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Mechanical behaviour of ultra-high strength concrete at elevated temperatures and fire resistance of ultra-high strength concrete filled steel tubes

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ABSTRACT

This paper introduces experimental study on mechanical behaviour of an ultra-high strength concrete (UHSC) at elevated temperatures and then a simple calculation method to predict the fire resistance of tubular column infilled with the UHSC. The cylinder compressive strength of the UHSC was 166 N/mm^2 at room temperature. The compressive strength and modulus of elasticity of the UHSC were measured up to 800 °C. Then the temperature-dependent mechanical properties were compared with those of normal/high strength concretes provided in Eurocode 2 and ANSI/AISC 360-10, and with those of concretes in literature. The comparisons showed that the compressive strength and elastic modulus of the UHSC were generally reduced less than those of normal/high strength concretes at the elevated temperatures. The temperature-dependent mechanical properties were proposed for evaluating fire resistance of steel tubular columns infilled with the UHSC. The UHSC investigated in this project was shown to markedly improve the fire resistance in a number of cases well documented in the literature concerning tubular columns filled with the normal- and high-strength concretes.
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1. Introduction

High strength concrete (HSC) has been used in high-rise buildings and the other structures because of its technical, architectural, and economical advantages over normal strength concrete (NSC). However, the need for sustainable constructions around the world, which aims to further reduce the consumption of construction materials, requires higher-strength concretes to be introduced. Nowadays, ultra-high strength concrete (UHSC) with compressive strength higher than 120 MPa has been available with the development of concrete technology and the availability of variety of materials such as silica fume and high-range water-reducing admixtures. However, the UHSC is mainly used in offshore and marine structures and for industrial floors, pavements and security barriers. It has not been used in building structures especially high-rise buildings. This may be due to the fact that there are design concerns on its brittleness and fire resistance. These concerns lead to the situations that the current standards allow the use of concrete only up to Class C90/105 for concrete structures and Class C50/C60 for steel-concrete composite structures [1–4].

To evaluate the fire resistance of structural members with the UHSC, the knowledge of the temperature-dependent mechanical properties, such as compressive strength and modulus of elasticity, is required. In literature, the said properties of the NSC and HSC have been extensively studied where the compressive strength was found to be affected by the type of aggregate [5–7]. Siliceous-aggregate concrete brought in greater strength losses than concrete with carbonate aggregate, whereas fire-brick aggregate exhibited superior performance. The strength was also affected by heating rate [8]. Higher heating rate generally yielded lower strength and was more likely to induce spalling. Furthermore, the loss of strength of HSC was larger than that of NSC [2,9–13]. The modulus of elasticity was generally governed by the type of aggregate and the water/cement ratio [14–16]. The loss of modulus increased as the water/cement ratio increased. According to the literature [7,8,17], the elastic modulus is less affected by the temperature in HSC compared with NSC. The addition of fibers is deemed to affect the mechanical properties of concrete. Steel fibers generally increase both of the compressive strength and elastic modulus [18]; whereas polypropylene fibers decrease the compressive strength but increase the elastic modulus [19]. Overall, there is still little information in the available literature

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Table 1
Mixing proportions of plain UHSC.

Water/D4	Water (kg)	D4 (kg)	UHSC Volume (m^3)
0.076	202.1	2659.6	1.0

concerning the mechanical properties of UHSC at high temperatures. Research efforts in this domain are, therefore, badly needed indeed.

Due to the brittleness, HSC is generally used in hollow steel tubes to form composite columns. Concrete filled steel tubular (CFST) column integrates the respective advantages of steel and concrete materials thus exhibits many advantages over conventional steel or reinforced concrete columns, such as high load bearing capacity, good ductility due to confinement effect, and convenience for fabrication and construction due to permanent formwork from steel tubes [20]. The CFST columns also have good fire resistance due to heat sink effect of the infilled concrete and prevention of spalling of the infilled concrete by the steel tube. Researches on the fire resistance of CFST columns started from 1970s. National Research Council of Canada (NRCC) is the pioneer in this area [21–24]. Until now, the researches on the CFST columns with HSC have been carried on by Kodur [25], Lu et al. [26–28] and Romero et al. [29]. However, little information is found for studies on CFST columns with the UHSC of compressive strength higher than 120 MPa.

A concept of CFST column with the UHSC was proposed for load-bearing system of the high-rise building constructions [30,31]. The compressive cylinder strength of the UHSC exceeded 160 MPa. This paper presents a study on the mechanical properties, such as the compressive strength and modulus of elasticity, of the UHSC under elevated temperatures. The temperature dependent properties were obtained through standard compression tests. With the tested mechanical properties, the fire resistance of CFST columns with the UHSC was evaluated when they were subject to standard ISO-834 fire, and compared with that of CFST columns with the NSC and HSC.

2. Basic materials

The basic materials to produce the UHSC were Ducorit® D4 and water. Ducorit® D4 is one of the commercial Ducorit® products. It is made from cementitious mineral powder, superplasticizer and fine bauxite aggregates with maximum sizes <4.75 mm and 49% <0.6 mm. The mixing proportions for the UHSC are shown in Table 1. Workability of the fresh UHSC was tested using the slump flow test in accordance with ASTM C1611/C1611M-09b. The slump flow spread was 735 mm and the density was 2700 kg/m^3 [32].

3. Standard compression tests at elevated temperatures

3.1. Test specimens

Spalling has been found for the HSC subject to high temperatures [33]. The spalling is basically caused by thermal stresses due to a temperature gradient in concrete during heating, and by splitting force due to the release of vapor above 100 °C. It is believed that the present UHSC is more likely to spall under high temperatures. With regard to this point, a series of trial tests have been done to investigate the spalling behavior of the UHSC [34]. It was found that the plain UHSC specimens and the UHSC specimens with steel fibers (dosage up to 1.0% in volume) spalled around 490 °C as shown in Figs. 1 and 2, respectively. The spalling was so severe that the cover plate of the casing was bent and the ceiling of the furnace was damaged. However, the UHSC specimens with 0.1% polypropylene fibers did not spall at elevated temperature up to 800 °C as shown in Fig. 3. The properties of steel and polypropylene fibers are shown in Table 2. It is worth noting that the workability and flowability of the UHSC were not affected by the addition of polypropylene fibers as the UHSC is most likely pumped into hollow tubes for CFST columns. The dosage of polypropylene fibers was lower than that recommended by Eurocode 2 where >2 kg/m^3 (0.25% in terms of volume) of monofilament propylene fiber should be included in the HSC mixtures to prevent spalling [2].

For the standard compression tests, cylinder specimens with a nominal diameter of 100 mm and a height of 200 mm were prepared. The actual diameters and heights were measured before the test started. The specimens were cured in lab air where the relative humidity was approximately 85% and the room temperature was around 30 °C at daytime and 25 °C at night. Owing to the fact that the moisture content in the UHSC is low, the effect of moisture on the mechanical properties is deemed to be insignificant [34]. On the other hand, the moisture is evaporated around 100 °C, it may only have minor influence at 100 °C but insignificant influences at higher temperatures. Considering these, the unsealed specimens were used.

3.2. Test setup

The compression tests were conducted by means of a servo-hydraulic testing machine with a maximum 300 mm stroke displacement and capacity of 10,000 kN. The heat system was a split-tube furnace with a two-zone configuration and an optional side entry extensometer port. The furnace is constructed with S304 stainless steel shell and alumina insulation material. Heating elements are coils of Fe—Cr—Al alloy 0Cr27a17mo2. A type K thermocouple is mounted in the center of each heating zone. The external dimensions (diameter × height) are 700 × 600 mm and internal heating dimensions (diameter × height)

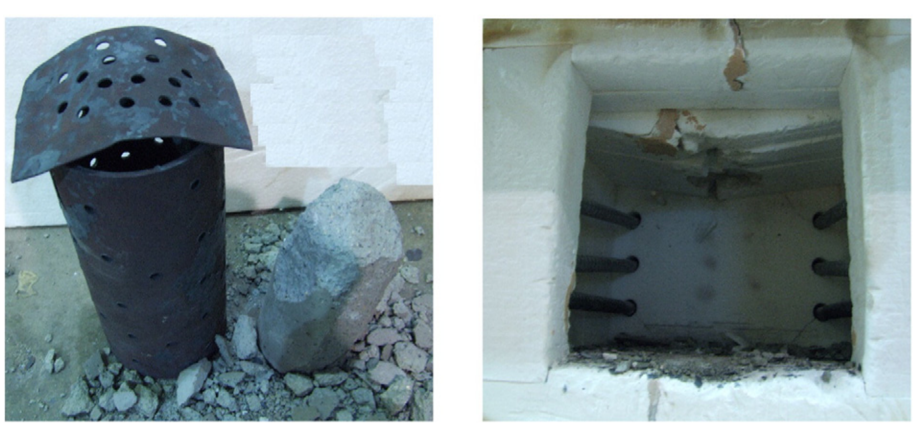

Fig. 1. Spalled UHSC specimens without fibers.

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