COMMENTS ON THE SHRINKAGE OF PASTE IN MORTAR CONTAINING SATURATED LIGHTWEIGHT AGGREGATE

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Abstract
Recently, there has been an increase in the desire to use saturated lightweight aggregates (LWA) to reduce shrinkage and shrinkage cracking in low w/c concrete. The use of saturated LWA as a method to provide internal curing involves the partial replacement of normal weight aggregate with saturated LWA. The saturated LWA provides additional water that can replenish the paste to compensate for the effects of self-desiccation. This paper uses Pickett’s model to determine the shrinkage of the cement paste portion of a mortar containing different volumes of saturated LWA. The results of the study indicate that while the inclusion of saturated LWA reduces the stiffness of the mortar, the reduction in shrinkage of the paste due to the supply of additional water is more crucial in reducing the overall shrinkage of the mortar. The size of the pores emptied due to self-desiccation is calculated using results from internal relative humidity measurements and are compared with mercury intrusion porosimetry test data. Similar pore sizes are observed with both methods.

1. INTRODUCTION
Shrinkage in mortar and concrete is a function of the shrinkage of the paste and the restraint provided by non-shrinking aggregate particles. Attempts have been made to model the shrinkage of concrete using two phase or multi-phase models [1, 2]. These models have been used in the past to describe shrinkage in normal weight concrete mixtures [3]. In this paper, the autogenous shrinkage of cement paste is calculated based on the autogenous shrinkage of internally cured mortar specimens that contain saturated LWA using a model developed by Pickett. The overarching goal is to develop tools to describe the shrinkage of the paste when additional water is supplied by the LWA.

2. MEASURING CONCRETE SHRINKAGE

2.1 Mechanism of Internal Curing
The reaction that occurs between cement and water during hydration results in a reduction in volume [4] known as chemical shrinkage. When chemical shrinkage occurs before set, the paste can collapse upon itself without developing a stress. However, after set occurs, the paste cannot collapse resulting in the formation of vapor filled spaces in the pore fluid [5]. This results in a reduction in the bulk volume which is known as autogenous shrinkage. When LWA is added to the system, the water stored in the LWA will be driven by a pressure gradient to leave the LWA and replenish the vapor filled spaces that were created by chemical
shrinkage. This is frequently measured in cement paste as an increase in internal relative humidity and an increase in the critical pore size that remain saturated [6].

2.2 Mixture Proportioning

Four different mixtures were prepared: one plain mortar mixture and three mortar mixtures where a portion of the sand was replaced with saturated LWA. The mixtures with saturated LWA replacement were designated as 7.3%, 14.3% and 25.3%, representing the percent of the total volume of the mixture composed of LWA. It is important to note that though the designations are based on the total volume of the mixture replaced by LWA, the volume of aggregate (LWA and sand) remained constant at 55% since only the sand was replaced with LWA. It should be noted the 25.3% volume replacement corresponds to the volume necessary to eliminate self-desiccation proposed by Bentz [7]. The mixture proportions for each mixture can be found in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Plain</th>
<th>7.3%</th>
<th>14.3%</th>
<th>25.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg/m³)</td>
<td>1228</td>
<td>1228</td>
<td>1228</td>
<td>1228</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>368</td>
<td>368</td>
<td>368</td>
<td>368</td>
</tr>
<tr>
<td>Fine Aggregate (kg/m³)</td>
<td>2390</td>
<td>2072</td>
<td>1755</td>
<td>1360</td>
</tr>
<tr>
<td>LWA (kg/m³)</td>
<td>0</td>
<td>192</td>
<td>384</td>
<td>624</td>
</tr>
<tr>
<td>HRWRA (g/gcem)</td>
<td>0.44</td>
<td>0.44</td>
<td>0.50</td>
<td>0.66</td>
</tr>
<tr>
<td>Additional Water Provided by LWA (mL/gcem)</td>
<td>0</td>
<td>0.016</td>
<td>0.032</td>
<td>0.053</td>
</tr>
<tr>
<td>w/c (without additional water)</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>

2.3 Constituent Materials

ASTM C150 Type I ordinary portland cement (OPC) was used, with a Blaine fineness of 370 m²/kg and an estimated Bogue phase composition of 56% C₃S, 16% C₂S, 12% C₃A, 7% C₄AF and a Na₂O equivalent of 0.68%.

The sand used was natural river sand with a fineness modulus of 3.13. The sand had a modulus of elasticity of approximately 70 MPa and a Poisson’s ratio of 0.25 [8]. Portions of the sand were replaced with manufactured rotary kilned expanded shale (commercially known as Kenlite) with a fineness modulus of 3.10. The 24 hour absorption of the LWA was determined to be 10.5% according to ASTM C128-07. The LWA was assumed to have a modulus of elasticity of approximately 30 MPa and a Poisson’s ratio of 0.22 [9].

2.4 Mixing Procedure

Mixing was performed in accordance with ASTM C192-06. The LWA was oven dried, air cooled, and then submerged in water for 24±1 hours before mixing. The volume of water used to submerge the LWA included both mixing water and the water the LWA would absorb in 24 hours. The mixing water (i.e., the extra water not absorbed in 24 hours) was then decanted and used in the mixing process. The sand was oven-dried and subsequently cooled to room temperature before it was added to the mixture.
2.5 Experimental Procedure

The autogenous deformation was measured using the corrugated tube procedure [10] for a period of seven days. This procedure involved placing fresh mortar or paste (approximately 15 minutes after water is added to the mixture) in a corrugated polyethylene tube. Length changes were measured using LVDT’s [11]. Specimens were placed in a dilatometer (two specimens per mixture) which was maintained in air at 23.0±1.0 °C. The transducers were connected to a PC to acquire automated length measurements every 5 minutes.

Internal relative humidity was measured starting at an age of 12 hours. For each mixture approximately 10 grams of cement paste was crushed and placed in a sealed glass vial. The sealed vial was then kept in an environmental chamber at 23.0 ± 0.1°C. A Digitron 2080R temperature and relative humidity meter was used to record relative humidity and temperature data inside the sealed vial at 2 hours intervals for a period of 7 days.

2.6 Experimental Results of Mortar Mixtures

Autogenous shrinkage measurements for the mortars are shown in Figure 1. These results are similar to those obtained by other researchers [6]. It can be seen that the volume fraction of LWA contained in the mixture has a significant effect on autogenous shrinkage. The plain mixture begins shrinking from the time of set, however the mixture containing 7.3% LWA expands slightly after set before shrinking after approximately 14 hours. The 14.3% mixture shows a much more dramatic expansion for the first day before it begins to shrink after 1 day. The 25.3% mixture expands during the first day and continues to expand (but at a lower rate) for the 7 days it was measured.

![Figure 1](image1.png)

**Figure 1** Autogenous shrinkage measurements for mortar specimens.

The shrinkage behavior of these mixtures can be explained by considering the water that is provided by the LWA. We can begin by examining the chemical shrinkage of the paste with a w/c of 0.30 as shown in Figure 2. As hydration occurs, the volume of the specimen is reduced. The chemical shrinkage denotes the entire volume reduction due to the hydration reaction while autogenous shrinkage denotes just the external volume change. The difference between the curves denotes the volume that would be attributed to the cavitation of vapor filled space.
When saturated LWA is added to the mixture, the cavitation of vapor filled space will cause a pressure difference resulting in water leaving the LWA and filling the voids created by chemical shrinkage. After the water in the LWA is depleted, shrinkage will occur due to the continued creation of void space. For the mixtures containing 7.3% LWA, water in the LWA is depleted at approximately 14 hours, which is when shrinkage begins to occur from Figure 1. The mixture containing 14.3% LWA shows that the water will deplete after the first day, which is approximately the time when shrinkage began. From the chemical shrinkage data, it would be expected that the water from the mixture with 25.3% LWA does not deplete over the 7 day time period.

![Figure 2 Chemical shrinkage and autogenous shrinkage measurements](image)

3. MODELING CONCRETE SHRINKAGE FROM PICKETTS EQUATION

3.1 General Considerations

Pickett [2] derived an expression to describe the shrinkage of mortar or concrete as a function of aggregate stiffness and volume as shown in equation 1:

\[
\varepsilon_c = \varepsilon_p \left(1 - V_{fa}\right)^n
\]  

(1)

where \(\varepsilon_c\) (m/m) is the shrinkage of the concrete/mortar, \(\varepsilon_p\) (m/m) is the shrinkage of the paste, \(V_{fa}\) (m³/m³) is the volume fraction of the aggregate and \(n\) is a parameter that describes the aggregate stiffness. The aggregate stiffness term is defined as:

\[
n = \frac{3(1 - \nu_c)}{1 + \nu_c + 2(1 - 2\nu_a)E_c / E_A}
\]

(2)

where \(\nu_c\) and \(\nu_A\) are the Poisson’s ratio of the concrete/mortar and the aggregate, respectively, and \(E_c\) and \(E_A\) are the elastic modulus of the concrete/mortar and the aggregate, respectively. Equation 2 applies to concrete consisting of one type of aggregate. To account for the replacement of sand with LWA, equation 1 was modified to the following expression:

\[
\varepsilon_c = \varepsilon_p \left(1 - V_{fa}\right)^n \left(1 - V_{LWA}\right)^{m_{LWA}}
\]

(3)
where $V_{FA}$ and $V_{LWA}$ are the volume fractions of sand and LWA, respectively. The aggregate stiffness for the fine aggregate and LWA are $n_{FA}$ and $n_{LWA}$, respectively. Several assumptions had to be made in order to use the expression derived from Pickett [3]:

1. The concrete consists of homogenous materials; paste, fine aggregate and lightweight aggregate.
2. The aggregates and paste behave elastically.
3. Microcracking of the paste does not reduce the stiffness.

Because shrinkage (or expansion) is a paste property, the resulting shrinkage of the paste could be determined by solving equation 3 for $\varepsilon_p$ in terms of the shrinkage of the mortar, the volume fraction of the aggregate and the aggregate stiffness.

### 3.2 Equivalent Paste Shrinkage

Figure 3 shows the equivalent paste shrinkage which was determined using results from the mortar specimens (equation 3). By comparing the experimental and modeling results for the plain mortar and plain paste, it can be noticed that the trend is similar however the experimental value is approximately 80 $\mu\varepsilon$ higher at 7 days. This difference may be due to the slight difference in set time. In addition, this difference may be due to the fact that Pickett’s model does not account for the interfacial transition zone [13], changes in bleed water or microcracking [14]. The model also shows large expansion of the 14.3% and 25.3% pastes.

![Figure 3 Plain paste measurement and modeling results of plain and LWA pastes using Pickett’s Model](image)

**Figure 3** Plain paste measurement and modeling results of plain and LWA pastes using Pickett’s Model

### 4. DESCRIBING SHRINKAGE USING MODIFIED MACKENZIE’S EQUATION

The strain developed in paste can be described using Mackenzie’s equation which was modified by Bentz to account for the degree of saturation [15]:

$$\varepsilon_p = \frac{S}{3} \left(2\gamma \left(\frac{1}{K_p} - \frac{1}{K_s}\right)\right)$$

where $S$ is the degree of saturation, $\gamma$ is the unit weight of the paste, and $K_p$ and $K_s$ are the stiffness of the paste and the mortar, respectively.
where \( S \) (unitless) is the degree of saturation of cement paste, \( K_p \) (Pa) is the bulk modulus of the porous body, \( K_s \) (Pa) is the bulk modulus of the solid skeleton, \( \gamma \) (N/m) is the surface tension of the pore fluid and \( r \) (m) is the critical Kelvin pore radius.

Figure 4a shows the pore size distribution obtained using mercury intrusion porosimetry (MIP) of the plain mortar mixture at 7 days. The pore size of the plain mixture that remains saturated after 7 days is approximately 7.0 nm (as determined from internal relative humidity measurements). The volume of water provided by the LWA (Table 1) would add water to the system causing the critical (i.e., emptied pore) size to increase to 9.6 nm, 11.0 nm and 19.0 nm for the mixtures containing 7.3%, 14.3% and 25.3% LWA, respectively. As expected, the effective pore size depleted due to self-desiccation is larger in a LWA system than in a plain system.

The critical pore radius (i.e., the depleted pore size) can also be obtained from the internal relative humidity measurements using the Kelvin-Laplace equation [16]:

![Figure 4a](image-url)  
Figure 4a Pores size distribution of plain mortar mixture at 7 days.

![Figure 4b](image-url)  
Figure 4b Affected pore size distribution of plain mortar mixture.
\[ r = \left( \frac{2\gamma}{\ln(RH)} \right) \left( \frac{V_m}{RT} \right) \]  

(5)

RH (unit less fraction) is the internal relative humidity, \( V_m \) (m\(^3\)/mol) is the molar volume of the pore solution, \( R \) (J/mol·K) is the universal gas constant and \( T \) (K) is the absolute temperature. The measured RH is a function of the consumption of water due to hydration (Kelvin effect) and the change induced in the activity of the pore solution due to the dissolution of salts (Raoult effect). Raoult’s law can then be used to account for the influence of salts in the pore solution to determine the internal RH purely as a function of water consumption (Kelvin RH), which is slightly higher than the measured RH [3].

The corrected critical pore size determined from the Kelvin-Laplace equation using the Kelvin RH at 7 days was 7.0 nm, 8.4 nm, 9.7 nm and 16.5 nm for the plain, 7.3%, 14.3% and 25.3% LWA mixtures, respectively. The experimental results yield a similar albeit slightly smaller pore radius than those obtained from calculations with the MIP data. A comparison between the measurements from the pore size distribution and the RH measurements (corrected and uncorrected) are detailed in Table 2.

<table>
<thead>
<tr>
<th>% LWA</th>
<th>From Pore Size Distribution</th>
<th>From RH Measurements</th>
<th>From RH Measurements (corrected)</th>
<th>% Reduction of Shrinkage Predicted using eqn 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.0</td>
<td>5.3</td>
<td>7.0</td>
<td>0%</td>
</tr>
<tr>
<td>7.3</td>
<td>9.6</td>
<td>6.5</td>
<td>8.4</td>
<td>27%</td>
</tr>
<tr>
<td>14.3</td>
<td>11.0</td>
<td>7.4</td>
<td>9.7</td>
<td>36%</td>
</tr>
<tr>
<td>25.3</td>
<td>19.0</td>
<td>10.8</td>
<td>16.5</td>
<td>63%</td>
</tr>
</tbody>
</table>

It is evident that if all the other parameters in equation 4 are held constant, while decreasing the radius of the pore size being depleted, the shrinkage increases. Alternatively, if LWA replenishes the pore, the depletion radius will increase resulting in decreased shrinkage. Table 2 shows the shrinkage for each the LWA mixtures as a percent reduction of the shrinkage of the plain paste mixture.

5. SUMMARY

This paper discussed the shrinkage of LWA systems. A summary of the observations are:

- Pickett’s model can be used to obtain the shrinkage of a paste given the shrinkage of the mortar.
- The inclusion of a sufficient volume of saturated LWA can significantly reduce autogenous shrinkage. Though the inclusion of LWA alters the stiffness of the mortars, this effect is less significant than the impact of the release of water from the LWA.
- The inclusion of saturated LWA will supply water to the paste to increase the effective pore radius that is emptied by self-desiccation, resulting in reduced shrinkage.
- While Mackenzie’s modified equation describes the trend in shrinkage, it does not describe the expansion that is observed in the mortars.
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REFERENCES