Experimental investigation of the fire resistance of ultra-lightweight foam concrete

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Abstract

The general response of the ultra-lightweight foam concrete under fire is investigated in this paper. Different formulae of fillers have been investigated to obtain the required lightweight concrete densities and mechanical properties, using diverse components, such as a plasticizer, lightweight aggregates, foaming agents, and mineral admixtures. It was shown that the behavior of ultra-lightweight concrete in fire depends on its mix proportions and constituents. Based on the results, the fire resistance and thermal conductivity increase as the density of the concrete increases. The fire resistance of ultra-lightweight concrete with the density of 400 kg/m³ was more than three times higher than the samples with the density of 150 kg/m³. The thermal conductivity increases approximately 2.6 times by increasing the density from 150 kg/m³ to 500 kg/m³. It is recommended that ultra-lightweight concretes should be designed with a density greater than 250 kg/m³, to have sufficient fire resistance.

Keywords Fire resistance - Foam concrete Thermal conductivity Ultra lightweight.
1 Introduction

In the industrialized world, new and modern materials have become common in today’s construction industry. These new materials are lightweight, energy efficient, aesthetically attractive and efficiently handled and erected. Lightweight concrete has been used in industrial buildings as precast panels (Peng et al., 2011). To achieve adequate features, researchers have used various components and additives within concrete mixtures (Kim et al., 2010). Lightweight concrete can be produced by different methods, e.g. by using only fine aggregate and introducing air voids into concrete structures with chemical admixtures and mechanical foaming (Othuman and Wang, 2011). This type of concrete is known as aerated or foam concrete. There are other production methods, but the most popular way to make lightweight concrete is to add natural lightweight or artificial aggregates.

A foam concrete composition consists of only a cement matrix (called a paste) or a cement and sand matrix (mortar) with homogeneous voids, which can be created by introducing small air bubbles. Introduction of air voids into concrete is carried out mechanically by foaming agents which are mixed with water. Many factors can affect the production of stable foam concrete, such as the foam preparation system, the foaming agent, the concrete mixture design, and the procedure for mixing foam concrete (Hossain and Lachemi, 2007). Some by-products, such as fly ash have been added to reduce the cost, improve workability of the mix, reduce heat of hydration, and increase the long term strength.

Lightweight concrete can be classified into three groups based on their use and physical properties: for structural use, for both structural/insulating purpose, and for insulating. Structural lightweight concrete normally contains lightweight aggregates, such as shales, clays, slates, expanded slag, expanded fly ash, and natural porous volcanic stones. Structural/insulating dual purpose concrete may incorporate air contents and structural lightweight aggregates, or they may be produced with both structural and insulating lightweight aggregates. Lightweight insulating concretes are very light, but not appropriate for structural use, as reported by Wang and Tang (2012). Other authors (see e.g. Parhizkar et al., 2012) classify lightweight concretes based on their properties, as shown in Table 1, and a full spectrum of lightweight concretes is available in Figure 1.

Although numerous investigations have been made on investigating the fire resistance of lightweight concrete (e.g. Oka et al., 2011; Al-Sibahy and Edwards, 2012; Go et al., 2012; Koksal et al., 2012), to date, there are only a few studies available about ultra-lightweight concrete. The current research is focused on characterization of the fire resistance of insulating concretes, as they have sufficient strength, low densities and better thermal insulation.
2 Materials and methods

Several mixtures of ultra-lightweight concrete were prepared at different densities by using Expanded Polystyrene beads (EPS) and foam concrete. To obtain each density, the quantity of EPS beads was varied in the EPS concrete mixes to reduce the concrete density of a lightweight concrete from initially 700 kg/m$^3$ to the required target densities as low as 150 kg/m$^3$.

Ordinary Portland Cement (OPC) was used for all the ultra-lightweight and foam concrete mixtures. The chemical composition of the cement and fly ash (FA), which were obtained from Golden Bay Cement Company, are given in Table 2. The lightweight aggregate for ultra-lightweight concrete used in this study consisted of EPS beads of 1 mm diameter. A superplasticizer Sikament HE200 was used only for ultra-lightweight concrete of a density lower than 250 kg/m$^3$, at 5 ml of plasticizer per kg of cement. The super plasticizer was used to improve the workability of the ultra-lightweight concrete (ULWC). Table 3 shows the mix proportions for foam concretes at four different densities.
Table 2. Chemical composition of mineral admixture.

<table>
<thead>
<tr>
<th>Composition [%]</th>
<th>OPC</th>
<th>FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide (SiO$_2$)</td>
<td>22.8</td>
<td>40.1</td>
</tr>
<tr>
<td>Aluminum oxide (Al$_2$O$_3$)</td>
<td>4.2</td>
<td>20.4</td>
</tr>
<tr>
<td>Iron oxide (Fe$_2$O$_3$)</td>
<td>2.3</td>
<td>10.1</td>
</tr>
<tr>
<td>Calcium oxide (CaO)</td>
<td>64.8</td>
<td>19</td>
</tr>
<tr>
<td>Magnesium oxide (MgO)</td>
<td>1.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Sodium oxide (Na$_2$O)</td>
<td>0.19</td>
<td>2.1</td>
</tr>
<tr>
<td>Potassium oxide (K$_2$O)</td>
<td>0.49</td>
<td>0.5</td>
</tr>
<tr>
<td>Sulfur trioxide (SO$_3$)</td>
<td>0.42</td>
<td>0.8</td>
</tr>
<tr>
<td>Titanium dioxide (TiO$_2$)</td>
<td>-</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 3. Mix Proportions.

<table>
<thead>
<tr>
<th>No</th>
<th>Target Density [kg/m$^3$]</th>
<th>Cement [kg/m$^3$]</th>
<th>Ash [kg/m$^3$]</th>
<th>Water [l]</th>
<th>Foam, [kg/m$^3$]</th>
<th>EPS [kg/m$^3$]</th>
<th>Superplasticizers [ml/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULWC1</td>
<td>400</td>
<td>248.50</td>
<td>124.25</td>
<td>20.11</td>
<td>7.28</td>
<td></td>
<td>757.45</td>
</tr>
<tr>
<td>ULWC2</td>
<td>250</td>
<td>151.49</td>
<td>75.75</td>
<td>12.24</td>
<td>10.93</td>
<td></td>
<td>594.15</td>
</tr>
<tr>
<td>ULWC3</td>
<td>200</td>
<td>118.83</td>
<td>59.41</td>
<td>9.62</td>
<td>12.14</td>
<td></td>
<td>432.16</td>
</tr>
<tr>
<td>ULWC4</td>
<td>150</td>
<td>86.43</td>
<td>43.22</td>
<td>6.98</td>
<td>13.36</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The foam concrete was obtained by mixing cement, water, and foam in a mortar mixer. The foam was prepared with a foam generator at a density of 56 kg/m$^3$. The Portland Cement and water were mixed for 5 minutes. Finally, the foam was added to the mortar, followed by an additional 2 minutes of mixing. To prepare the foam, Ultrafoam was used as the foaming agent and Quick Gel as the viscosifier. These were mixed with water in the foam generator, until the foam bubble size was uniform and stable (usually 2 minutes). Then, the foam was added to the cement matrix while under stir, with continual mixing for 1 to 2 minutes. When the mix of foam and the cement matrix was uniform, the prepared foam concrete was poured into the test mold with slight vibrations to fill up the mold completely.

Under standard conditions, specimens were demoulded after 24 hours and then moist cured in a standard curing room for a further 28 days, in order to test the samples with a standard testing machine. Ultra-lightweight concrete samples were prepared at densities of 500, 400, 250, 200, and 150 kg/m$^3$. After 7 days, a small scale sandwich panel with a square footprint of 100 mm$^2$ was placed on top of a heating unit, as shown in Figures 2 and 3.
The EPS-foam concrete sample was perforated to insert four thermocouple scions into the sample. A square galvanized steel sheet (305 mm² and 0.55 mm thick) was placed on top of the heating unit. This steel sheet represents the opposite side of the sandwich panel. An EPS-foam concrete sample was placed on the square galvanized steel sheet. A thin steel mold was placed on the square galvanized steel sheet and separated from this device with four pieces of heat resistant fibers. The thermocouples were inserted into the center of the foam concrete sample in a vertical line and the steel mold was filled with insulating fibers around the foam concrete block. Thermocouples were connected to a four thermocouple data loggers outside the heating unit.
The heating unit was turned on and the ceramic elements were set to reach the maximum temperature of 900 °C. An insulation failure criterion was applied to the fire tests (Won et al., 2011). The small scale sandwich panels were considered to have failed when the cold face temperature had reached 160 °C, which occurred when thermocouple T4 reached the threshold value of 160°C. Every 5 seconds the temperature was recorded with a thermometer. The temperature of thermocouples T1, T2, and T3 were simultaneously recorded. Thus, a chart (time versus temperature profiles) was created to collect experimental data in order to analyse the results.

Foam concrete has excellent thermal insulating properties derived from its microcellular structure. A thermal conductivity range of 0.06–0.16 W/mK can be obtained for foam concretes of 200–650 kg/m³ densities (Ramamurthy et al., 2009). Thermal conductivity coefficients k can reach 0.06–0.064 W/mK for lighter concretes of 150–170 kg/m³ with cement composites and EPS granules as components (Laukaitis et al., 2005).

Three conductivity samples of a size of 200×200×40 mm were prepared with ultra-lightweight concrete of 500 and 150 kg/m³ densities. A thermal conductivity analyzer (Anacon TCA-8) was used for k-factor measurements of the insulation samples. The measurements were made with a sample contacting a 10cm diameter hot and cold plate, maintained at 37 °C and 10 °C respectively. The Anacon TCA-8 thermal conductivity analyzer maintains a fixed temperature difference across a sample by controlled hot and cold plate temperatures. A heat-flow transducer produces a signal proportional to the heat passing through the sample. The TCA-8 automatically measures the thickness of the sample and combines the reading with the heat-flow measurement to yield a direct digital readout of thermal conductivity. The tests were run and k-values were determined during the period while k-values were being stabilised. During the test, the k-values changed until they eventually maintained a consistent reading value.

3 Results and discussions

Aerated concrete is incombustible and has excellent fire resistance properties as compared to normal weight concrete. Fire resistance tests on different densities of foam concrete indicated that the fire endurance is enhanced with reductions in density. As mentioned in previous section, four small scale sandwich panels filled with ultra-lightweight concrete were prepared at densities of 150, 200, 250 and 400 kg/m³. After 7 days, each sample was placed on top of a heating unit. The heating unit was turned on and set to reach 900 °C. An insulation failure criterion was applied to the fire tests. The small scale sandwich panels were considered to have
failed when the cold face temperature had reached 160 °C, which occurred when thermocouple T4 reached the threshold value of 160°C. The test was run until thermocouple T4 reached the threshold value of >160°C.

Every 5 seconds the temperature was recorded with a thermocouple datalogger, and the temperature of thermocouples T1, T2, and T3 were simultaneously recorded. Thus, a chart (time versus temperature profiles) was created to display experimental data for data analysis. The fire test results are shown in Figures 4-10. The insulation failure criterion value of >160 °C was reached after 60 minutes for the ULWC sample of 150 kg/m³. ULWC had completely disintegrated, as shown in Figure 5. After 17 minutes, a small amount of smoke was observed. This became abundant after 36 minutes, and then began to diminish 20 minutes later.

It was observed that the threshold value of > 160 °C was reached after 1h 41m for the ULWC sample of 200 kg/m³ density (Figure 6). The ULWC-200 sample had almost disintegrated and provided no strength to touching anymore. This sample is shown in Figure 7. The insulation threshold value of > 160 °C was reached after 1h 56m for the ULWC sample of 250 kg/m³ density (Figure 8). The ULWC sample had partially disintegrated, as shown in Figure 9. After 1 h 55m a small amount of smoke was produced. It was necessary to stop the test after 3 hours because the heating elements were running at maximum power and continuing for more than 3 hours can damage them. The insulation threshold value > 160 °C was not reached after 3 hours for the ULWC sample of 400 kg/m³ density (Figure 10).

![Figure 4. Time-temperature curve ULWC 150 [kg/m³].](image-url)
Figure 5. ULWC of 150 [kg/m$^3$] after test.

Figure 6. Time-temperature curve ULWC 200 [kg/m$^3$].
Figure 7. ULWC of 200 [kg/m$^3$] after test.

Figure 8. Time-temperature curve ULWC 250 [kg/m$^3$].
The results from this investigation indicate that the percentage of cement is a significant parameter for the fire resistance properties. For the small scale sandwich panels from 150 kg/m$^3$ to 400 kg/m$^3$ the fire resistance improved from failure at 60 minutes with 150 kg/m$^3$ to no failure after 3 hours with 400 kg/m$^3$. This means that the fire resistance for 400 kg/m$^3$ was more than 3 times higher than the samples of 150 kg/m$^3$. In addition, the fire
resistance was 68% and 93% higher for samples with 200 and 250 kg/m$^3$ density respectively, when comparing with samples of 150 kg/m$^3$ density.

Three conductivity samples of 200×200×40 mm were prepared with ultra-lightweight concrete of 150 and 500 kg/m$^3$ densities. One of two samples of ULWC of 150 kg/m$^3$ was prepared with a thin layer of plaster on the contact surface. The experiment was designed to analyze the effect of roughness of the contact surfaces on thermal properties. A thermal conductivity analyzer (Anacon TCA-8) was used for k-factor measurements of the insulation samples. The test was run and k-values were determined after they stabilized. The thermal conductivity results are shown in Table 4. The results show that the ULWC sample of 150 kg/m$^3$ density covered with plaster obtained better k values than the ULWC 150 kg/m$^3$ sample without plaster. Density of ULWC is a significant parameter for thermal conductivity. The results showed that for the 500 kg/m$^3$ sample, the thermal conductivity was approximately 2.6 times higher than for samples of 150 kg/m$^3$.

![Table 4. Thermal conductivity results.

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Thermal Conductivity [W/m.K]</th>
<th>Density [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULWC-150-Plaster</td>
<td>0.0724</td>
<td>150</td>
</tr>
<tr>
<td>ULWC-150</td>
<td>0.0848</td>
<td>150</td>
</tr>
<tr>
<td>ULWC-500</td>
<td>0.1930</td>
<td>500</td>
</tr>
</tbody>
</table>

4 Conclusions

The fire resistance and thermal conductivity of ultra-lightweight foam concrete with different densities were investigated in this paper. Several mixtures of ultra-lightweight concrete were prepared with five different densities by using Expanded Polystyrene beads and foam concrete. Precautions must be taken when preparing foam concrete to prevent differences between casting densities of lightweight foam concrete and target densities. When mixing variables such as the foam preparation system, the kind of foaming agent, foam concrete mix preparation, the percentage of additives, and the duration of the mixing process affect the cast densities. The results from this investigation indicate that ultra-lightweight concrete based on EPS beads is an excellent potential infill material for wall panels. It is recommended that these infill materials should be designed with a density greater than 250 kg/m$^3$, as the insulation failure criterion (160°C) applied during the fire tests indicated sufficient fire resistance compared with less dense lightweight concretes. An innovative ultra-lightweight concrete was also developed at 150 kg/m$^3$ density. Foam concrete and EPS beads were
mixed to reduce the density of the concrete to the lowest possible value. This novel ultra-lightweight concrete could be also a potential filler material for wall systems, if some precautions are taken to reduce the fire risk.

References


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