Water Absorption in Internally Cured Mortar Made with Water-Filled Lightweight Aggregate

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Abstract

The increased propensity for shrinkage cracking in low water-to-cement ratio (*w/c*) concrete has inspired the development of new technologies that can reduce the risk of early-age cracking. One of these is internal curing. Internal curing uses saturated lightweight aggregate to supply 'curing water' to low *w/c* paste as it hydrates. Significant research has been performed to determine the effects of internal curing on shrinkage and stress development; however, relatively little detailed information exists about the effects of internal curing on fluid transport properties such as water absorption or diffusivity. This study examines the absorption of water into mortar specimens made with saturated lightweight aggregates (SLWA). These results indicate that the inclusion of SLWA can reduce the water absorption of mortar specimens. This observation was reinforced with electrical conductivity measurements that exhibited similar reductions.

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1. Introduction

High performance concrete (HPC) mixtures have been increasingly promoted due to potential long-term benefits in performance [1]. HPC mixtures generally have a low water-to-cement ratio (*w/c*) and may contain finely ground supplementary cementitious materials, (e.g., silica fume). While the fine pore system is beneficial for increased strength [2] and reduced fluid transport [3, 4], the finer pore network can lead to increased volumetric changes in sealed systems as a result of self-desiccation [5] and the inability of external water to penetrate readily to the interior of HPC members. This volume change (autogenous shrinkage) is an issue as it can result in cracking if the concrete is restrained from shrinking freely.

One strategy to mitigate autogenous shrinkage is the incorporation of water filled inclusions [6-8]. The use of saturated lightweight aggregate (SLWA), enables water from the SLWA to be supplied to the paste after setting [9], thereby reducing the effects of self-desiccation. This strategy has proven to be quite effective in reducing autogenous shrinkage and cracking [10, 11].

The influence of SLWA inclusions on the fluid transport and water absorption properties of concrete is much less understood. This study provides experimental results to quantify the performance of plain and SLWA systems in absorption tests and electrical conductivity measurements. The performance of the SLWA systems is related to aspects of the pore structure of the paste, the pore structure of the LWA, and the pore structure of the interfacial transition zone (ITZ).

1.1. Background in sorptivity

The durability of concrete subjected to aggressive environments depends largely on the penetrability of the pore system [12, 13]. Three mechanisms can be used to describe transport in cementitious systems: (1) permeability, (2) diffusion and (3) absorption. Permeability is the measure of the flow of water under a pressure gradient while diffusion is the movement of ions due to a concentration gradient. Absorption can be described as the materials ability to take in water by means of capillary suction. Water absorption is an important factor for quantifying the durability of cementitious systems [14-16] and is the primary focus in this study.

The test method that is most commonly used to determine the absorption and rate of absorption (sorptivity) of water in unsaturated hydraulic cement concretes is ASTM C1585 [13]. This test consists of exposing the bottom surface of a sample to water and measuring the increase in mass resulting from absorption. Before the test is conducted, samples are conditioned for 18 days. The samples are first placed in a 50 ˚C and 80 % RH environment. After three days of conditioning, the samples are removed from the oven and placed in individually sealed containers where the samples are retained for 15 days to allow internal moisture equilibrium before the test begins. The absorption test involves recording incremental mass change measurements during the first six hours after the sample came in contact with water and taking one measurement every day for the next eight days. The amount of absorbed water is normalized by the cross-section area of the specimen exposed to the fluid using Equation 1.

$$I = \frac{m_t}{(a \cdot d)} \qquad\qquad \text{Equation 1}$$

72   where: I (mm^3/mm^2) is the normalized absorbed water, m$_t$ (g) is the change in specimen
73   mass at time t; a (mm^2) is the area of the specimen exposed to water (i.e., that of the bottom
74   face), and d (g/mm^3) is the density of the water (taken to be 0.001 g/mm^3 at 23 °C).
75   These absorption measurements are then plotted as a function of the square root of time.
76   The initial sorptivity is determined for the slope of the curve during the first six hours, while
77   secondary sorptivity is determined using the slope of the same measurements between one to
78   eight days as outlined in ASTM C1585 [13].
79   The initial and secondary sorptivity can be used to evaluate the connectivity of the pore
80   network [15]. Additionally, the secondary sorptivity, combined with exposure conditions, has
81   been used for performing service life predictions [16].

82   1.2. Background on the effects of internal curing on sorptivity

83   Low *w/c* mixtures undergo self-desiccation, especially in sealed curing conditions. Self-
84   desiccation occurs as a result of chemical shrinkage. During hydration, the hydration products
85   occupy a volume that is approximately 10 % smaller than the initial reactants [17-19]. This
86   results in the creation of vapor filled voids inside the concrete [20]. These vapor-filled voids
87   grow with increased hydration and penetrate smaller and smaller pores. Lightweight aggregate
88   can be used as a water reservoir to supply water to replenish the water demanded by the
89   hydrating cement paste thereby reducing the vapor-filled voids and therefore mitigating the
90   effects of self-desiccation in low *w/c* concrete mixtures. A more thorough description of this
91   process can be found elsewhere [10, 21].
92   The inclusion of SLWA is hypothesized to influence the absorption of water; reasons can
93   be given for either an increase or a decrease in the water absorption. At first glance, one would
94   think that the incorporation of porous inclusions (i.e., LWA) would result in an overall increase
95   in the porosity of the system. The pores in the LWA are large and in the size range of or slightly
96   larger than the largest capillary pores. As a result, the addition of larger pores into the system
97   could result in higher water absorption.
98   However, alternate reasons exist to explain why a reduction in the water absorption could
99   also occur. When water leaves the LWA, the paste continues to hydrate resulting in a denser
100   microstructure in the paste. This is similar to the supply of extra water from external curing.
101   This concept is shown using Powers' Model in Figure 1(a) for cement paste with a *w/c* of 0.30.
102   As the paste hydrates, hydration products are formed. When the water supply is exhausted,
103   hydration ceases. In the case of a paste with a *w/c* of 0.30, hydration stops at a degree of
104   hydration of 0.73 for hydration under sealed conditions.
105   If however, additional water is supplied, hydration can continue. Figure 1(b) shows
106   Powers' model for a mixture that provides an extra 3.2 % volume of water (by total volume) to
107   the system, designated 11.0 % in the mixtures to follow (Table 1). The 11.0 % indicates the
108   volume fraction occupied by the pre-wetted lightweight fine aggregates in the mortar mixture.
109   Note that this water is not included in the total volume used to calculate the porosity (shown as
110   being greater than 1) since it is not part of the paste pore structure at the time of setting. After
111   approximately 32 % hydration, the water in the LWA has been drawn out of the LWA by the
112   hydrating cement paste to fill the voids within the capillary porosity created by chemical
113   shrinkage. During this process, the water from the LWA has resulted in further hydration. The
114   theoretical maximum degree of hydration for this mixture would occur when the system runs out
115   of water at approximately 0.77. A 23.7 % LWA mixture provides more water for the cement to
116   hydrate and hydration for the 23.7 % mixture is complete at a degree of hydration of 0.83. This

117 is shown in Figure 1(c). The maximum theoretical degree of hydration increases as the volume
118 replacement increases but comes to a limiting value for an LWA addition of 23.7 % (Figure
119 1(d)). This is because at that degree of hydration, no pore space remains within the hydrating
120 specimen. It is believed that the water provided does not leave the LWA before set for curing
121 under sealed conditions [9], which explains why the initial paste porosity would be expected to
122 be the same for the paste in these mixtures. The continued hydration that occurs due to the
123 additional water from the LWA results in a denser microstructure that could slow the ingress of
124 water into the system [22].
125 The last aspect to consider for a reduction in the water absorption is that the ITZs of the
126 normal weight aggregate (NWA) could be percolated across the 3D microstructure, and the
127 inclusion of the LWA could depercolate these ITZ pathways [23, 24]. If LWA, with its more
128 dense ITZs [25, 26], were added to the system, the NWA ITZs may not be as percolated,
129 resulting in a lower absorption. The effect of different volume replacements of LWA on ITZ
130 percolation was simulated using the hard core/soft shell model developed at the National
131 Institute of Standards and Technology (NIST) [27-29]. This was similar to the method used by
132 Bentz [24] to examine the ingress of chloride ions into mortars with and without internal curing.
133 The aggregate particles (both LWA and NWA) are represented as circular 'hard cores' and the
134 ITZ around the normal weight aggregates only is represented as a surrounding ring or 'soft
135 shell'. The results of simulations for the mortars investigated in this study are shown in Figure 2.
136 As the replacement volume of LWA increases, the volume of ITZ around the NWA decreases as
137 indicated by the upper curve in Figure 2 [30]. This implies that as more LWA is used, the less
138 porous ITZ around the LWA results in a reduction in absorption. As more LWA is used, the
139 potential for percolation of the NWA ITZs also dramatically decreases as indicated by the lower
140 curve in Figure 2. If enough LWA is used, the ITZs of the NWA would depercolate. For these
141 two reasons, it is expected that the absorption of mortars with LWA could be less.

142 **2.   Materials**

143 ASTM C150 Type I ordinary portland cement (OPC) was used in this study, with a Blaine
144 fineness of 370 m^2/kg and an estimated Bogue composition of 56 % C_3S, 16 % C_2S, 12 % C_3A,
145 7 % C_4AF and a Na_2O equivalent of 0.68 % by mass.
146 A polycarboxylate-based high-range water-reducing admixture (HRWRA) was added in
147 varying rates depending on the mixture. For the mortar mixture with a *w/c* of 0.25, the HRWRA
148 was added at a rate of 0.75 g per 100 g of cement. For the *w/c* = 0.25 paste, the addition rate was
149 0.60 g per 100 g of cement. For the mortar mixture with a *w/c* of 0.30, the HRWRA was added
150 at a rate of 0.70 g per 100 g of cement while for the mortar mixture with a *w/c* of 0.35, the
151 HRWRA was added at a rate of 0.60 g per 100 g of cement. For LWA mortars, the HRWRA
152 was added at rates of 0.50 and 0.66 g per 100 g of cement for the 11.0 % and 23.7 % mixtures,
153 respectively. Different rates of HRWRA addition were employed to maintain similar
154 consistencies (i.e., workability) of these mixtures.
155 The normal weight sand used was natural river sand with a fineness modulus of 2.71 and an
156 apparent specific gravity of 2.58. Portions of the normal weight sand were replaced with rotary
157 kilned expanded shale with a fineness modulus of 3.10 and a specific gravity of 1.56 (LWA).
158 The 24-hour absorption of the LWA was determined to be 10.5 % according to ASTM
159 C128-07 [31].

2.1. Mixture proportioning

Nine different mixtures were prepared in total. Four mixtures were cement paste with different *w/c* (*w/c* of 0.25, 0.30, 0.35, and 0.40). These mixtures were designated as 0.25, 0.30, 0.35 and 0.40, with the numbers representing the different *w/c*. Three mixtures were plain mortar with a single volume fraction of fine aggregate and different *w/c* (designated as 55/0.25, 55/0.30, and 55/0.35) with the number on the left representing the volume fraction of fine aggregate and the number on the right representing *w/c*. Two mortar mixtures were prepared with different volumes of sand replaced by saturated LWA and a *w/c* of 0.30. These mixtures were designated as 11.0 % and 23.7 %. It is important to note that though the designations are on a total volume basis, the volume of aggregate (LWA and sand) remained constant at 55 % since only the sand was replaced with LWA. The numbers in the designations for the LWA mixtures represent the total volume of the mixture occupied by the LWA (in percent). It should be noted that 23.7 % corresponds to the amount of LWA necessary to eliminate self-desiccation [10]. A list of the mixture proportions can be found in Table 1.

2.2. Mixing procedure

The mixing procedure used for the mortar was in accordance with ASTM C192-06 [32] while the procedure for the paste was in accordance with ASTM C305-06 [33]. The LWA was oven dried, air cooled, and then submerged in water for 24±1 h prior to mixing. The volume of water used to submerge the LWA included both mixing water and the water the LWA would absorb in 24 h. The excess water (water not absorbed in 24 h) was then decanted and used as the mixing water. The normal weight sand was oven dried and cooled for 24 h before mixing. For the plain mortar mixtures and the pastes, the water and cement were conditioned for 24 h at room temperature.

3. Experimental methods

3.1. Degree of Hydration

To measure the degree of hydration, fresh cement paste (in the case of LWA mixtures, paste with LWA) was cast that was identical to the mortar without NWA in air-tight plastic vials. At ages of 1 d, 7 d, 28 d, 56 d and 210 d, approximately 10 g of cement paste was crushed and placed in ceramic crucibles. The samples were placed in an oven at 105 ºC for 24 h. The sample was weighed and then placed in a furnace at 1050 ºC for 3 h. The weights were recorded to monitor the evaporable and non-evaporable water contents. The measurements were corrected to account for loss on ignition of the cement. There is no measurable loss-on-ignition for the LWA since it goes through a furnace during manufacturing.

3.2. Sorptivity

Five 100 mm × 200 mm cylinders were cast for each mixture. After one day of curing, the samples were demolded and three 50 mm ± 2 mm thick samples were cut from the central portion of each cylinder with a wet saw. The samples were sealed in double plastic bags until they reached ages of 7 d, 28 d, and 90 d. After curing in the plastic bags was complete, samples were conditioned by placing them in a desiccator over a potassium bromide (KBr) salt solution which provided an 80 % relative humidity environment at 50 °C [34]. The desiccator was placed

200 in an oven at 50 °C for 3 d. The samples were removed, then stored in sealed containers for 15 d
201 to allow the moisture to equilibrate within the samples. It should be noted that the 1 d samples
202 were not stored in plastic bags but were placed directly in the desiccator after cutting. Once the
203 samples were removed from the sealed containers, the side surface was sealed with aluminum
204 tape and the top surface was covered with plastic to avoid evaporation from the sample during
205 testing. After the samples were prepared, testing occurred in accordance with ASTM
206 C1585-04 [13].

207 3.3. Electrical Impedance Spectroscopy

208   After the sorptivity measurements were completed (120 d), the conductivity of the samples
209 was measured using electrical impedance spectroscopy (EIS). The samples were vacuum
210 saturated using tap water and weighed. After EIS testing, the samples were oven dried at 105 ºC
211 until mass equilibrium was reached (until the difference between two successive 24 h
212 measurements was less than 0.1 %). This was done to determine the total volume of water that
213 was in the system after vacuum saturation.
214   Electrodes were placed on the top and bottom surface of the samples; however contact
215 issues with the samples and electrode existed [35, 36]. For this reason, wet sponges were placed
216 between the samples and the electrodes. Two other methods were compared with the wet
217 sponges. The first involved placing conductive silver paint and copper electrodes on the surfaces
218 of the samples before the EIS measurements were taken. The second method involved placing
219 conductive gel [37] on the top and bottom surfaces to which the electrodes were attached. The
220 methods were applied on 3 different samples and similar results were achieved. The wet sponge
221 method was selected instead of the conductive gel or the conductive silver paint because of its
222 simplicity. After a reliable method was determined, all of the samples were tested. The
223 impedance measurements were made over a frequency range from 10 MHz to 10 Hz, using a 500
224 mV AC signal.
225

226 **4.   Experimental results and discussion**

227 4.1. Effects of internal curing on the degree of hydration

228   Figure 3 shows the degree of hydration (DOH) for five of the mixtures tested. As the *w/c*
229 increases, the DOH also increases. The 11.0 % mixture has a slightly higher DOH than the
230 55/0.30 mixture. This is likely due to the fact that a small volume of additional water in the
231 LWA is available in the 11.0 % mixture. The 23.7 % mixture has a higher DOH than the 55/0.30
232 mixture and it is approaching the DOH of the 55/0.35 mixture. Again, this is due to the extra
233 water provided by the LWA hydrating more cement. The maximum standard deviation for these
234 measurements was 0.006 %.

235 4.2. Effects of internal curing on initial and secondary sorptivity

236   Figure 4(a) through Figure 4(d) show the initial and secondary rates of water absorption for
237 samples cured for 1 d, 7 d, 28 d, and 90 d. The absorbed water is expressed as grams of water
238 per unit volume of paste. The volume percentage of cement paste in the mortar samples was
239 approximately 45 %.

240   Comparing the mixtures with a similar *w/c* (55/0.30, 11.0 %, 23.7 %), it can be seen the
241   absorption for the 55/0.30 was the highest, with the absorption decreasing with increasing LWA
242   replacement volume. It can also be seen that the 23.7 % mixture has a lower absorption than the
243   55/0.25 mixture. This behavior was observed on all sorption tests performed on samples cured
244   for different periods. The lower absorptions seen are likely due to the increased hydration, the
245   fact that the LWA is not re-saturating even as the hydrated cement paste is absorbing water due
246   to an improved interfacial transition zone, and the depercolation of the interfacial transition
247   zones surrounding the NWA.

248   Figure 5(a) shows the initial rate of absorption for samples cured for different periods. The
249   addition of LWA reduces the initial rate of absorption. Comparing the mixtures with a similar
250   *w/c* (55/0.30, 11.0 %, 23.7 %), the 55/0.30 mixture exhibits the highest initial sorptivity with
251   lower sorptivity being observed with increasing volume replacement of LWA. The 23.7 %
252   mixture has an even lower initial sorptivity than the 55/0.25 mixture. The 11.0 % LWA mixture
253   has an average reduction of 4 % on initial sorptivity and 1 % on secondary sorptivity in
254   comparison to the 55/0.30 mixture. Similarly, the 23.7 % LWA mixture has an average reduction
255   of 46 % on initial sorptivity and 28 % on secondary sorptivity.

256   Longer curing times reduce the initial sorptivity. However, the main reduction of initial
257   sorptivity in samples containing LWA is achieved during the first week of curing. The 11.0 %
258   LWA mixture reaches a sorptivity that is similar to the 55/0.25 mixture when samples are cured
259   for 90 d. At all ages, the 23.7 % LWA mixtures reach lower initial sorptivity values than the
260   55/0.25 mixtures.

261   When samples without LWA are analyzed, a considerable difference is observed when the
262   *w/c* changes. The mixture with a higher *w/c* (55/0.35) has an important reduction of the rate of
263   absorption when longer curing times are allowed. Mixtures with *w/c* = 0.3 show a reduction in
264   the absorption for the first day. The mixture with *w/c* = 0.25 does not show a statistically
265   significant difference on sorptivity with the change of curing time.

266   Figure 5(b) shows the secondary rate of absorption. Similar to the initial sorptivity, the
267   23.7 % mixture produces a reduction of the secondary rate of absorption. This reduction is
268   comparable with the one obtained using a plain mixture with *w/c* of 0.25. Results from the
269   11.0 % mixture can not be clearly distinguished from the 55/0.30 mixture, likely because of the
270   inherent variability of the measurements.

271   4.3. <u>Effects of internal curing on the amount of absorbed water during the sorption test</u>

272   Figure 6(a) shows the cumulative absorbed water after 8 d of testing for samples cured for
273   different periods. All the mixtures exhibit a decrease in the total amount of absorbed water when
274   a longer curing period is used. A longer curing period will provide time to develop a more dense
275   internal structure, reducing the size and connectivity of the pore network.

276   It can be observed that the mixture with a lower LWA replacement volume (11.0 %) has a
277   lower absorption than the 55/0.30 mixture. The 23.7 % mixture has a lower total absorption than
278   the 55/0.25 mixture. Mixture 11.0 % has an average reduction of 8 % on absorbed water after 8 d
279   of test in comparison to the 55/0.30 mixture. Mixture 23.7 % has an average reduction of 38 %
280   on absorbed water after 8 d of test.

281   Figure 6(b) shows the cumulated absorption of water on samples with *w/c* = 0.30 (including
282   cement paste), cured for 28 d. It can be observed that the addition of 23.7 % LWA significantly
283   reduces the amount of absorbed water, showing a performance very similar to the cement paste
284   samples. This result supports the concept of depercolation of the interfacial transition zone.

285   Figure 7(a) shows the relationship between the amount of absorbed water at 8 d and the *w/c*
286   for samples cured for 28 d. Because of the continued hydration of the LWA mixtures, they
287   exhibit behavior of a conventional mortar with a lower *w/c*. A "mortar equivalent *w/c*" (i.e., the
288   *w/c* of a mortar sample that would exhibit a similar absorption to the absorption in the LWA
289   mixtures) is shown in Figure 7(a). The 11.0 % LWA mortar with *w/c* = 0.30 has a performance
290   similar to a mortar with a *w/c* of 0.28, while the 23.7 % LWA mixture exhibits a performance
291   equivalent to a mortar with *w/c* of 0.23.
292   Figure 7(b) shows the same data as Figure 7(a), but now is used to determine a "cement
293   paste equivalent *w/c*". The 55/0.30 mixture has a performance similar to a paste sample with *w/c*
294   of 0.37. The 11.0 % LWA mortar has a performance similar to a paste with a *w/c* of 0.35, while
295   the 23.7 % LWA mixture exhibits a performance equivalent to a paste with *w/c* of 0.30. In
296   general, a conventional mortar of a specific *w/c* such as 0.30 exhibits a higher absorption per unit
297   volume of paste than an equivalent cement paste, suggesting the porous and well connected ITZs
298   surrounding each NWA are contributing in increased sorption relative to a plain paste where no
299   such ITZs are present.
300

301   4.4. Effects of internal curing on electrical conductivity properties

302   Figure 8 shows the relationship between the electrical conductivity and the *w/c* for samples
303   cured for 28 d. Similar to the results for absorbed water, a "mortar equivalent *w/c*" was
304   calculated. The 11.0 % LWA mortar has a performance similar to a mortar of a *w/c* of 0.29,
305   while the 23.7 % LWA mixture exhibits a performance equivalent to a mortar with *w/c* of 0.23,
306   consistent with the sorptivity results from Figure 7(a).
307   Due to the continued hydration, the porosity of the LWA mixtures will be reduced as
308   compared to the plain mortar mixture. Figure 9(a) shows the amount of absorbed water at 8 d for
309   the samples cured for 28 d as a function of the porosity (excluding the gel porosity) of the
310   mixtures. The conductivity is also plotted as a function of the porosity in Figure 9(b), and a
311   similar result is seen. Mixtures with 11.0 % and 23.7 % LWA have average conductivity
312   reductions of 13 % and 53 %, respectively. Similar magnitude reductions have been observed
313   for chloride ion diffusivity in mortars containing LWA [24].
314

315   4.5. Effects of available space on both sorptivity and total amount of absorbed water

316   From a fundamental point of view, sorptivity and absorbed water are directly related to the
317   unsaturated interconnected porosity of the system as this describes the space that is available to
318   be filled with water during the sorption test.
319   Figure 10(a) shows the relationship between the open porosity and the initial sorptivity.
320   The open (unsaturated) porosity (i.e., the porosity which can be filled with water during the
321   sorption test) was determined by subtracting the initial water content from the total porosity. The
322   initial water content is considered to be the water that is initially contained in the total porosity at
323   the start of the sorption test. The initial water content was determined by subtracting the oven
324   dry weight at the end of the sorption test from the weight at the beginning of the sorption test,
325   resulting in the volume of water initially in the sample. The total porosity was determined by
326   subtracting the oven dry weight after the sorption test from the vacuum saturated weight,
327   resulting in the total volume of water (i.e. the total porosity) in the sample. From Figure 10(a), it

8

can be seen that the initial sorptivity is a function of the open porosity of the system. Figure 10(b) show the relationship between the open porosity and the total absorbed water after the sorption test. A similar trend can be seen and it can be said that the amount of water absorbed is also a function of the open porosity.

To observe the long term absorption, mixtures cured for 28 d were monitored past the eight days suggested by ASTM C1585 and were measured for 120 d, as shown in Figure 11(a). This plot indicates that the mixtures will continue to absorb water for an extended period of time. Because the LWA mixtures (11.0 % and 23.7 %) continually show lower absorption than the plain mixture (55/0.30), it can also be said that during the testing period, it does not appear that the LWA re-saturates. However, under vacuum saturation, the LWA appears to re-saturate, as seen in Figure 11(b), where the LWA mixtures (11.0 % and 23.7 %) have a higher total vacuum absorption. The LWA likely does not re-saturate during standard testing because of the improved ITZ, however it does re-saturate with a large pressure from the vacuum forcing water through the ITZ into the pores of the LWA. Even when resaturated, these mortars still exhibited a significant reduction in conductivity, due to their overall denser microstructure.

5. Conclusions

This paper has described the absorption behavior of mortars made with SLWA. The inclusion of a sufficient volume of LWA can significantly reduce water absorption. A summary of the general conclusions from the data presented in this paper are:

- The addition of LWA as an internal curing agent increases the degree of hydration, producing a denser microstructure. The denser microstructure results in less water absorption, less sorptivity and a decrease in the electrical conductivity of the samples,
- According to computer modeling results, the addition of LWA, which has a more dense ITZ due to continued hydration, as an internal curing agent produces a system with less percolated normal weight aggregate ITZs that could provide a further reduction in sorptivity,
- From a sorptivity and conductivity perspective, the $w/c = 0.3$ mixture with 23.7 % LWA performs better than the conventional mortar mixture with a $w/c = 0.25$. The average reduction using this mixture was 46 % on initial sorptivity, 28 % on secondary sorptivity, 38 % on absorbed water after 8 d of test, and 53 % on electrical conductivity, and
- A reduction in electrical conductivity was observed on vacuum-saturated specimens, indicating that the influences of increased hydration and denser bulk and ITZ microstructures overwhelm those of the increased water-filled porosity of the vacuum-saturated LWA. Thus, isolated water-filled inclusions do not substantially increase conductive/diffusive transport in a well-hydrated dense mortar microstructure.

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473   **List of Figures**

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475   (a)   (b)
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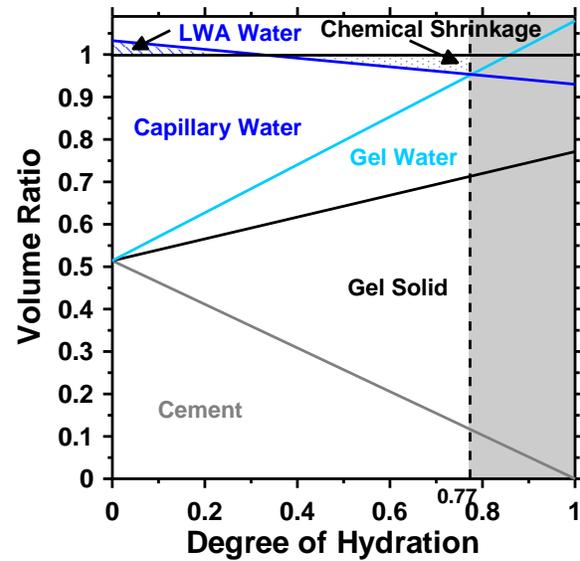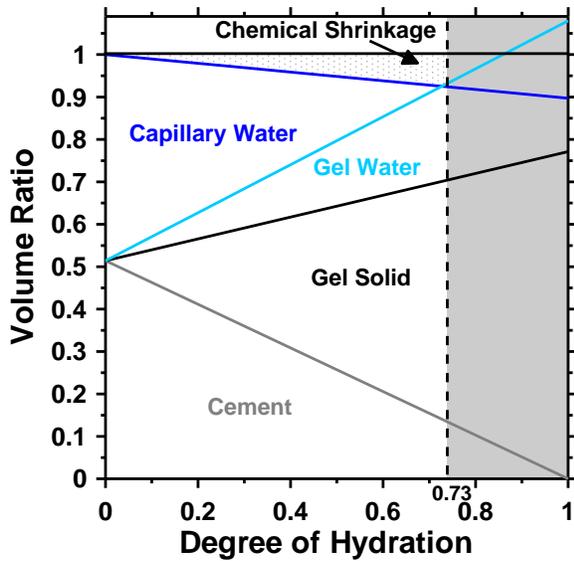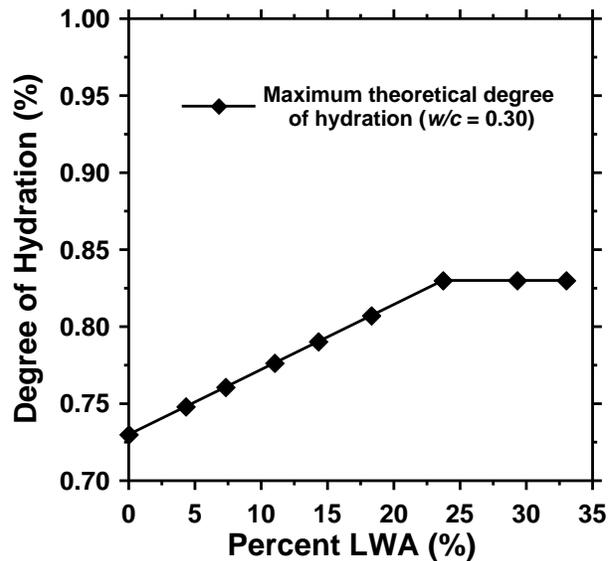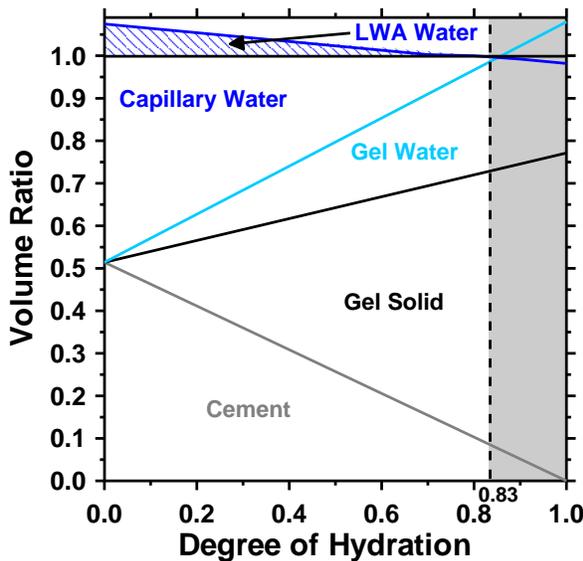
478   (c)   (d)
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480   Figure 1 – Powers' Model showing phase distributions for (a) *w/c* =0.30 paste (b) 11.0 % LWA
481   and (c) 23.7 % LWA mixtures. (d) Maximum theoretical degree of hydration as a function of
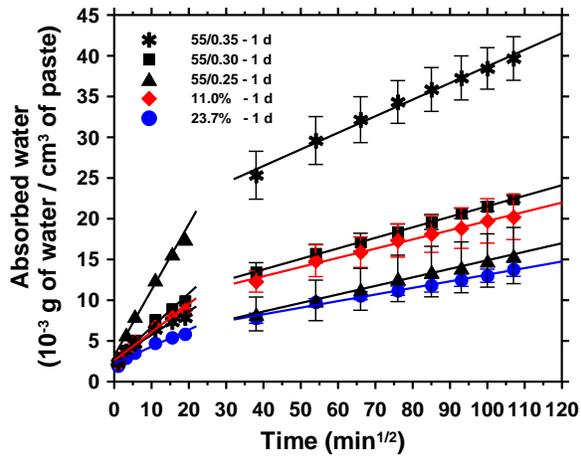482   LWA volume.
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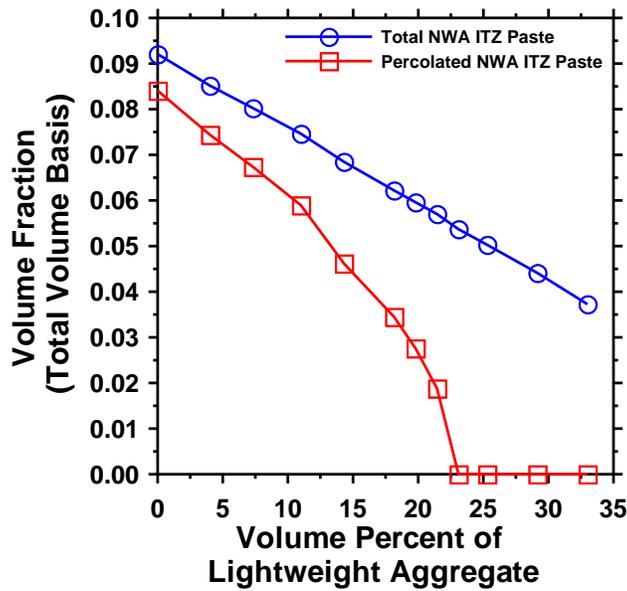
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487   Figure 2 – Volumes of NWA ITZ paste and percolated NWA ITZ paste as a function of
488   replacement volume of LWA.
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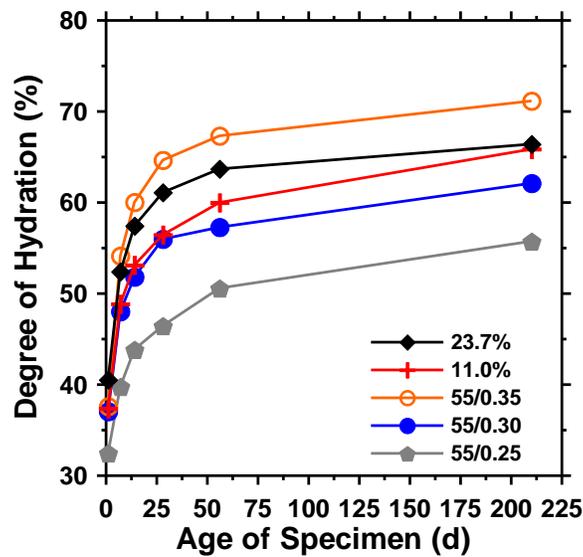
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492   Figure 3 – Degree of hydration as a function of specimen age.
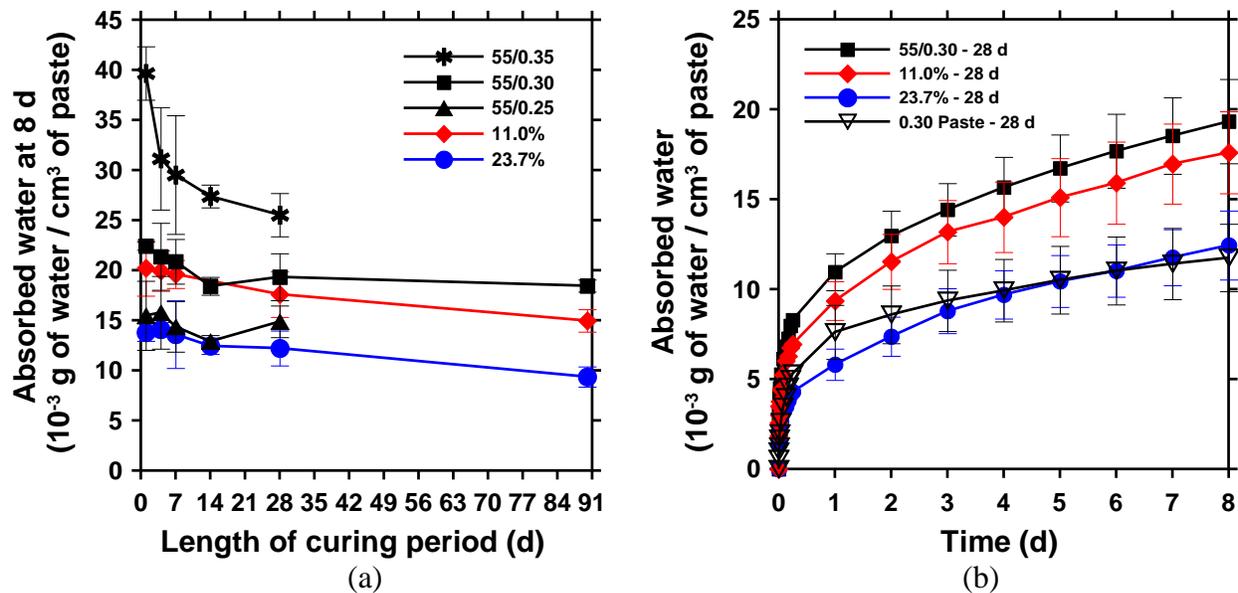493
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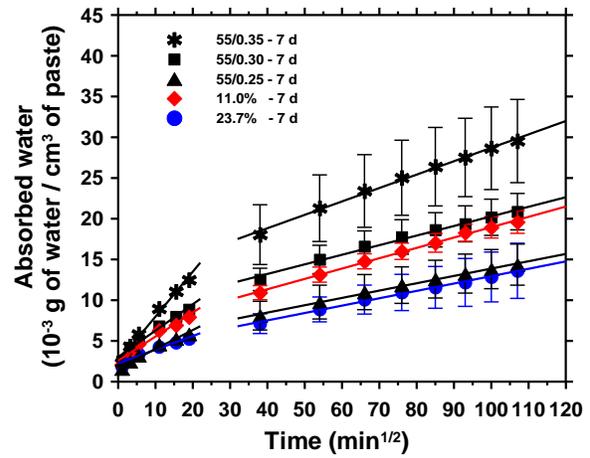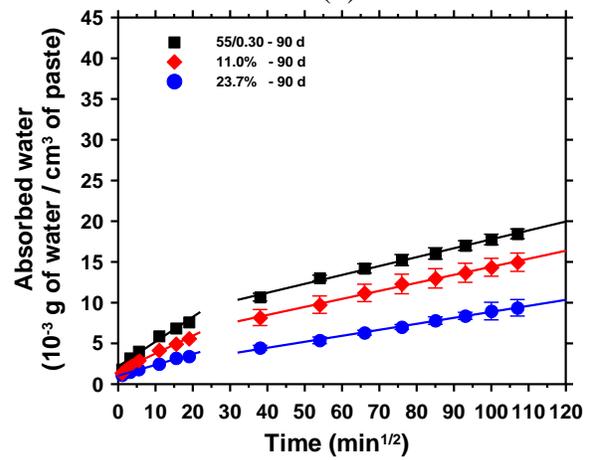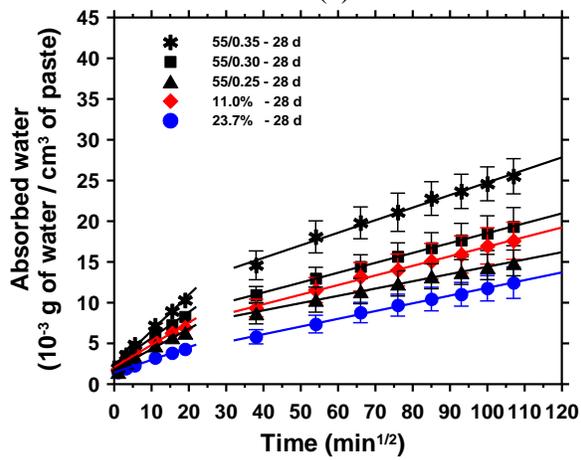
Figure 4 – Sorption test on samples cured for (a) 1d, (b) 7 d, (c) 28 d, and (d) 90 d. Error bars indicate standard deviation for the three specimens evaluated for each mixture.

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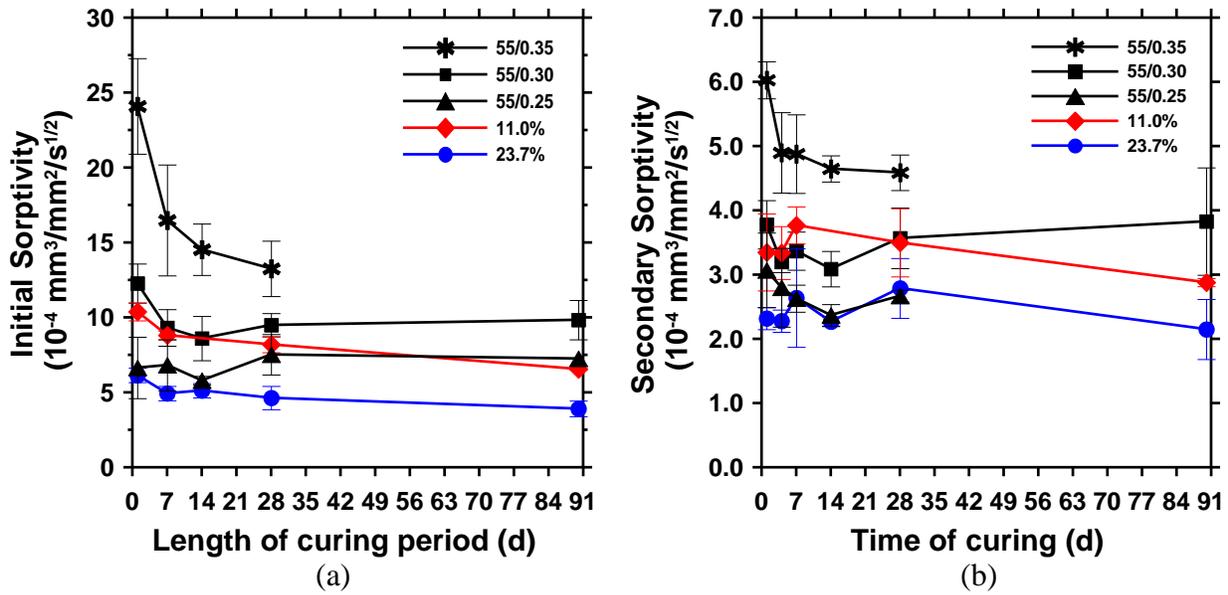
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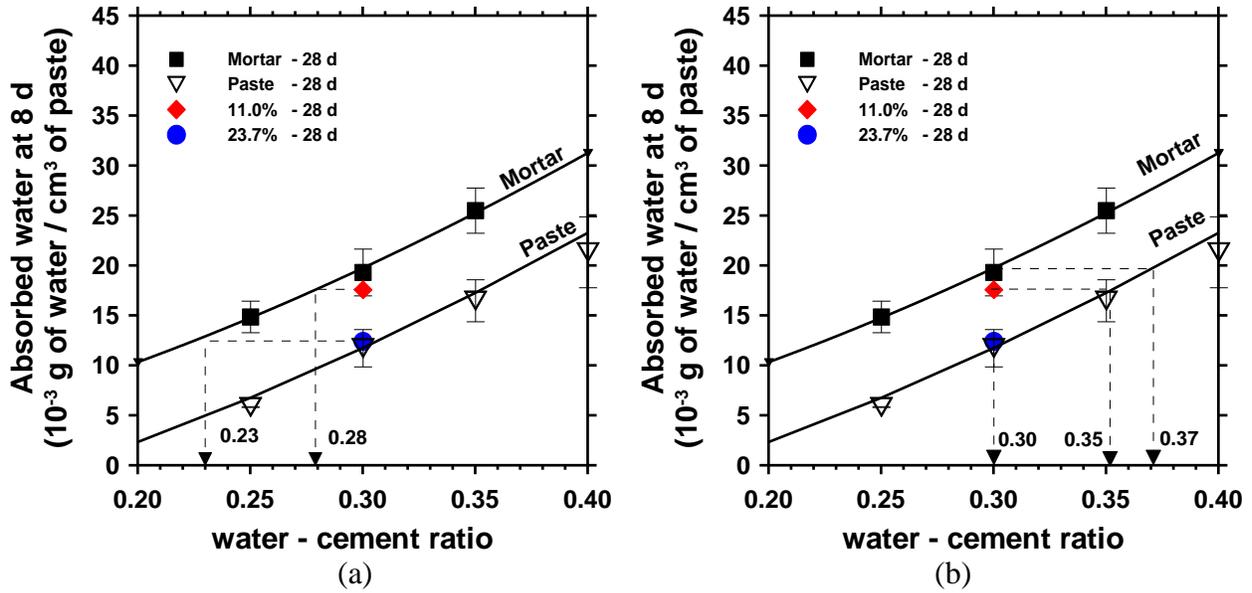512   (a)   (b)
513   Figure 5 – (a) Initial rate of absorption and (b) secondary rate of absorption for samples cured for
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521   (a)   (b)
522   Figure 6 – (a) Cumulated absorbed water at 8 d for samples cured for different periods and
523   (b) absorption water for samples with *w/c* = 0.30 cured for 28 d.
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530 (a) (b)
531 Figure 7 – (a) Mortar equivalent *w/c* and (b) cement paste equivalent *w/c*, both determined from
532 cumulated absorbed water at 8 d on samples cured for 28 d. Solid lines are provided to show a
533 general tendency in the data.
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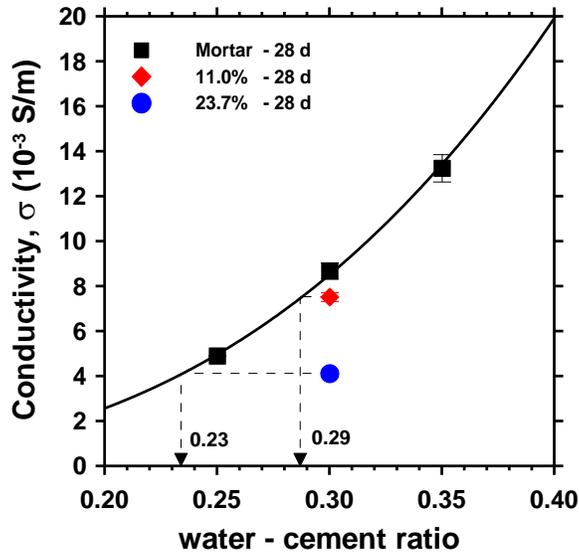
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539 Figure 8 – Mortar equivalent *w/c* determined from electrical conductivity on samples cured for
540 28 d. Solid line shows a general tendency in the data.
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(a)   (b)
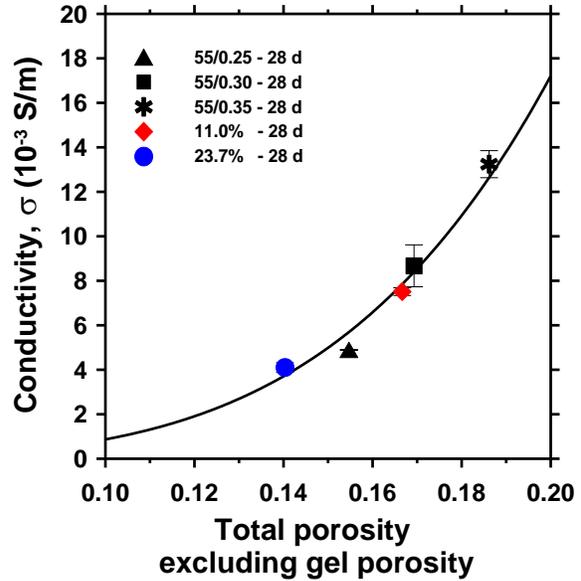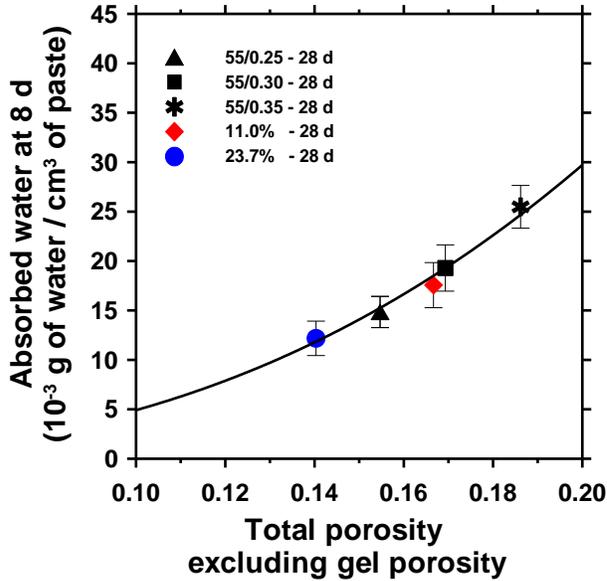
Figure 9 - Porosity as a function of the (a) cumulated absorbed water at 8 d on samples cured for
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(a)   (b)
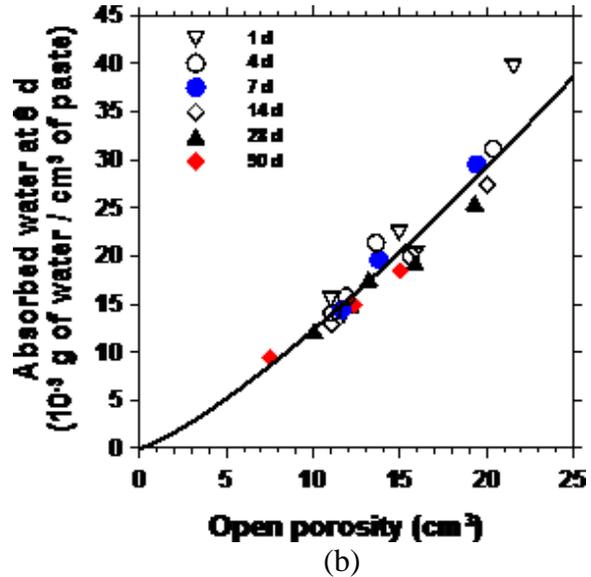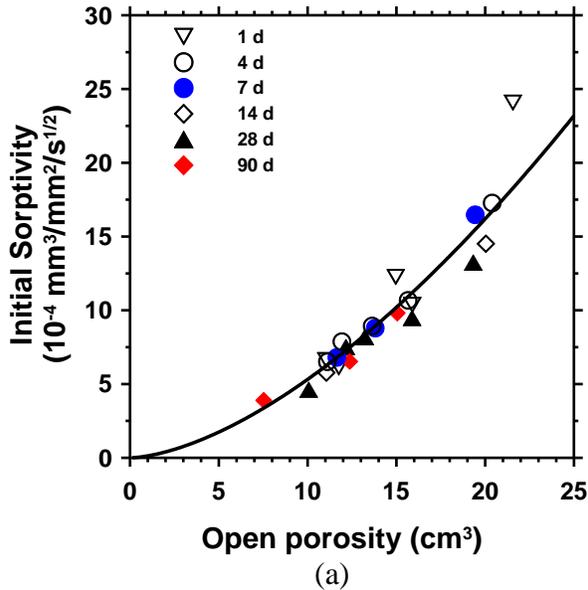
Figure 10 – Relationship between open porosity and (a) initial sorptivity and (b) total absorbed
water after 8 d of sorption test (typical variability in the average of 3 samples is 0.6 10^{-3} g of
water / cm^3 of paste). Solid lines are provided to show a general tendency in the data.

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564 (a) (b)
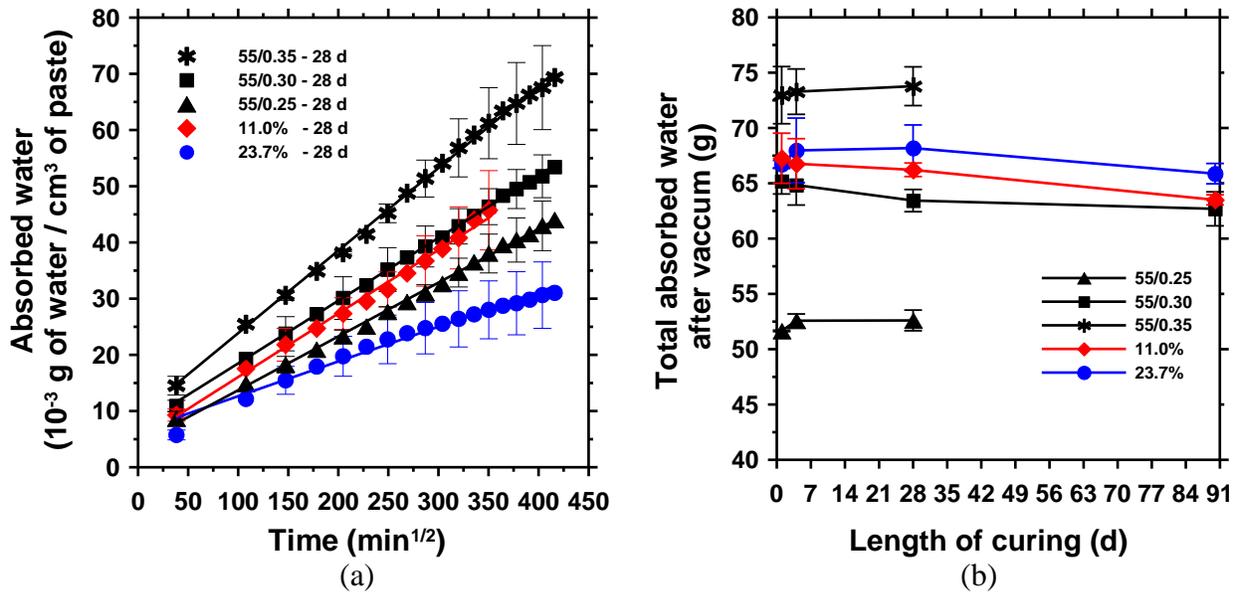
565 Figure 11 – (a) Long term sorption of samples cured for 28 d and (b) the total absorption for the
566 samples after vacuum saturation.

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568 **List of Tables**

569 Table 1 Mixture Proportions

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Material	0.25	0.30	0.35	0.40	55/0.25	55/0.30	55/0.35	11.0%	23.7%
Cement (kg/m^3)	1761	1619	1498	1393	793	728	674	728	728
Water (kg/m^3)	440	486	524	557	198	218	236	218	218
Fine Aggregate (kg/m^3)	0	0	0	0	1418	1418	1418	1135	808
Dry LWA (kg/m^3)	0	0	0	0	0	0	0	172	369
HRWRA (g / 100 g cement)	0.60	0	0	0	0.75	0.50	0.6	0.50	0.66
Additional Water Provided by LWA (kg/m^3)	0	0	0	0	0	0	0	18	39

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