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Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures

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ABSTRACT

This paper presents the results of an extensive experimental study on the compressive and splitting tensile strength of high-strength concrete with and without polypropylene (PP) fibers after heating to 600 °C. Mixtures were prepared with water to cementitious materials ratios of 0.40, 0.35, and 0.30 containing silica fume at 0%, 6%, and 10% cement replacement and polypropylene fibers content of 0, 1, 2, and 3 kg/m^3. A severe strength loss was observed for all of the concretes after exposure to 600 °C, particularly the concretes containing silica fume despite their good mechanical properties at room temperature. The range of 300–600 °C was more critical for concrete having higher strength. The relative compressive strengths of concretes containing PP fibers were higher than those of concretes without PP fibers. The splitting tensile strength of concrete was more sensitive to high temperatures than the compressive strength. Furthermore, the presence of PP fibers was more effective for compressive strength than splitting tensile strength above 200 °C. Based on the test results, it can be concluded that the addition of 2 kg/m^3 PP fibers can significantly promote the residual mechanical properties of HSC during heating.

1. Introduction

Nowadays, high-strength concrete (HSC) can be produced by the most concrete plants and is extensively used throughout the world. HSC exhibits significantly higher mechanical strengths as well as superior performances under severe conditions in comparison with normal-strength concrete (NSC). With the increasing use of HSC, the risk of subjecting it to elevated temperatures in the forms of accidental fires or continuous high temperatures also increases.

The behavior of NSC under elevated temperatures has been clearly understood based on the results of an enormous amount of work carried out since the 1920s [1–3]. In recent years, there have been many research studies to determine the thermal behavioral differences between HSC and NSC [4–13]. In general, stressed, unstressed, and unstressed residual property methods are three common test conditions to evaluate the behavior of concrete after exposure to elevated temperatures. Phan and Carino [9] carried out a comprehensive research programme to evaluate the behavior of concrete exposed to high temperatures under different test conditions. However, the rate of strength loss and the occurrence of explosive spalling are identified as two main differences between HSC and NSC after exposure to elevated temperatures.

In terms of the rate of strength loss, in spite of conflicting data, there is general agreement between the researchers on the relative residual strength above 400 °C. Some researchers have shown that at elevated temperatures, HSC maintains the same or a greater proportion of its normal temperature strength than NSC [4,14]. Others have reported no significant differences in the behavior of HSC and NSC [5,15]. These conflicting data may be related to factors such as strength grade [16], moisture content [6,17–19], aggregate type [7,8,20,21], test methods [9,10], supplementary cementitious materials [4,20], the high-temperature conditioning including the heating rates [11,22], and the maximum test temperature [12,13,23,24]. Min et al. [25] showed that the relative residual splitting tensile strength of 70-MPa concrete containing 27% fly ash as cement replacement and water to cementitious materials ratio (w/cm) of 0.26 was 86%, 82%, 52% and 17% after exposure to 200, 400, 800, and 1000 °C, respectively. Chen and Liu [26] reported similar trends in splitting tensile strength loss and compressive strength loss with increase in temperature up to 800 °C. Based on their results, the relative residual splitting tensile strength of the concrete mixture

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containing 10% fly ash and w/cm of 0.3 was approximately 95%, 40%, 20%, and less than 10% after subjecting to 200, 400, 600, and 800 °C, respectively.

Occurrence of explosive spalling is known to be another main difference between HSC and NSC after exposure to elevated temperatures. However, some inconsistent information has been reported regarding the characteristics of spalling so that different temperatures have been reported as the critical temperatures for occurrence of this phenomenon. Also, different failure mechanisms including a thermomechanical process [27,28], a thermo-hydral process [9–11], and a combination of them [29] have been suggested as the main causes for spalling of HSC. Zeiml et al. [30] reported that spalling occurs when the permeability of the dry zone (a region without liquid water) of the concrete member is not sufficient to avoid a continuous pressure build-up as a consequence of vaporization of evaporable water. They presented an illustration of mechanism of spalling based on the results of some work [31–33] as shown in Fig. 1.

However, the use of polypropylene (PP) fiber has been recommended by all of the researchers to reduce and eliminate the risk of the explosive spalling in HSC at elevated temperatures. From the industrial point of view, a dosage of 2 kg/m^3, a fiber length between 10 and 20 mm, and a fiber diameter of 50–200 μm are generally adopted for preventing current HSCs from spalling [34]. Polypropylene fibers are produced from homopolymer polypropylene resin [35]. PP fibers significantly decrease the plastic shrinkage cracking as well as drying shrinkage cracking [36,37]. Furthermore, PP fibers improve the ductility, toughness, and impact resistance of concretes. With regard to these advantages of the presence of PP fibers, they are successfully used for overlays and pavements, slabs, floor systems, crack barrier, precast pile shells, and shotcrete for tunnel linings, canals, and reservoirs [38]. Another area of using PP fibers is concrete-filled steel hollow sections. As mentioned earlier, several researchers have reported the preventative effect of PP fibers against spalling under elevated temperatures. Kalifa et al. [34] showed the good efficiency of PP fibers regarding spalling even at dosages as low as 0.9 kg/m^3. However, different researchers have inconsistently reported the relative residual strength of HSC containing PP fibers after exposure to high temperatures. Poon et al. [39] reported that after exposure to 600 °C the relative residual compressive strength of ordinary Portland cement (OPC) concretes was slightly increased if 0.22% (by volume) of PP fibers was added, whereas the relative compressive strengths of OPC and PP fiber concretes were approximately the same at 800 °C. They also observed significant reductions in the relative compressive strength of concretes containing 10% silica fume (SF) by the presence of 0.22% PP fibers (by volume) after heating to 600 and 800 °C, which were approximately 9% and 30%, respectively. Chan et al. [40] reported that the relative residual compressive strengths of concretes containing 10% SF were decreased around 6.1% by adding 1.82 kg/m^3 of PP fibers after subjecting to 800 °C. Chen and Liu [26] reported that the relative residual compressive strength of concretes with and without PP fibers was the same at 200 °C, whereas the relative strength losses of concretes containing 6% PP fibers (by volume) were approximately 8%, 24%, and 20% higher than those of concretes without PP fibers after heating to 400, 600, and 800 °C, respectively. Hoff et al. [5] reported that the relative compressive strengths of limestone coarse aggregate concretes were increased about 18.9% and 12.7% at 100 and 200 °C, respectively, by adding 1.5 kg/m^3 of PP fibers, whereas the relative compressive strengths of PP fiber concretes were significantly lower than those of non-fiber concretes at 300 and 500 °C. Furthermore, the relative residual compressive strengths of concretes with and without fibers were approximately the same above 700 °C.

In addition to an enormous amount of experimental data that has been reported, some mathematical and numerical models have been proposed for modeling concrete behavior at high temperatures as a multi-phase porous material [41–43].

In general, it can be concluded that there is inconsistent information on the residual compressive strength of high-strength

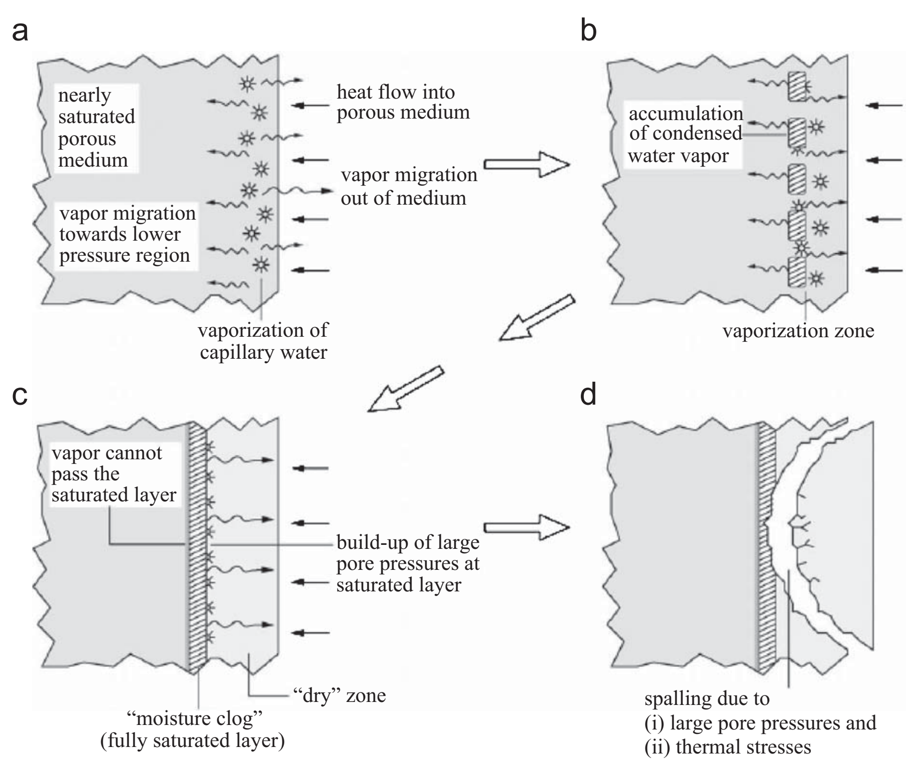

Fig. 1. Proposed mechanism of spalling of concrete subjected to fire [30-33].