



Estimation of chloride diffusion coefficients of high-strength concrete with synthetic fibres after fire exposure



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HIGHLIGHTS

- The durability of concrete exposed to fire was investigated.
- The specimens were soaked in salt water after heating.
- The chloride penetration depth was measured with electron-probe microanalysis.
- Chloride penetration was deeper in specimens exposed to higher temperatures.
- The chloride diffusion coefficient also increased with the exposure temperature.

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ABSTRACT

Tracer analysis was used to investigate the durability of concrete exposed to fire and then soaked in salt water. Two types of concrete specimens—high-strength concrete (HSC) and HSC with polypropylene (PP) fibres—were heated to different temperatures before being soaked for 30 days in a 10% NaCl solution. The chloride penetration depth was then measured with electron probe microanalysis, and the apparent chloride diffusion coefficients were estimated. The apparent chloride penetration was deeper in specimens exposed to higher temperatures. HSC with PP fibres exhibited greater penetration because the fibres melted. The chloride diffusion coefficient increased with the exposure temperature.

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1. Introduction

High-strength concrete (HSC) has recently become a widely used construction material for high-rise buildings, bridges, and various infrastructure because of its high levels of performance, strength, and stability and its technical, architectural, and economic advantages over conventional concrete. However, HSC experiences explosive spalling when exposed to high temperatures during a fire. There are two mechanisms by which concrete can be damaged by fire: restrained thermal dilation resulting in biaxial compressive stress states parallel to the heated surface, which leads to tensile stress in the perpendicular direction (Fig. 1) [1]; and the build-up of concrete pore pressure due to vaporisation of physically/chemically bound water resulting in tensile loading on

the microstructure of the heated concrete (Fig. 2) [2]. Polypropylene (PP) fibres are often added to HSC as an effective measure for preventing explosive spalling (Fig. 3) [3,4]. Recent studies [5–8] have shown that, when HSC is exposed to high temperatures, it gradually or quickly loses its mechanical strength and durability, which greatly threatens the safety of fire-damaged structures. After a fire, the deterioration of HSC manifests in the form of surface cracks, spalling, and disintegration. The pore structure changes, which is known as ‘pore-structure coarsening’. The gas permeability of the concrete cover through these pores formed after fire exposure has recently been identified as a key parameter in explosive spalling [9]. The increased permeability of the concrete cover facilitates the penetration of oxygen, carbon dioxide, and chloride from the environment through these pores [5]. The reinforcement inside such concrete corrodes because of the penetrating chloride ions in the presence of oxygen and moisture [10]. When the chloride build-up within the structure exceeds a

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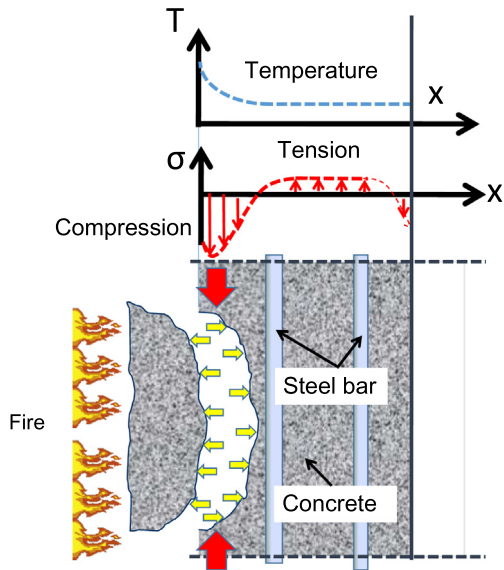


Fig. 1. Thermal dilation.

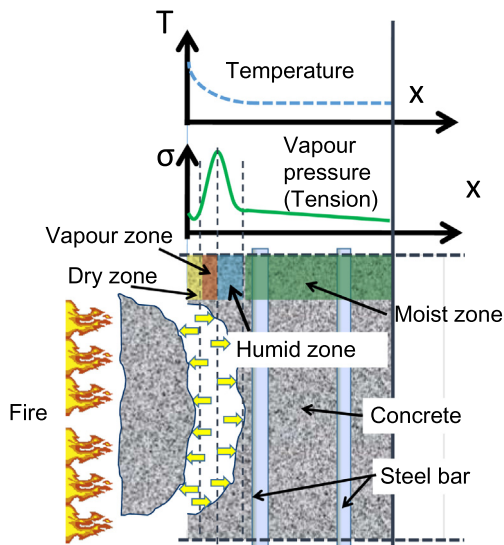


Fig. 2. Vapour pressure.

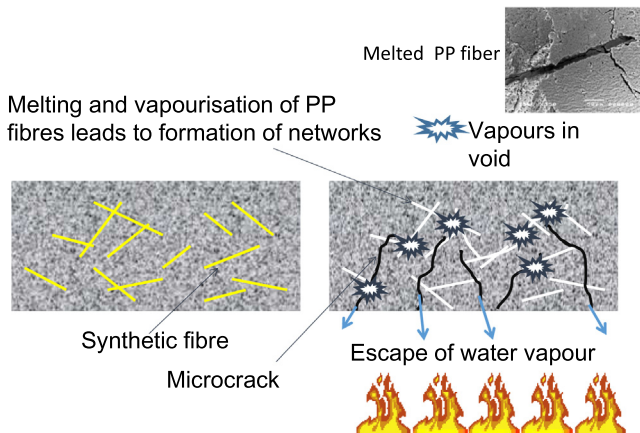


Fig. 3. Effect of PP fibres on spalling.

certain threshold, the reinforcing steel corrodes [11]. This results in the accumulation of a large amount of corrosion products. These generate internal stresses and subsequently enhance the cracking of the concrete, which can seriously impair the structural integrity [12].

Chloride penetration in concrete is a complex phenomenon because of the nonhomogeneous material and microdefects that form after fire damage [13]. The transport of chloride ions in concrete includes a variety of mechanisms, such as diffusion due to a concentration gradient [13], pressure [14], and capillary suction under the action of a humidity gradient [15]. Among these, the chloride diffusion coefficient is the most commonly used parameter in models for quantifying the chloride ingress rate into concrete because diffusion controls the chloride transport in saturated concrete [16]. Some papers [17,18] have reported that the chloride ion diffusion in concrete is accelerated by microdefects in the structures caused by the actions of loads, the environment, and climate conditions. Therefore, the chloride ion diffusion coefficient is a function of time; it decreases with increasing time and ion movement speed due to a rise in temperature. Some studies [19,20] have investigated the influence of carbonation on chloride ion transport in concrete, but the precise influence of carbonation is complicated, and it is difficult to determine whether carbonation accelerates or retards damage to durability due to chloride ions. Although carbonation and chloride ion ingress take place simultaneously, chloride ion diffusion is much faster than the rate of carbonation. Researchers have noted that using PP fibres can mitigate the spalling [21–24] and post-cracking behaviour of HSC [25,26]. Hence, PP fibres are often added to HSC to prevent explosive spalling. However, this makes HSC more vulnerable to chloride attack after fire because of the micro-pores that form when the PP fibres melt. Fig. 4 illustrates the concrete damage due to the development of micro-cracks, which result in greater permeability after fire. Generally, concrete buildings with little fire damage are reused after repair and renovation. However, the penetration of chloride ions and CO₂ through the pores formed by the melted PP fibres, micro-cracks, and spalled areas makes the repaired concrete further vulnerable to chloride attack and corrosion of structural steel. Hence, the chloride ion penetration of HSC also needs to be considered after a fire. For the reasons described above, it is important to examine the durability of fire-damaged concrete, especially, that from viewpoint of substances penetration resistance.

At present, many researchers have developed transport model for chloride ions in HSC before exposure to fire. However, very little information is available on the diffusion of chloride ions after fire exposure. Therefore, the objective of this study was to develop a method for assessing the durability of HSC based on chloride penetration analysis after exposure to fire. Chloride was used as a tracer to estimate the durability of concrete after fire exposure. Specimens were soaked in salt water. After the soaking period, the chloride penetration depth was measured by electron probe microanalysis (EPMA) [27], and the data were used to estimate the chloride diffusion coefficients. During fire, micro-cracks in concrete were found to increase due to dehydration of the cement paste and chemical decomposition of the hydrates, which led to a drastic change in the tensile strength of the concrete.

2. Materials and methods

2.1. Preparation of concrete specimens

Tables 1 and 2 list the concrete mix proportions and materials used to fabricate the control specimen (HSC) and the specimens containing PP fibres (HSC + PP). The water-to-cement ratio was 0.3 for both cement mixtures, and high early strength Portland cement (3.13 g/cm³) was used to prepare all of the specimens. Table 3 provides the chemical composition of high early strength Portland cement. Dense riverbed sandstone with a maximum size of 20 mm were used as the coarse aggregate

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