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A meso-level investigation into the explosive spalling mechanism of high-performance concrete under fire exposure

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ABSTRACT

High-performance concrete (HPC) is prone to spalling under fire conditions. However, few quantitative theoretical studies on the spalling mechanism are available in the literature and the spalling mechanism has not been well interpreted. In this paper, the spalling behavior of cubic specimens is numerically modeled and the spalling mechanism is investigated at a meso-level. In modeling, the temperature field, the thermal decomposition of cement paste, the build-up vapor pressure, the moisture transport, and the distribution and evolution of thermal stresses in concrete are analyzed in a quantitative manner. Based on the numerical results, the spalling mechanism is interpreted from different angles. It is concluded that the explosive spalling of HPC specimens under fire exposure is mainly attributed to the temperature gradient-induced thermal stress.

1. Introduction

Compared with normal-strength concrete, high-performance concrete (HPC) is of higher strength and better durability and therefore has been widely used in various structures. However, under fire conditions, HPC undergoes material degradation, cracking, or even explosive spalling. Among those damages, explosive spalling is the most detrimental as it can cause sudden disintegration of concrete. To prevent spalling and hence to minimize the disadvantages of HPC, the spalling mechanism should be understood first. To this end, considerable experimental investigations and numerical analyses have been conducted. Hertz [1] found that dense concrete is more likely to spall and the risk of spalling increases with the increase of the heating rate and the moisture content of concrete. Sanjayan and Stocks [2] investigated the fire spalling of reinforced concrete slabs and observed that fire spalling generally occurs in the early stage of fire. From the experimental results on cylinder specimens, Phan and Carino [3] concluded that, for fire spalling, vapor pressure might be the primary cause and the thermal stress induced by the temperature gradient is secondary. Peng [4] performed an experimental program to quantify the probability of fire spalling of cubic HPC specimens and found that the higher the strength and moisture content of concrete are, the higher the probability of fire spalling is. Jansson [5] inferred from the experimental results on slabs that fire spalling of HPC is mainly caused by the temperature gradient-induced thermal stress. Lately, other influencing factors have also been investigated. Kirnbauer and Schneider [6] found that concrete with crushed aggregate is more sensitive to spalling than that with round aggregate. Guerrieri and Fragomeni [7] observed that thicker and larger high strength concrete panels suffer higher degrees of spalling. Debicki et al. [8] found that heated concrete spheres with different diameters spall in different manners. Jansson and Boström [9] observed that aged dried concrete I-shape beams have a lower risk of fire spalling than new concrete beams. Rahim et al. [10] concluded that HPC blended with silica fume is more vulnerable to spalling than that blended with fly ash and blast furnace slag. They also observed that external loading leads to more severe spalling.

To further understand spalling, various theoretical models have been developed. To date, two hypotheses have been proposed to explain spalling: the vapor pressure mechanism [2–4,11] and the temperature gradient-induced thermal stress mechanism [5,12–14]. In the former, a theory of moisture-clog spalling has also been proposed. Bažant [11] pointed out that vapor pressure could only trigger the happening of fire spalling and the thermal stress-induced potential energy might play a dominant role. Ulm et al. [13,14] developed a chemoplastic model to analyze the fire spalling of the concrete rings in the Channel Tunnel. They used the plastic strain to evaluate the spalling depth of concrete and showed that fire spalling is caused by the compressive stress induced by the restrained thermal dilatation. Gawin et al. [15] used a fully coupled model to analyze the thermomechanical behavior of concrete and four indices were used to predict spalling. Ichikawa and England [16] and Dwaikat and Kodur [17] used one-dimensional models to simulate the spalling of concrete elements. Zhang and Davie [18] and Ožbolt et al. [19] also modeled the fire

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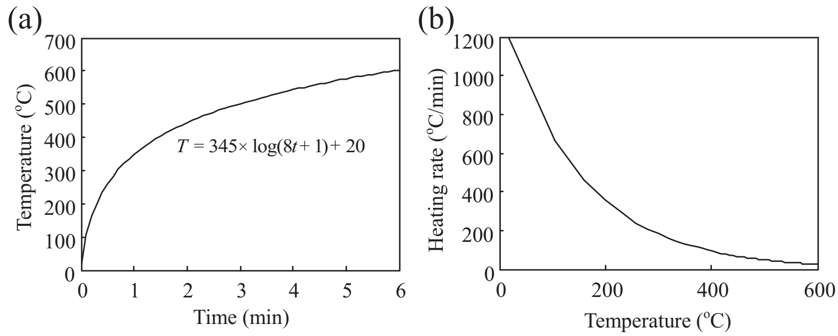

Fig. 1. (a) ISO 834 heating curve and (b) heating rate.

damage to concrete elements. Davie et al. [20] numerically studied the effect of the variation of mechanical parameters on the damage to heated concrete. Some small specimen-based macro-level studies were also conducted by Gawin et al. [21], Pont et al. [22], Li et al. [23], and de Morais et al. [24]. Compared with the macro-level analyses of fire spalling, meso-level studies are relatively few. Tenchev and Purnell [25] investigated spalling on an arithmetic parallel-averaged meso-level. In the model, equal strains and different stresses were assumed. They concluded that the plane of spalling is parallel to the applied compressive stress. By using a mesoscopic thermal-elastic damage model and fracture-based zero-thickness interface elements, respectively, Fu et al. [26–28] and Rodríguez et al. [29] studied the cracks induced by the temperature gradient and the thermal volume mismatch between aggregates and the cement paste matrix in heated concrete.

From the above references, the following limitations in the current study can be summarized: First, the fire spalling mechanism of HPC has not been well interpreted and the quantitative analysis is still lacking. Second, the spalling phenomenon is usually analyzed at a macro-level, where concrete is modeled as a homogenous material. Thus, some details, such as the effect of aggregates on the moisture transport, the decomposition of cement paste, and the local effect of vapor pressure on the stress/strain field, could not be fully considered. Third, when the degree of moisture saturation in concrete is high, water vapor could not be simply treated as an ideal gas. Finally, the effect of the heating history on the chemical reactions and hence on the material properties has not been incorporated in a proper way.

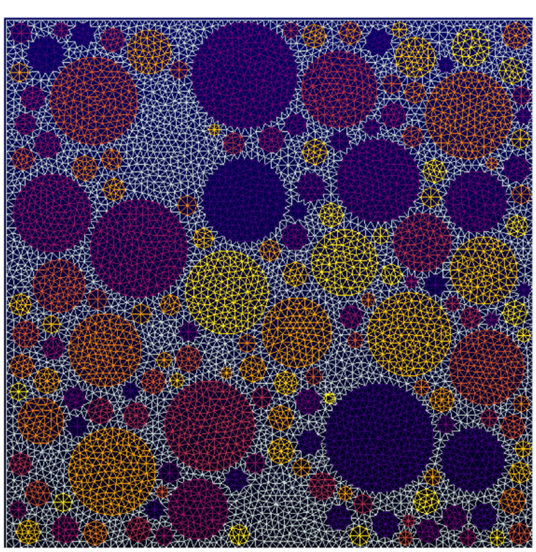

Fig. 2. Aggregate distribution and domain discretization.

The present paper is intended to investigate the explosive spalling mechanism of HPC exposed to fire at a meso-level. The thermo-chemo-hydro-mechanical reactions of concrete to high temperatures are numerically modeled. The effects of the heating-history on the thermal decomposition of cement paste and hence on the material properties are considered in the analysis. The spalling mechanism is quantitatively interpreted based on the numerical results.

2. Model concrete

To analyze the spalling mechanism of HPC, the experiment conducted by Peng [4] is considered since relatively detailed experimental information was provided compared with other experiments. In the experiment, an ordinary Portland cement (OPC 52.5) with chemical composition of C_3S-55.8%, C_2S-15.8%, C_3A-9.2%, and C_4AF-9.1% by mass was used. Ten percent cement by mass was replaced by silica fume with a density of 2200 kg/m^3. A crushed granite with a density of 2620 kg/m^3 was used as coarse aggregate and a river sand with a density of 2610 kg/m^3 was used as fine aggregate. The aggregate volume fraction was 64.8%. The water-to-binder ratio ranged from 0.21 to 0.6 for making different concretes and cubic specimens with a side length of 100 mm were cast. After 90-day curing at room temperature, the fire spalling test was conducted by exposing the specimens with different moisture contents to the ISO 834 standard fire up to 600 °C (Fig. 1). The temperature evolution in the specimens was recorded. The experimental results showed that explosive spalling occurred when the surface temperature of the specimens was in the range of 480 to 510 °C and the heating duration was around 3 min. The higher the strength and moisture content of concrete are, the higher the probability of spalling is. The un-spalled specimens were sawn in half for the observation of internal cracks. It was found that the internal cracks reside in the central region of the specimens.

To investigate the fire spalling mechanism, the spalling behavior of concrete cube with 0.26 water-to-binder ratio, 110 MPa compressive strength, and 90% moisture content is numerically modeled in this paper. A two-dimensional analysis is conducted and the concrete cube is molded as a two-phase material, consisting of aggregates and cement paste in view of the fact that the ITZ effect is negligibly small for HPC [4]. The aggregates are modeled as spheres and randomly distributed according to the aggregate gradation [4,30] as shown in Fig. 2. Three-node triangle elements are used for the discretization.

Table 1
Thermal parameters and mass densities of aggregate and cement paste.

Material	Thermal conductivity (W/m·°C)	Specific heat (J/kg·°C)	Mass density (kg/m^3)
Aggregate	5.0	710.0	2620.0
Cement paste	4.0	1175.0	2078.0