Effect of geometry in concrete spalling risk subjected to high temperatures for thermal inertia studies

T. Lucio-Martín¹, J. Puentes¹ & M.C. Alonso¹,*
¹ Eduardo Torroja Institute for Construction Sciences (IETcc-CSIC), Madrid, Spain
* Corresponding author (mcalonso@ietcc.csic.es, Serrano Galvache 4, CP: 28033, Madrid, Spain)

ABSTRACT

Several studies have demonstrated the feasibility of using concrete as a thermal energy storage material. An experimental procedure must be established during the concrete mix design to validate its performance when subjected to high temperature (up to 600ºC) in order to extend the service life. The initial cement paste dehydration is considered to be the most critical part of the start-up of the concrete, due to the high probability of spalling. In addition, the material after this stage starts to be following heating and cooling cycles between 290 and 550ºC.

The aim is to evaluate the thermal inertia of the concrete in order to minimise the risk of spalling in the dehydration stage of the concrete, as well as the damage evolution in the successive thermal fatigue cycles. A small-scale experimental study has been carried out using a Self-compacting concrete (SCC) thermally designed for energy storage in concrete. Specimens of different geometries were made to assess the behaviour against several factors: heating rate, thermal gradient, sample geometry and crack formation.

For this purpose, three different sizes and geometries of SCC samples have been manufactured. The temperature gradient has been monitored during the test at different depths. Results indicate that the geometry determines the heating rates within the material and hence, the risk of spalling. Not only thermal gradients affected the spalling, but it also was influenced by the time of exposure. On the other hand, the long-term performance of the concrete mix was proved to be used as suitable for thermal storage because of its low degradation propagation after exposure of concrete to thermal fatigue cycles.

KEYWORDS: High temperature, thermal gradient, self-compacting concrete, spalling

INTRODUCTION

The behaviour of concrete exposed to high temperatures has been studied for a long time from the point of view of the material in the presence of fire. However, in recent years, new applications in energy infrastructures have consolidated their own line of research. The use of concrete as thermal energy storage in concentrated solar power plants (CSP) has been verified recently [1-3]. The highest concern in relation to this type of use of concrete is the thermal stability of the concrete when exposed to heat charge and discharge.

From the point of view of the development of high temperature concrete design, several alternatives have allowed a better performance. The use of polypropylene fibres (PPF) [2, 4], thermal stable and low expansion aggregates and its size distribution in the mix [2] has been proved useful to have a better performance. Concrete spalling risk is one of a major case of
failure of concrete when exposed to high temperature and fire. Different authors have related the concrete spalling with the specimen dimensions [5-6] but the geometry effect is not clear yet and needs to go for deeper study.

One of the riskiest factors, when concrete is exposed to high temperature in a CSP, is the spalling. The first heating, when the concrete undergoes dehydration, is fundamental in the operation of the elements used for energy storage in CSP. The maximum temperature of use is limited up to 600ºC [2] and it is considered the most critical stage. Besides the further thermal stability of the concrete element under heat cycles is critical and no much experience exist [1, 3].

In order to go deeper, this study investigates both the first heating and the thermal fatigue cycles for concrete designed to resist high temperature, to be suitable for thermal storage up to 550ºC. The present paper studies the effect of geometry in the risk of spalling during the dehydration of concrete and the thermal gradients owing to the heating process. Moreover, the thermal stability of concrete exposed to fatigue thermal cycles has been studied through the crack evolution.

**EXPERIMENTAL PROCEDURE**

**Material and production of samples**

Concrete was fabricated using CEM II containing 30% of micro blast furnace slag. This binder was blended with fly ash class F up to 20%. Calcareous and basalt aggregates (0-6 and 6-12 mm) were selected as considered to have good thermal stability up to the maximum temperature (550ºC). Also, clinker as aggregate (0-5.6 mm size) was added. Finally, limestone filler was included to achieve the self-compacting ability to produce the concrete. Table 1 shows the concrete composition and Table 2 summarizes mechanical properties at fresh and hardened conditions.

**Table 1** Concrete composition

<table>
<thead>
<tr>
<th>Component</th>
<th>C-1 mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM II/B-S 52.5 R (kg/m³)</td>
<td>319</td>
</tr>
<tr>
<td>Fly Ash (kg/m³) / %bcm</td>
<td>130/20</td>
</tr>
<tr>
<td>Limestone Filler (kg/m³)</td>
<td>157</td>
</tr>
<tr>
<td>Calcareous (0-6mm) (kg/m³)</td>
<td>465</td>
</tr>
<tr>
<td>Basalt (0-6mm) (kg/m³)</td>
<td>212</td>
</tr>
<tr>
<td>Clinker (0-5.6mm) (kg/m³)</td>
<td>191</td>
</tr>
<tr>
<td>Calcareous (6-12 mm) (kg/m³)</td>
<td>531</td>
</tr>
<tr>
<td>Basalt (6-12 mm) (kg/m³)</td>
<td>315</td>
</tr>
<tr>
<td>Superplasticizer additive 1</td>
<td>1</td>
</tr>
<tr>
<td>Superplasticizer additive 2</td>
<td>1.2</td>
</tr>
<tr>
<td>Viscosity modifier additive</td>
<td>0.9</td>
</tr>
<tr>
<td>w/b</td>
<td>0.39</td>
</tr>
</tbody>
</table>

**Table 2** Mechanical properties of fresh and hardened concrete

<table>
<thead>
<tr>
<th>Fresh properties</th>
<th>Hardened properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-ring SFJ (mm)</td>
<td>SF1-520</td>
</tr>
<tr>
<td>J-ring t500J (s)</td>
<td>21</td>
</tr>
<tr>
<td>J-ring Final PJ (mm)</td>
<td>20</td>
</tr>
<tr>
<td>Air content %</td>
<td>2.5</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2400</td>
</tr>
<tr>
<td>Open porosity (%)</td>
<td>4.51</td>
</tr>
<tr>
<td>f&lt;sub&gt;a&lt;/sub&gt; 7 days (MPa)</td>
<td>66.1</td>
</tr>
<tr>
<td>f&lt;sub&gt;a&lt;/sub&gt; 28 days (MPa)</td>
<td>84.5</td>
</tr>
<tr>
<td>MIP porosity (%)</td>
<td>6.61</td>
</tr>
</tbody>
</table>

The influence of heat on spalling has been analysed in one concrete mix varying the type of...
geometry and size of the element: cylindrical (Ø 75 mm x H 150 mm), cubic (150 x 150 x 150 mm$^3$), and prismatic (150 x 150 x 400 mm$^3$). The samples had K-type thermocouples embedded. Figure 1 shows the samples and thermocouples embedded in each specimen, and Table 3 specifies the location of thermocouples with respect to the reference system shown in Figure 1.

Figure 1  Geometries and thermocouples located inside the concrete samples

Table 3  Location of thermocouples

<table>
<thead>
<tr>
<th>Geometry</th>
<th>ID</th>
<th>Coordinates (mm)</th>
<th>Geometry</th>
<th>ID</th>
<th>Coordinates (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylindrical</td>
<td>T1</td>
<td>0 37.5 75</td>
<td>Prismatic</td>
<td>T6</td>
<td>75 50 50</td>
</tr>
<tr>
<td>Cubic</td>
<td>T2</td>
<td>30 30 75</td>
<td></td>
<td>T7</td>
<td>75 115 50</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>120 30 75</td>
<td></td>
<td>T8</td>
<td>75 75 200</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>120 120 75</td>
<td></td>
<td>T9</td>
<td>75 50 350</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>30 120 75</td>
<td></td>
<td>T10</td>
<td>75 115 350</td>
</tr>
</tbody>
</table>

Before starting the thermal test, samples were stored in a humidity chamber at 20ºC and 98% of relative humidity (RH). At the time of testing, the samples had an age varying between 28 and 90 days, as it is shown in Table 4. The variables under study were: the effect of geometry in spalling risk, the thermal fatigue and thermal cracking. The sample geometry, dimensions, and the surface (S), the volume (V) and the S/V ratio are included in Table 4.

Table 4  Specimen characteristics and the relationship between shape, size and volume

<table>
<thead>
<tr>
<th>Test</th>
<th>Curing Conditions</th>
<th>Ageing (days)</th>
<th>Shape</th>
<th>Dimensions (mm)</th>
<th>S/V (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of geometry in spalling risk</td>
<td>20ºC/98%RH</td>
<td>≈ 28</td>
<td>Cylindrical</td>
<td>75x150</td>
<td>66.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≈ 90</td>
<td>Cubic</td>
<td>150x150x150</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≈ 28</td>
<td>Prismatic</td>
<td>150x150x400</td>
<td>31.67</td>
</tr>
<tr>
<td>Thermal fatigue effect</td>
<td></td>
<td>≈ 28</td>
<td>Cylindrical</td>
<td>75x150</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≈ 90</td>
<td>Cubic</td>
<td>150x150x150</td>
<td>-</td>
</tr>
<tr>
<td>Thermal cracking</td>
<td></td>
<td>≈ 28</td>
<td>Cylindrical</td>
<td>75x25</td>
<td>-</td>
</tr>
</tbody>
</table>

Thermal test

Before starting the thermal tests, samples were dried inside the furnace at 105ºC for 3 days to reduce the free water from the pores. After that, the thermal test was launched. Two stages are under consideration in the study:

- **Dehydration stage (25-550ºC):** During the first heating, the dehydration of cement paste takes place liberating vapour. During this stage, the risk of spalling is higher
mainly because of two aspects: i) The thermal gradients generated between the heated surfaces and the core of the samples, which induce high thermal stresses. ii) The accumulation of vapour in the bulk of the concrete limiting the vapour to be released and generating high pressures in the bulk [5, 7-9]. For these reasons, the first heating stage must be slow (1°C/min) in order to decrease the risk of spalling. Once the concrete has been dehydrated, the risk of spalling decreases and the following thermal cycles are performed at higher heating rates simulating daily charge and discharge heat processes of a real case.

- **Thermal fatigue stage (290°C to 550°C)**: The second stage began after dehydration and consists of performing cycles between 290-550°C since it will be the operating regime of the concrete in the application studied. In this stage, the heating rate was 8°C/min. The plateaus at constant temperature (290 and 550°C) have been considered to last 2 hours to guarantee stabilisation of the bulk of the concrete sample at each heat cycle level. It was repeated a number of thermal cycles to evaluate the thermal fatigue effect.

The different heating regimes is summarised in Figure 2.

![Thermal fatigue test](image)

**Thermal cracking**

The microcracking generation due to heating was studied in cylinders of Ø 75 mm x H 25 mm, to quantify the effect of thermal fatigue on durability performance. Cracking development and propagation was studied after 1, 25 and 75 thermal fatigue cycles. Pictures were taken in several regions of the sample by using an optical microscope Nikon SMZ-2T. The crack-mappings were obtained through analysis of digital images by using open software GIMP. With these mappings, it was possible to establish the percentage of cracks per area. Moreover, the maximum crack width was determined by measuring ten times and the result is the mean value for every thermal cycle.

**RESULTS AND DISCUSSION**

**The risk of spalling during dehydration stage**

- **Thermal gradients**

The first to be analysed regarding the spalling risk at high temperature is the dehydration stage. Figure 3 shows the evolution of temperature recorded by thermocouples located inside the specimens and in the furnace during the first heating from room temperature up to
550°C. According to geometry, cylindrical and cubic specimens adapted fast to temperature changes following almost the same heating rate of the furnace as shown in Figure 3. This is mainly due to the smaller specimen size, which means that heat reaches the geometrical centre of the specimen earlier and vapour evacuate also easily. Moreover, smaller specimen sizes mean a higher amount of air inside the furnace, which improves the convection heat transfer mechanism between the furnace and the samples.

Regarding thermal gradients, the difference in temperature inside the concrete sample was higher in the cubic and lower in the cylindrical. Thermocouples T2, T3, T4 and T5 distanced 30 mm from the heated surface recorded almost the same temperature than T1 located 37.5 mm from the heated surface. This is explained because of the “corner effect” that makes the heat cross more slowly through the sample before arriving at the geometrical centre of the specimen. Taking into account that the temperature in the centre of the cubic sample was not recorded, this critical point would have experienced higher thermal gradients because of the distance from the heat source and the corner effect. The furnace heating rate was fixed in 1°C/min but the real heating rate inside the samples was 0.9°C/min for both specimens.

Figure 3  
First dehydration stage: CYLINDRICAL and CUBIC samples

- **Spalling risk**

The risk of spalling in relation to the sample geometry is appreciated in Figure 4. The evolution of temperature is recorded with the thermocouples in the prismatic sample. During the first 5 hours of testing, the thermal gradients between the furnace and the internal part of the sample increased achieving more than 100°C of difference. Thermocouple T8 recorded the highest difference because it distanced 75 mm to the heated surfaces, and this location was the critical point of the specimen. When the furnace was at 400°C the sample underwent spalling. At this time, T8 was at 250°C and the difference of temperature was 150°C in 75 mm. This generated high thermal stresses within the concrete and the material underwent spalling, as it is shown in Figure 5. In spite of having the same cross-section than the cubic sample, the thermal gradients were bigger in the prismatic one. Therefore, thermal gradients are not only influenced by the distance from the heat source but also for the geometry.
Effect of geometry in spalling risk

Analysing the three geometries of samples with the same concrete, Figure 6 shows the evolution of temperature inside the three geometries during the dehydration stage up to 550°C. Moreover, Table 5 quantifies the difference of temperature between the furnace and the thermocouple T1 (cylindrical), T4 (cubic) and T8 for the prismatic. The heating rate of the heat source (furnace) was fixed in 1°C/min but the real heating rate inside the samples was 0.9°C/min for the cylindrical and cubic and 0.6 for the prismatic geometry, determined from the temperature evolution over time in the core of the specimens. This is owing to internal stresses, which increase the risk of spalling when the sample size is increased. For that reason, the geometry and dimensions of the specimens should be considered when carrying out the dehydration process before starting the high temperature test.

Several authors have evaluated the section size effect on concrete spalling. For the same concrete mix and heating rate (1°C/min), a reduction of size by 50-75% eliminated the risk of spalling [10]. Kanéma et al. [5] also analysed the effect of size and observed that spalling happened only in large samples despite undergoing the same thermal gradients than the small
ones. Liu et al. [6] give the explanation that smaller samples facilitate the escape of moisture out of the concrete and this induces lower pore pressure. In the present study, the thermal gradients were higher in the prismatic specimen (Table 5) and the spalling happened after being exposed to high thermal gradients for a long time (6 hours).

On the other hand, thermal gradients were bigger in the first heating instants because of thermal inertia, Table 5. At those moments, the furnace was being heated but the core of the material needed time to receive the heat. After that, thermal gradients decreased in both the cylindrical and cubic specimens whereas the prismatic sample continued increasing with the time of exposure, Figure 6.

In order to reduce the spalling risk during the first heating in case of concrete for CSP heat storage, the geometry must be taken into account. The spalling risk might be avoided by doing the first heating by steps and remain at plateaus of constant temperature until the core reaches a homogeneous temperature. Doing that, the thermal gradients would be reduced and, hence, the risk of spalling too. An additional contingency is the incorporation of PPF.

\( \begin{align*}
\text{Figure 6} & \quad \text{First dehydration stage for all geometries} \\
\begin{array}{c}
\text{Table 5} \\
\text{Thermal gradients between the furnace and the core of the specimens} \\
\end{array}
\end{align*} \)

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Thermal gradient, ( \Delta T ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Furnace</td>
</tr>
<tr>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
</tr>
<tr>
<td>4.5</td>
<td>335</td>
</tr>
<tr>
<td>6</td>
<td>428.5</td>
</tr>
<tr>
<td>7.5</td>
<td>531</td>
</tr>
<tr>
<td>Heating rate (°C/min)</td>
<td>1</td>
</tr>
</tbody>
</table>

Thermal fatigue of concrete during heat charge/discharge cycles

- **Thermal gradients**

The second stage analysed was the thermal fatigue in the cylindrical and the cubic samples
when temperature ranges between 290-550ºC. Figure 7 shows the evolution of the temperature of the furnace and the thermocouples embedded inside the samples. The cylindrical specimen reached the maximum temperature (550ºC) and the minimum (290ºC) in less than 2 hours. This indicates that the concrete reaches the proposed temperature range and the material remains an approximate period of 1.5 hours at a constant temperature, either at 550ºC or at 290ºC. On the contrary, the cubic specimen did not reach the set temperatures. It has been verified that the cube would need 2.67 hours to reach 550ºC in the thermocouples, but more time would be needed to reach the maximum temperature in the geometric centre. The same happened when cooling down the cubic sample to 290ºC. Again, the sample needed 3.5 hours to reach the lowest temperature. This cooling time was even longer than the heating time owing to the thermal inertia related to the mass and hence to the S/V ratio. So, the influence of geometry in thermal gradients has been identified.

**Figure 7**  Thermal fatigue response for cubic and cylindrical specimens

![Thermal fatigue response for cubic and cylindrical specimens](image)

- **Crack evolution**
  The patterns of cracks were obtained for cylindrical samples and some examples are shown in Figure 8. Before the thermal cycles, the cement paste in the concrete between the aggregates shows a structure with no cracks and good interface between the aggregate and the cement paste. After thermal cycles, the cracks followed mainly the cement paste and the interface aggregate-paste owing to the change in volume of aggregates because of expansion at high temperatures and the cement paste shrinkage.

**Figure 8**  Crack pattern after 1, 25 and 75 thermal cycles

<table>
<thead>
<tr>
<th>N</th>
<th>Crack pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>![Crack pattern image]</td>
</tr>
</tbody>
</table>
Figure 9-left shows the percentage of cracks and what is remarkable is the maintenance of the parameter after 25 and 75 thermal cycles. This gives information on long-term durability because the concrete subjected to high temperature thermal cycles would operate adequately for the application of thermal energy storage. Figure 9-right shows the maximum width of the cracks and once again, no great variability was found after the cycles.

Figure 9  Percentage of cracks (left) and crack width (right) after thermal cycles

CONCLUSIONS

The present study has led to the following conclusions:

- The sample geometry and size influence on the thermal gradients generated in the concrete. Higher specimen size generated higher thermal gradients that resulted in spalling failure for the same concrete type.