Cement and Concrete Research 39 (2009) 883–892

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Water absorption in internally cured mortar made with water-filled lightweight aggregate

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ARTICLE INFO

Article history:
Received 9 February 2009
Accepted 9 June 2009

Keywords:
Interfacial transition zone
Internal curing
Lightweight aggregate
Sorptivity

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.

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 fine supplementary cementitious materials, (e.g., silica fume). While the fine pore system is beneficial for increased strength [2] and reduced fluid transport [3,4], the finer pore network can lead to increased volumetric changes in sealed systems 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 on 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

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doi:10.1016/j.cemconres.2009.06.009

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-sectional area of the specimen exposed to the fluid using Eq. (1).

$$I = \frac{m_t}{(a \cdot d)} \tag{1}$$

where: I (mm^3/mm^2) is the normalized absorbed water, m_t (g) is the change in specimen mass at time t; a (mm^2) is the area of the specimen exposed to water (i.e., that of the bottom face), and d (g/mm^3) is the density of the water (taken to be 0.001 g/mm^3 at 23 °C).

The absorption measurements are then plotted as a function of the square root of time. The initial sorptivity is the slope of the curve during the first six hours, while secondary sorptivity is the slope of the same measurements between one to eight days as outlined in ASTM C1585 [13].

The initial and secondary sorptivity can be used to evaluate the connectivity of the pore network [15]. Additionally, the secondary sorptivity, combined with exposure conditions, has been used for performing service life predictions [16].

1.2. Background on the effects of internal curing on sorptivity

Low *w*/*c* mixtures undergo self-desiccation, especially in sealed curing conditions. Self-desiccation occurs as a result of chemical shrinkage. During cement hydration, the hydration products occupy a volume that is approximately 10% smaller than the initial reactants [17–19]. This results in the creation of vapor filled voids inside the concrete [20]. These vapor-filled voids grow with increased hydration and penetrate smaller and smaller pores. Lightweight aggregate can be used as a water reservoir to supply water to replenish the water demanded by the hydrating cement paste thereby reducing the vapor-filled voids and therefore mitigating the effects of self-desiccation in low *w*/*c* concrete mixtures. A more thorough description of this process can be found elsewhere [10,21].

The inclusion of SLWA is hypothesized to influence the absorption of water; reasons can be given for either an increase or a decrease in the

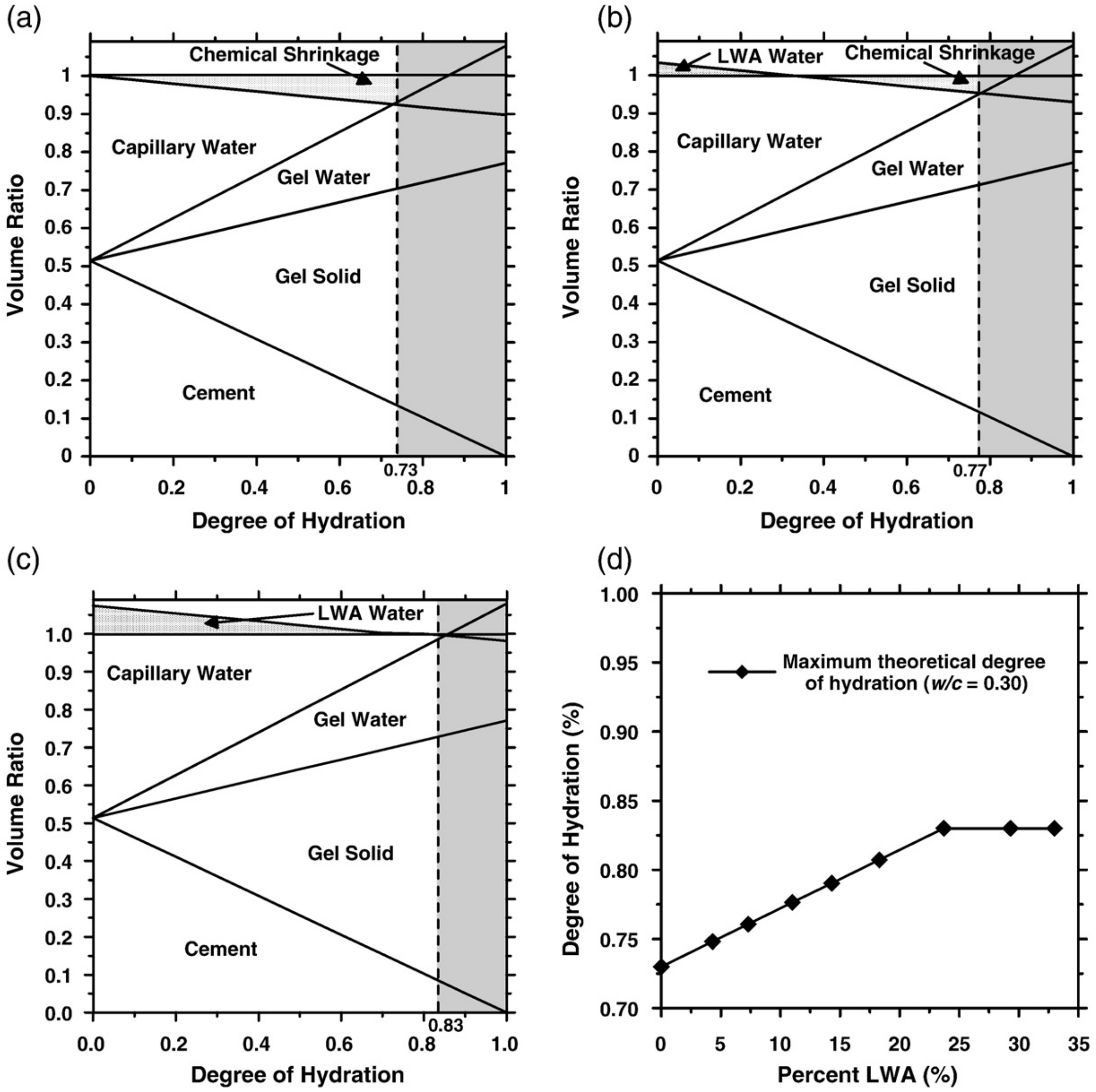

Fig. 1. Powers' model showing phase distributions for (a) *w*/*c* = 0.30 paste (b) 11.0% LWA and (c) 23.7% LWA mixtures. (d) Maximum theoretical degree of hydration as a function of LWA volume.

Table 1
Mixture proportions.

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	0.70	0.60	0.50	0.66
Additional water provided by LWA (kg/m^3)	0	0	0	0	0	0	0	18	39

water absorption. At first glance, one would think that the incorporation of porous inclusions (i.e., LWA) would result in an overall increase in the porosity of the system. The pores in the LWA are large and in the size range of or slightly larger than the largest capillary pores. As a result, the addition of larger pores into the system could result in higher water absorption.

However, alternate reasons exist to explain why a reduction in the water absorption could also occur. When water leaves the LWA, the paste continues to hydrate resulting in a denser microstructure in the paste. This is similar to the supply of extra water from external curing. This concept is shown using Powers' model in Fig. 1(a) for cement paste with a *w*/*c* of 0.30. As the paste hydrates, hydration products are formed. When the water supply is exhausted, hydration ceases. In the case of a paste with a *w*/*c* of 0.30, hydration stops at a degree of hydration of 0.73 for hydration under sealed conditions.

If however, additional water is supplied, hydration can continue. Fig. 1(b) shows Powers' model for a mixture that provides an extra 3.2% volume of water (by total volume) to the system, designated 11.0% in the mixtures to follow (Table 1). The 11.0% indicates the volume fraction occupied by the pre-wetted lightweight fine aggregates in the mortar mixture. Note that this water is not included in the total volume used to calculate the porosity (shown as being greater than 1) since it is not part of the paste pore structure at the time of setting. After approximately 32% hydration, the water in the LWA has been drawn out of the LWA by the hydrating cement paste to fill the voids within the capillary porosity created by chemical shrinkage. During this process, the water from the LWA has resulted in further hydration. The theoretical maximum degree of hydration for this mixture would occur when the system runs out of water at approximately 0.77. A 23.7% LWA mixture provides more water for the cement to hydrate and hydration for the 23.7% mixture is complete at a degree of hydration of 0.83. This is shown in Fig. 1(c). The maximum theoretical degree of hydration increases as the volume replacement increases but comes to a limiting value for an LWA addition of 23.7% (Fig. 1(d)). This is because at that degree of hydration, no pore space remains within the hydrating specimen. It is believed that the water provided does not leave the LWA before set for curing under sealed conditions [9], which explains why the initial paste porosity would be expected to be the same for the paste in these mixtures. The continued hydration that occurs due to the additional water from the LWA results in a denser microstructure that could slow the ingress of water into the system [22].

The last aspect to consider for a reduction in the water absorption is that the ITZs of the normal weight aggregate (NWA) could be percolated across the 3D microstructure, and the inclusion of the LWA could depercolate these ITZ pathways [23,24]. If LWA, with its more dense ITZs [25,26], were added to the system, the NWA ITZs may not be as percolated, resulting in a lower absorption. The effect of different volume replacements of LWA on ITZ percolation was simulated using a hard core/soft shell model developed at the National Institute of Standards and Technology (NIST) [27–29]. This was similar to the method used by Bentz [24] to examine the ingress of chloride ions into mortars with and without internal curing. The aggregate particles (both LWA and NWA) are represented as circular 'hard cores' and the ITZ around the normal weight aggregates only is represented as a surrounding ring or 'soft shell'. The results of simulations for the mortars investigated in this study are shown in Fig. 2. As the replacement volume of LWA increases, the volume of ITZ around the NWA decreases as indicated by the upper curve in Fig. 2 [30]. This implies that as more LWA is used, the less porous ITZ around the LWA results in a reduction in absorption. As more LWA is used, the potential for percolation of the NWA ITZs also dramatically decreases as indicated by the lower curve in Fig. 2. If enough LWA is used, the ITZs of the NWA would depercolate. For these two reasons, it is expected that the absorption of mortars with LWA could be less.

2. Materials

ASTM C150 Type I ordinary Portland cement (OPC) was used in this study, with a Blaine fineness of 370 m^2/kg and an estimated Bogue composition of 56% C_3S, 16% C_2S, 12% C_3A, 7% C_4AF and a Na_2O equivalent of 0.68% by mass.

A polycarboxylate-based high-range water-reducing admixture (HRWRA) was added in varying rates depending on the mixture. For the mortar mixture with a *w*/*c* of 0.25, the HRWRA 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 0.60 g per 100 g of cement. For the mortar mixture with a *w*/*c* of 0.30, the HRWRA was added 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 HRWRA was added at a rate of 0.60 g per 100 g of cement. For LWA mortars, the

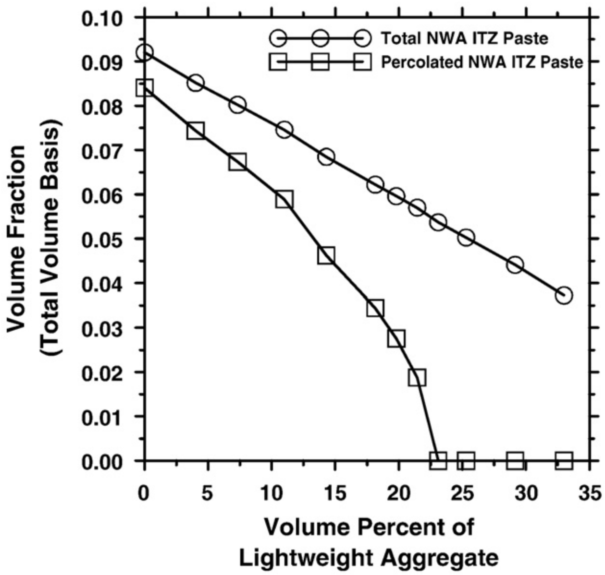

Fig. 2. Volumes of NWA ITZ paste and percolated NWA ITZ paste as a function of replacement volume of LWA.

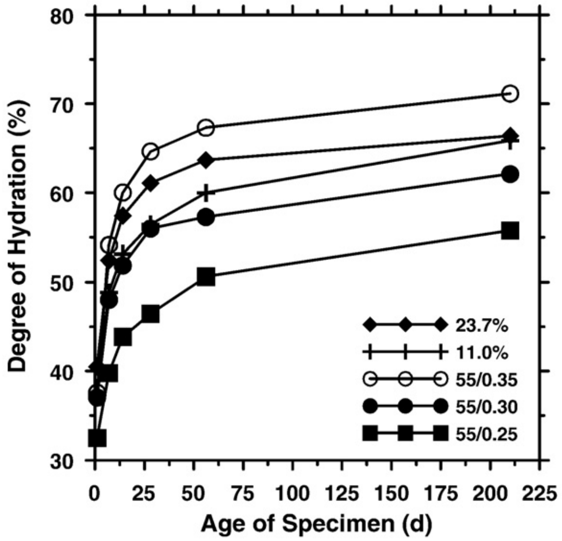

Fig. 3. Degree of hydration as a function of specimen age.

HRWRA was added at rates of 0.50 and 0.66 g per 100 g of cement for the 11.0% and 23.7% mixtures, respectively. Different rates of HRWRA addition were employed to maintain similar consistencies (i.e., workability) of these mixtures.

The normal weight sand used was natural river sand with a fineness modulus of 2.71 and an apparent specific gravity of 2.58. Portions of the normal weight sand were replaced with rotary kilned expanded shale with a fineness modulus of 3.10 and an apparent specific gravity of 1.56 (LWA). The 24-hour absorption of the LWA was determined to be 10.5% according to ASTM 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.

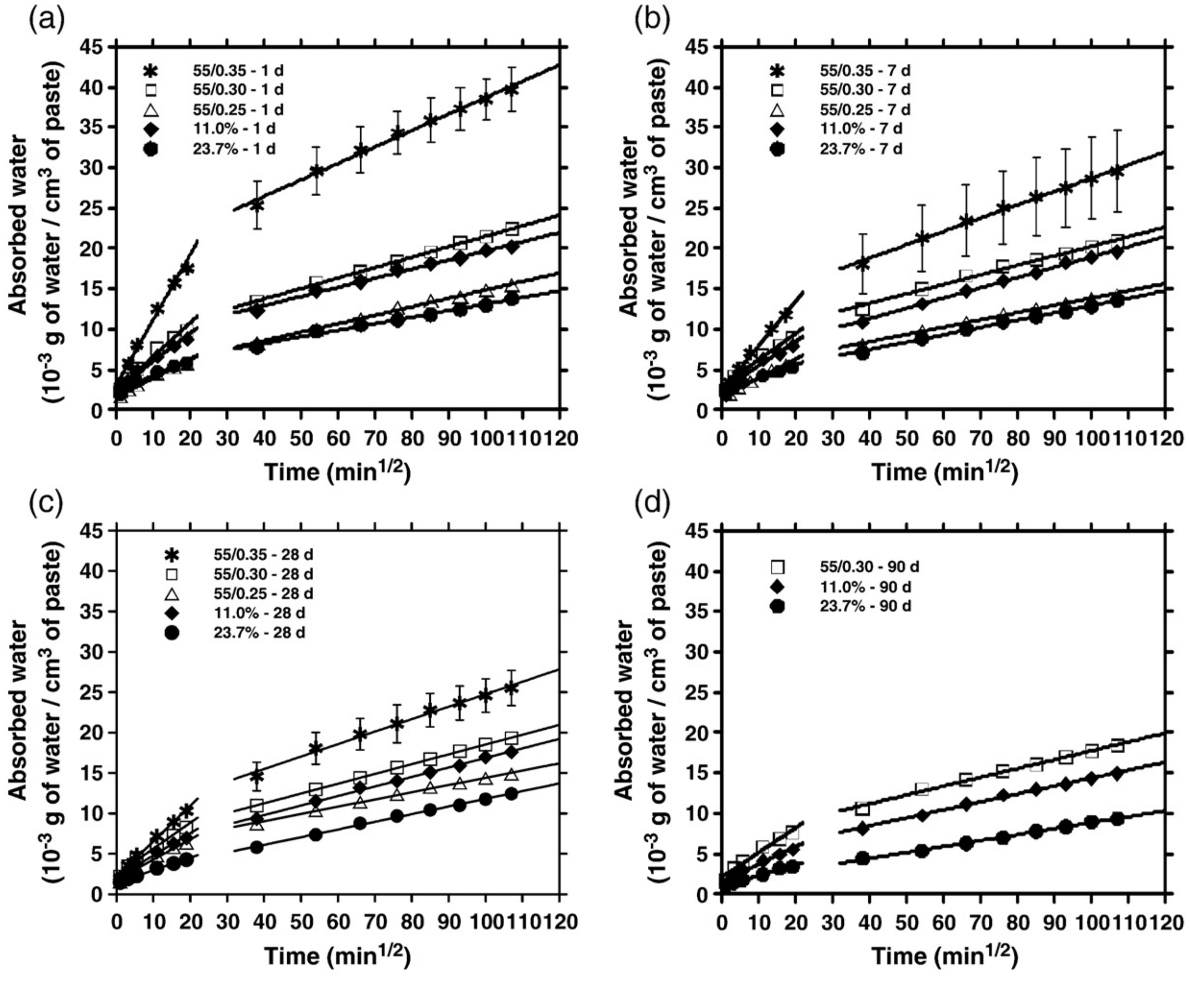

Fig. 4. Sorption test on samples cured for (a) 1 d, (b) 7 d, (c) 28 d, and (d) 90 d. Error bars indicate standard deviation for the three specimens evaluated for each mixture.

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 °C for 24 h. The sample was weighed and then placed in a furnace at 1050 °C 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 kiln 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 in an oven at 50 °C for 3 d. The samples were removed, and then stored in sealed containers for 15 d to allow the moisture to equilibrate within the samples. It should be noted that the 1 d samples were not stored in plastic bags but were placed directly in the desiccators after cutting. Once the samples were removed from the sealed containers, the side surface was sealed with aluminum tape and the top surface was covered with plastic to avoid evaporation from the sample during testing. After the samples were prepared, testing occurred in accordance with ASTM C1585-04 [13].

3.3. Electrical impedance spectroscopy

After the sorptivity measurements were completed (120 d), the conductivity of the samples was measured using electrical impedance spectroscopy (EIS). The samples were vacuum saturated using tap water and weighed. After EIS testing, the samples were oven dried at 105 °C until mass equilibrium was reached (until the difference between two successive 24 h measurements was less than 0.1%). This was done to determine the total volume of water that was in the system after vacuum saturation.

Electrodes were placed on the top and bottom surface of the samples; however contact issues with the samples and electrode existed [35,36]. For this reason, wet sponges were placed between the samples and the electrodes. Two other methods were compared with the wet sponges. The first involved placing conductive silver paint and copper electrodes on the surfaces of the samples before the EIS measurements were taken. The second method involved placing conductive gel [37] on the top and bottom surfaces to which the electrodes were attached. The methods were applied on 3 different samples and similar results were achieved. The wet sponge method was selected instead of the conductive gel or the conductive silver paint because of its simplicity. After a reliable method was determined, all of the samples were tested. The impedance measurements were made over a frequency range from 10 MHz to 10 Hz, using a 500 mV AC signal.

4. Experimental results and discussion

4.1. Effects of internal curing on the degree of hydration

Fig. 3 shows the degree of hydration (DOH) for five of the mixtures tested. As the *w*/*c* increases, the DOH also increases. The 11.0% mixture has a slightly higher DOH than the 55/0.30 mixture. This is likely due to the fact that a small volume of additional water in the LWA is available in the 11.0% mixture. The 23.7% mixture has a higher DOH than the 55/0.30 mixture and it is approaching the DOH of the 55/0.35 mixture. Again, this is due to the extra water provided by the

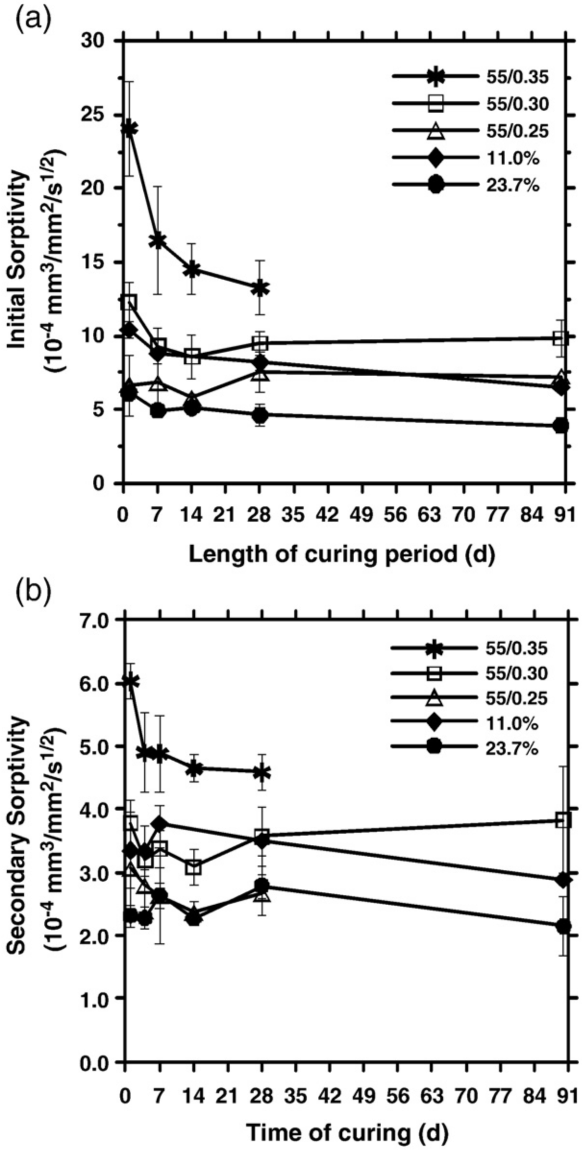

Fig. 5. (a) Initial rate of absorption and (b) secondary rate of absorption for samples cured for different periods.

LWA hydrating more cement. The maximum standard deviation for these measurements was 0.006%.

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

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

For all mixture except the 55/0.35, the typical standard deviation in the average of 3 samples was lower than 2×10^{-3} g of water/cm^3 of paste and it is not included in the plot. For mixture 55/0.35 variability was higher and error bars are included indicating the standard deviation for the three specimens evaluated.

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

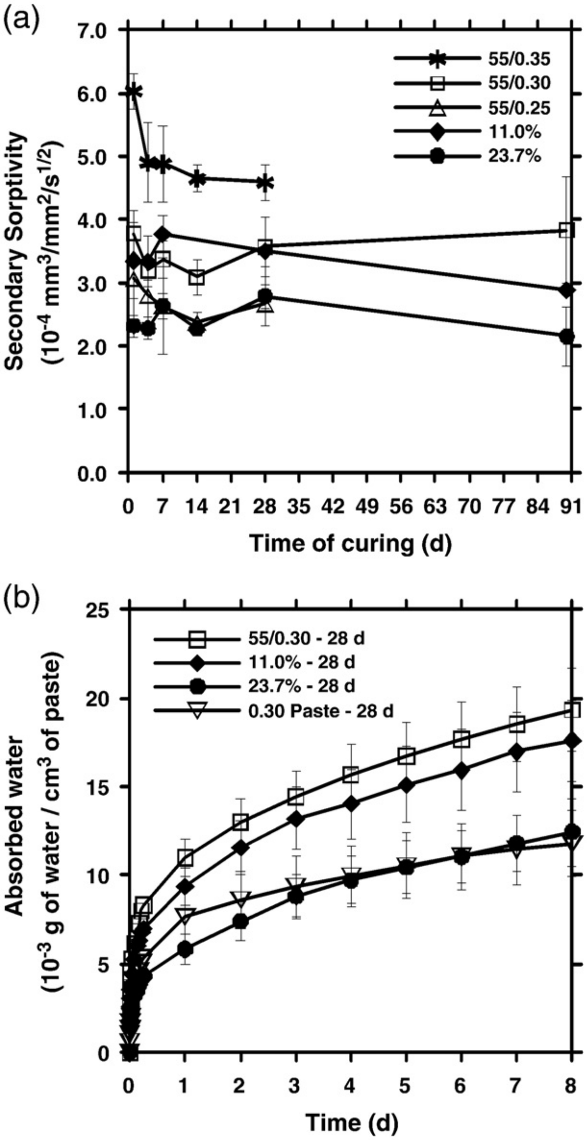

Fig. 6. (a) Cumulated absorbed water at 8 d for samples cured for different periods and (b) absorption water for samples with *w/c* = 0.30 cured for 28 d.

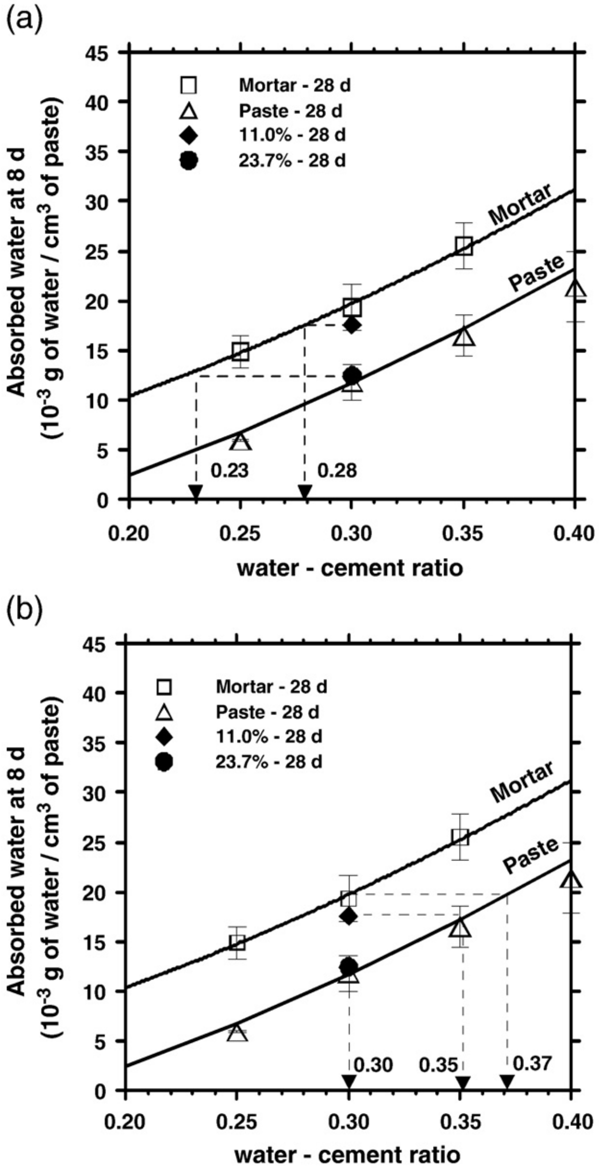

Fig. 7. (a) Mortar equivalent *w/c* and (b) cement paste equivalent *w/c*, both determined from cumulated absorbed water at 8 d on samples cured for 28 d. Solid lines are provided to show a general tendency in the data.

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

Longer curing times reduce the initial sorptivity. However, the main reduction of initial sorptivity in samples containing LWA is achieved during the first week of curing. The 11.0% LWA mixture reaches a

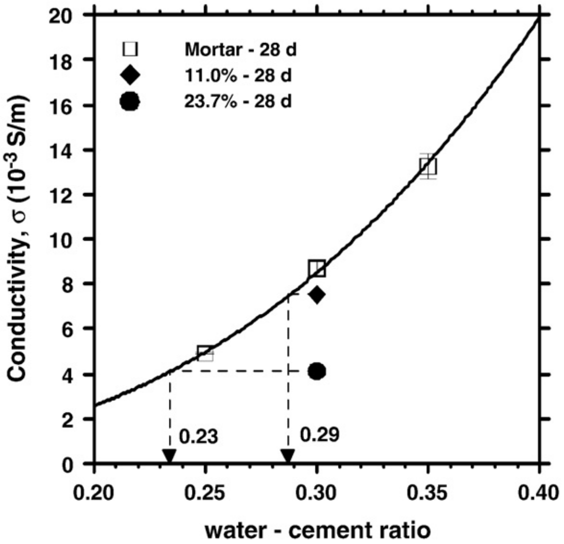

Fig. 8. Mortar equivalent *w/c* determined from electrical conductivity on samples cured for 28 d. Solid line shows a general tendency in the data.

sorptivity that is similar to the 55/0.25 mixture when samples are cured for 90 d. At all ages, the 23.7% LWA mixtures reach lower initial sorptivity values than the 55/0.25 mixtures.

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

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

4.3. Effects of internal curing on the amount of absorbed water during the sorption test

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

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

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

Fig. 7(a) shows the relationship between the amount of absorbed water at 8 d and the *w/c* for samples cured for 28 d. Because of the continued hydration of the LWA mixtures, they exhibit behavior of a conventional mortar with a lower *w/c*. A "mortar equivalent *w/c*" (i.e., the *w/c* of a mortar sample that would exhibit a similar absorption to the absorption in the LWA mixtures) is shown in Fig. 7(a). The 11.0% LWA mortar with $w/c = 0.30$ has a performance similar to a mortar with a *w/c* of 0.28, while the 23.7% LWA mixture exhibits a performance equivalent to a mortar with *w/c* of 0.23.

Fig. 7(b) shows the same data as Fig. 7(a), but now is used to determine a "cement paste equivalent *w/c*". The 55/0.30 mixture has a performance similar to a paste sample with *w/c* of 0.37. The 11.0% LWA mortar has a performance similar to a paste with a *w/c* of 0.35, while the 23.7% LWA mixture exhibits a performance equivalent to a paste with *w/c* of 0.30. In general, a conventional mortar of a specific *w/c* such as 0.30 exhibits a higher absorption per unit volume of paste than an equivalent cement paste, suggesting the porous and well connected ITZs surrounding each NWA are contributing in increased sorption relative to a plain paste where no such ITZs are present.

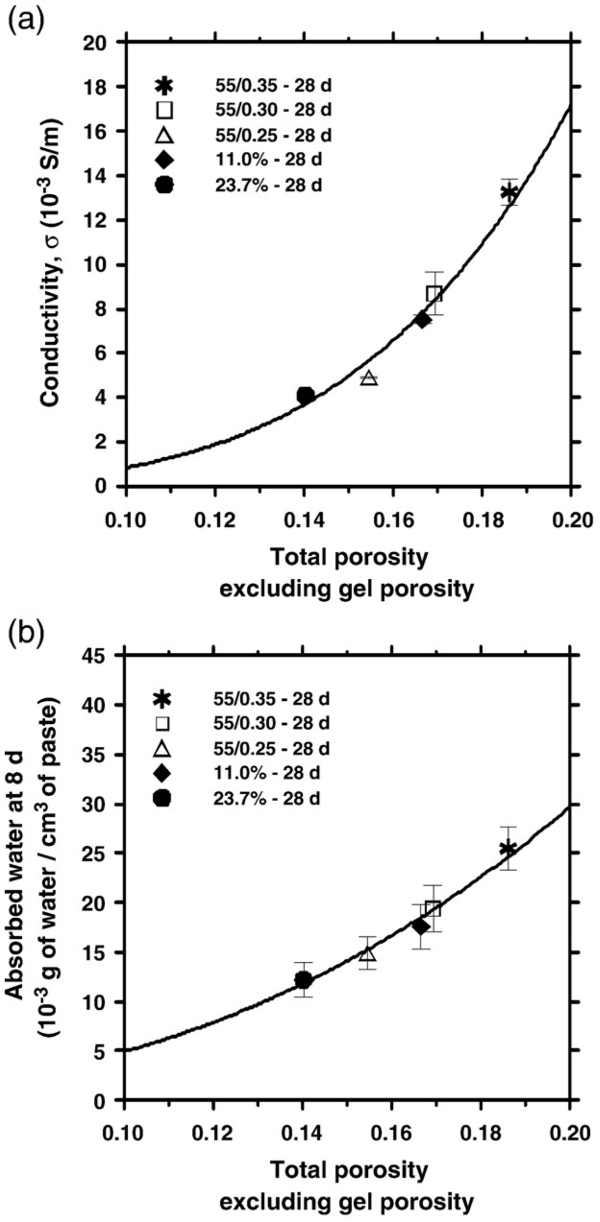

Fig. 9. Porosity as a function of the (a) cumulated absorbed water at 8 d on samples cured for 28 d and (b) conductivity. Solid lines are provided to show a general tendency in the data.

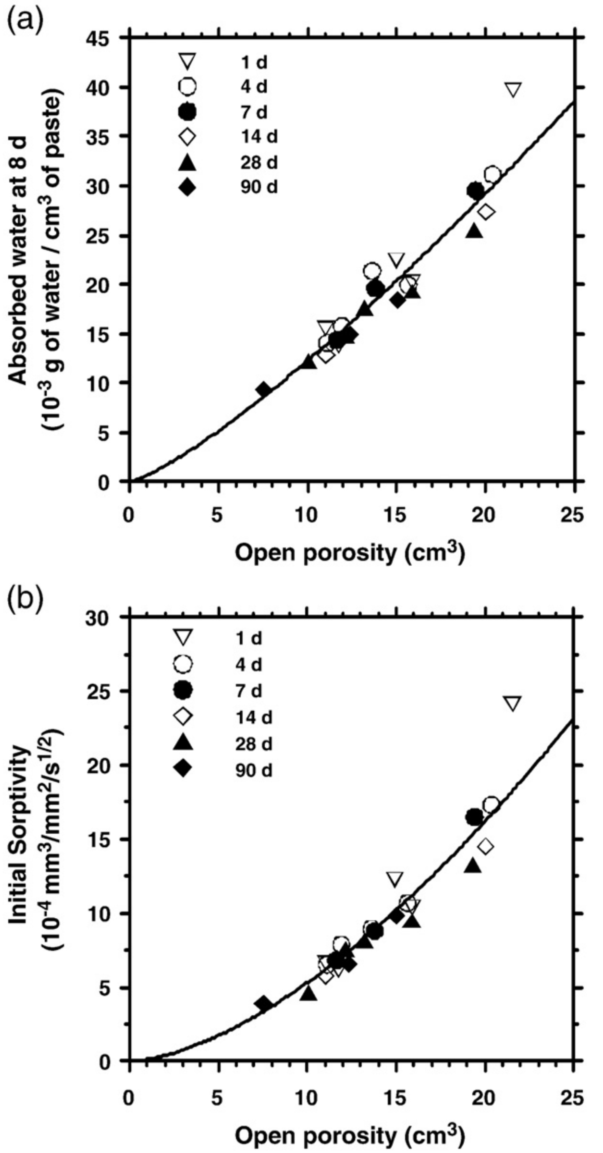

Fig. 10. Relationship between open porosity and (a) initial sorptivity and (b) total absorbed water after 8 d of sorption test (typical variability in the average of 3 samples is 0.6 10^{-3} g of water/cm^3 of paste). Solid lines are provided to show a general tendency in the data.

4.4. Effects of internal curing on electrical conductivity properties

Fig. 8 shows the relationship between the electrical conductivity and the *w*/*c* for samples cured for 28 d. Similar to the results for absorbed water, a "mortar equivalent *w*/*c*" was calculated. The 11.0% LWA mortar has a performance similar to a mortar of a *w*/*c* of 0.29, while the 23.7% LWA mixture exhibits a performance equivalent to a mortar with *w*/*c* of 0.23, consistent with the sorptivity results from Fig. 7(a).

Due to the continued hydration, the porosity of the LWA mixtures will be reduced as compared to the plain mortar mixture. Fig. 9(a) shows the amount of absorbed water at 8 d for the samples cured for 28 d as a function of the porosity (excluding the gel porosity) of the mixtures. The conductivity is also plotted as a function of the porosity in Fig. 9(b), and a similar result is seen. Mixtures with 11.0% and 23.7% LWA have average conductivity reductions of 13% and 53%, respectively. Similar magnitude reductions have been observed for chloride ion diffusivity in mortars containing LWA [24].

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

From a fundamental point of view, sorptivity and absorbed water are directly related to the unsaturated interconnected porosity of the system as this describes the space that is available to be filled with water during the sorption test.

Fig. 10(a) shows the relationship between the open porosity and the initial sorptivity. The open (unsaturated) porosity (i.e., the porosity which can be filled with water during the sorption test) was determined by subtracting the initial water content from the total porosity. The initial water content is considered to be the water that is initially contained in the total porosity at the start of the sorption test. The initial water content was determined by subtracting the oven dry weight at the end of the sorption test from the weight at the beginning of the sorption test, resulting in the volume of water initially in the sample. The total porosity was determined by subtracting the oven dry weight after the sorption

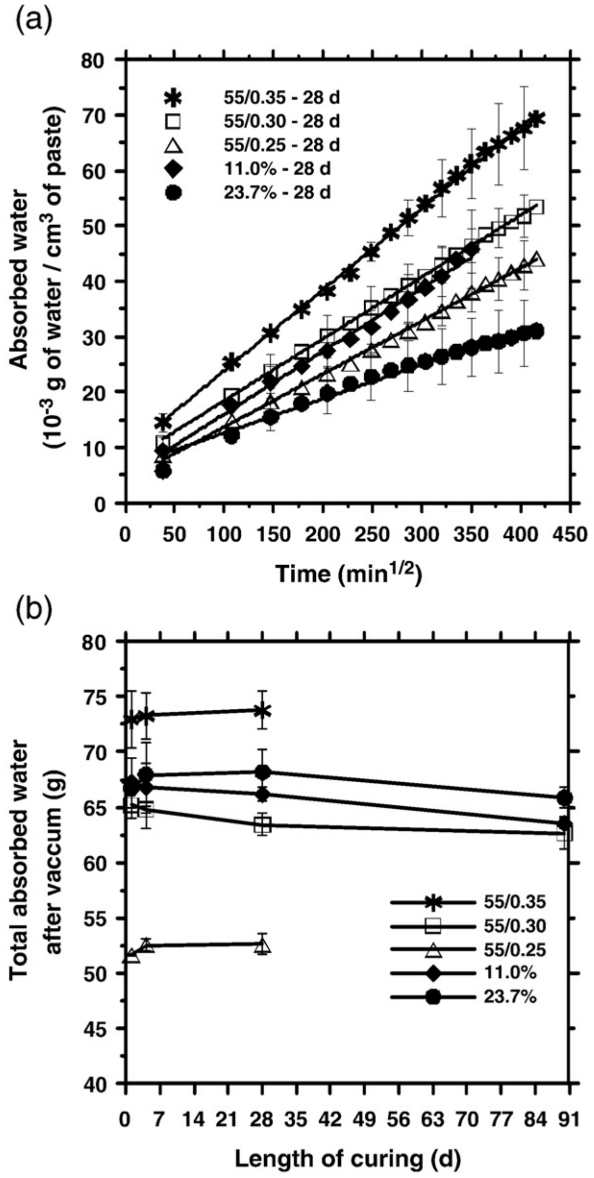

Fig. 11. (a) Long term sorption of samples cured for 28 d and (b) the total absorption for the samples after vacuum saturation.

test from the vacuum saturated weight, resulting in the total volume of water (i.e. the total porosity) in the sample. From Fig. 10(a), it can be seen that the initial sorptivity is a function of the open porosity of the system. Fig. 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 Fig. 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 Fig. 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.
- 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.

Acknowledgements

This work was supported in part by the Joint Transportation Research Program administered by the Indiana Department of Transportation and Purdue University (Project SPR 3211 and SPR 3093). The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the Federal Highway Administration and the Indiana Department of Transportation, nor do the contents constitute a standard, specification, or regulation. The authors gratefully acknowledge support received from the Center for Advanced Cement Based Materials as well as material supplied by Northeast Solite Corporation and Hydraulic Press Brick Company.

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