PERMEABILITY OF HIGH STRENGTH CONCRETE WITH DIFFERENT FIBERS AT HIGH TEMPERATURE

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Abstract

This paper presents the results of permeability testing on preheated high-strength concrete treated with different types of fiber. The concrete specimens used had a water-cement ratio of 0.30 (fc ≈ 75 MPa) and dimensions of 50 mm in diameter and 50 mm in length. The fibers used were water soluble polyvinyl alcohol (WS-PVA) fibers (length: 4 mm; volume content: 0.15 vol%), Jute fibers (length: 12 mm; volume content: 0.075 vol%) and polypropylene (PP) fibers (length: 12 mm; volume content: 0.15 vol%). The permeability tests were performed on the specimens at 200 and 500°C, and significant differences in the permeability of the heated concrete were observed. The permeability of PP fiber-mixed concrete after heating to 500°C was about 12 times higher than before heating, that of WS-PVA fiber-mixed concrete was about 4 times higher, and that of Jute fiber-mixed concrete was about 3.5 times higher.

1. INTRODUCTION

Fire represents one of the most severe risks to buildings and concrete structures because it often results in explosive concrete spalling. Spalling of concrete subjected to fire is related to two phenomena. The first is restrained thermal dilation resulting in biaxial compressive stress states parallel to the heated surface, which leads to tensile stress in the perpendicular direction. The second is the build-up of concrete pore pressure due to vaporization of physically/chemically bound water resulting in tensile loading on the microstructure of the heated concrete [1, 2]. Polypropylene fibers are often added to high-strength concrete (HSC) as an effective measure to prevent explosive spalling [3–6]. However, few recent reports have dealt with the reduction of spalling risk in high-temperature conditions by adding water-soluble polyvinyl alcohol fibers and Jute fibers. Accordingly, this paper presents the results of permeability testing on preheated high-strength concrete treated with different types of fiber. The fibers used were polyvinyl alcohol (WS-PVA) fibers, Jute fibers and polypropylene (PP) fibers.

2. OUTLINE OF EXPERIMENTS

The experiments involved fire endurance testing on specimens of four different concrete types. One was a control specimen without fibers, and the three others were a Jute fiber specimen, a WS-PVA fiber specimen and a PP fiber specimen.
2.1 Concrete

Table 1 shows the mixture proportions of the HSC. A water-cement ratio of 0.3 and ordinary Portland cement (density: 3.15 g/cm³) were used in this study. Crushed stone with a maximum grain size of 15 mm was used as coarse aggregate. The main component of the super-plasticizer (SP) was polymeric acid. After being cast, the concrete specimens were left in the formwork for one day, and were then wet cured at 20 ± 2°C for 75 days. Heating tests for all specimens were performed after this time. Tables 2 show the fresh-concrete properties of the specimens along with their average compressive strength and elastic modulus values as determined from testing after 75 days.

Table 1 Mixture proportions

<table>
<thead>
<tr>
<th>Specimens</th>
<th>W/C</th>
<th>Unit weight (kg/m³)</th>
<th>Fiber</th>
<th>Volume Content ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.3</td>
<td>132</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jute</td>
<td></td>
<td>440</td>
<td>Jute</td>
<td>0.075</td>
</tr>
<tr>
<td>WS-PVA</td>
<td></td>
<td>814</td>
<td>WSPVA</td>
<td>0.15</td>
</tr>
<tr>
<td>PP</td>
<td></td>
<td>1048</td>
<td>PP</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 2 Fresh properties and Mechanical properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Air content</th>
<th>Slump</th>
<th>Temperature</th>
<th>Compressive strength</th>
<th>Elastic Modulus</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unit %</td>
<td>cm</td>
<td>°C</td>
<td>(MPa)</td>
<td>(GPa)</td>
<td>(MPa)</td>
</tr>
<tr>
<td>Control</td>
<td>1.9</td>
<td>3</td>
<td>35</td>
<td>75.4</td>
<td>38.6</td>
<td>4.1</td>
</tr>
<tr>
<td>PP</td>
<td>1.5</td>
<td>-</td>
<td>31</td>
<td>72.5</td>
<td>36.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Jute</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
<td>79.2</td>
<td>38.9</td>
<td>4.2</td>
</tr>
<tr>
<td>WSPVA</td>
<td>1.1</td>
<td>21</td>
<td>35</td>
<td>79.8</td>
<td>37.9</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 3 Properties of fibers

<table>
<thead>
<tr>
<th>Type of fiber</th>
<th>Density (g/cm³)</th>
<th>Heating characteristic</th>
<th>Melt point (°C)</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>0.91</td>
<td>Meltdown</td>
<td>170</td>
<td>0.11</td>
<td>12</td>
</tr>
<tr>
<td>Jute</td>
<td>1.38</td>
<td>Carbonization</td>
<td>-</td>
<td>0.02</td>
<td>12</td>
</tr>
<tr>
<td>WSPVA</td>
<td>1.3</td>
<td>Meltdown, dissolving</td>
<td>230</td>
<td>0.012</td>
<td>4</td>
</tr>
</tbody>
</table>

2.2 Fibers

Table 3 shows the properties of the natural Jute [7] fibers and the synthetic WS-PVA [7] and PP fibers used (Jute fiber addition ratio by volume: 0.075vol%; length: 12 mm; WS-PVA fiber addition ratio by volume: 0.15vol%; length: 4 mm; PP fiber addition ratio by volume: 0.15vol%; length: 12 mm). Photos 1 and 2 show Jute fibers and WS-PVA fibers. Straw-like structures in the Jute fibers are seen in the image, which was obtained using a scanning electron microscope (SEM). WS-PVA fibers, which have low melting and dissolving points, are also used for explosion prevention in concrete. They have a lower dissolving point than the other fiber types, and have been used in Japan for more than 30 years. Although the mechanism behind the prevention of explosion by adding fibers has not yet been fully elucidated, synthetic fibers are considered to improve concrete permeability by reduce dissolving/melting and vaporization. Figure 1 shows the results of thermal analysis for Jute fiber using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). The exothermic peak (which represents the heat released from the sample) of the DSC curve in the case of Jute fibers was observed at a maximum temperature of 360°C. The TGA curve
for Jute fibers initially indicated a slight decrease in weight below 100°C due to loss of moisture. Thereafter, the two curves began to decompose at 265 and 340°C, respectively. The decomposition temperature of the Jute fiber sample at 80% weight loss was 390°C. Figure 2 shows the DSC and TGA results in the case of PP fibers. The melting, vaporization and burning points of these fibers were 173°C, 341°C and 447°C, respectively. Higher temperatures reduce their viscosity via the two mechanisms of increased molecular energy and reduced molecular size due to thermal degradation [2]. Figure 3 shows DTA and TGA results for WS-PVA fiber. The melting, vaporization and burning points of these fibers were 227°C, 246°C and 470°C, respectively.

Figure 1  DSC-TGA results(Jute)                 Figure 2  DTA-TGA results(WSPVA)

Figure 3  DSC-TGA results(PP)                     Figure 4 Preparation of heating specimens

2.3 Specimens

Figure 4 shows the preparation of the permeability specimens. The experiments were conducted with four different types of concrete. The concrete was first cast in pre-molded cans (diameter: 50 mm; height: 100 mm, and the specimens were then wet cured at 20°C for 28 days before being cut in half using a concrete cutter and insulated (except the surface part). Only one surface was heated, which was achieved by thermally isolating the other
surfaces with a thermal blanket. Thermal couples were placed in the specific locations shown by the red dots in Fig. 4. Permeability testing was conducted after the specimens were heated.

2.4 Pre-heating tests

All specimens were heated in a muffle furnace with an operating temperature range between 100°C and 1,150°C, and the maximum temperature was reached at around 80 minutes. The unit used was a 2.5 kW iron-chrome wire heater with a 220-V power source. Figure 5 shows the heating rate and the times taken for the heating tests. In order to determine how the permeability of concrete changes at different temperatures, three different conditions of no heat, 200°C and 500°C were set. The permeability of each of the three specimens was measured for each temperature. The heating rate was 100°C/hr. for the 200°C specimens and 125°C/hr. for the 500°C specimens. After the target temperature was reached, it was maintained for four hours and the specimens were then allowed to cool naturally.

2.5 Permeability tests

The specimens to be considered for permeability testing (as determined from the heating tests) were HSC with and without natural and synthetic fibers. Specimens with a height of 50 mm were obtained by cutting blocks in half. No-heating specimens and heating specimens at 200, 500°C were used in this study, and permeability testing was conducted according to ISO 8841:1991 (Dense, shaped refractory products – Determination of permeability to gases). Permeability was calculated from Eq. (1).

\[
\mu = \frac{V}{t \times \eta \times \delta} / A \times \frac{1}{(p_1 - p_2) \times 2P / (p_1 + p_2)} \tag{1}
\]

Where \( \mu \) represents permeability (m²), \( V \) is the volume of gas pass through the specimen at pressure \( p_i \) (m³), \( t \) is the time taken for gas to pass through the specimen, \( \eta \) is the viscosity of the gas (Pa·s), \( A \) is the area of gas passing through the specimen (m²), \( \delta \) is the thickness of gas pass through the specimen (m), \( P \) is the absolute pressure of the gas (Pa), \( p_1 \) is the initial pressure of the gas (Pa), and \( p_2 \) is the pressure of gas pass through the specimen (Pa).

Figure 6 gives details of the permeability test apparatus. Nitrogen gas was used, and the measurement time was 60 seconds. The specimens were set into metallic cells, gas was percolated through them at the initial pressure, and the pressure of the gas pass through was measured. Generally, three levels of static pressure were considered to estimate permeability.

3. RESULTS AND DISCUSSION

3.1 Internal temperature

Figures 7 and 8 show the internal temperature of the specimens at 200°C and 500°C, respectively. From Fig. 7, it can be seen that the maximum internal temperature of the specimens ranged from 154°C to 173°C when the heating temperature was set to 200°C.
Figure 8 shows that the maximum internal temperature measured for each specimen ranged from 354°C to 358°C when the temperature was set to 500°C. The temperature used for permeability analysis of each specimen was not the set temperature but the highest temperature measured by the thermal couple inside the concrete specimen.

![Figure 7 Internal temperature (200°C)](image1)

![Figure 8 Internal temperature (500°C)](image2)

### 3.2 Permeability tests

Figures 9 to 12 show the permeability test results for the HSC (control), PP, WS-PVA and Jute specimens, while Fig. 13 shows the average permeability values for all specimens at all set temperatures. From Fig. 13, it can be seen that when the temperature was around 10°C, the HSC (control) specimen showed the lowest permeability value compared with the other specimens before heating. This can be explained by the fact that HSC has the highest density of all the analyzed specimens. The PP and WS-PVA specimens had basically the same levels of permeability, and Jute had the highest. This can be explained by the fact that Jute fibers have a straw-like structure, and even before heating there are already links in the microstructure inside the concrete. Overall, the PP specimen demonstrated a high level of permeability compared to the HSC (control) specimen. This can be seen in Fig. 13, where the blue line (for the PP specimen) is above the red line (for the HSC specimen). This is because the PP fibers melted in the heating test, resulting in the opening of microscopic pathways through the concrete and consequently higher permeability. However, an alternative hypothesis is that PP fibers expand before melting, causing pressure that results in the generation of micro-cracks, which in turn increases the permeability of the concrete. The WS-PVA specimen showed basically the same results as the control specimen after heating, with the green line in Fig. 13 reaching almost the same values of 5.52 and 5.6 x 10^{-15} m^2 at 200°C. The normalized gas permeability (Fig. 14) value identified for the WS-PVA specimen was lower than that identified for the PP specimen. The WS-PVA fibers had a length of 4 mm, while the PP fibers were 12 mm in length, making the permeability of the PP specimen higher. As Jute fibers have a straw-like structure, the Jute specimen showed the highest permeability among the specimens that were not heated. After the specimen was heated, it also showed a high level of permeability, but the normalized gas temperature was not significant. This is related to the fact that Jute fibers do not melt like the others, meaning that there is less free space inside the matrix.
3.3 SEM observation

One of the main objectives of this research was to gain a better understanding of the microstructure inside concrete after heating. In order to identify changes inside the matrix, SEM images (Fig. 15) were captured before and after heating (set temperature: 500°C).

It can be seen from Figures 15 (a) and (b) that although PP and WS-PVA fibers were identified before heating, only cavities were seen after heating, which was a result of the fibers melting. Figures 15(c-1) and (c-2) confirms the presence of Jute fibers both before and after heating.
4. CONCLUSIONS

1) All three specimen types exhibited increased permeability after being heated.
2) The PP specimen permeability values after heating to 170°C and 350°C were 3.4 and 12.8 times their initial levels, respectively; the WS-PVA specimen permeability values after heating to 154°C and 357°C were 1.2 and 4.3 times their initial levels, respectively; and the Jute specimen permeability values after heating to 168°C and 353°C were 3 and 3.5 times their initial levels, respectively.
3) After heating was performed, SEM images were captured; no fibers were seen inside the PP and WS-PVA specimens, but were identified in the Jute fiber specimen.
4) Although the Jute fiber specimen did not show a permeability increase ratio as high as that for the PP fiber specimen, it was confirmed that adding Jute fibers was effective because of their straw-like structure, which meant that the free space inside the matrix remained constant.

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REFERENCES


