Estimation of Chloride Diffusion Coefficients of High-Strength Concrete with Synthetic Fibers after Fire Exposure

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ABSTRACT

In this study, the durability of concrete exposed to fire was investigated based on tracer analysis after the specimens had been soaked in salt water. Two types of concrete specimens: high-strength concrete (HSC) and HSC with polypropylene (PP) fibers were subjected to heating tests at temperatures of 100, 200, 300 and 500°C before being soaked for 30 days in a 10% sodium chloride (NaCl) solution. After the soaking period, chloride penetration depth was measured using electron-probe microanalysis (EPMA), and the relevant chloride diffusion coefficients were estimated. Relative chloride penetration was found to be deeper in specimens exposed to higher temperatures. HSC with PP fibers also exhibited greater penetration due to the melting of its fiber content. The chloride diffusion coefficient also increased with higher exposure temperatures.

1. INTRODUCTION

High-strength concrete (HSC) is widely used in the construction of buildings. Fire possesses a serious risk to concrete buildings and structures because it often results in explosive spalling of concrete. Polypropylene (PP) fibers are usually added to HSC as an effective measure to prevent such spalling (Zeiml M. et al., 2008). When concrete is exposed to high temperatures, its mechanical properties deteriorate and it gradually or quickly loses its mechanical strength and durability. The effects of high-temperature exposure on HSC manifest in the form of surface cracks, spalling and disintegration, which may seriously impair structural integrity (Poon C. S. et al., 2001). As a consequence, very strong temperature gradients are observed in reinforcement cover during fire, and the severity of material thermal damage decreases with depth from the heating surface (Mendes A. et al., 2012). The gas permeability of concrete has been

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recently identified as a key parameter in explosive spalling (Zeiml M. et al., 2008). This permeability in cover concrete increases as a result of exposure to fire and facilitates penetration of oxygen, carbon dioxide and chloride. Consequently, corrosion of reinforcements inside such concrete occurs due to penetrated chloride in presence of oxygen and moisture when the chloride build-up within the structure exceeds a certain threshold value (Elfmarkova V. et al., 2015). Fire exposure also increases gas permeability and the risk of steel corrosion in HSC with PP fibers. However, few recent studies have focused on the ability to assess the durability of concrete with PP fibers after exposure to fire. Figure 1 illustrates concrete damaged due to the development of micro cracks, which result in greater permeability.

In this study, a method of assessing the durability of HSC after exposure to fire was investigated by soaking specimens in salt water and performing tracer analysis. After the soaking period, chloride penetration depth was measured using EPMA (electron probe microanalysis) (Mori D. et al., 2006). Chloride diffusion coefficients were estimated from the resulting data, and chloride penetration analysis was performed.

![Image](image.png)

(a) Before fire exposure  
(b) Cracking initiation and hydration product degradation during fire exposure  
(c) Penetration of degradation factors (chloride ions) into concrete after fire exposure

Fig. 1. Fire-related damage of high-strength concrete

2. ESTIMATION OF CHLORIDE DIFFUSION COEFFICIENTS

2.1 EPMA observation

The relationship between chloride content and distance from the surface of concrete specimens has been investigated via EPMA observation (Ozawa M. et al., 2015). In this investigation, concrete immersion tests were carried out in line with JSCE-G 572-2005 (JSCE 2005). For all the specimens, the mold surface was heated to 100, 200, 300 and 500°C at a rate of 1°C/min and allowed to cool naturally. After the heating stage, the specimens were immersed in a 10% NaCl solution at 20°C for 28 days. Figure 2 shows areas of EPMA focus on chloride concentration distribution and chloride
concentration profiles in HSC and HSC with PP, respectively. The presence of chloride and its concentration depth in both concrete types were then observed using color mapping images of the results obtained within the EPMA focus area. For HSC and HSC with PP heated to 100°C or below (Figs. 2 (b) and (f), respectively), chloride concentration distribution essentially exhibited little change from that of unheated concrete (Figs. 2 (a) and (e), respectively). In HSC exposed to a temperature of 300°C (Fig. 2 (c)), the presence of chloride was observed up to a depth of 40 mm from the heating surface. This is because cracking and other forms of heat damage as well as the decomposition of cement hydration products increased gradually as the temperature rose. In HSC with PP exposed to a temperature of 200°C (Fig. 2 (g)), a chloride mass of up to 35 kg/m³ was measured in the heating surface area. This is because PP fibers in the specimen melted and heat damage increased gradually as the temperature rose. However, after exposure to temperatures of 300°C (Fig. 2 (h)) and above, the concentration of chloride ions observed up to 40 mm from the heating surface was higher. This is because cracking as well as decomposition of cement hydration products increased gradually as PP fibers melted.
Fig. 2 (c) EPMA (HSC: 300°C)

Fig. 2 (d) EPMA (HSC: 500°C)

Fig. 2 (e) EPMA (HSC+PP: unheated)

Fig. 2 (f) EPMA (HSC + PP: 100°C)

Fig. 2 (g) EPMA (HSC+PP: 200°C)

Fig. 2 (h) EPMA (HSC + PP: 300°C)
2.2 Estimation of apparent chloride diffusion coefficients after heating tests

The presence of chloride ions on structures exposed to severe environments leads to their diffusion into concrete pores with a certain concentration gradient, resulting in the corrosion of internal steel bar reinforcements. The apparent coefficient of chloride diffusion depends on the pore structure of the concrete, and characterizes chloride flow under conditions of a given external chloride concentration (Elfmarkova V. et al., 2015). Concrete exposed to fire sustains heat damage due to cracking and decomposition of cement hydration products, which increases gradually as PP fibers melt. In this study, the apparent chloride diffusion coefficient of fire-damaged concrete was estimated using EPMA data. Equations (1) and (2) show Fick’s second law (M. Collepardi, 1972) and chloride concentration with age and distance from the concrete surface, respectively.

\[
\frac{\partial c}{\partial t} = D \left( \frac{\partial^2 c}{\partial x^2} \right),
\]

\[
C(x, t) = C_0 \left\{ 1 - \text{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right\},
\]

where,
- \( C(x, t) \) : chloride concentration (kg/m\(^3\))
- \( C_0 \) : chlorine content of surface concrete (kg/m\(^3\))
- \( x \) : distance from surface concrete
- \( t \) : age (from service commencement)
- \( \text{erf} \) : error function

Table 1 shows estimated chloride diffusion coefficients and heating temperatures. Figure 3 illustrates the relationship between the chloride diffusion coefficient (D) and heating temperature for HSC and HSC with PP fibers. The results of this study showed that D increases with temperature. In concrete not exposed to fire, the D values of HSC and HSC with PP fibers were 0.8 and 1.1 cm\(^2\)/year, respectively; after exposure to a temperature of 300°C, the corresponding values were 27 and 35 cm\(^2\)/year. This increase is due to the movement of chloride ion through micro-cracks and the decomposition of cement hydration products. Additionally, voids developed due to the melting of PP fibers in HSC with PP fibers.

<table>
<thead>
<tr>
<th>Heating temperature (°C)</th>
<th>Chloride diffusion coefficient (D) (cm(^2)/year)</th>
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<tbody>
<tr>
<td>Non-heated</td>
<td>0.8</td>
</tr>
<tr>
<td>100</td>
<td>2.2</td>
</tr>
<tr>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>300</td>
<td>27</td>
</tr>
<tr>
<td>500</td>
<td>69</td>
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3. CHLORIDE PENETRATION ANALYSIS

Numerical analysis of chloride penetration in concrete after heating is based on the finite element method. Figure 4 shows a one-dimensional (1D) chloride penetration analytical model, and Table 2 shows the conditions for calculation of chloride penetration. In the experiment using HSC with PP fibers, a sample with a thickness of 10 cm was heated to 300°C and subsequent chloride penetration at a point 10 cm from the heated surface was calculated. The measured initial chloride content at the surface of the specimen was 5 kg/m$^3$. The chloride diffusion coefficients with no heating and heating to 300°C were 1.135 and 35 cm$^2$/year, respectively. Figures 5 and 6 show the results of chloride penetration calculation for no heating and heating to 300°C. In unheated concrete, chloride penetration values after 1,000 days at depths of 3 and 10 cm from the surface were 1 and 0.2 kg/m$^3$, respectively, which are below the range of critical chloride content associated with steel corrosion. For the specimen heated to 300°C, the corresponding values exceeded 1.2 kg/m$^3$ (within the range of critical chloride content associated with steel corrosion) within 50 and 100 days, respectively. This indicates that the penetration resistance of concrete is impaired by exposure to heat. As a result, its post-exposure durability is reduced.

Fig. 4 One-dimensional analytical model for chloride penetration analysis
Table 2  Conditions for calculation of chloride penetration

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Heating temperature</th>
<th>Co</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
<td>kg/m³</td>
<td>cm²/year</td>
</tr>
<tr>
<td>HSC + PP fibers</td>
<td>Non-heated</td>
<td>5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td></td>
<td>35</td>
</tr>
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Fig. 5 Calculation of chloride penetration in non-heated concrete

Fig. 6 Calculation of chloride penetration in concrete heated to 300°C
4. CONCLUSIONS

In this research, the diffusion coefficients of concrete heated to different temperatures were examined. The following conclusions were drawn:

1) The chloride diffusion coefficient ($D$) of concrete increases with the heating temperature.

2) After specimens of HSC and HSC with PP fibers were heated to 300°C, their chloride diffusion coefficients ($D$) were 27 and 35 cm$^2$/year, respectively. The increased chloride penetration after heating to higher temperatures was due to the movement of chloride ions through micro-cracks and the decomposition of cement hydration products. Voids also developed in HSC with PP fibers due to fiber melting.

3) Chloride penetration at depths of 3 and 10 cm in the specimen heated to 300°C exceeded 1.2 kg/m$^3$ (within the range of critical chloride content associated with steel rusting) within 50 and 100 days, respectively. This indicates that the penetration resistance of heat-damaged concrete decreases, causing reduced durability.

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