johansson, 2010) to examine the desorption of aggregates at these higher relative humidities. This method also has the advantage of being able to test a larger sample, however the testing requires a longer duration (approximately 1 week) for each relative humidity selected.

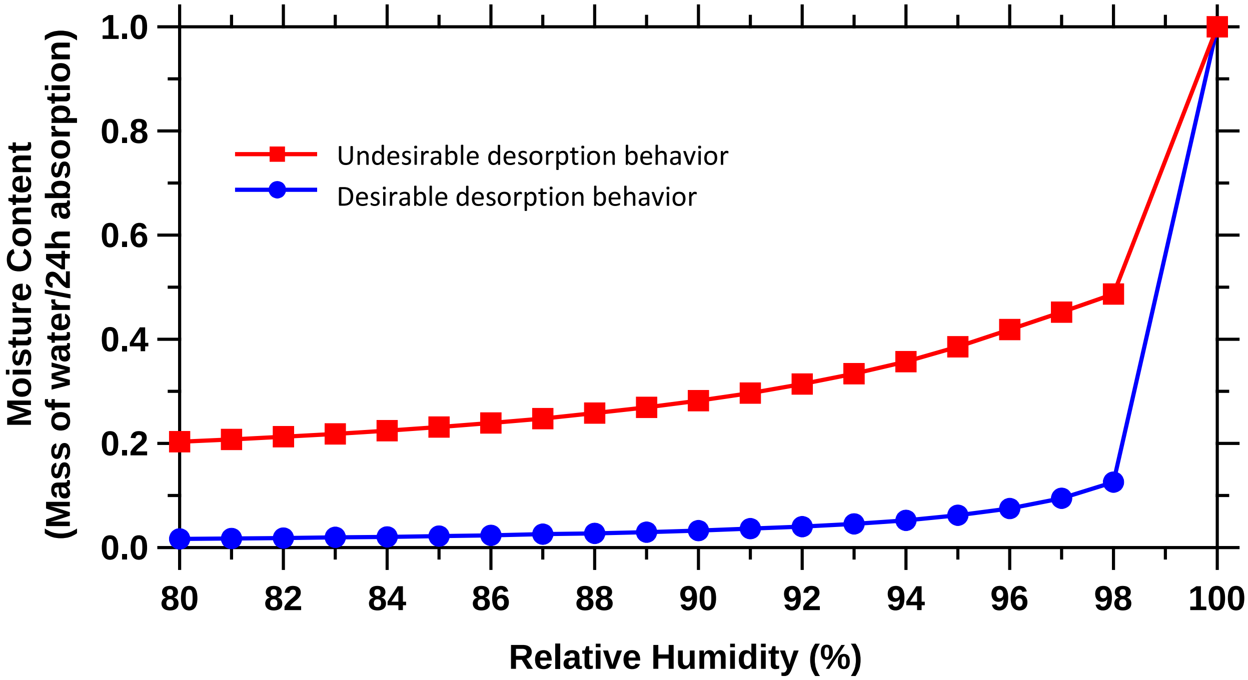


Figure 8. An illustration of desirable and undesirable aggregate desorption behavior (Castro, 2011).

While questions as to the best method for quantitatively measuring the sorption properties of LWA remain, the question of whether water contained within the LWAs does indeed migrate to the surrounding cement paste during curing has been addressed by using either X-ray microtomography or neutron tomography techniques. For example, in August 2005, studies were conducted at the Center for Quantitative Imaging at the Pennsylvania State University to directly observe water movement during the first three days of the curing of a *w/c*=0.3 mortar specimen containing pre-wetted fine LWA (Bentz, Halleck, Grader, & Roberts, 2006). As shown in Figure 9, much of the water within the pre-wetted LWA was observed to depart during the first day of (rapid) hydration of the cementitious matrix. Furthermore, a quantitative analysis of the volume fraction of water migrating from the LWAs exhibited a one-to-one agreement with the measured chemical shrinkage of the cement paste as shown in Figure 10 (Bentz, Halleck, Grader, & Roberts, 2006a), illustrating that the internal curing law of "supply and demand" was adequately met in this case.

Lura et al. used two-dimensional X-ray analysis to estimate water movement; however, their approach used a relatively large X-ray spot size (Lura, Bentz, Lange, Kovler, Bentur, & van Breugel, 2003). Henkensiefken et al. used an X-ray camera with improved resolution to detect water movement from LWA to a paste with a *w/c* of 0.30 (Henkensiefken, Nantung, & Weiss, 2009). While initially the water movement appeared uniform throughout the specimen, at an age of 24 h, the distance the water moved was estimated to be 2 mm.

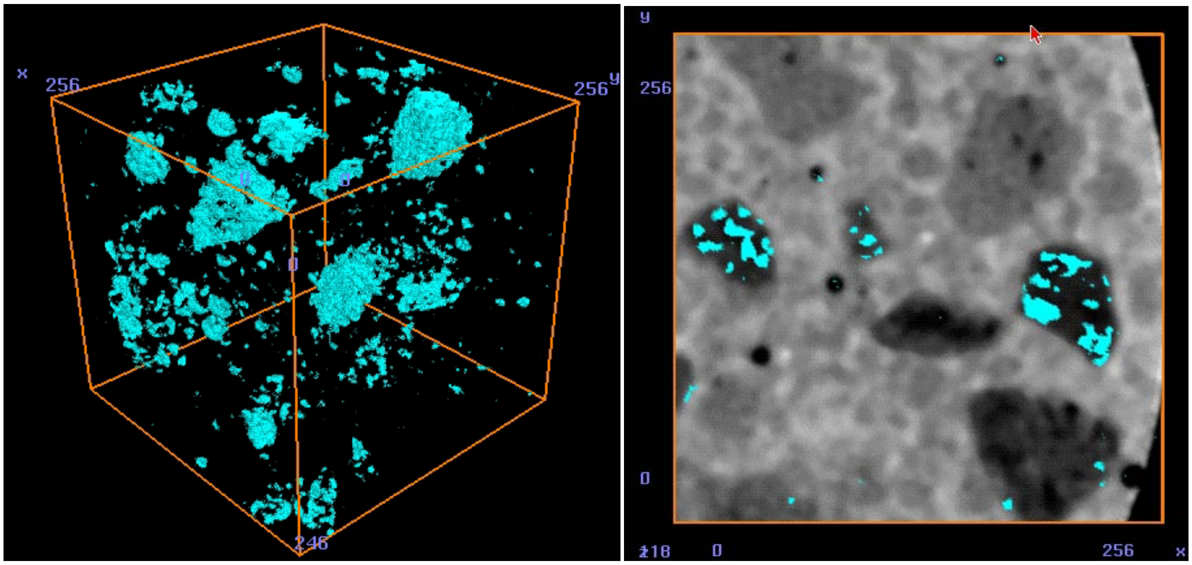


Figure 9. Left: Three-dimensional color-coded image of original data set subtracted from that obtained after 1 day of hydration. Aqua-colored globules indicate regions where LWA particles have lost water to the surrounding cement paste. The 3-D volume is 4.6 mm x 4.6 mm x 4.7 mm. Right: Two-dimensional image (4.6 mm x 4.6 mm) of a portion of the original mortar microstructure with the locations of the evacuated water (in aqua) superimposed to provide further verification of the water movement from the LWA into the surrounding cement paste (Bentz, Halleck, Grader, & Roberts, 2006).

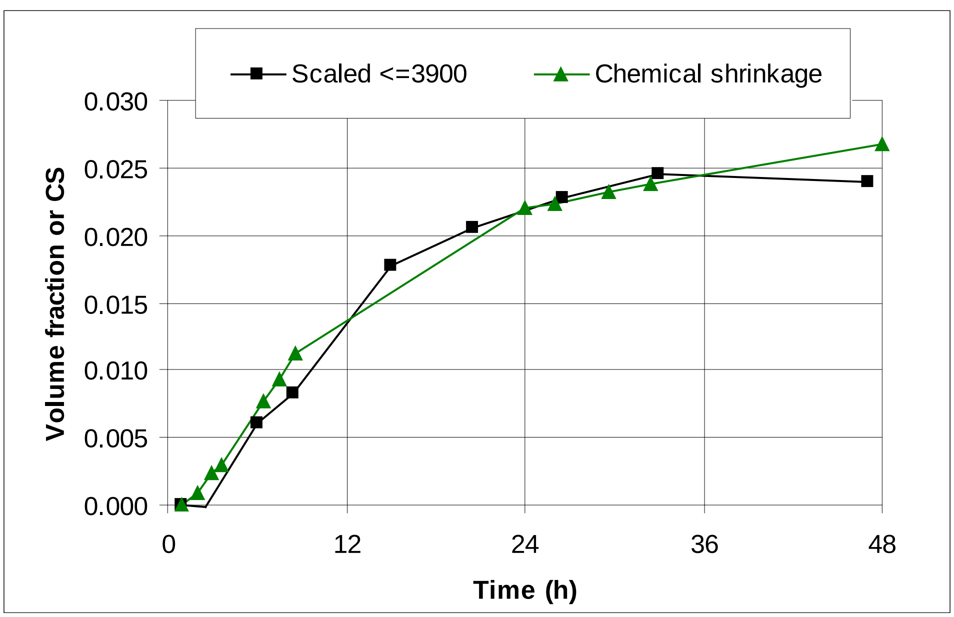


Figure 10. Comparison of measured chemical shrinkage volume fraction to scaled emptied LWA pore volume fraction vs. time (Bentz, Halleck, Grader, & Roberts, 2006a).

More recently, Trtik et al. have tested a sealed cement paste that contained both a pre-wetted LWA (24 h of absorption) and an oven-dry LWA particle using neutron radiography between 0.5 h and 20 h (specific sampling times were 0.5 h, 3.1 h, 7.3 h, 11.2 h, 14.4 h, and 20.4 h) (Trtik, et al., 2011). Changes in local water distribution were evaluated by subtracting the subsequent neutron tomographies from the initial observation. In addition to the neutron tomography, a high-resolution image of the sample was subsequently captured by X-ray tomography so that these images could be synchronized. Figure 11 illustrates a two-dimensional slice from the neutron images at various ages, with the cement paste appearing as the light grey rectangle in the center of the images. The dry LWA is visible as the darker inclusion in the top part of the cross-section, while the pre-wetted LWA is on the bottom and cannot be easily distinguished in the first images after mixing. With the progress of hydration (moving left to right across the top and bottom rows), water is released from the LWA aggregate to the cement paste. Locations in which the neutron signal increased correspond with water being absorbed from the paste and are shown in red, while the locations where the neutron signal decreased correspond with the release of water to the paste and are shown in blue. Water released from the LWA traveled at least 3 mm from the LWA into the cement paste in the first day. There was nearly no measurable gradient in the water content of the cement paste with distance from the LWA, suggesting that the internal curing process is fast and that the water is distributed homogeneously from the LWA to at least 3 mm into the hydrating paste. When an oven-dry LWA was inserted dry into the paste, the oven dry LWA first absorbed pore solution from the cement paste. This absorption took place until as late as 3 h after mixing. A portion of this water was then released back into the paste after setting.

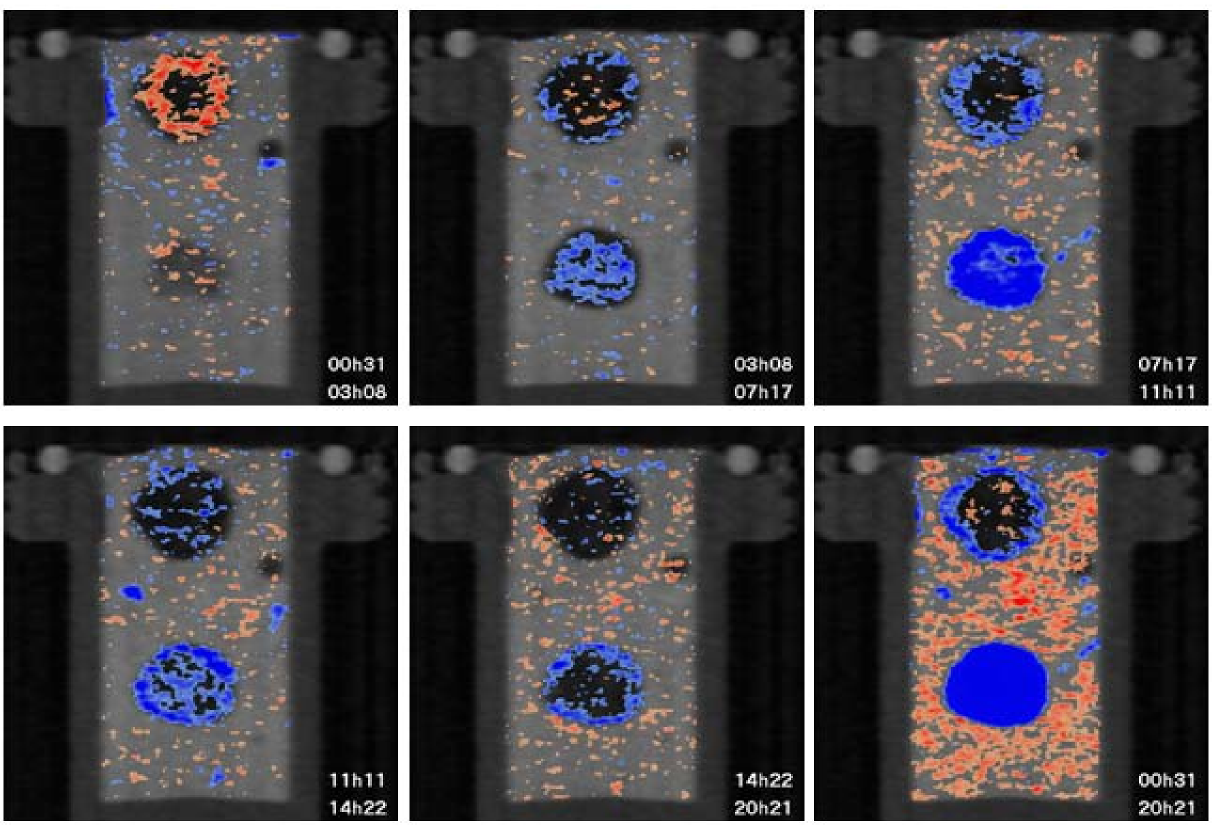


Figure 11. An example of neutron tomography to assess water movement between lightweight aggregate and cement paste during internal curing (Trtik, et al., 2011). Cement paste specimen is 6 mm by 13 mm. The two indicated times in the lower right corner of each frame correspond to the times that were subtracted to create the shown image.

4.3 LWA Spatial Distribution for Internal Curing

The two remaining questions to consider are what is a reasonable estimate of the distance that water can travel from the internal reservoirs into the hydrating cement paste and what fraction of the hydrating cement paste is therefore 'protected' by being within this estimated distance of the surface of an internal reservoir? An estimate for the expected water travel distance can be obtained by equating the projected water flow rate to the value needed to maintain saturation in the surrounding cement paste at its current rate of hydration. A web-based form for performing this estimate, based on extending the analysis first developed by Weber and Reinhardt (Weber & Reinhardt, 1999), is available at the NIST internal curing web site, http://concrete.nist.gov/~bentz/water_distance.html. It requires three sets of input parameters to calculate 1) the pressure drop between the pores in the internal reservoirs and those in the cement paste, 2) the flow required to maintain saturation at the current hydration rate, and 3) the estimated flow distance, respectively. In addition to the mixture proportions and binder chemical shrinkage, needed inputs include expected pores sizes in the paste and in the internal reservoirs, the surface tension, density, and viscosity of the pore solution, and the cement paste permeability. Supplying reasonable values for these inputs at early, middle, and late ages produces the estimated water travel distances shown in Table 2. The early and middle age estimates are in reasonable agreement with measurements for mortars with a water-to-cementitious materials ratio by mass (*w/cm*) of 0.4, based on X-ray absorption profiles obtained during curing (Bentz, 2002). In that study, a water penetration depth of about 20 mm was observed for specimens immediately exposed to a drying environment, while a penetration of only 4 mm to 6 mm was observed for specimens first cured under saturated conditions for 3 d.

Table 2. Distance of Water Travel from the Surfaces of Internal Reservoirs (Bentz, Koenders, Monnig, Reinhardt, van Breugel, & Ye, 2007)

Hydration Age	**Estimated Travel Distance of Water**
Early (i.e., < 1 day)	20 mm
Middle (i.e., 1 day to 3 days)	5 mm
Late (i.e., 3 days to 7 days)	1 mm
Worst Case (i.e., > 28 days)	0.25 mm

Once an estimate of the travel distance has been established, the remaining question concerns the fraction of the cement paste that is 'protected' by being located within that distance of an internal reservoir surface. This concept is quite similar to the 'protected paste volume' concept developed for characterizing air void systems in concrete (Bentz & Snyder, 1999) and can be readily investigated using a hard core/soft shell computer code (Bentz, Garboczi, & Snyder, 1999), available for execution at http://concrete.nist.gov/~bentz/intcuring.html. The user provides the sieve size distribution for the aggregates, the fractional replacement of LWA for NWA for each sieve on a volume basis, and the total volume fraction of all aggregates in the mixture to obtain a table of the protected paste volume (0 to 1) as a function of distance from the LWA surfaces. An example of results returned by the simulation is provided in Table 3, while Figure 12 provides an example two-dimensional color-coded image that is also provided to the user. In the case shown in Table 3 and Figure 12, all of the cement paste is within a 1 mm distance of an LWA surface, thus satisfying even the late age criteria listed in Table 2.

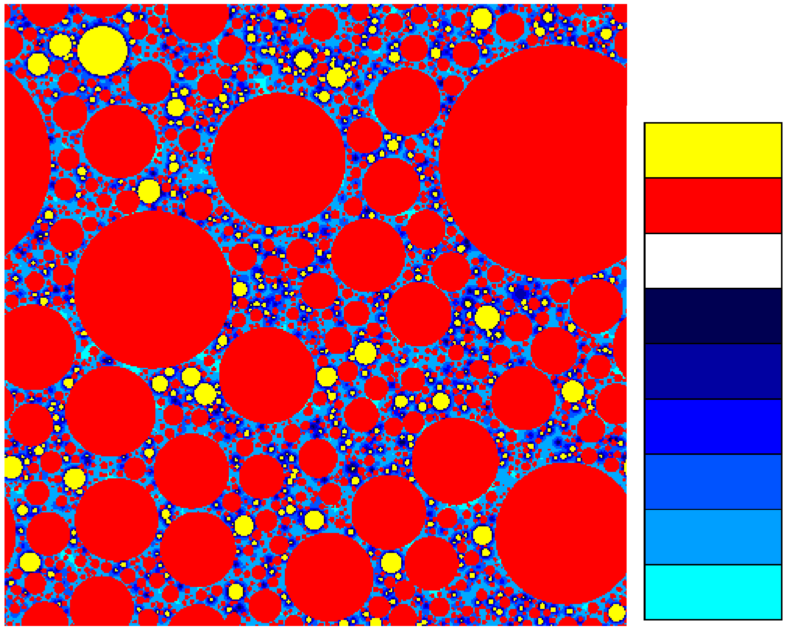


Figure 12. Example two-dimensional image (3 cm x 3 cm) from internal curing simulation (Bentz, Lura, & Roberts, 2005).

Table 3. ‘Protected Paste’ Volume as a Function of Distance from the LWA Surfaces (Bentz, Lura, & Roberts, 2005).

Distance from LWA Surface	Protected Paste Fraction
0.02 mm	0.0459
0.05 mm	0.1281
0.1 mm	0.2804
0.2 mm	0.5629
0.5 mm	0.9783
1.0 mm	1.0000

Using the hard core/soft shell model, Henkensiefken et al. modeled 16 different mixtures with different size aggregates and sands with different fineness modulus values (Henkensiefken, Nantung, & Weiss, 2009). Figure 13 shows the volume of protected paste in concrete when 30 % of the aggregate (either coarse or fine, respectively) on a volume basis is replaced by pre-wetted lightweight aggregate and water movement is assumed to be limited to 2 mm. If 30 % of the coarse aggregate is replaced, regardless of the selected size, no LWA will protect more than 50 % of the paste volume. Conversely, if the LWA used for internal curing had a lower fineness modulus (finer sand), nearly all the paste would be within 2 mm of an LWA particle. When a coarser LWA (higher fineness 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 such LWA was used, the volume of the sand might have to be increased to ensure that an adequate fraction of the paste was protected. It was not the intention of the authors to suggest that LWAs with a fineness modulus greater than 3.2 should not be used or will not work, but rather to illustrate that the particle size distribution is important and should be properly considered.

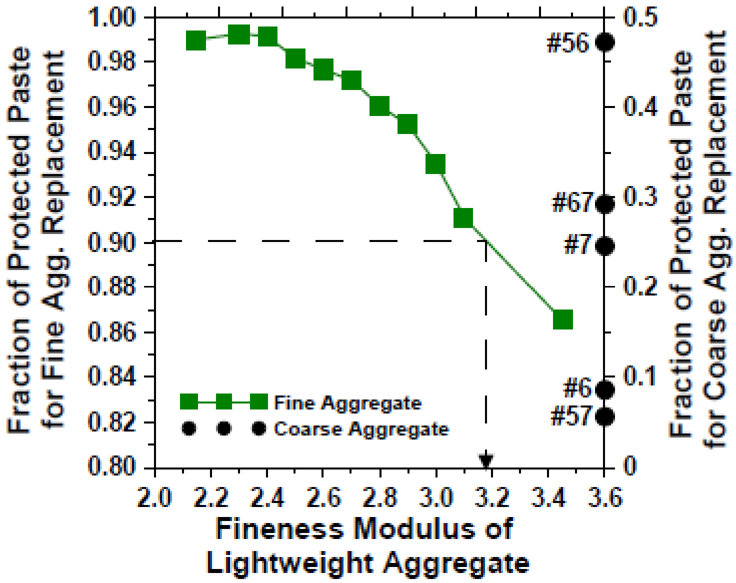


Figure 13. Volume of protected paste in concrete where 30 % of the aggregate by volume is replaced with different coarse aggregate or sand with different fineness modulus values (Henkensiefken, Nantung, & Weiss, 2009).

5 Internal Curing in Present Practice: Lab Studies

5.1 Plastic Shrinkage

Concrete can also be susceptible to cracking at the time of placement, if the evaporation rate is high (Villarreal & Crocker, 2007). While these cracks are not generally a cause for concern in terms of the load the structure can carry, they are often unsightly and can lead to the ingress of aggressive agents that could accelerate the corrosion of reinforcing steel. Recently, studies have been conducted to compare the plastic shrinkage and cracking tendencies of concretes with and without internal curing (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010). To evaluate their potential for plastic shrinkage cracking, samples were tested following ASTM C1579 "Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)" (ASTM International, 2006). In addition, tests were performed to measure the settlement and evaporative weight loss of concrete slabs (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010).

Figure 14 shows the measured crack width distributions that were obtained for *w/c* = 0.55 concretes made with different volume replacements of LWA (exposure conditions of 32 ºC ± 1 ºC, 25 % RH ± 3 % RH, and 15 km/h wind speed; each curve is the average of three panels and the *y*-intercept represents the probability of observing a crack within the sampled grid mask) (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010). The panels were photographed from a constant height and their images were analyzed for cracks and crack widths using image analysis software. The plastic shrinkage tests were performed on concrete mixtures with 30 % by volume coarse aggregate, and 30 % by volume of a mixture of normal weight fine aggregate and LWA. The examined volume fractions of LWA in these mixtures of fine aggregates for the concretes remained the same as the volume fractions of LWA from previous studies of mortars (Henkensiefken, Bentz, Nantung, & Weiss, 2009). Here, the naming convention of 18.0 % (as a percentage of concrete volume) LWA represents the volume of LWA needed to meet the chemical shrinkage demands based on equation (5), with the 6 % and the 10 % mixtures therefore representing under dosages with respect to equation (5). The control mixture (0 % LWA) shows the earliest cracking and the largest crack widths, while the potential for plastic shrinkage cracking and crack widths decrease as the LWA replacement volume increases. When a sufficient volume of LWA is used (18 % in this case), plastic shrinkage cracking was completely eliminated for the environmental exposure conditions tested in the study (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010).

It is hypothesized that plastic shrinkage cracking is reduced with internal curing as water in the LWA replenishes water lost due to evaporation as shown schematically in Figure 15 (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010). Immediately after placement, the system is in a fluid state and the aggregate and cement particles tend to settle due to gravity, simultaneously forcing pore fluid (water) to the surface. This is commonly observed in practice as 'bleed water.' During this initial period, a thin layer of bleed water covers the surface of the concrete and evaporates at a relatively constant rate (provided the environmental exposure

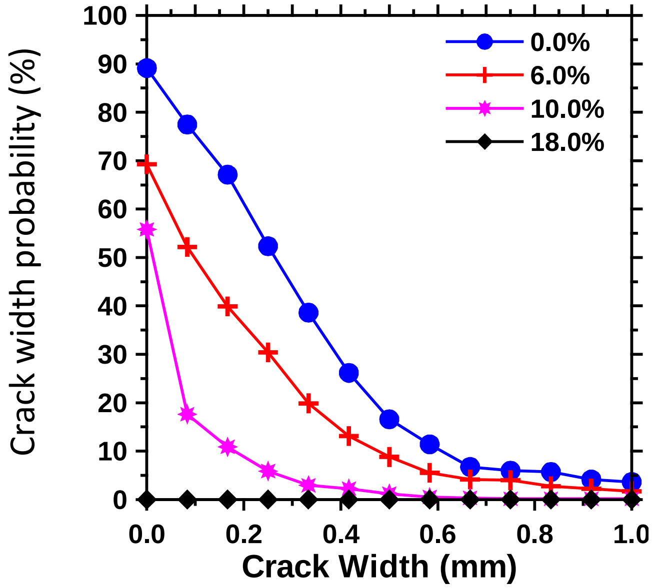


Figure 14. Probability distribution of crack width occurrences in concrete with different replacement volumes of pre-wetted LWA as indicated in the legend (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010).

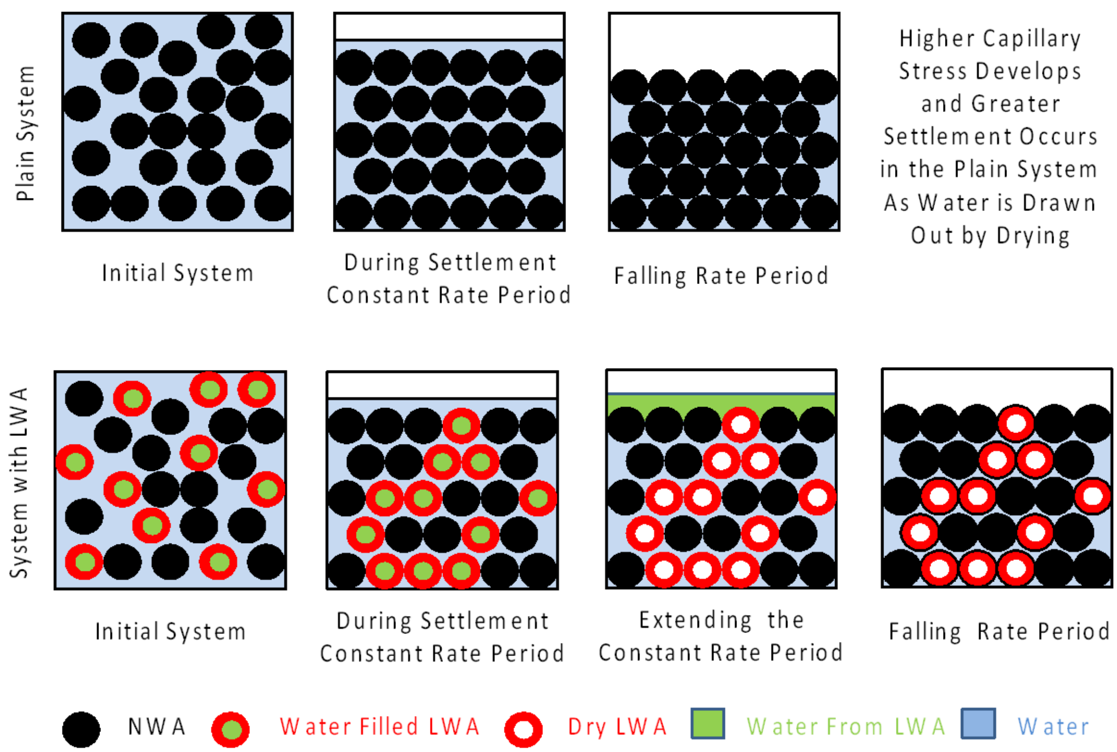


Figure 15. A conceptual illustration of the role of water-filled lightweight aggregate at the surface of a concrete exposed to drying immediately after placement (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010).

conditions are relatively constant). As a result, this is referred to as the constant rate period of drying (Lura, Pease, Mazzotta, Rajabipour, & Weiss, 2007). During this time, the system continues to consolidate in the vertical direction resulting in settlement of the surface. After some time, the rate of settlement dramatically reduces as the particles begin to come in contact with one another. Assuming that the rate of evaporation is relatively high, the layer of bleed water will be lost from the surface. When the water available to evaporate decreases, a slower rate of evaporation occurs, referred to as the falling rate period (Lura, Pease, Mazzotta, Rajabipour, & Weiss, 2007). During the falling rate period, evaporation draws water from between the particles resulting in the development of capillary stresses in the system that produce further consolidation and may lead to plastic shrinkage cracking. In conventional concrete systems, the stresses will rise relatively dramatically during this period. In a system with internal curing, however, water is provided by the pre-wetted and rigid LWAs to replenish the water evaporating from the surface of the concrete. This helps to reduce the capillary stress during the falling rate period. The water from the rigid LWAs reduces the capillary stress in the system resulting in less consolidation and settlement (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010) and a dramatically lower potential for plastic shrinkage cracking. This preferential removal of water from LWA while the surrounding cement paste remains saturated during a drying exposure of the fresh material has been verified using three-dimensional X-ray absorption microtomography measurements (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010). Conversely, in a sealed system not exposed to drying, the water remains within the LWA until it is drawn out to the surrounding cement paste by capillary forces generated during hydration (Bentz, Halleck, Grader, & Roberts, 2006).

While the use of water-filled LWA is beneficial in reducing the potential for plastic shrinkage cracking and reducing the width of any cracks that do develop, it should be noted that any water consumed in this phase will not be available later to reduce autogenous and/or drying shrinkage.

5.2 Autogenous Deformation and Internal Relative Humidity

Because one of the major objectives of incorporating internal curing into a concrete mixture is to reduce autogenous shrinkage and the cracking that may accompany it, numerous studies have provided measurements of autogenous deformation in pastes (with SAP or pre-wetted fibers), mortars, and concretes with and without internal curing (RILEM, 2007). For pastes and mortars, autogenous deformation is commonly assessed using ASTM C1698 “Standard Test Method for Autogenous Strain of Cement Paste and Mortar” (ASTM International, 2009), based on the method originally developed by Jensen and Hansen (Jensen & Hansen, 1995). In this method, a sample of the paste or mortar is placed in a sealed corrugated polymeric tube and its deformation periodically assessed after setting to indicate any expansion/shrinkage that is occurring in the cement-based material. For paste samples, free shrinkage measurements using the corrugated tubes have been observed to correlate well with non-contact laser measurements (Pease, Hossain, & Weiss, 2004), as well as with volumetric measurements (Sant, Lura, & Weiss, 2006). For mortars and concretes, methods to assess autogenous strains have included measurements made on sealed prisms (Weiss, Borischevsky, & Shah, 1999) (Cusson, 2008), blocks (Duran-Herrera, Petrov, Bonneau, Khayat, & Aitcin, 2008), cylinders (Craeye & De Schutter, 2006), or larger corrugated tubes (Tian & Jensen, 2008). Restrained stress development has been assessed using the ASTM C1581 restrained ring test (ASTM International, 2009b), temperature stress testing machines (RILEM, 2003), and a dual ring test setup (Schlitter, Senter, Bentz, Nantung, & Weiss, 2010).

One of the earlier studies on internal curing evaluated internal curing, using either pre-wetted LWA or SAP, of a *w/cm*=0.35 mortar prepared with a blended cement containing 8 % silica fume (FSF) by mass and cured at 30 °C (Geiker, Bentz, & Jensen, 2004). To supply additional water for internal curing, pre-wetted LWA was used to replace either 8 % or 20 % of the normal weight sand by mass, while SAP was added at 0.4 % by mass of cement. Figure 16 shows the internal relative humidities and autogenous deformations measured on sealed specimens. All three mortars with internal curing exhibit the maintenance of a substantially higher internal relative humidity that would correspond to a reduction in autogenous stress generation according to equation (4). While the 8 % replacement level of LWA significantly reduces the autogenous shrinkage, it is basically eliminated entirely with the 20 % replacement level. The 0.4 % addition of SAP is also highly effective in reducing the autogenous deformation, as the measured shrinkage at 14 d is less than 50 microstrain (μm/m).

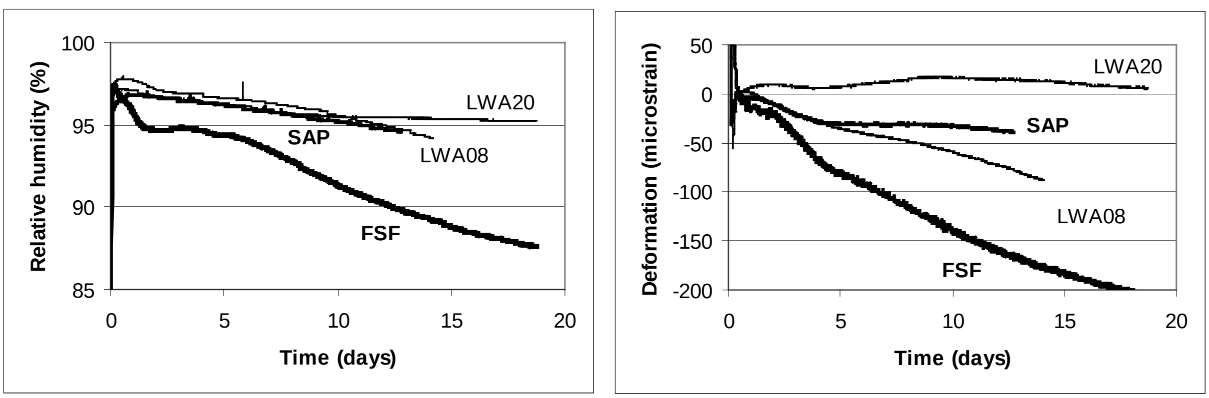


Figure 16. Internal relative humidity (left) and autogenous deformation measurements (right) on silica fume blended cement mortars with and without internal curing (Geiker, Bentz, & Jensen, 2004).

More recently, mortars with various replacement levels of pre-wetted LWA have been evaluated for a variety of early-age properties, including internal relative humidity and autogenous deformation (Henkensiefken, Bentz, Nantung, & Weiss, 2009). In that study, mortars with a *w/c*=0.3 were prepared with replacement levels of LWA below, equal, and above that prescribed by equation (5), with 23.7 % by volume being the replacement level directly corresponding to equation (5). Figure 17 provides the measured internal relative humidities and autogenous deformations for the mortars with eight different levels of internal curing (including no internal curing in the 0 % mixture). The results exhibit the expected progression in performance, as the internal relative humidity increases with increasing replacement level of LWA, while the autogenous shrinkage concurrently decreases. In this particular case, equation (5) provided a very valid estimate of the requisite LWA dosage, as the system designated as 23.7 % basically exhibited only an autogenous expansion (most of which occurred immediately after setting) during 28 d and maintained a higher internal relative humidity throughout the first 7 d of sealed curing.

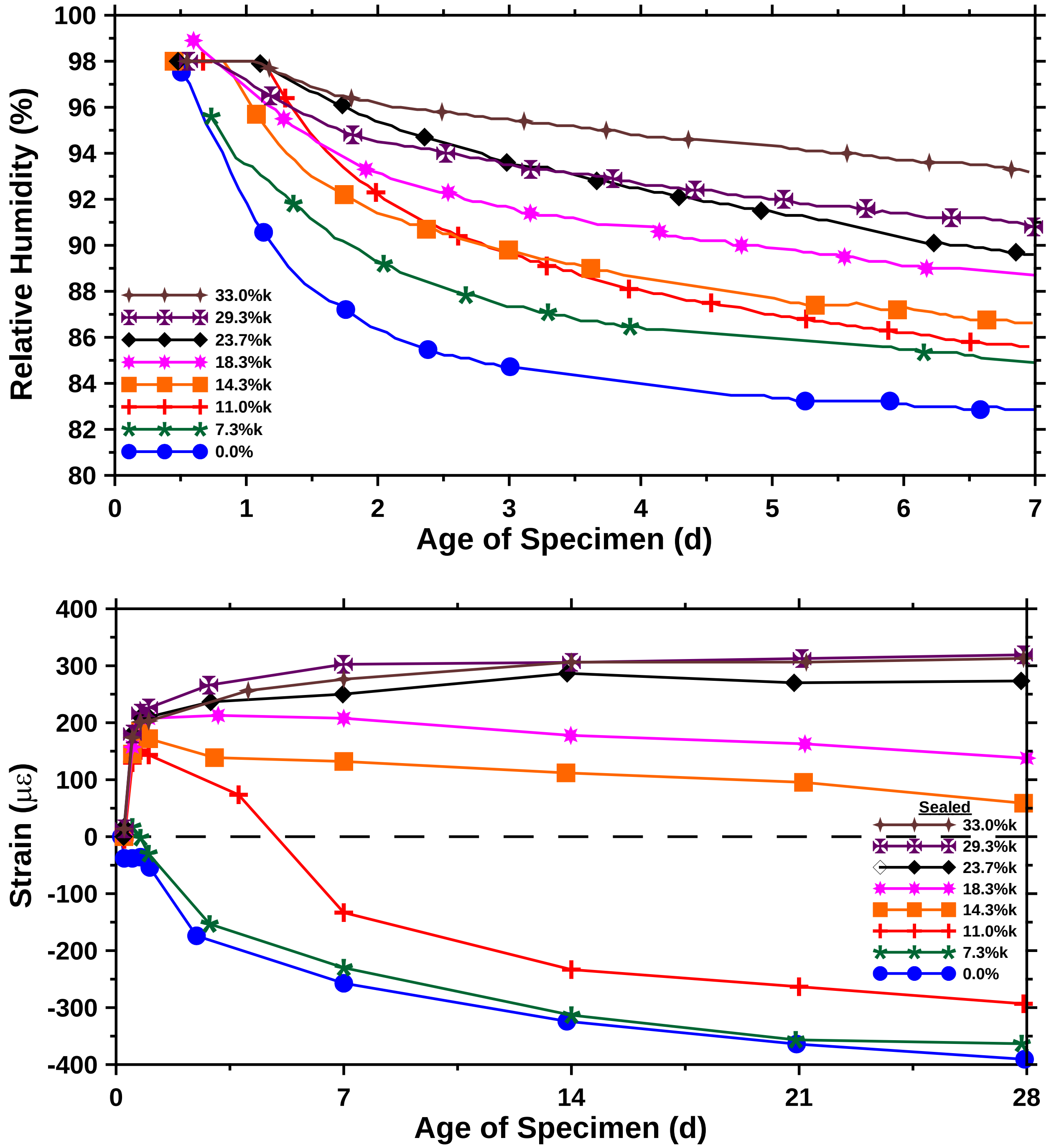


Figure 17. Internal relative humidity (top) and autogenous deformation measurements (bottom) on *w/c*=0.3 cement mortars with various levels of pre-wetted LWA replacement to provide internal curing (Henkensiefken, Bentz, Nantung, & Weiss, 2009).

In some cases, attempts at applying equation (5) to internal curing mixture proportioning have produced mixtures where autogenous shrinkage, although substantially reduced, is not totally eliminated. Potential causes can include:

1) Because the pores in the internal curing agent are being emptied, some reduction in internal relative humidity will be observed and (much lower) finite autogenous stresses will induce a small level of shrinkage, as the autogenous stress is inversely proportional to the pore size being emptied, according to equation (2);

2) A portion of the 'internal curing' water in the internal curing agent may be lost to the concrete mixture during initial mixing, hauling, and placement, potentially increasing the *w/cm* of the mixture, but likely maintaining a high level of workability and finishability (Villareal, 2008);

3) A portion of the internal curing water may remain within the internal curing agents due to differences between their absorption and desorption properties (Bentz, Lura, & Roberts, 2005) (Castro, Keiser, Golias, & Weiss, 2011);

4) Any internal curing water lost to evaporation/drying, while reducing plastic shrinkage (cracking), will not be available for subsequent 'internal curing' (Henkensiefken, Briatka, Bentz, Nantung, & Weiss, 2010);

5) In blended cement concretes, some autogenous shrinkage may be due to the pozzolanic reaction between the supplementary cementitious materials and calcium hydroxide (loss of micro-reinforcement) and thus will not be eliminated by internal curing (Jensen & Hansen, 1996) (Bentz, 2007);

6) The internal curing water may not be distributed uniformly enough within the concrete microstructure to travel the required distances to the hydrating cement paste (Bentz, Lura, & Roberts, 2005), especially at later ages; and

7) In the real world, autogenous deformation is nearly always confounded with thermal expansion/contraction (Schlitter, Senter, Bentz, Nantung, & Weiss, 2010).

Using the ASTM C1581 restrained ring shrinkage test (ASTM International, 2009b), it was demonstrated that the reduction in autogenous shrinkage indeed resulted in a reduction in cracking as shown in Figure 18 (Henkensiefken, Bentz, Nantung, & Weiss, 2009). For these mortars, cracking was effectively eliminated for replacement levels greater than or equal to the 23.7 % of LWA by volume computed using equation (5).

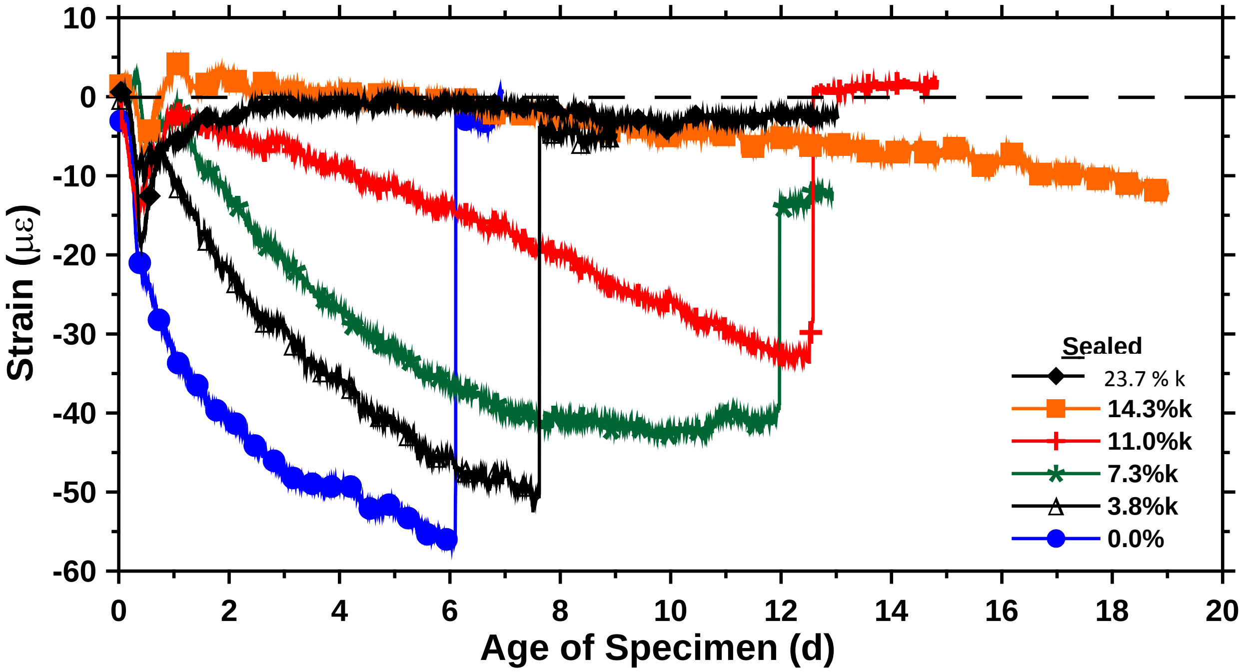


Figure 18. Restrained shrinkage results for mortars with various levels of internal curing under sealed curing conditions. A sharp rise in the strain curve indicates the occurrence of cracking in the specimen (Henkensiefken, Bentz, Nantung, & Weiss, 2009).

5.3 Drying Shrinkage

By modifying the volume of readily available water within the concrete mixture and its elastic and creep properties, internal curing will also influence their drying shrinkage. To examine drying shrinkage as a function of LWA replacement level, prismatic mortar specimens were prepared and exposed to a 50 % RH environment after 1 d of sealed curing (Henkensiefken, Bentz, Nantung, & Weiss, 2009). Figure 19 provides plots of measured mass loss and deformation vs. time during 27 d of drying exposure. In this case, while low replacement levels proved ineffective in mitigating shrinkage caused by the combined effects of internal and external drying, higher replacement level mixtures significantly reduced the measured shrinkage, even while losing more mass than the mixture without internal curing. Water within the pre-wetted LWA is readily available as needed to maintain saturation of the cement paste and thereby reduce plastic, autogenous, and/or drying shrinkage. Because of the larger pore sizes in the LWA relative to those in the hydrating cement paste, water is preferentially drawn from the LWA to the surrounding paste and the emptying of these larger pores produces a much lower capillary stress, which reduces both the measured strain and the propensity for early-age cracking. Using a restrained ring shrinkage experimental set up, this reduction in cracking was directly observed for these same mortar mixtures, as shown by the results provided in Figure 20 (Henkensiefken, Bentz, Nantung, & Weiss, 2009). For these mortars, the time to cracking was substantially delayed for replacement levels above the 23.7 % by volume level computed using equation (5).

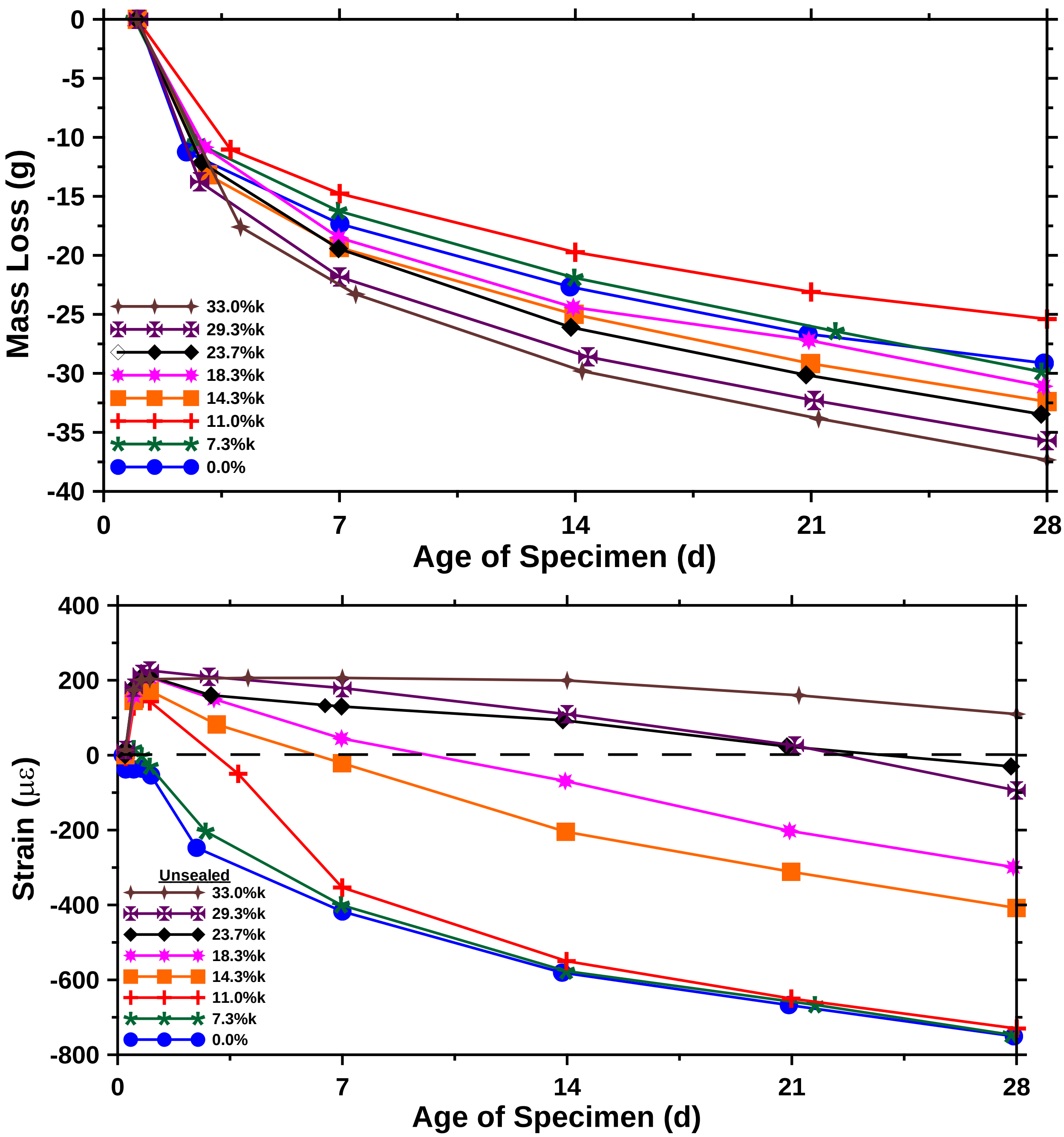


Figure 19. Mass loss (top) and measured deformation (bottom) of free shrinkage specimens of mortars with various levels of internal curing under unsealed curing conditions (Henkensiefken, Bentz, Nantung, & Weiss, 2009).

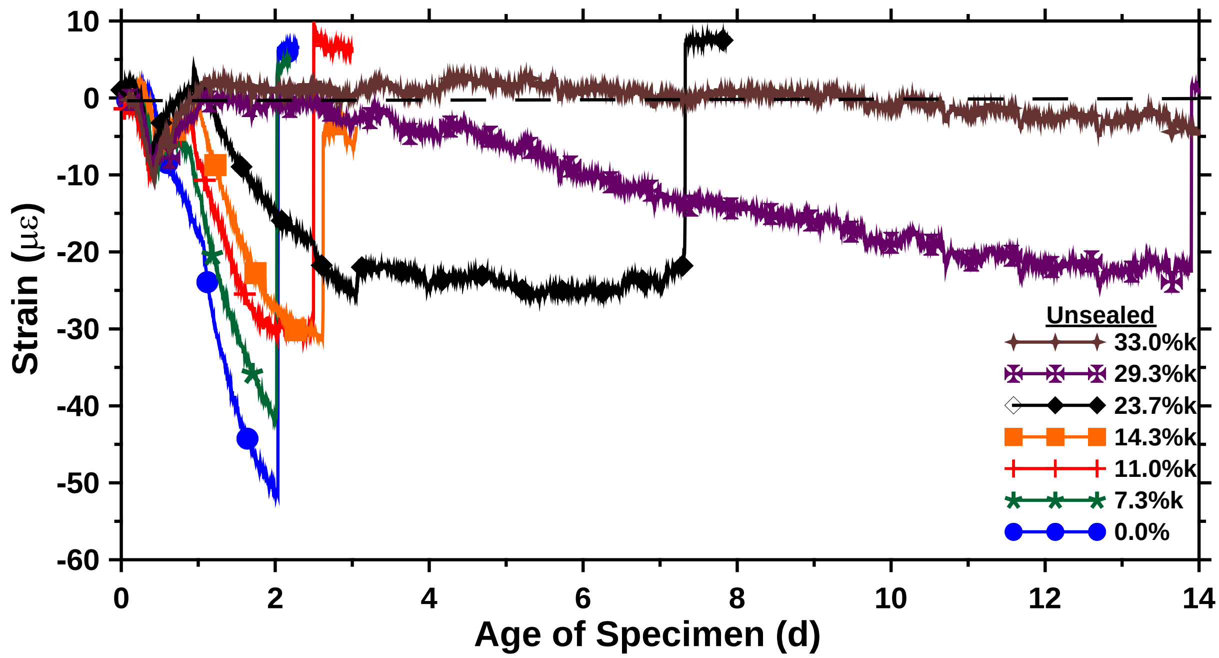


Figure 20. Restrained shrinkage results for mortars with various levels of internal curing in unsealed curing conditions. A sharp vertical rise in the strain curve indicates occurrence of cracking in the specimen (Henkensiefken, Bentz, Nantung, & Weiss, 2009).

5.4 Degree of Hydration and Isothermal Calorimetry

The available additional water within the internal curing reservoirs will generally increase the degree of hydration of the cementitious binder, particularly at later ages. This increase in degree of hydration can be quantified by measuring either the loss-on-ignition (LOI) or the heat of hydration. While no standard test method for the former currently exists, estimating heat of hydration using isothermal calorimetry is well specified in ASTM C1702, "Standard Test Method for Measurement of Heat of Hydration of Hydraulic Cementitious Materials using Isothermal Conduction Calorimetry" (ASTM International, 2009a).

Degree of hydration and isothermal calorimetry data are available from a variety of studies. Figure 21 shows the results of LOI-based degree of hydration measurements for the mortars utilized in the X-ray microtomography experiments presented in Figure 9 and Figure 10 (Bentz, Halleck, Grader, & Roberts, 2006). In this case, even though the mortar with internal curing was formulated with only a 3 d supply of internal curing water (as it was envisioned to freeze the specimen after 3 d and hopefully observe ice formation within the empty pores in the LWA), a significant increase in its degree of hydration was measured at 3 d and 8 d. More recent results for a *w/cm*=0.3, 40 % by volume fly ash mortar with three levels of internal curing (0 %, 50 %, and 100 % of the water supply according to equation (5)) obtained via isothermal calorimetry measurements are provided in Figure 22 (de la Varga, Castro, Bentz, & Weiss, submitted). In this case, the extra hydration due to internal curing is apparent after 4 d and continues to increase throughout the 14 d extent of the measurements.

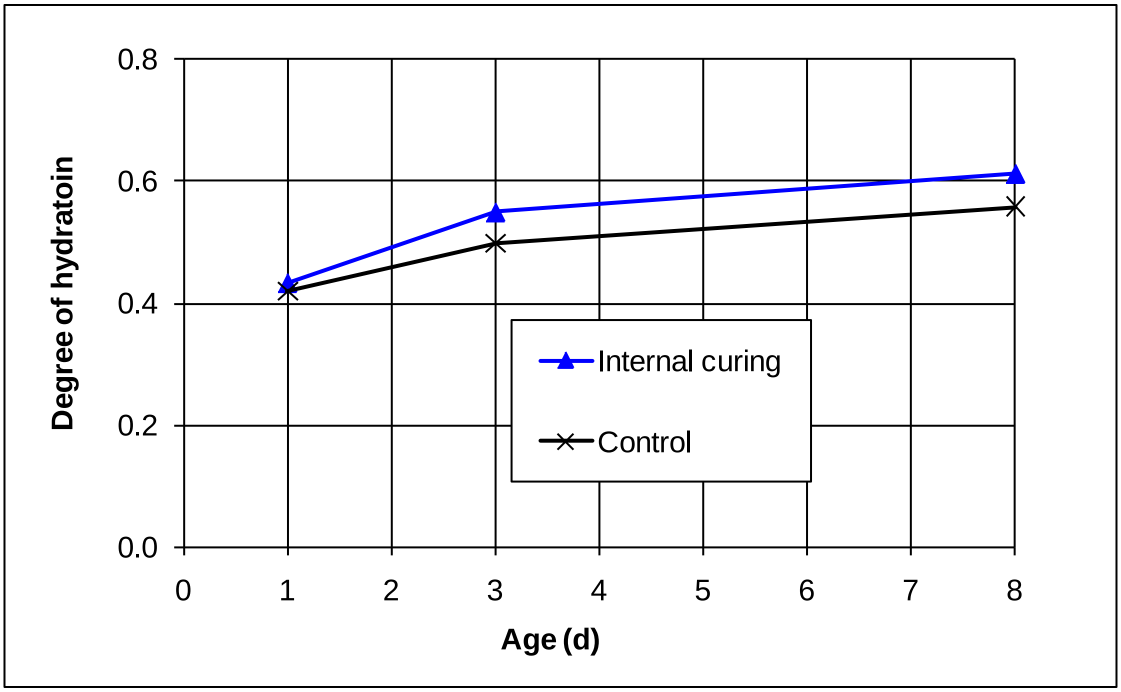


Figure 21. Measured degree of hydration for *w/c*=0.3 mortars with and without internal curing under sealed curing conditions (Bentz, Halleck, Grader, & Roberts, 2006).

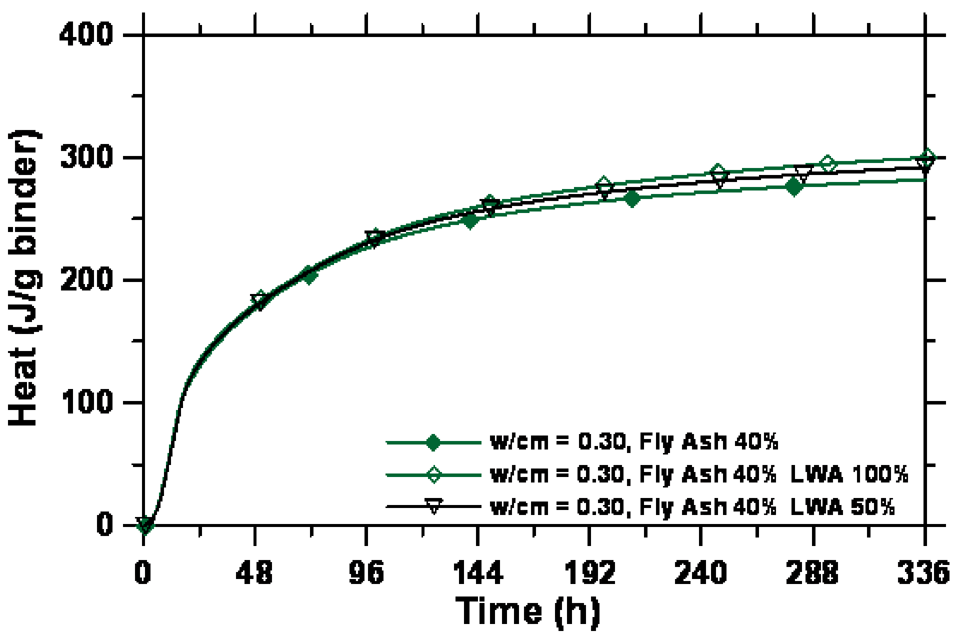


Figure 22. Effect of changing internal curing LWA replacement level on measured cumulative heat release for a blended cement/fly ash mortar (de la Varga, Castro, Bentz, & Weiss, submitted).

Espinoza-Hijazin and Lopez have recently measured the 90 d LOI-based degree of hydration for five concretes with *w/c* of 0.4 to 0.5, exposed to poor curing conditions of 50 % RH and 23 °C immediately after demolding at 1 d (Espinoza-Hijazin & Lopez, 2010). In each case, the concrete with internal curing exhibited at least a 10 % absolute increase in measured degree of hydration, further verifying the tendency of internal curing to increase hydration, compared with systems without LWA.

The influence of *w/c* (*w/cm*) can play a significant role in determining the extent of additional curing that may be expected due to the provision of internal curing. For example, Castro performed tests with internal curing over a wide range of *w/c* (Castro, 2011). At very early ages (i.e., less than 24 h), all the specimens showed a similar degree of hydration. However, at later ages, as shown in Figure 23 at 3 d, the degree of hydration in the lower *w/c* systems is restricted when compared with higher *w/c* systems. At lower *w/c*, internal curing increases the degree of hydration, with this increase being even more pronounced at later ages (Castro, 2011).

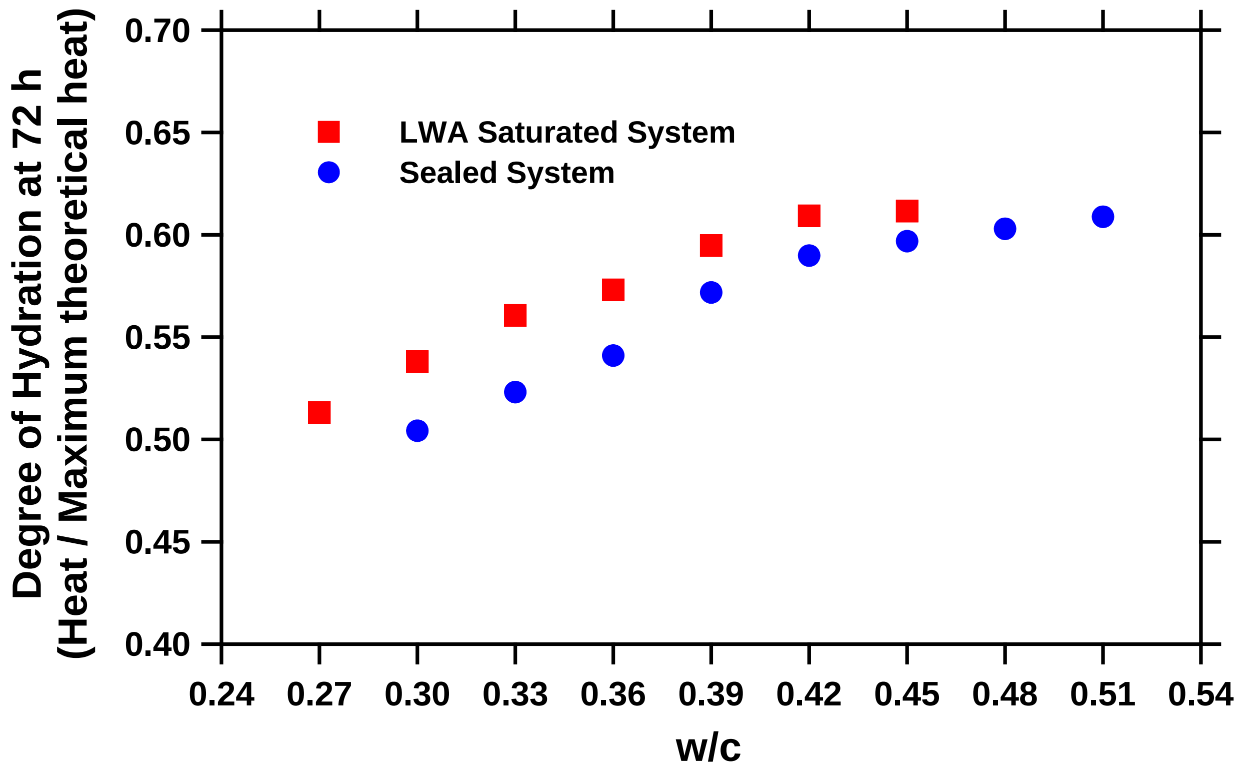


Figure 23. Influence of *w/c* and internal curing on the degree of hydration (Castro, 2011).

5.5 Strength and Elastic Modulus

The effects of internal curing on compressive and tensile strength depend on the specific mixture proportions, curing conditions, and testing age. While mixtures with internal curing could increase strengths and moduli due to an increase in the degree of hydration of the cementitious binder, conversely, a decrease in strength could be observed as the internal curing agents are likely mechanically weaker than the NWAs that they are replacing (and SAP particles ultimately end up as additional air voids within the hardened concrete). In practice, both increases and decreases in strengths have been observed due to these competing effects. In general, decreases are observed at earlier testing ages (< 7 d) while increases are obtained at later testing ages.

As a first example, a recent study based on *w/c*=0.30 ordinary portland cement mortars with a constant volume fraction of sand (normal weight and LWA) of 55 %, both with and without internal curing is considered (Raoufi, Schlitter, Bentz, & Weiss, submitted). In this case, internal curing was provided by various replacement levels of two different LWAs (LWAK and LWAH), with the mortars being cured under sealed conditions and evaluated for mechanical properties after 1 d, 3 d, and 7 d. Fitted curves for the measured values for tensile strength and elastic modulus are provided in Figure 24. LWA-0 represents the plain mortar mixture, while the LWAK-8 and LWAK-16 mixtures had 8.25 % and 16.5 % of their total volume replaced with a pre-wetted LWA. For LWAH, from a second LWA source, these two replacements levels were 11.85 % and 23.7 %, respectively. In the figure, it can be seen that the highest level of LWA replacement produced up to about a 25 % reduction in 7 d tensile strength, with increasing levels of LWA replacement producing further reductions in strength. Although the relative influence on elastic modulus is less than that on compressive strength, the early-age elastic moduli of the mixtures with internal curing are lower than those of the mixture without internal curing. It is well known that lightweight concretes generally exhibit lower elastic moduli than their normal weight counterparts and may exhibit a different strength-modulus relationship (Holm, Bremner, & Newman, 1984).

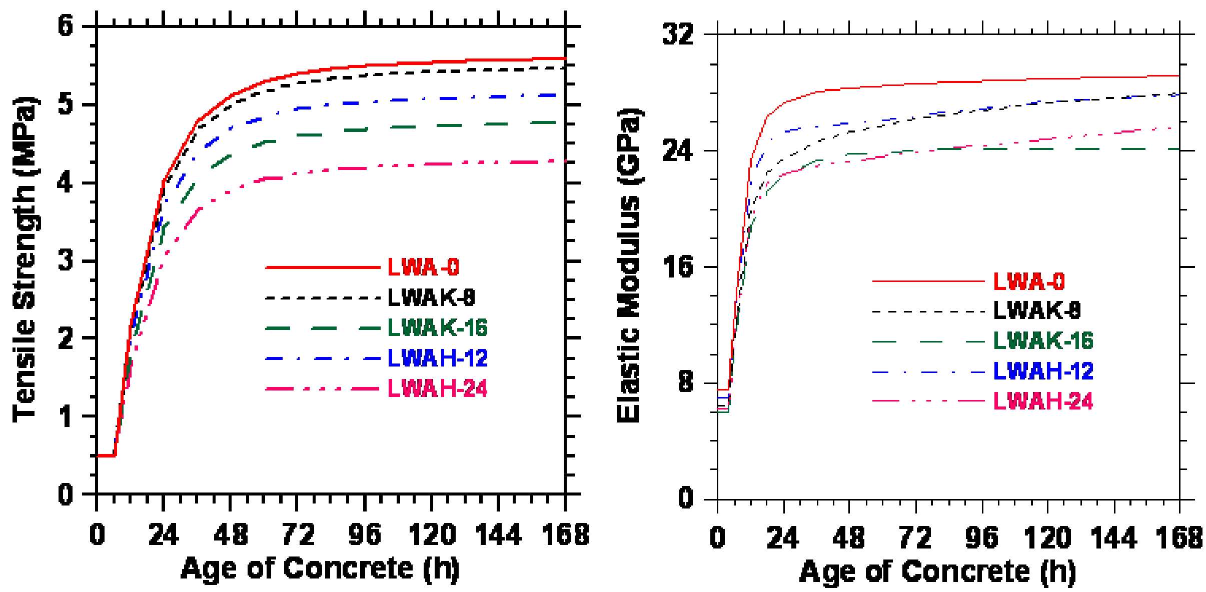


Figure 24. Measured tensile strength (left) and elastic modulus (right) for mortars cured under sealed conditions, with various levels of internal curing supplied by two different pre-wetted LWA (denoted as K and H) (Raoufi, Schlitter, Bentz, & Weiss, submitted).

In systems with supplementary cementitious materials, internal curing often enhances strength at later ages, as the additional water supplied by the internal curing reservoirs is available for the longer term pozzolanic and hydraulic reactions. Table 4 provides compressive strengths for *w/cm*=0.3 mortars prepared with three different blended cement binders, with and without internal curing (Bentz, 2007). The silica fume blended cement contained 8 % silica fume by mass, the slag cement 20 % slag, and the fly ash cement 25 % of a Class F fly ash. For the sealed curing conditions employed in that study, internally-cured mortars produced strength gains on the order of 10 % at ages of 28 d and beyond, while producing equivalent strengths to their respective control mixtures at an age of 3 d.

Table 4. Measured Mortar Cube Compressive Strengths for Various Mixtures Cured under Sealed Conditions (SF=silica fume, FA=fly ash) (Bentz, 2007)

Mixture	3 d strength (MPa)	8 d strength (MPa)	28 d strength (MPa)	56 d strength (MPa)
SF – Control	68.1 (2.0)[A] 9878 psi	80.4 (3.0) 11665 psi	-----	98.0 (2.7) 14232 psi
SF – IC (8)	67.9 (4.6) 9843 psi	87.9 (4.6) 12743 psi	-----	105.6 (6.9) 15312 psi
SF – IC (10)	66.7 (1.4) 9670 psi	85.0 (2.9) 12327 psi	93.3 (4.7) 13531 psi	-----
SLAG – Control	60.9 (0.9) 8827 psi	71.5 (2.0) 10376 psi	81.8 (3.2) 11863 psi	84.3 (5.7) 12226 psi
SLAG – IC	59.2 (4.2) 8581 psi	71.7 (2.3) 10399 psi	88.8 (3.9) 12873 psi	94.6 (1.0) 13729 psi
FA – Control	58.0 (0.5) 8407 psi	70.5 (3.3) 10224 psi	85.3 (3.4) 12365 psi	95.3 (4.0) 13827 psi
FA – IC	57.4 (2.3) 8324 psi	67.5 (3.5) 9794 psi	92.9 (3.8) 13471 psi	101.1 (2.9) 14665 psi

[A]Numbers in parentheses indicate standard deviation in units of MPa for compressive strengths of three replicate cubes at each age for each mixture.

Similar results have been obtained in a more recent study by de la Varga et al. on high volume fly ash (HVFA) mortars (de la Varga, Castro, Bentz, & Weiss, submitted). As shown in Figure 25, for HVFA mortars with *w/cm*=0.3, based on a Class C fly ash and proportioned according to equation (5), internal curing produced strength enhancements at ages beyond 3 d. These strength increases were observed for the HVFA mixtures with either a 40 % or a 60 % volumetric replacement of cement by fly ash.

The influence of SAP on compressive strength is also dependent on mixture proportions. Hasholt et al. have measured compressive strengths of concretes with different *w/c* and different levels of SAP addition (Hasholt, Seneka Jespersen, & Jensen, 2010). For *w/c*=0.4 and *w/c*=0.5 concretes, they observed up to a 10 % reduction in compressive strength as SAP levels were increased from 0.1 % to 0.6 %. However, for a series of *w/c*=0.35 concretes, strengths at 7 d and beyond were increased by the addition of 0.1 %, 0.2 %, or 0.4 % SAP, while the 0.6 % addition level of SAP reduced strength. The authors illustrated that these results were adequately described by assuming that compressive strengths of the mortars are proportional to those of their component pastes, then applying Powers' gel-space ratio with a correction for air voids created by the SAP particles according to Bolomey's formula. In the lower *w/c* concrete, the strength loss due to the additional (SAP) voids is more than offset by the increased degree of hydration provided by the additional curing water contained within the swollen SAP particles.

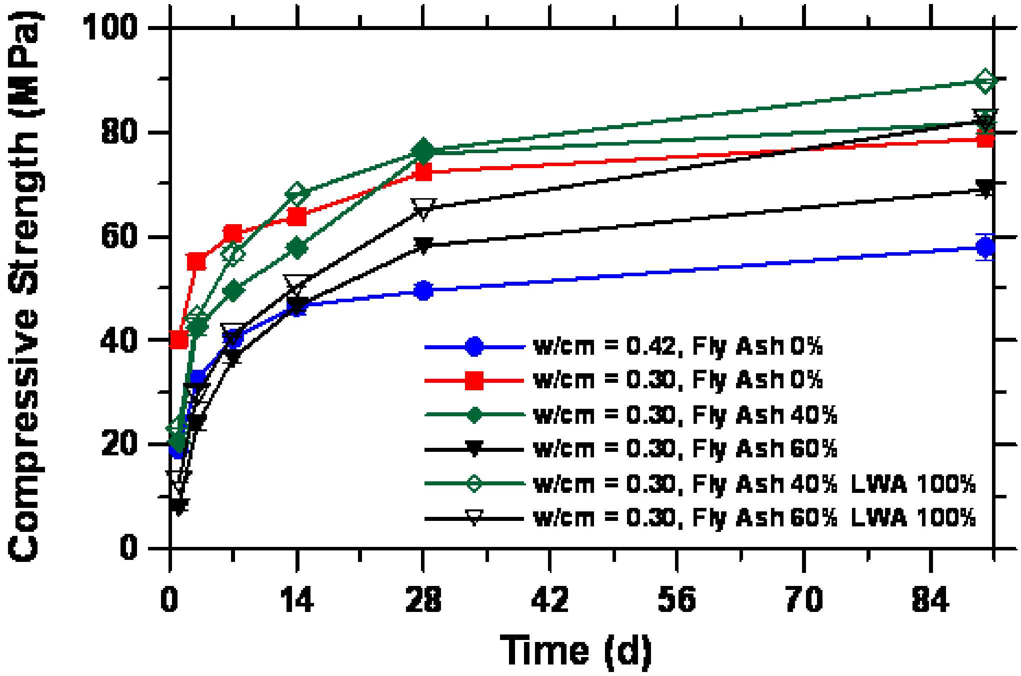
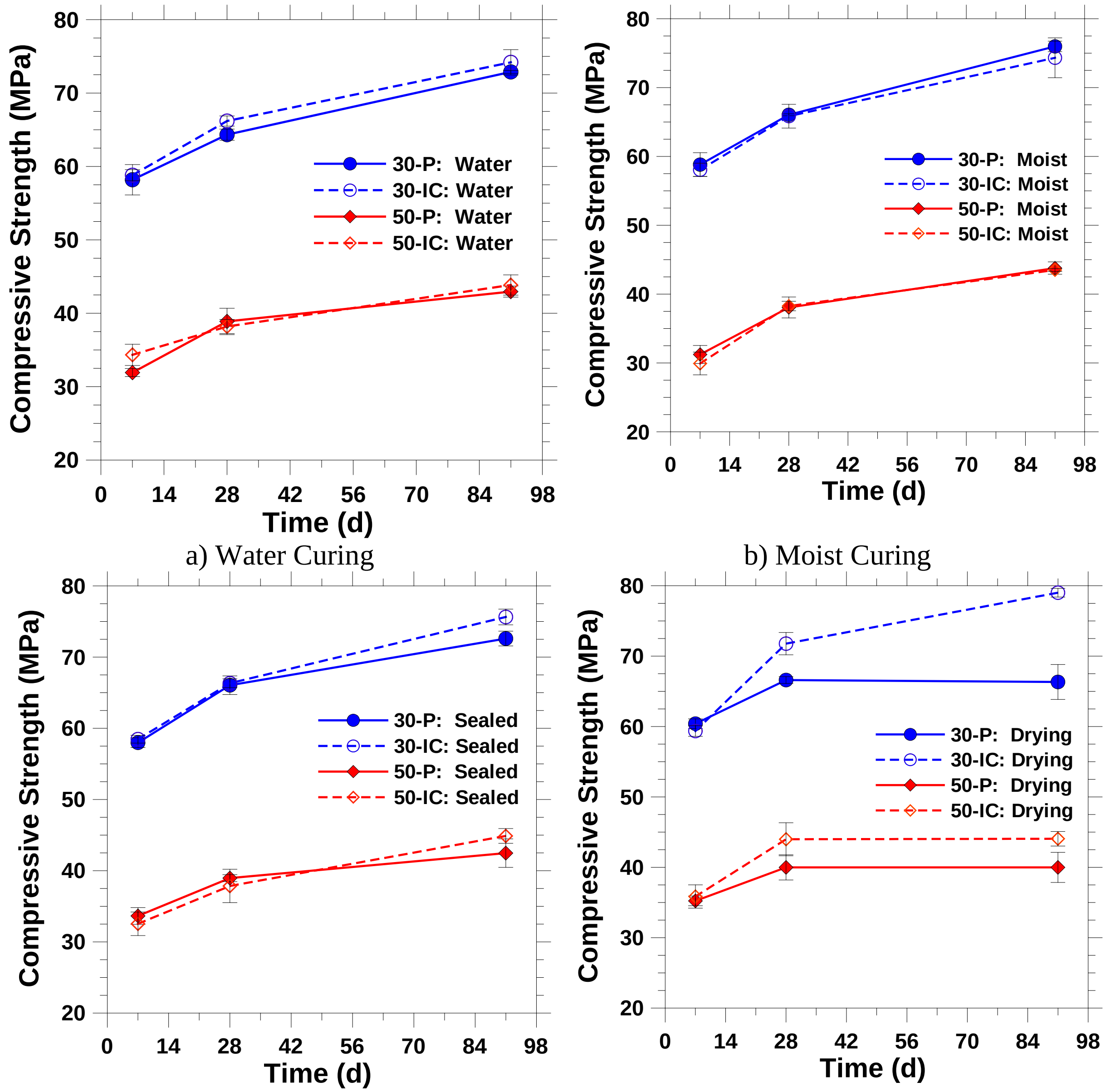


Figure 25. Influence of internal curing on compressive strength of high volume fly ash mortars cured under sealed conditions (de la Varga, Castro, Bentz, & Weiss, submitted).

An extension of this study (Hasholt, Seneka Jespersen, & Jensen, 2010a), considered the elastic moduli of these same mixtures. The elastic modulus was also successfully related to Powers' gel-space ratio, with the additional 'voids' from the SAP particles producing a substantial reduction in elastic modulus relative to the control mixture without internal curing.

To better understand the influence of curing conditions on compressive strength, Golias examined four mortar mixtures with *w/c* of 0.3 or 0.5 (Golias, 2010). For each *w/c*, one mixture had internal curing while the other did not. Results can be seen in Figure 26. In the water-cured or moist-cured samples, little difference exists between the internally cured mortar and the plain mortar without internal curing. This is expected since both mortars were provided with sufficient external water to aid in hydration. Although the performance of the sealed specimens was similar to that of the moist-cured ones at early ages, the influence of additional curing water becomes evident at the latest tested age (e.g., 91 d). The influence of internal curing is most dramatic for the samples stored in a drying environment (50 % RH), where the plain mortar shows a substantially reduced strength relative to the mixtures that incorporated internal curing.

The influence of internal curing on elastic modulus is shown in Figure 27. The modulus is lower for both systems containing LWA. To explain the reason for the decrease in stiffness, a plot has been developed based on composite theory as shown in Figure 28. The influence of the LWA aggregate is more pronounced in the lower *w/c* system where the modulus of the paste is higher. The increase in modulus associated with increasing aggregate volume is also complimented by the increase in modulus due to additional hydration. This causes the upper bound to be slightly non-linear; however, this is a relatively small influence for most mixtures.



a) Water Curing b) Moist Curing

c) Sealed Curing d) Drying

Figure 26. Influence of curing conditions on compressive strength development in plain (P) and internally-cured (IC) mortars (Golias, 2010).

A reduced elastic modulus can also be related to the reduction in cracking potential (Weiss, Yang, & Shah, 1999) (Shah & Weiss, 2000) (Shin, Bucher, & Weiss, 2011) (Raoufi, Schlitter, Bentz, & Weiss, submitted). Reducing the elastic modulus has a beneficial influence on reducing the residual stress due to restraint as a function of time. Raoufi et al. conducted a series of simulations to better understand the influence of reduced stiffness on early age cracking potential (Raoufi, Schlitter, Bentz, & Weiss, submitted). Results from that study are illustrated in Figure 29. Stresses are reduced by approximately 10 % to 20 %, due to the reduction in elastic modulus caused by the LWA. The significant influence of the water being released from the LWA to reduce shrinkage, and thus residual stress development, is also shown in Figure 29.

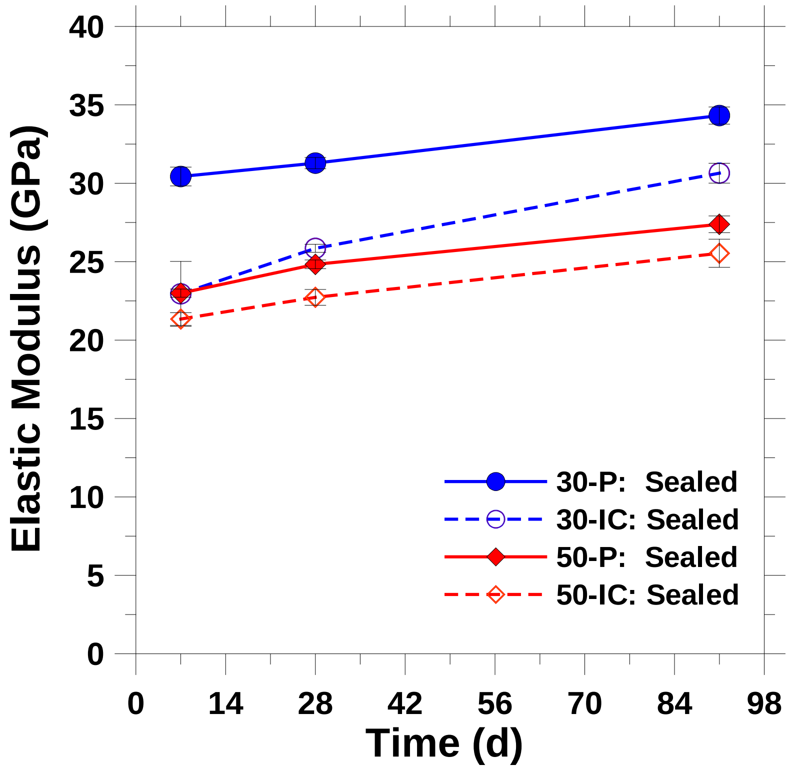


Figure 27. Influence of internal curing on elastic modulus of sealed specimens (Golias, 2010).

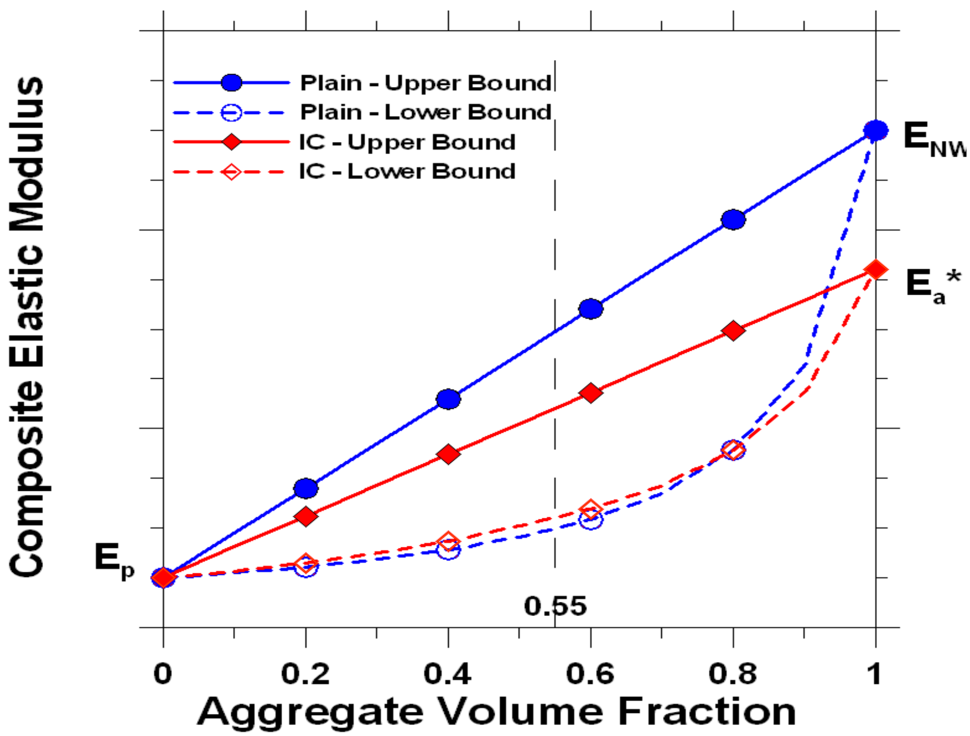


Figure 28. An illustration of composite theory to describe the influence of LWA on stiffness (Golias, 2010). E_p **and** E_a **are the elastic moduli of the paste and aggregate, respectively.**

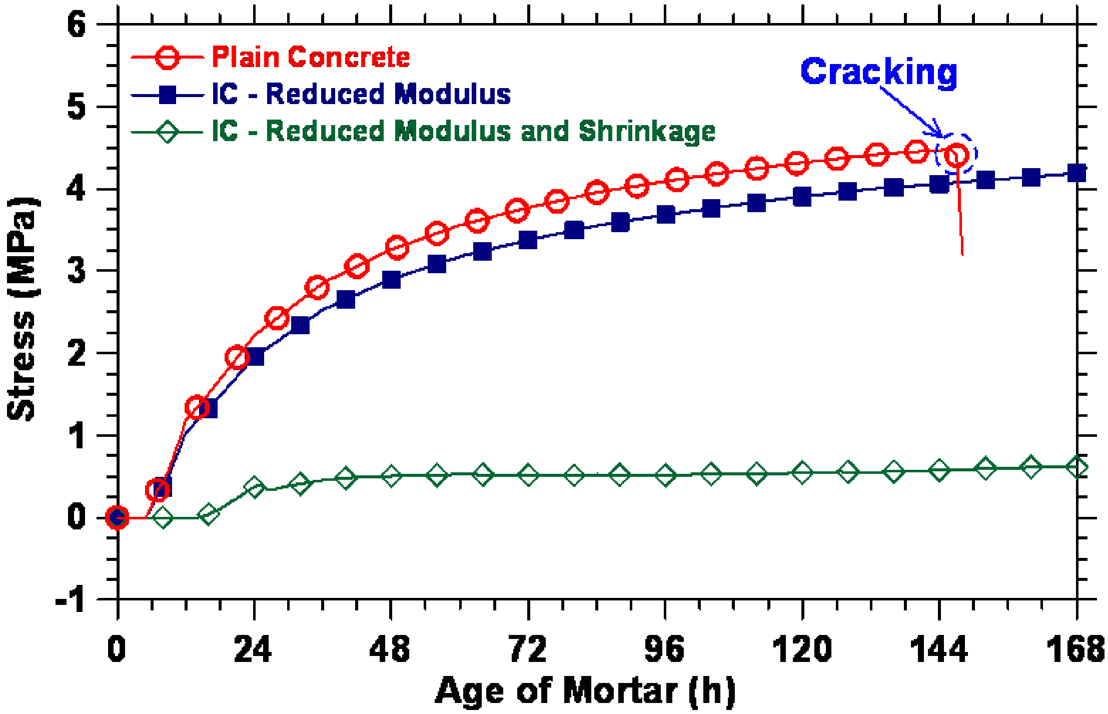


Figure 29. Influence of reduced elastic modulus on residual stress development (Raoufi, Schlitter, Bentz, & Weiss, submitted).

5.6 Creep

Few studies concerning creep of systems with internal curing have been conducted. Lopez et al. have examined the creep behavior of *w/cm*=0.23 high performance concretes with and without internal curing, contrasting the performance of using pre-wetted vs. dry LWA (with additional water added to the mix to account for the expected absorption by the dry LWA) (Lopez, Kahn, & Kurtis, 2008). After moist curing, the normal weight high performance concrete exhibited substantially higher compressive strengths than the concretes with internal curing at ages less than one year, and achieved strengths in excess of 100 MPa at 28 d. In this case, replacing the high quality granite used in the control mixture with LWA in the mixtures with internal curing produced a large enough reduction in compressive strength that it could not be offset by enhanced hydration. The mixture with pre-wetted LWA exhibited less creep (about 10 %) than the control mixture, while the mixture with dry LWA exhibited the greatest creep. Conversely, Cusson and Hoogeveen measured a moderate increase in the tensile creep coefficient of *w/c*=0.34 concrete mixtures with internal curing measured at 7 d vs. a control mixture (Cusson & Hoogeveen, 2005).

5.7 Curling and Warping

By maintaining a higher and more uniform RH through the thickness of a concrete member, internal curing may provide the additional benefit of a reduction in curling/warping. Wei and Hansen have observed that during a drying time of 16 d, warping was reduced by 70 % by incorporating internal curing into a *w/c*=0.45 concrete (Wei & Hansen, 2008). This improvement in performance was due both to the release of water from the LWA during drying and the enhanced hydration producing a denser layer of concrete at the top surface, thus reducing the evaporation. Such results need to be extended to longer drying periods to verify the efficacy of internal curing for reducing warping in the longer term.

Neithalath et al. examined the role of moisture gradients on early-age cracking potential (Neithalath, Pease, Moon, Rajabipour, Weiss, & Attiogbe, 2005). Shrinkage caused by external drying has a high gradient near the surface, while shrinkage caused by self-desiccation is more uniform throughout the cross section. This is illustrated conceptually in Figure 30. The more uniform moisture content (RH) results in reduced curling; however, this can also result in a residual stress field that is more uniform, making unstable crack growth more likely. Internal curing also produces lower diffusion rates and a higher overall moisture content (internal RH).

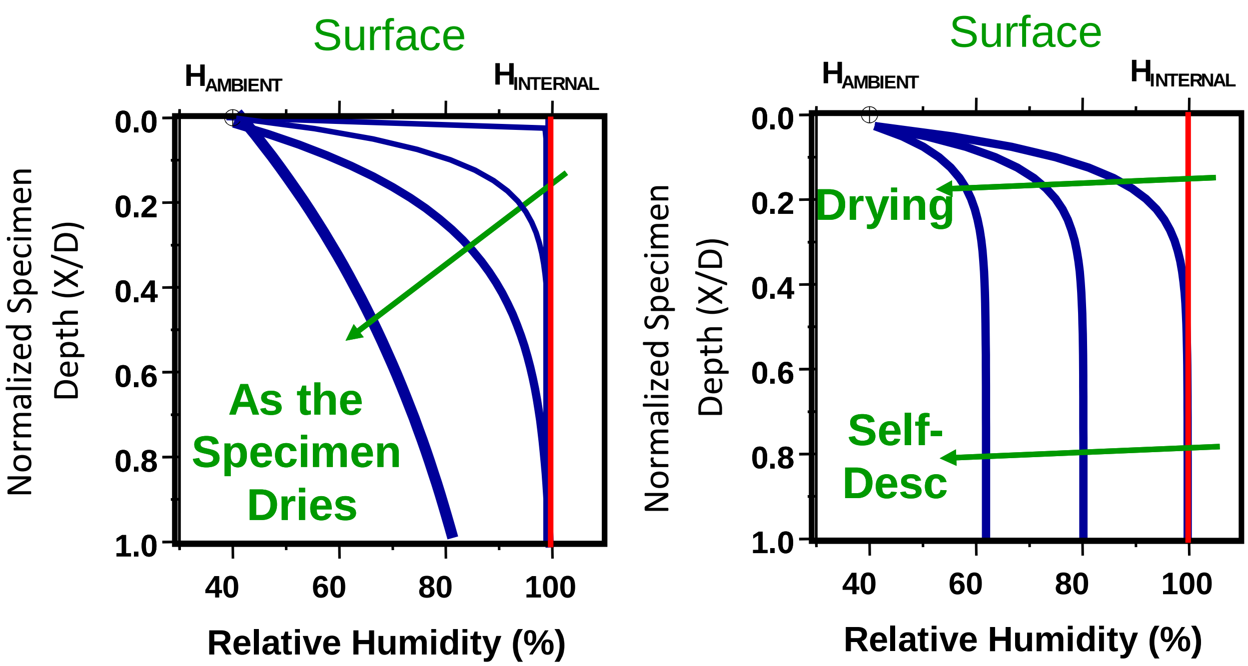


Figure 30. Influence of external drying and self-desiccation on the moisture gradients in a slab (Neithalath, Pease, Moon, Rajabipour, Weiss, & Attiogbe, 2005). Arrows indicate the progression of time.

5.8 Microstructure

The microstructure of high performance blended cement mortars with and without internal curing has been examined using scanning electron microscopy by Bentz and Stutzman (Bentz & Stutzman, 2008). Representative images are provided for cements blended with silica fume, slag, and fly ash in Figure 31, Figure 32, and Figure 33, respectively. In contrasting the microstructures of specimens with internal curing and those without, the former contain fewer and smaller unhydrated cement particles (indicating enhanced hydration), fewer and smaller empty pores (indicating less self-desiccation), and a denser and more homogeneous interfacial transition zone (ITZ) between lightweight aggregates and hydrating cement paste (as has been observed in previous studies on lightweight concrete (Holm, Bremner, & Newman, 1984)).

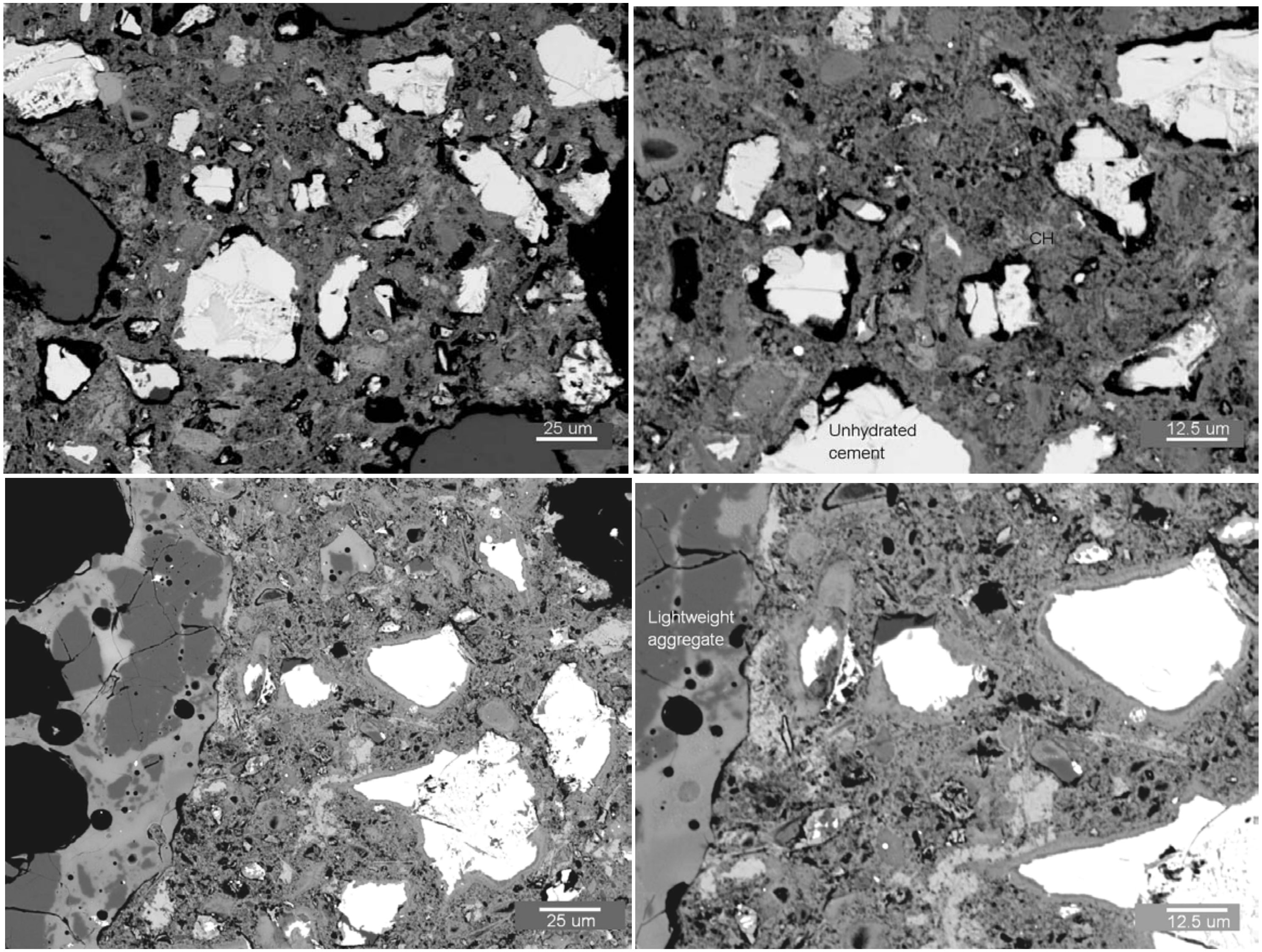


Figure 31 - BSE/SEM images of mortar microstructures for silica fume blended cement without (top) and with (bottom) internal curing at low (left) and high (right) magnifications (Bentz & Stutzman, 2008). Scale bar for each image is located in lower right corner.

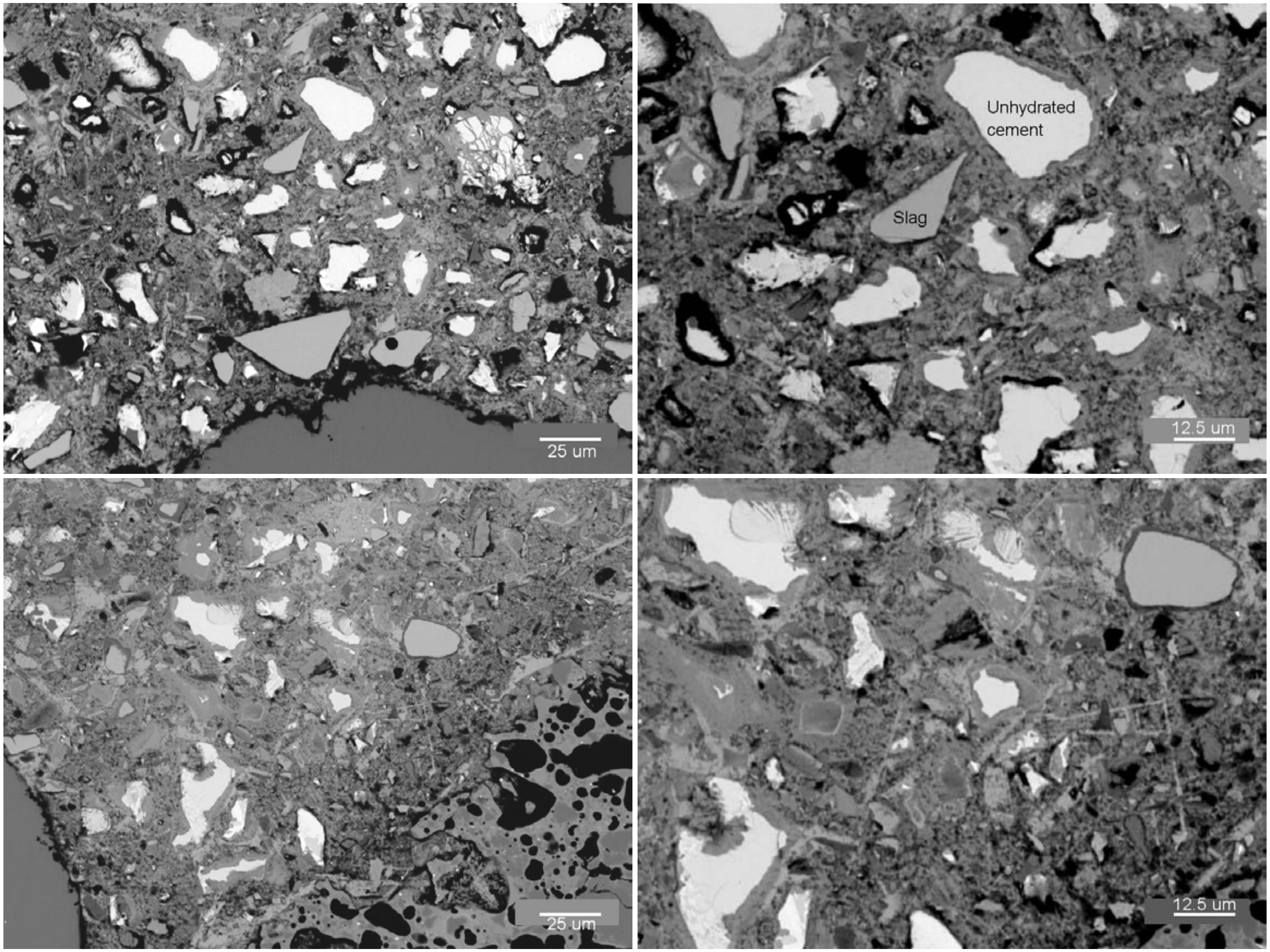


Figure 32. BSE/SEM images of mortar microstructures for slag blended cement without (top) and with (bottom) internal curing at low (left) and high (right) magnifications (Bentz & Stutzman, 2008). Scale bar for each image is located in lower right corner.

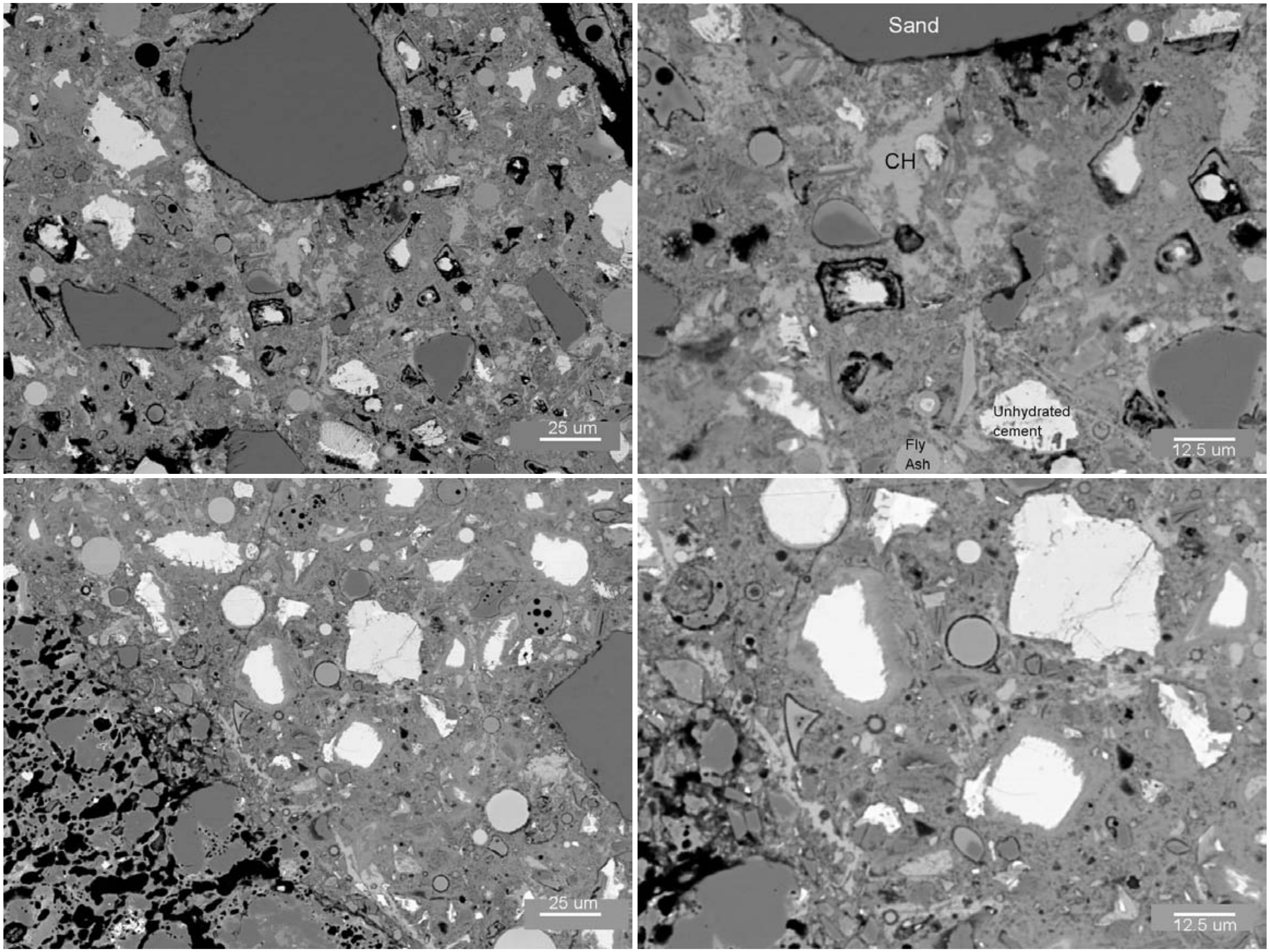


Figure 33. BSE/SEM images of mortar microstructures for fly ash blended cement without (top) and with (bottom) internal curing at low(left) and high (right) magnifications (Bentz & Stutzman, 2008). Scale bar for each image is located in lower right corner.

5.9 Restrained Shrinkage and Thermal Cracking

Earlier, results of restrained shrinkage cracking were discussed for sealed (autogenous) and total (drying plus autogenous) shrinkage. Figure 34 illustrates the age of cracking for these mixtures as a function of the amount of internal curing (i.e., volume of LWA used). It should be noted that the percent of LWA that corresponds to that predicted by equation (5) is 23.7 % by volume. Mixtures exposed to drying in addition to autogenous shrinkage are more likely to crack than mixtures experiencing autogenous shrinkage only. As the volume of LWA increases, the age of cracking is delayed, until an asymptote appears to be reached.

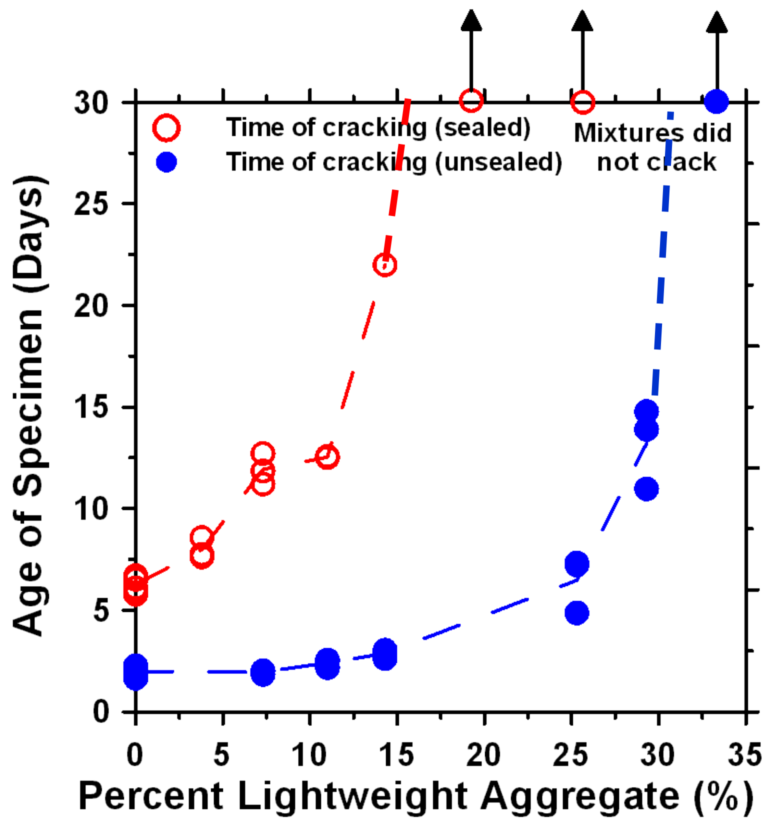


Figure 34. Influence of internal curing on restrained shrinkage cracking (Henkensiefken, Bentz, Nantung, & Weiss, 2009)

Although supplementary cementitious materials such as silica fume, slag, and fly ash may exhibit a greater chemical shrinkage per unit mass than ordinary portland cement, this chemical shrinkage may occur at a later age. This results in stress development plots like those shown in Figure 35 where the plain system develops stress rapidly and plateaus after approximately 14 d. While the mixtures containing fly ash show lower stress development initially, this stress develops for a longer time and makes these materials more likely to crack at slightly later ages. When internal curing is used, the residual stress is substantially reduced, which corresponds to a dramatic reduction in cracking potential.

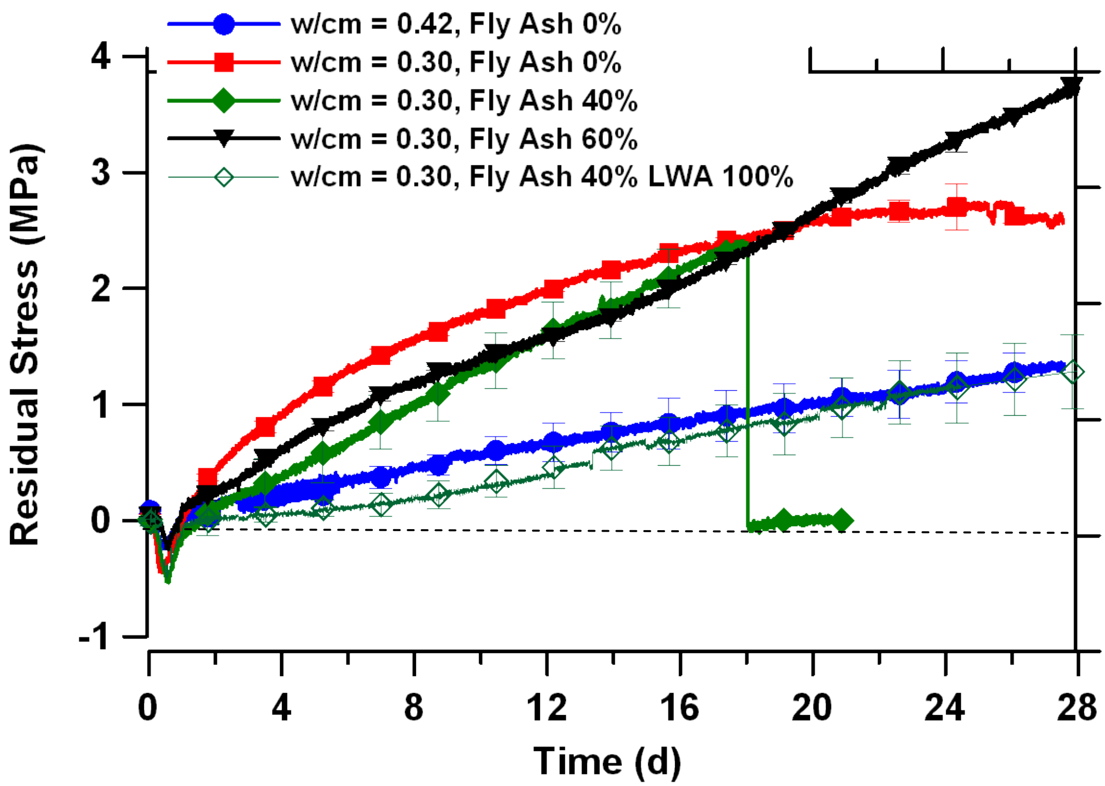


Figure 35. Influence of internal curing on restrained shrinkage and cracking for mixtures containing a Class C fly ash (de la Varga, Castro, Bentz, & Weiss, submitted).

In addition to reducing the potential of cracking due to autogenous shrinkage, Figure 36 shows examples of the residual tensile stress development in a plain mixture and a mixture with internal curing (Schlitter, Bentz, & Weiss, 2011). By reducing the stress that is developed due to autogenous shrinkage, a greater reserve capacity exists in the internally cured mortar to resist stresses due to thermal and/or applied loading. In a typical concrete structure, the temperature increases during the first few days of curing due to the heat released by the hydration reactions and then decreases towards ambient. As the structure cools from its maximum temperature to ambient, thermal cracking may occur (Bentz, Bognacki, Riding, & Villarreal, 2011). Figure 37 indicates that a more substantial reduction in temperature is needed to crack the samples with internal curing. During the first 72 h, no cracking occurred in the internally cured specimens when the temperature was reduced by as much as 32 °C, while the plain mortar specimens cracked when the temperature was reduced by only 10 °C or 12 °C. This shows a substantial increase in the potential robustness of materials made using internal curing at early ages with respect to thermal shock, cooling, or diurnal temperature changes.

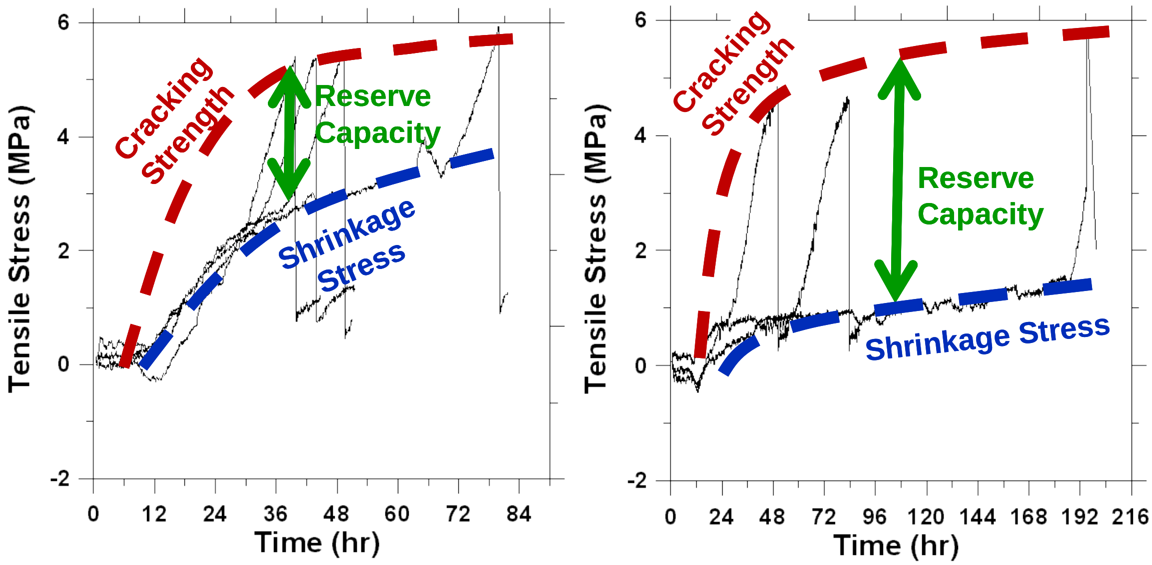


Figure 36. Influence of internal curing on the residual stress development and reserve stress capacity. A plain mixture is shown on the left and a mixture containing internal curing on the right (Schlitter, Bentz, & Weiss, 2011).

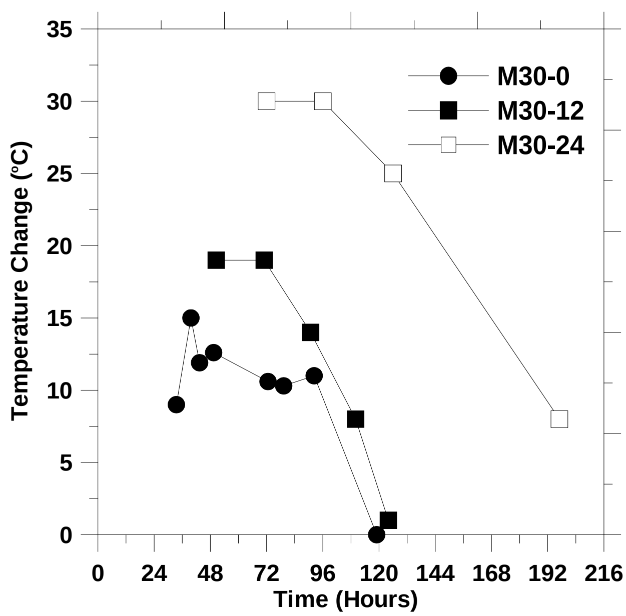


Figure 37. The temperature change permitted before cracking occurs in mortars with *w/c*=0.3, illustrating a benefit of internal curing (mixtures M30-12 and M30-24) (Schlitter, Bentz, & Weiss, 2011).

5.10 Transport Coefficients and Service Life

Internal curing positively impacts the transport coefficients and service life of cement-based materials. Enhanced hydration densifies the pore structure of the material, resulting in reduced transport. Additionally, as shown in Section 5.8, the ITZ formed between LWA and its surrounding cement paste is denser and more homogeneous than the ITZ formed between a NWA and its surrounding cement paste. Often, the ITZ regions surrounding NWAs are more porous than the bulk hydrated cement paste and can provide preferential pathways for the ingress of deleterious species (Halamickova, Detwiler, Bentz, & Garboczi, 1995). Here, the percolation or connectivity of these individual ITZ regions is as important as their porosity. As illustrated schematically in two dimensions in Figure 38, the replacement of a portion of the NWAs (sand) by LWA could significantly reduce the connectivity of the ITZ regions surrounding the NWAs, as well as reduce the volume fraction of this more porous ITZ paste (Bentz, 2009).

These positive attributes of the LWA must be balanced against the fact that the LWA itself is a porous particle that can contribute its own transport pathways. With this in mind, the net effect of internal curing on transport will likely depend on the nature of the cementitious matrix. If a high *w/cm* (> 0.45) is employed, the capillary porosity may remain percolated and its percolated pathways can easily link up with those in the LWA to provide increased transport. However, in a lower *w/cm* matrix, the capillary porosity will depercolate (Powers, Copeland, & Mann, 1959) and the porous LWA particles will soon be surrounded by a dense layer of hydration products. In this case, similar to the case of air voids in concrete, the isolated porous regions will not contribute substantially to transport. In fact, the overall transport coefficients of the mortar or concrete may be reduced due to the enhanced hydration and denser ITZs as discussed above. Indeed, Zhang and Gjorv have observed that the permeability of high-strength lightweight concrete is more dependent on the properties of the cement paste than the porosity of the LWA (Zhang & Gjorv, 1991). Additionally, Pyc et al. and Castro et al. have recently performed mass measurements that suggest that once the pores in LWA empty while supplying water to the hydrating cement paste during internal curing, they are not subsequently resaturated, even upon complete immersion of the specimen (Pyc, Caldarone, Broton, & Reeves, 2008) (Castro, Keiser, Golias, & Weiss, 2011).

Several recent studies have directly examined the influence of internal curing on chloride diffusion coefficients and sorptivity coefficients of mortars. Figure 39 shows the estimated diffusion coefficients for *w/c*=0.4 mortars (55 % fine aggregate by volume) with and without internal curing (Bentz, Snyder, & Peltz, 2010). In this study, mortars were first cured for 28 d, those without internal curing saturated limewater and those with internal curing under sealed conditions. Then, the cylindrical specimens were placed into a 1 mol/L chloride solution for exposure times of 28 d, 56 d, 182 d, and 365 d. At each evaluation time, replicate cylinders from each mixture were split and the level of chloride ion ingress determined using a silver nitrate ($AgNO_3$) spray technique (Baroghel-Bouny, Belin, Maultzsch, & Henry, 2007). The penetration depth at each age was reduced significantly in the mortar with internal curing relative to that of the control mixture. As shown in Figure 39, the diffusion coefficients for the mortar with internal curing relative to those of the control varied from 50 % after 28 d exposure to about 90 % after 365 d. Significant reductions in diffusion coefficients for high-performance lightweight aggregate concretes relative to their normal weight counterparts have also been obtained by Thomas (Thomas, 2003). In that study, while short term diffusion coefficients were only reduced by 15 % to 25 % due to the incorporation of LWA, long term (3 years) values were decreased by as much as 70 %.

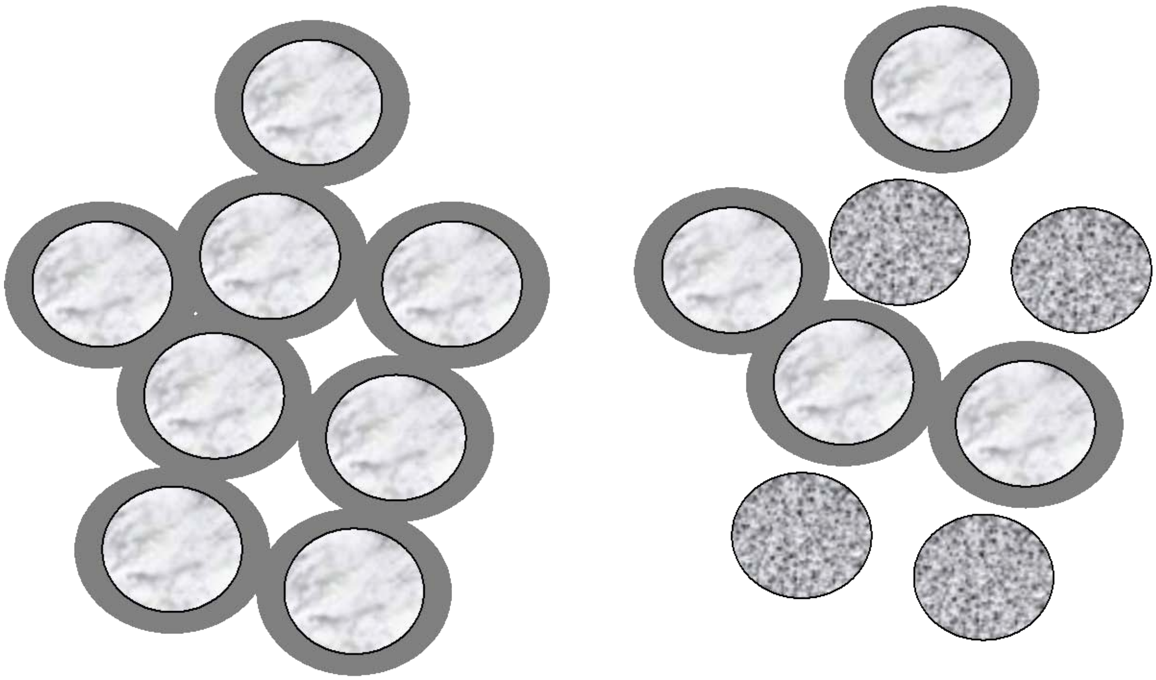


Figure 38. Comparison of model mortars with normal weight sand particles only (left) with their surrounding ITZs and with a 50:50 blend (volume basis) of sand and LWA (right). Both the volume fraction of ITZ (grey) paste and its percolation are reduced by the incorporation of the LWA (Bentz, 2009).

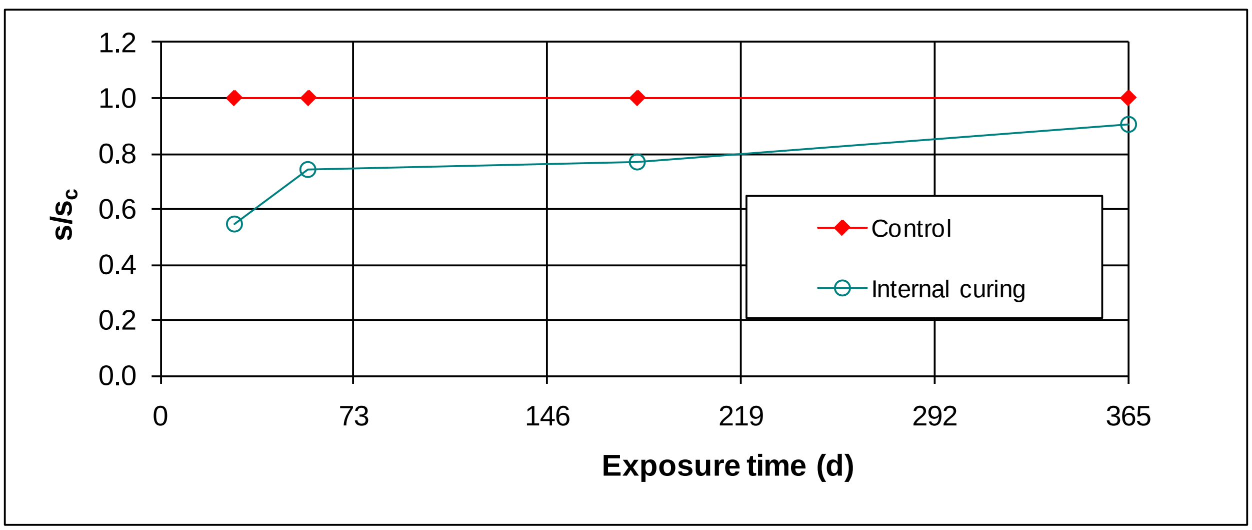


Figure 39. The diffusivity ratio S/S_c (proportional to the diffusion coefficient) for *w/*c=0.4 mortars with and without internal curing, first cured for 28 d, and then exposed to a 1 mol/L chloride ion solution (Bentz, Snyder, & Peltz, 2010).

Henkensiefken et al. examined the sorption characteristics of mortars prepared with and without internal curing (Henkensiefken, Castro, Bentz, Nantung, & Weiss, 2009). For *w/c*=0.3 mortars cured under sealed conditions, measured sorption coefficients were significantly reduced for specimens with internal curing vs. those without, as shown in Figure 40. The mixtures with internal curing (11.0 % or 23.7 % LWA by volume) exhibited a sorption behavior similar to that of a mortar without internal curing of a significantly reduced *w/c* ratio (on the order of *w/c*=0.23), as illustrated in Figure 41. Concurrently, they measured a reduction in the electrical conductivity of the specimens with internal curing, even when these specimens were vacuum-saturated prior to the electrical measurements (Figure 42). This further supports the conjecture that at lower *w/c*, the influences of increased hydration and denser bulk and ITZ microstructures overwhelm those of the increased water-filled porosity of the vacuum-saturated LWA (Henkensiefken, Castro, Bentz, Nantung, & Weiss, 2009).

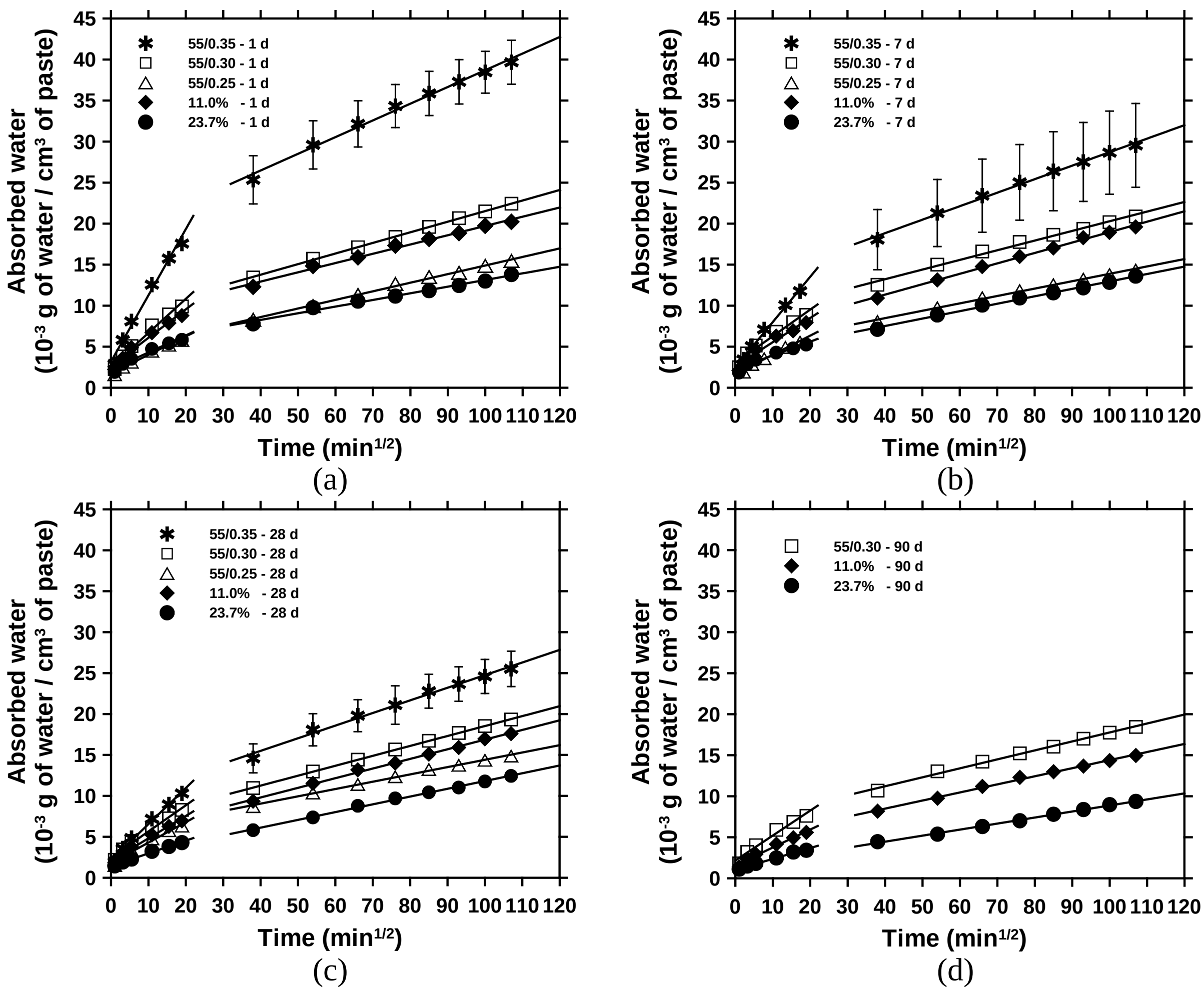


Figure 40. Sorption test on samples cured for (a) 1d, (b) 7 d, (c) 28 d, and (d) 90 d. Results are shown for plain mortars with 55 % sand and three *w/c* (0.25, 0.3, and 0.35) and for two *w/c*=0.35 mortars with internal curing (LWA replacements of 11 % and 23.7 %). Error bars indicate standard deviation for the three specimens evaluated for each mixture (Henkensiefken, Castro, Bentz, Nantung, & Weiss, 2009).

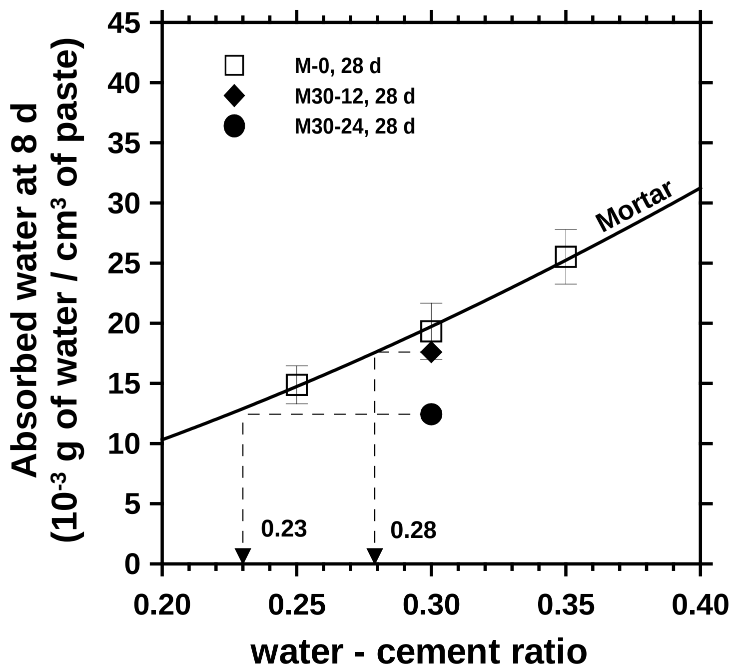


Figure 41. Influence of internal curing on water absorption (Henkensiefken, Castro, Bentz, Nantung, & Weiss, 2009). Solid line is provided to indicate a general tendency in the data.

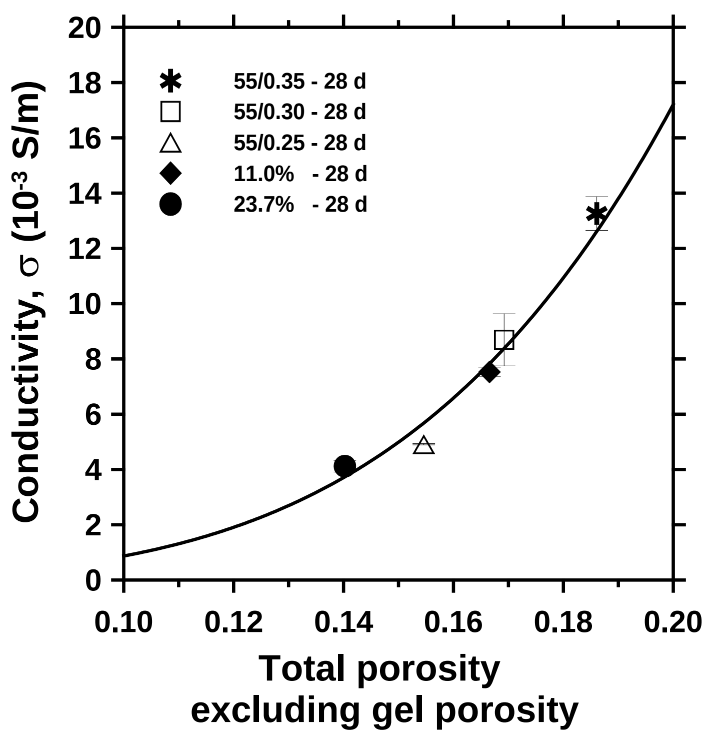


Figure 42. Influence of internal curing on electrical conductivity. Results are shown for plain mortars with 55 % sand and three *w/c* (0.25, 0.3, and 0.35) and for two *w/c*=0.35 mortars with internal curing (LWA replacements of 11 % and 23.7 % by volume) (Henkensiefken, Castro, Bentz, Nantung, & Weiss, 2009). Solid line is provided to indicate a general tendency in the data.

This beneficial effect of internal curing is not limited to low *w/c* mixtures, however, as illustrated in Figure 43 (Castro, 2011) which evaluates the effects of internal curing on water absorption and electrical conductivity. While the results at early ages show little impact of internal curing, the total amount of absorbed water was reduced when the amount of lightweight aggregate was increased for all *w/c*. (100 % IC corresponds to the volume of water predicted from equation (5)). Electrical conductivity tests performed on sealed samples a year after casting also show a reduction when using internal curing. However, care must be exercised to obtain a correct interpretation of the electrical conductivity results at early ages, due to the higher amount of fluid present in the pores of the LWA in the system when pre-wetted LWA are added.

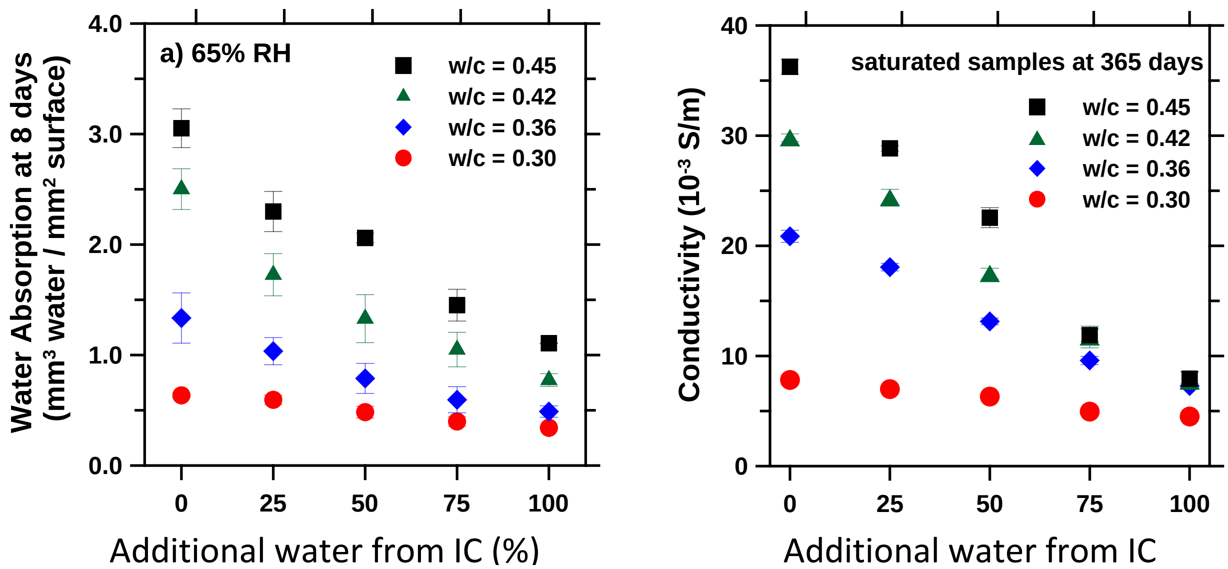


Figure 43. Influence of internal curing on water absorption and electrical conductivity for samples with different *w/c* (Castro, 2011).

Recently, Cusson et al. compared the service lives of high-performance concrete bridge decks with and without internal curing (Cusson, Lounis, & Daigle, 2010). They compared a conventional concrete bridge deck to two high-performance decks, namely with and without internal curing. The high-performance concrete deck without internal curing provided a reduction in the expected diffusion coefficient for chloride attacking the steel reinforcement, but also exhibited initial cracking due to excessive early-age autogenous and thermal stresses. The high-performance concrete with internal curing did not exhibit any early-age cracking and provided a further 25 % reduction in the expected diffusion coefficient. Based on these and other assumptions presented in the study (Cusson, Lounis, & Daigle, 2010), the following service life estimates were obtained for the bridge decks: conventional concrete – 22 years, high-performance concrete without internal curing – 40 years, and high-performance concrete with internal curing – 63 years. In this case, internal curing should produce a bridge deck with an increased service life and a significantly reduced life cycle cost.

5.11 Freeze/Thaw Degradation

Freeze/thaw durability is one concern that is frequently raised with the use of pre-wetted LWA, since the additional internal curing water may raise the moisture content of these samples, and the increased porosity of the LWA could provide locations for additional water in the long term. This can be a concern in the late fall construction season if freezing occurs shortly after casting and the aggregates do not have time to desorb. Schlitter et al. (Schlitter, Henkensiefken, Castro, Raoufi, Weiss, & Nantung, 2010) tested a series of internally cured concretes, cured for 14 d under sealed conditions, and did not observe freeze-thaw damage after 300 cycles (two cycles per day with temperature cycling between 10 °C and -18 °C). This suggests that the LWA might be contributing to the entrained air volume.

One thing to keep in mind, however, when considering potentially equivalent air void protection provided by pores within or from the internal curing reservoirs is that the volume of equivalent air voids will likely not be greater than the volume fraction of additional curing water being provided by the reservoirs. For example, for a typical concrete made with *w/c*=0.40 and having a cement content of 550 kg/m^3, using the numerator of equation (5), the internal curing water demand will be (550*0.07)= 38.5 kg/m^3or 3.85 % on a volume basis. Thus, if one required a concrete with an air content of 5 %, it is unlikely that internal curing can provide that quantity of air in its entirety. However, the fact that a mixture proportioned for internal curing may not provide all of the potential void volume needed for freeze/thaw protection doesn't detract from its ability to provide a set of supplemental voids that can contribute to the overall air void system and serve as an insurance policy in the case of marginal or variable air entrainment dilemmas. As previously exemplified by its influence on settlement and plastic shrinkage cracking, internal curing can increase the overall robustness of a concrete mixture with respect to numerous characteristics, including freeze/thaw performance.

5.12 Alkali-Silica Reaction

Alkali-silica reaction (ASR) is a chemical process in which alkali ions, coming primarily from the cement, can react with amorphous silica within the aggregates, resulting in the formation of an expansive alkali-silica gel. The use of LWA for internal curing in materials susceptible to ASR can be complicated as described by Shin and Weiss (Shin, et al., 2010). Internal curing could influence ASR by:

1) Decreasing the overall porosity of the cement paste due to enhanced hydration, thereby reducing the rate of fluid ingress and the rate of ASR reaction;
2) The porosity of the LWA can provide spaces for the expansive gel to deposit, thereby reducing the pressure generated by the gel in the matrix and reducing the potential for expansion;
3) The LWA could replace a portion of the reactive fine aggregate, diluting the volume of reactive particles and thereby reducing expansion; and
4) Increasing the internal relative humidity of the concrete, thereby enabling more ASR reaction to occur.

Figure 44 illustrates measured length changes for specimens tested according to ASTM C1260 (with the exceptions that the boundary conditions were 38 °C and an initial submersion in NaOH after 7 d of curing) (ASTM International, 2007a). The expansion is low for all mixtures in the first 10 d. The samples with LWA showed a rapid expansion at a later age (approximately 20 d of exposure for the system where 15 % by volume of the reactive sand was replaced with LWA (M30R-15m) or a non-reactive sand (M30R-15N) and approximately 30 d of exposure for the system where 28 % by volume of the reactive sand was replaced with LWA (M30R-28m) or a non-reactive sand (M30R-28N)). This delay is believed to be primarily due to a dilution effect (i.e., reducing the volume of reactive sand), since it is observed for both aggregates (LWA and non reactive sand); however, the samples with LWA (m) do show a slower rate of expansion when compared with their non reactive sand (N) counterparts at both replacement levels.

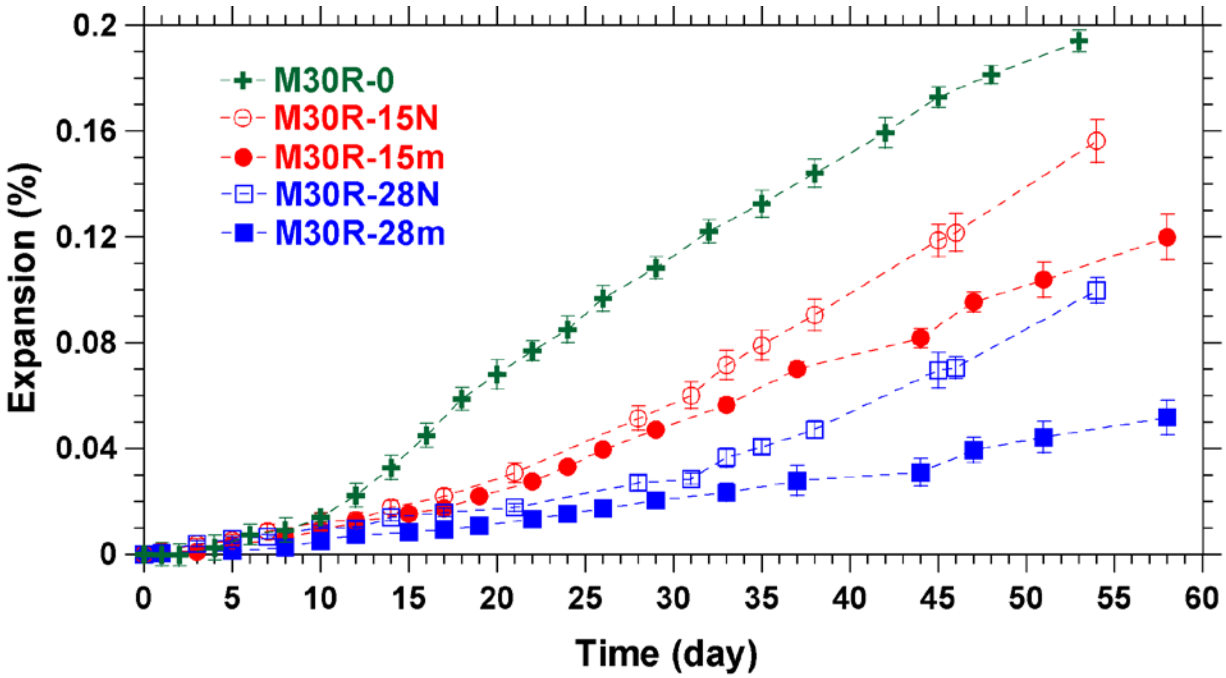


Figure 44. Influence of non-reactive aggregate (denoted by N) and LWA (denoted by m) replacement on ASR expansion (Shin, et al., 2010).

6 Internal Curing in Production: Ready-Mix Operations

Procedures for implementing internal curing in production are essentially the same as those employed for producing lightweight concretes for more than 50 years. Villarreal provides valuable guidance for ready-mix production and emphasizes the criticality of proper LWA moisture conditioning (Villareal, 2008). At the ready-mix plant, a separate bin may be used for the LWA or they may be kept in (sprinkled) piles at the site. The New York Department of Transportation (NYDOT) requires sprinkling cornrows of LWA until shortly before use when the sprinklers are turned off. The time required for sprinkling a new pile prior its use in concrete is dependent on the application rate of the water and the LWA's absorption characteristics. According to Villarreal, "the aggregate piles must be turned and remixed to obtain a homogeneous aggregate moisture content just prior to the beginning of the production cycle" (Villareal, 2008). He also suggests that a system be implemented for recycling the excess runoff water back into the sprinkler system. The bottom few inches of the aggregate in these piles can have a substantially different moisture content than aggregate in the rest of the pile and thus there may be a practical value in not using these bottom portions in standard mixing operations.

As with any aggregate being incorporated into a concrete, the moisture content and absorption capacity of the LWA must be known prior to the final proportioning of the concrete mixture. These quantities are critically important for mixture proportioning for internal curing, as they determine the denominator when using equation (5) to perform the proportioning. Proper quality control is essential to providing a high quality concrete with internal curing. Since saturated surface-dry is a nebulous concept for LWA, it is best if the LWA can be provided in a known and maintainable state of moisture equilibrium. When this necessary moisture conditioning is not achieved, additional problems with variable unit weight, slump loss, pumpability, segregation, and finishability will likely occur (Villareal, 2008).

While it is frequently reported that 'saturated LWA' needs to be used to make internally cured concrete, this is an oversimplification. Golias (Golias, 2010) studied the influence of the moisture contents of LWA used for internal curing by adding the LWA in three states: oven dry, 24 h pre-wetted, and vacuum saturated. By adjusting the mixture proportions to account for the saturation level of the aggregate (such as including extra water in the mixture when oven dry LWAs were employed), it was possible to achieve the same internal curing benefits (increase in strength and degree of hydration and decrease in autogenous shrinkage and water sorption) using the oven dry or the 24 h pre-soaked LWA. The use of vacuum saturated LWA was not as efficient as the other cases, since additional water may be held in the smallest pores, making it more difficult for that internal curing water to be desorbed. The purpose of this study was not to advocate the use of oven dry LWA, as LWA in this state would not be expected to be encountered in the field. Rather, it was conducted to show that internal curing is possible with a wide range of LWA moisture conditions from a theoretical perspective, if the moisture content of the aggregate and its absorption are properly considered. While laboratory studies have shown that LWA added in a partially saturated state will generally absorb water from the fresh mixture in a predictable and repeatable manner, the large number of additional variables that come into play for a field concrete suggest that, for the current state-of-the-practice, it is best to provide the LWA in a known and consistent pre-wetted condition.

7 Internal Curing in Present Practice: Field Experiences

As of the end of 2010, internal curing has been employed in a variety of concrete mixtures for diverse applications including bridge decks, pavements, transit yards, and water tanks.

One of the first documented field studies of concrete with internal curing was a large railway transit yard in Texas requiring 190 000 m^3 of concrete, constructed in 2005 (Villarreal & Crocker, 2007). In this application, an intermediate sized LWA (178 kg/m^3 concrete) was blended with NWAs to fill in a gap in the overall aggregate gradation. The internal curing provided by the pre-wetted intermediate LWA resulted in a noticeable (> 15 %) increase in 28 d strength, elimination of plastic and drying shrinkage cracking, and a reduction in concrete unit weight that may translate into reductions in fuel requirements and equipment wear (Villarreal & Crocker, 2007). Since 2007, several informal crack surveys have been conducted at the railway transit yard, with only two or three cracks found (one of these being where a construction joint was inadvertently omitted). This concrete mixture design has steadily increased in popularity in the north Texas region (Villareal, 2008), with over 2 000 000 m^3 of internally-cured concrete now in place.

In 2006, internal curing was employed for a continuously reinforced concrete pavement placed using a slip-form paving machine (Friggle & Reeves, 2008). The concrete mixture with internal curing was formulated to meet the Texas Department of Transportation (TxDOT) requirements of a minimum flexural strength of 3.93 MPa and a minimum compressive strength of 24.1 MPa, both at 7 d. Ten months after the successful placement of the pavement, a crack survey indicated "an overwhelming reduction in the number of cracks (21 vs. 52 in a comparable section of normal concrete) and a significant reduction in the measured width of the cracks" for the test section placed using the mixture with internal curing relative to a control section placed with the TxDOT standard mixture (Friggle & Reeves, 2008).

Internal curing has been used in bridges in New York, Ohio, and Indiana. In Ohio, the department of transportation employed a modified HPC #4 mixture that contained 356 kg/m^3 of cementitious materials and silica fume (http://www.nesolite.com/appofmonth.htm). Approximately 120 kg/m^3 of LWA were used. The mixture was pumped to the deck without incident and maintained sufficient entrained air, which was monitored using a pressure meter. The mixture was reported to have strengths that were similar or superior to the conventional mixture without internal curing.

The NYDOT has also used internal curing on 9 bridges that have been built and it is planned for several additional bridges. The NYDOT uses a special mixture design that is similar to their conventional deck design (nearly 385 kg/m^3 of cementitious material with silica fume), where 120 kg/m^3 of fine LWA are used. A 2 % to a 10 % increase in strength was noted between 7 d and 28 d with the use of internal curing on the Court Street bridge and a 5 % reduction in strength at 7 d with a 15 % increase in strength at 28 d on the Bartell Road bridge (Figure 45) (Wolfe 2010). In discussions with the NYDOT, it was reported that there were no negatives associated with using internal curing; however, the potential benefits still needed to be quantified through comparisons with conventional concrete bridge deck materials. Three internally cured decks were walked to assess their performance after 1 year to 3 years and only one very small crack was observed in the negative moment region of one internally cured bridge. Conversely, the parapet walls and sidewalks produced with concrete without internal curing showed several larger cracks. The decks appear to be wearing as expected. The NYDOT permits these concretes to be pumped and no problems have been reported. Air is typically monitored using a pressure meter.

Figure 45. Internally cured concrete being cast at Bartell Road in New York (Wolfe, 2010).

Two bridges were cast in close proximity in Monroe Co., IN, just outside of Bloomington, in September of 2010. The bridges were box girder assemblies and a 100 mm topping slab was made in one case for a conventional INDOT class C mixture. In the other case, the mixture was similar, however approximately 240 kg/m^3 of fine LWA was used (it should be noted that the LWA used in Indiana was less absorptive (approximately 10 % by mass) than the LWA used in Ohio or New York (approximately 16 % by mass)). Figure 46 shows the internally cured bridge deck being cast using a bucket to place the concrete while the conventional deck was pumped. Both decks were cured using wet burlap (Figure 47) and plastic sheeting for 7 d (Figure 48). The benefit of casting these decks at the same time, with the same materials, and with similar construction procedures is that the field performance will be able to be more directly compared. Approximately 40 d after casting, the bridges were walked and no cracking was observed in either deck.

Figure 46. Internally cured concrete bridge deck being cast near Bloomington, IN (Di Bella, Schlitter, & Weiss, 2010).

Figure 47. Wet burlap being used on the internally cured concrete bridge deck near Bloomington, IN (Di Bella, Schlitter, & Weiss, 2010).

Figure 48. Plastic sheeting being used to cover the wet burlap on the internally cured concrete bridge deck near Bloomington, IN (Di Bella, Schlitter, & Weiss, 2010).

8 Internal Curing in the Future

As internal curing continues to proliferate in practice, research on this topic continues to find new avenues for exploration. Two of these are the utilization of crushed returned concrete fine aggregates as internal curing reservoirs and the pre-wetting of the LWA with other materials instead of just water. Two examples for the latter case would be a solution of a chemical admixture or a phase change material. Both of these new developments will be presented in some detail below.

8.1 Crushed Returned Concrete Fine Aggregates (CCA) for Internal Curing

A recent study has considered the blending of crushed returned concrete fine aggregates (CCA) with fine LWA as a sustainable approach to produce mortars with reduced autogenous deformation, but equivalent strength relative to a control mortar prepared without internal curing (Kim & Bentz, 2008). In this joint NIST/National Ready Mixed Concrete Association (NRMCA) study, pre-wetted fine CCA[1] (passing a 4.75 mm sieve) with three strength levels (designated as 1000, 3000, and 5000, indicative of their 28 d strength in units of psi) were investigated as replacements for a portion of the normal weight sand in high performance mortars with a *w/cm* of 0.3, utilizing the mixture proportions provided in Table 5. Aggregate characteristics are summarized in Table 6 and Table 7. For this study, the high percentage of minus 200 (0.003 in or 0.075 mm) particles in the CCA fines was removed to avoid extra variance. In Table 5, 'free' water was determined as the quantity of water desorbed from pre-wetted conditions down to 93 % RH for each internal curing agent.

Autogenous shrinkage was assessed from time of set using the corrugated tube protocol as developed by Jensen and Hansen (Jensen & Hansen, 1995) and recently standardized as ASTM C1698-09 (ASTM International, 2009). While some reduction in measured autogenous deformation (Figure 49 and Table 8) was produced with the CCA alone as a replacement material, substantially lower mortar cube compressive strengths were also measured, as summarized in Table 9. In contrast, mixtures with a pre-wetted LWA as the replacement material exhibited a substantial reduction in autogenous shrinkage and a 10 % to 20 % strength increase at ages of 28 d and 56 d. However, a more economical and sustainable solution may be to blend the two materials, as exemplified by the results for the LWA-CCA 1000 blend in Table 8 and Table 9. This mortar contained a blend of 43 % CCA 1000 and 57 % LWA by (dry) mass to provide the necessary internal curing water. It greatly reduced both early age and long term autogenous shrinkage, while producing an equivalent 56 d cube strength as the control mortar with no internal curing. To ensure that the CCA 1000 material in the blend was indeed contributing to the long term autogenous shrinkage reduction, the LWA-2 mixture was formulated to contain the same LWA content as the CCA-1000/LWA blend. The results in Table 8 confirm that the CCA-LWA blend has a greater reduction in long term autogenous shrinkage than the LWA-2 mixture containing an equivalent quantity of only LWA.

[1] The fine CCA were available from a separate NRMCA study on the reuse of crushed returned concrete as aggregate. See Obla, K., Kim, H., and Lobo, C. (2007). "Crushed Returned Concrete as Aggregates for New Concrete", NRMCA Report, Project 05-13, for further details.

Table 5. Mortar Mixture Proportions for NIST/NRMCA study (Kim & Bentz, 2008)

Material or Property	Control (g)[A]	LWA-1 (g)	LWA-2 (g)[B]	CCA-1000 (g)	CCA-3000 (g)	CCA-5000 (g)	CCA-1000 / LWA (g)
Blended cement (20 % slag)	2000	2000	1000	2000	2000	2000	2000
Water	584.6	584.6	292.3	584.6	584.6	584.6	584.6
Type A admixture	25.6	25.6	12.8	25.6	25.6	25.6	25.6
F95 fine sand	950	696.1	379.8	569.8	625.0	466.6	664.6
Graded sand	722	613.2	320.2	341.8	356.3	238.6	545.4
20-30 sand	722	576.9	306.6	278.4	295.4	57.3	502.3
GS16 coarse sand	1406	704.9	440.1	497.7	491.8	16.2	653.1
SSD LWA	-	833.7	312.6	-	-	-	625.3
SSD CCA	-	-	-	1740.0	1735.8	2488.9	435
"Free" water in SSD LWA	-	160	60	-	-	-	120
"Free" water in SSD CCA	-	-	-	160	160	160	40
Fresh air content (from cup mass)	3.1 %	2.9 %	4.2 %	6.6 %	4.0 %	4.4 %	5.0 %

[A]Masses are reported in grams as these were the units employed in preparing the mortar mixtures.
[B]The mixture size of the LWA-2 mortar is only 50 % of that of the other mixtures due to material supply limitations.

Table 6. Measured Particle Size Distributions after Removing Minus 200 Sieve Fraction (Kim & Bentz, 2008)

Sieve no. (opening)	Percent passing			
	LWA	**CCA-1000**	**CCA-3000**	**CCA-5000**
4 (4.75 mm)	98.6	99.6	99.1	97.0
8 (2.36 mm)	70.1	71.6	69.9	58.6
16 (1.18 mm)	44.7	58.3	55.0	42.8
30 (0.6 mm)	29.6	37.7	35.2	26.3
50 (0.3 mm)	20.4	5.5	11.7	9.4
100 (0.15 mm)	14.5	1.0	0.0	2.6
Pan	0.0	0.0	0.0	0.0

Table 7. Fine Aggregate Properties (Kim & Bentz, 2008)

Fine Aggregate	*Normal weight sand*	*LWA*	*CCA-1000*	*CCA-3000*	*CCA-5000*
Specific Gravity (SSD)	2.61	1.80	2.15	2.23	2.15
Absorption (mass %)	Negligible	23.8	16.0	12.4	12.0
Minus 200 sieve (mass %)	0.57	Not meas.	7.31	9.50	7.64
Fineness Modulus	Not meas.	3.2	2.73	2.71	3.05

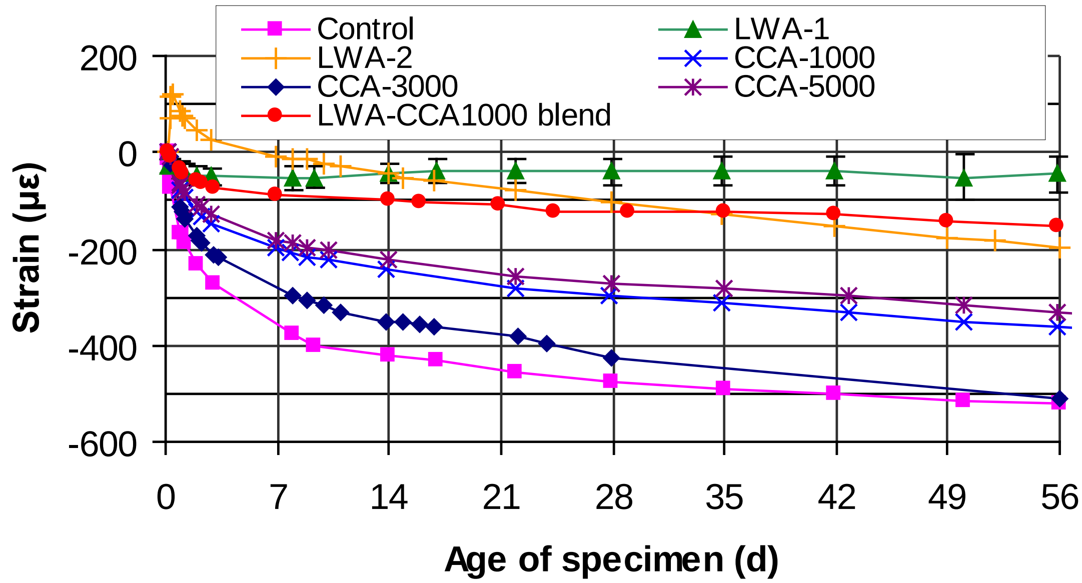


Figure 49. Autogenous deformation in microstrain ($\mu\varepsilon$) vs. time for mortar mixtures with and without internal curing using various LWA/CCA blends. A typical standard deviation between three specimens is illustrated by the error bars on the LWA-1 data points (Kim & Bentz, 2008).

Table 8. Autogenous Deformation Results for Mortar Mixtures (Kim & Bentz, 2008)

	Control	**LWA-1**	**LWA-2**	**CCA-1000**	**CCA-3000**	**CCA-5000**	**CCA-1000 / LWA**
Net Autogenous Shrinkage[A] (ε_{min} - ε_{max}) (Microstrain)							
1 d	-167	-37	-41	-79	-122	-69	-35
8 d	-376	-53	-131	-209	-297	-189	-89
28 d	-476	-39	-220	-298	-425	-274	-121
56 d	-519	-45	-318	-363	-511	-329	-153
1 d reduction, % of control	-	78 %	75 %	53 %	27 %	59 %	79 %
8 d reduction, % of control	-	86 %	65 %	44 %	21 %	50 %	76 %
56 d reduction, % of control	-	91 %	39 %	30 %	2 %	37 %	71 %

[A] Net autogenous shrinkage has been computed as the difference between the initial maximum and the minimum deformation values achieved up to the specific age being evaluated (Cusson, 2008)

Table 9. Compressive Strength Results for Mortar Cubes Cured under Sealed Conditions (Kim & Bentz, 2008)

Age	**Control (psi)**	**LWA-1 (psi)**	**LWA-2 (psi)[A]**	**CCA-1000 (psi)**	**CCA-3000 (psi)**	**CCA-5000 (psi)**	**CCA-1000/ LWA (psi)**
3 d	8,830 (125)[B] 60.9 MPa	8,580 (602) 59.2 MPa	9,070 (27) 62.5 MPa	5,110 (35) 35.2 MPa	6,500 (90) 44.8 MPa	5,570 (44) 38.4 MPa	7,910 (271) 54.5 MPa
7 d	---	---	---	6,030 (131) 41.6 MPa	---	6,370 (259) 43.9 MPa	9,390 (151) 64.8 MPa
8 d	10,380 (285) 71.5 MPa	10,400 (327) 71.7 MPa	---	---	7,970 (88) 55.0 MPa	---	---
28 d	11,860 (458) 81.8 MPa	12,870 (566) 88.8 MPa	13,790 (464) 95.0 MPa	7,490 (136) 51.6 MPa	9,600 (442) 66.2 MPa	7,730 (82) 53.3 MPa	11,110 (281) 76.6 MPa
56 d	12,230 (820) 84.3 MPa	13,730 (148) 94.7 MPa	14,660 (57) 101.4 MPa	8,280 (123) 57.1 MPa	9,640 (924) 66.5 MPa	8,230 (454) 56.8 MPa	12,230 (1160) 84.3 MPa
28 d, % control	100	109	116	63	81	65	94
56 d, % control	100	112	120	68	79	67	100

[A]For LWA-2 mixture, two cubes tested at each of 3 ages.
[B]Standard deviation in units of psi for testing three (or two) cubes at each age.

8.2 LWA as Reservoirs for Admixtures and Phase Change Materials

The concept of using LWA to provide additional internal curing water to a concrete mixture has been extended to pre-wetting the LWA with materials other than water. Examples explored to date include filling the LWA with the liquid form of a phase change material (Bentz & Turpin, 2007) or with a concentrated solution of a chemical admixture, such as a shrinkage-reducing admixture (Bentz, 2005). In the former case, the transition temperature of the phase change material within the LWA could be engineered to reduce the maximum temperature achieved in a mass concrete pour, to provide energy conservation via an increased thermal lag in residential wall construction, or to reduce the number of freeze/thaw cycles experienced by a field concrete structure (Bentz & Turpin, 2007).

Recently, a new technology for reducing diffusion into concrete by increasing the viscosity of the pore solution has been developed (Bentz, Snyder, & Peltz, 2010). The technology has been given the acronym VERDiCT: Viscosity Enhancers Reducing Diffusion in Concrete Technology. While the viscosity-enhancing admixture (typically used as a 10 % by mass solution) reduces transport rates when added directly to the mixing water, a better performance is achieved when a solution of the concentrated (50:50 in water for example) chemical admixture is employed to pre-wet LWA. Previous results on mortars with *w/c*=0.4 have indicated that a factor of two reduction can be achieved in diffusion rates by incorporating this type of admixture into the mixture, which should translate into a doubling of the service life in cases where the service life is regulated by the diffusion rates of ingressing species such as chlorides or sulfates (Bentz, Snyder, & Peltz, 2010). Figure 50 provides relative chloride penetration depths, assessed according to AASHTO TP64 (Standard Method of Test for Predicting Chloride Penetration of Hydraulic Cement Concrete by the Rapid Migration Procedure), for *w/cm*=0.42 blended cement concretes containing 25 % fly ash replacement for cement on a mass basis. While adding the VERDiCT chemical directly to the mixture or incorporating internal curing reduces the chloride penetration depths by about 15 % or 25 %, respectively, a 50 % reduction is achieved when the LWA is pre-wetted with a 50:50 solution of the VERDiCT admixture in water. Evaluation of this technology in laboratory concrete mixtures as well as field concrete exposures is continuing. Using LWA to distribute chemicals within a concrete mixture is likely most promising for those admixtures formulated to have an impact on the longer term properties of the concrete, including shrinkage-reducing admixtures, corrosion inhibitors, and alkali-silica reaction mitigating admixtures.

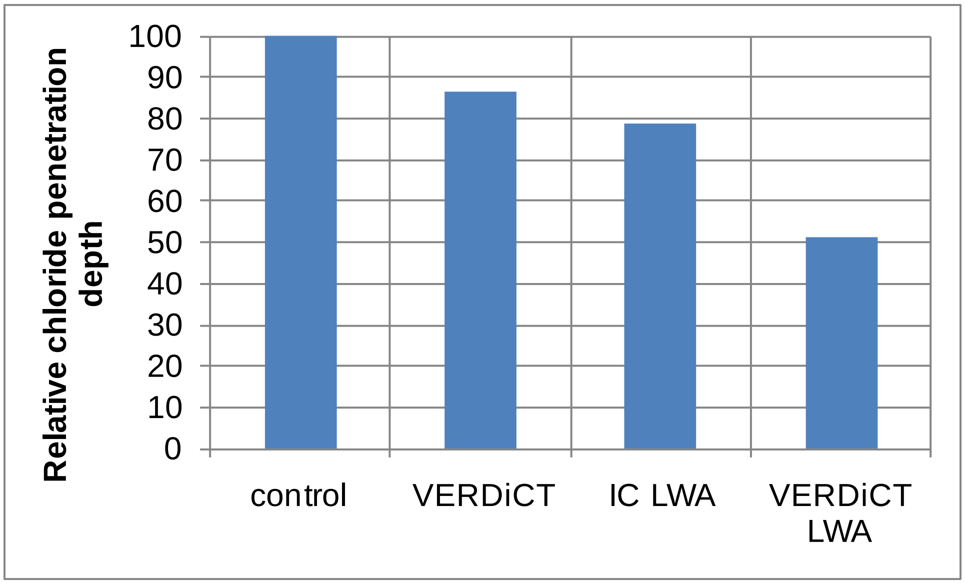


Figure 50. Reduction in chloride penetration depth for concretes with viscosity-enhancing admixture and/or internal curing, cured for 56 d and evaluated according to AASHTO TP64 (Standard Method of Test for Predicting Chloride Penetration of Hydraulic Cement Concrete by the Rapid Migration Procedure). Average standard deviation in penetration depth was 1.4 mm for two replicate specimens, with an average coefficient of variation of 17 %.

9 Internal Curing in Perspective

Currently in 2010, it appears that internal curing has the potential to make a substantial impact on the durability and life-cycle costs of concrete structures. The reported costs for the projects in New York and Indiana (discussed in Section 7) were between a 0 % and a 20 % increase in the cost of the concrete, with a typical cost increase estimated to be in the 10 % to 12 % range, compared with concretes typically used in these applications. However, as discussed in this report, the reduced risk of cracking and the reduced chloride ingress should contribute to a more durable structure that has a longer life and lower life-cycle costs. Further, this could have substantial benefits in a reduced disruption to the traveling public, generally producing a more sustainable solution.

These benefits are balanced by a need for additional quality control (for example, the NYDOT requires an LWA representative on site during the batching of internally cured mixtures), additional costs associated with handling and wetting, and the additional costs and energy consumption incurred during the manufacture of the LWA. With time, and increased industry familiarization with internal curing, there will be a broad base of practical experiences, and new engineering solutions to storing and delivering LWA in the desired saturation state.

Internal curing is just one of the many tools in a sustainability toolbox. For example, recent work with the use of supplementary cementitious materials has suggested that substantially less clinker can be used in a mixture, resulting in a lower carbon footprint (de la Varga, Castro, Bentz, & Weiss, submitted). This may also be true for mixtures with increased limestone powder replacement for cement (Bentz, Irassar, Bucher, & Weiss, 2009).

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Appendix A – Internal Curing Bibliography

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Available at: http://concrete.nist.gov/~bentz/phpct/database/ic.html

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