Spalling Properties of Hybrid Fibre-Reinforced High Strength Concrete at Elevated Temperatures

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Introduction

Historically, the fire performance of concrete has often been taken for granted considering its non-combustible nature and ability to function as a thermal barrier, preventing heat and fire spread. Concrete has a low thermal conductivity (50 times lower than steel) and therefore heats up very slowly in a fire. It is the low thermal conductivity that provides good inherent fire resistance of concrete structures. With time however, advancement in concrete technology has led to the manufacture of High Strength Concrete (HSC) which outperforms conventional concrete in almost all aspects with the exception of when it is exposed to fire. Fire accidents which have occurred involving infrastructures have shown that high strength concrete performance is highly susceptible to high temperature condition. Thermal instability in form of spalling has been observed which leads to breaking-off of layers or pieces of concrete from the thermally exposed surface and this significantly compromises the structural integrity of the concrete structures [1, 2]. Thus the material behavior of high strength concrete under fire exposition needs to be clearly understood since it greatly impacts on structural integrity and load-bearing capacity of structural elements.

Since the undoubted benefits of HSC in terms of high strength and durability renders it very desirable to use in future constructions, improving its fire performance is critical due to its increased usage in high rise buildings and tunnel structures. Therefore, understanding the basic mechanisms behind the spalling behavior of HSC and the ability of polypropylene fibres to prevent spalling as well as the capacity of steel fibres to maintain mechanical properties during and after exposure to high temperatures is critical to the design and construction of safe and durable structures.

The present experimental study aims at improving the performance of high strength concrete during exposure to high temperature through mitigation of spalling and development of a better understanding of the mechanisms of pressure development and relief inside heated concrete. Also, improvement of the residual mechanical properties of high strength concrete after heat exposure has been studied.

Experimental Methodology

Materials and Mix Proportions

Concrete series were prepared using OPC (Ordinary Portland Cement) and crushed stone with the maximum nominal size of 13 mm. W/C of 0.5 was used for Normal Strength Concrete (NSC) while W/C of 0.3 was used for High Strength Concrete (HSC) series. Some parameters of the mix proportion were kept constant for all series: water content of 170 kg/m$^3$ and sand to aggregate ratio (s/a) of 50%. Addition of polypropylene (PP) monofilament fibres, polyvinyl alcohol (PVA) fibres, and a combination of PP or PVA with steel fibres i.e. hybrid fibres was the main differentiation of the series. Two types of steel fibres were used in this experimental study and the fibre properties are as shown in Table 1. A polycarboxylate ether superplasticiser was used at a dosage of 0.9 % of cement content to achieve the desired workability. Concrete mix proportions of all series cast are shown in Table 2. The convention for naming different series according to fibre type, fibre length and fibre diameter was used. For example HY PP 6-18 is explained as follows: HY means its hybrid concrete containing steel and organic fibres, PP 6-18 mean the organic fibre added is polypropylene (PP) with length of 6 mm and diameter of 18 µm (0.018 mm).

Cast specimens included cylindrical specimens of 100 mm in diameter by 200 mm in height for strength tests, 175 mm in diameter by 100 mm in height for pore pressure tests and beam specimens of 400 × 100 × 100 mm (length × width × depth) for the flexural tests. After casting, the specimens were covered with wet burlap under polyvinyl sheet. After 24 hours, the specimens were demolded and cured under lime-saturated water at temperature of 20 ± 2°C for 28 days for strength tests. Pore pressure specimens were also cured under the same conditions for about 3 and 6 months in order to achieve a homogenous moisture state. The initial moisture content of beam specimens was between 4 and 5 % while that of pore pressure specimens was between 6 and 7.5 % by mass.
Experimental Set-Up for Pore Pressure

All specimens tested during the pore pressure measurement experiment were 175 mm in diameter and 100 mm in height. Thermal load was applied on one face of the concrete specimen by means of a computer-controlled radiant heater placed 10 mm above the specimen as shown in Figure 1. The heater of power 500 watts exposes the whole surface of the specimen and generates maximum temperature of up to 600°C. Ceramic fibre was used to heat-insulate the lateral faces of the specimens to ensure quasi-unidirectional thermal load upon it. For all concrete series studied, two specimens were tested for each series and if the results were different and inconsistent, then more specimens were tested in order to obtain consistent results.

Figure 1. During pore pressure test

Three heating patterns were applied in this experimental study. In the first pattern, a slow heating rate (5°C/min), the specimen is set under the heating device and temperature increased gradually at a rate of 5°C/min until it reaches the maximum temperature of 600°C. Then this maximum temperature is maintained for 3 hours. In the second pattern, a moderate heating rate (10°C/min), the specimen is set under the heating device and temperature increased gradually at a rate of 10°C/min until it reaches the maximum temperature of 600°C. Then this maximum temperature is maintained for 3 hours. In the third pattern, a relatively fast heating rate which is though slower than the ISO 834 fire curve, was conducted by thermally shocking the specimen after the heating device has reached the designated maximum temperature of 800°C. The specimen was exposed to the maximum temperature of 800°C lasting for 4 hours.

During the study of the effect of measuring technique on pore pressure, all specimens were instrumented with three different pressure gauges that allow pore pressure measurements using three different measurement techniques. The first technique involved gauges made of a disk of porous sintered metal (Ø 12 mm×4mm) with evenly distributed pores of diameter 2 µm which was encapsulated into a metal cup that was brazed to a metal tube with an inner diameter of 1.5 mm. The second technique consisted of a metal cup that is brazed to a metal tube but without a porous sintered metal. The third technique consisted of just a metal tube without both the metal cup and a porous sintered metal. The three different gauges are shown in Figure 2. All three different gauges used for studying the measurement techniques were instrumented in the same specimen at the same depth of 30 mm from the heated face using Plain concrete and the free end of the tube then stuck out at the rear face of the specimen. The free end of the tube is then carefully connected to the pressure transducers which in turn are connected to the data logger. Prior to setting up of the experiment and heating, one set of specimens was filled with silicon oil having a flash point of 315°C and a thermal expansion of 0.00095 cc/cc°C while the others were left empty in order to clarify the effect of a medium used in the pipe to transform pressure to the outside on pore pressure measured. Thus, silicon oil and air are two types of media used in the study of effect of a measuring system on pore pressure. K-type of thermocouples of diameter 0.65 mm having a covering material of glass fibre were placed on the heated surface of the specimen to measure and monitor the build-up of temperature.

During all other pressure measurement studies, all specimens were instrumented with the same type of pressure gauges as described in the first technique of the study of the effect of measuring technique on pore pressure. The three similar gauges were placed within the central zone of the specimen at 10, 30 and 50 mm depths respectively, from the heated face and K-type of thermocouples were attached on the sides of the gauges which were used to measure the temperature inside the heated specimens.

Figure 2. Different pressure gauges

Experimental Set-Up for a Blowtorch Spalling Test

Prism specimens in form of 90x150x550 mm were prepared and un-cut faces of 90x150 mm were exposed to the flame with the thermal load characterized by a very steep temperature increase during the first minutes of the fire.
The spalling test was set up as shown in Figure 3 with the nozzle positioned 30 mm from the surface of the concrete specimen. The flame of an average heating rate of about 200°C/min was aimed at the centre of the specimen in order to achieve uniform distribution of the heat on the specimen. The surface temperature rise was continuously observed using an infra-red thermometer at a distance of about 5 metres away from the experiment because of the dangerous nature of explosive spalling of some concrete specimens. A timer was used to record roughly the time from when spalling began to occur until when it ended. The test was ended once the surface temperature of the heated face of the specimen exceeded 700 °C since no further spalling was expected after that.

**Experimental Set-Up for Furnace Spalling Test**

Prism specimens of size 90×150×150 mm were tested for spalling in a furnace, and an ISO 834 heating pattern was applied in the furnace for one hour after which the specimens were left to cool naturally. The furnace experimental set-up is shown in Figure 4.

**Results and Discussions**

**Effect of Silicon Oil and a Sintered Metal**

As shown in Figure 5(a), it was clearly observed that specimens with gauges filled with silicon oil measured higher pore pressures compared to when the pressure gauges were left empty (filled with air) as shown in Figure 5(b). A maximum pressure of 4.36 MPa was measured for the specimen filled with oil compared to maximum pressure of 3.62 MPa in the specimen whose gauges were left empty.

Also as shown in Figures 5(a) and 5(b), higher pore pressures were measured when using pressure gauges comprising of a cup with a sintered metal compared to both the tube and when no sintered metal is used. It is thought that pressure gauges comprising of a cup with sintered metal measure higher pressures compared to others gauges probably because the sintered metal is able to collect moisture vapour in an evenly manner since it contains an even pore distribution leading to very stable measurements.

**Table 1. Characteristics of fibres**

<table>
<thead>
<tr>
<th></th>
<th>PP</th>
<th>PVA</th>
<th>Steel (S13)</th>
<th>Steel (S30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (µm)</td>
<td>18, 28</td>
<td>16, 40</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>6, 12</td>
<td>6</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>Shape</td>
<td>Filament</td>
<td>Filament</td>
<td>Straight</td>
<td>Indent</td>
</tr>
<tr>
<td>Density (gr/cm³)</td>
<td>0.9</td>
<td>1.3</td>
<td>7.8</td>
<td>7.8</td>
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<tr>
<td>T&lt;sub&gt;melt&lt;/sub&gt; (°C)</td>
<td>160-170</td>
<td>200-230</td>
<td>1370</td>
<td>1370</td>
</tr>
<tr>
<td>T&lt;sub&gt;vaporize&lt;/sub&gt; (°C)</td>
<td>341</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 2. Mixture proportions**

<table>
<thead>
<tr>
<th>Series</th>
<th>W/C (%)</th>
<th>s/a (%)</th>
<th>Fiber vol. (%)</th>
<th>W</th>
<th>C</th>
<th>S</th>
<th>G</th>
<th>SPAE*1 (%xC)</th>
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</thead>
<tbody>
<tr>
<td>Plain NSC</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td>340</td>
<td>893</td>
<td>867</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plain HSC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>340</td>
<td>893</td>
<td>867</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP 6-18</td>
<td>30</td>
<td>50</td>
<td>0.1</td>
<td>170</td>
<td>567</td>
<td>795</td>
<td>771</td>
<td>0.9</td>
</tr>
<tr>
<td>PP 12-18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP 12-28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVA 6-16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PVA 6-40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HY(PP 6-18)</td>
<td>0.4</td>
<td>0.1</td>
<td></td>
<td>788</td>
<td>764</td>
<td></td>
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<tr>
<td>HY(PVA 6-40)</td>
<td>0.4</td>
<td>0.1</td>
<td></td>
<td>788</td>
<td>764</td>
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</tr>
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</table>

SPAE*1: Super plasticizer and air entraining agent
Figure 4. Set-up of a furnace spalling test

Figure 5. Pressure rise with time in heated specimen

Furthermore, it is thought that using the tube is an unstable technique since the potential risk of disturbance of the system is higher e.g. a piece of coarse aggregate blocking the entire measuring point of the tube where as the pressure gauge comprising of a cup with a sintered metal will easily compensate for such a risk due to the larger diameter of a sintered metal.

Therefore silicon oil and a sintered metal are important parts of the pore pressure measurement technique to be used since they greatly contributes to the effectiveness of the measuring system when carrying out pore pressure measurements in heated concrete.

**Effect of Heating Rate**

PP concrete series under slow and fast heating rates are shown in Figures 6(a) and 6(b) respectively. It was observed that pore pressure near the surface of concrete at a depth of 10 mm from the heated surface was nearly the same for both slow and fast heating rates at 0.3 and 0.35 MPa respectively. However, it was observed that in deeper regions of concrete at a depth of 50 mm from the heated surface, a fast heating rate leads to a much higher pore pressure of 2 MPa which is more than twice that of a slow heating rate at 0.9 MPa. This clearly showed that a fast heating rate leads to higher pore pressures in the deeper regions of concrete compared to a slow heating rate. Pore pressures near the surface being nearly the same for both heating rates is attributed to surface cracking of concrete which was observed on concrete specimens exposed to a fast heating rate which resulted in high amounts of water vapour escaping outside the specimen and thus a low build-up in pore pressure near the surface compared to deeper regions of concrete under a fast heating rate.

**Influence of Fibre Type and Geometry**

Pressure rise with respect to time inside concrete containing PP fibres of varying lengths and diameters is shown in Figure 7. A comparison between Figure 7(a) showing concrete containing PP 6-18 (length 6 mm and diameter of 18 µm) and Figure 7(b) containing PP 12-18 (length 12 mm and diameter of 18 µm) was carried out. The main difference between the two PP fibres is the length where by PP 6-18 has a shorter length of 6 mm compared to PP 12-18 with a length of 12 mm. It was observed that higher maximum pore pressures were measured for PP 6-18 than PP 12-18 at all depths of concrete. This shows that longer PP fibres are more effective in mitigating pressure rise inside concrete compared to shorter ones. Furthermore, a comparison between PP 12-18 and PP 12-28 as shown in Figures 7(b) and 7(c) respectively, whose main differentiation is the diameter, showed lower maximum pore pressures for PP 12-18 than PP 12-28 at all depths of concrete. This simply means that smaller diameter PP fibres are more effective compared to bigger diameter fibres in mitigating pressure rise inside heated concrete. It is believed that longer lengths provided better interconnectivity of the fibres than the shorter ones which resulted in a well connected network of spaces inside concrete during heating. Then, smaller diameter will lead to an increased total length of fibres and their total surface area per unit volume compared to larger diameters. Thus total length of fibres and their total surface area per unit volume, which are affected by the
diameter, are one of the most important parameters which affect the effectiveness of organic fibres in pore pressure rise mitigation inside heated HSC.

Pressure rise with respect to time inside concrete when incorporating PP and PVA fibres, is shown in Figure 7(a) and Figure 8 respectively. Pressures measured inside PP concrete are relatively low with a maximum pressure of 1.1 MPa at a depth of 50 mm. However, pressures inside PVA concrete are higher with a maximum pressure of 1.5 MPa at a depth of 30 mm. This shows that PP fibres are more effective in mitigating pressure rise inside heated concrete. Thus the type of organic fibres in relation to its bonding properties with concrete could play some role in mitigating pressure rise and hence consequently mitigating the possibility of spalling inside heated concrete.

![Graph showing pressure rise with temperature in PP concrete](image)

**Figure 6.** Pressure rise with temperature in PP concrete

**Comparison between Furnace and Blowtorch Tests**

A similar spalling behavior was encountered in Plain HSC for both furnace and blowtorch tests. However, in fibre reinforced HSC series, spalling was only observed during the blowtorch test and no spalling was encountered in the furnace test. This clearly shows that the blowtorch test is a more effective method for carrying out spalling tests in small specimens compared to the furnace test. It is thought that the blowtorch test shows better spalling results compared to the furnace test because of the manner of exposure of the specimens. During the furnace test, multiple sides of the specimen are exposed to elevated temperatures resulting in rapid escape of moisture vapour hence mitigating the build-up of pore pressures and consequently spalling. However, during the blowtorch test, specimens are heated from one side with the thermal load characterized by a very steep temperature increase during the first minutes of the fire hence increasing the possibility of spalling. However, other studies [3] have showed that spalling was less likely when concrete was heated from one side and only occurred at higher heating rates. Also, large specimens...
were more prone to spalling when heated at higher heating rates than smaller specimens heated at lower rates [4]. Thus, factors such specimen size and heating rates could influence the likelihood of spalling in concrete under exposure to different heating profiles. Furthermore, it has been observed that furnace spalling tests on small, unloaded and unrestrained specimens almost always do not lead to spall compared with tests on realistic size elements which normally experience severe spalling. Since spalling is being encountered in small, unloaded and unrestrained specimens during the blowtorch spalling test, it is very likely that it will occur on realistic size elements. Therefore, the blowtorch test provides a promising, effective and economical test method for spalling at a small scale level in small, unloaded and unrestrained specimens, which can help to provide relevant and useful data for mitigation of spalling in realistic size elements.

**Prediction of Relative Maximum Pressures in Heated Concrete**

Based on the knowledge of the influence of fibre geometry and type on pore pressure development in heated concrete, a relationship to predict relative maximum pressures was developed. The relative predicted maximum pressure ($P_{r,p}$) is calculated using the relationship developed by multiple regression analysis as showed below:

$$P_{r,p}= 0.0113f'_C - 0.05T_f - 0.01L_f - 0.0021SA_{OF} - 0.001SA_{SF} \quad (1)$$

where $f'_C$ is the compressive strength of concrete, $T_f$ is a constant for type of organic fibre with values of 1 and 0.2 for PP and PVA fibres respectively, $L_f$ is length of organic fibres, $SA_{OF}$ is the cumulative surface area of organic fibres and $SA_{SF}$ is the cumulative surface area of steel fibres.

**Relationship between Maximum Pressure and Spalling**

A similar effect of fibre type and geometry was observed in the study of the blowtorch spalling test as was noted in the study of maximum pore pressures in heated concrete. This clearly showed that there is a direct relationship between pore pressure and spalling.

Based on relative maximum pressures measured in different fibre-reinforced concrete series and the corresponding average spalling depths, a linear relationship for predicting average spalling depth ($D_{s,p}$) in fibre-reinforced concrete was developed as showed below:

$$D_{s,p} = (P_{r,p} - 0.183) / 1.1701 \quad (2)$$

If $P_{r,p} \leq 0.183$ then $D_{s,p} = 0$

It was observed that occurrence of spalling in fibre-reinforced HSC started above a relative measured maximum pressure of 0.183 and therefore this value could be used as a threshold value in heated concrete above which spalling is most likely to occur.

**Conclusions**

The experimental results showed that silicon oil and a sintered metal are important parts of a pore pressure measurement technique and therefore a pressure measurement system which comprises of both silicon oil and a sintered metal is the most effective system. It was also observed that fast heating leads to higher pressures in deeper regions of concrete compared to slow heating.

When using organic fibres to mitigate pore pressure rise inside heated HSC, regardless of the type of fibres, longer fibres made of smaller diameters generally perform better than shorter ones made of larger diameters. However, PP fibre-reinforced HSC performed better during exposure to high temperatures compared to PVA fibre-reinforced HSC. Thus, the type of organic fibres in relation to its bonding properties with concrete as well as its melting temperature is important in mitigating pressure rise and consequently the possibility of spalling inside heated concrete.

The blowtorch test is a more effective method for carrying out spalling tests and evaluating the effect of fibre type and geometry on spalling in small specimens compared to the furnace test. Therefore, the blowtorch test provides a promising, effective and economical test method for spalling at a small scale level in small, unloaded and unrestrained specimens which can help to provide relevant and useful data for mitigation of spalling in realistic size elements.

Therefore this study proposes useful information for safeguarding against spalling in concrete structures during fires by means of addition of organic fibres of different types and geometries for different concrete mixes.

**References**