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Mechanical properties of high-strength concrete after fire

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Abstract

With compressive strength grade of C40, C60, and C70, respectively, normal-strength concrete (NSC) and high-strength concrete (HSC) were used to investigate compressive strength, splitting tensile strength, and bending strength after high temperature. The oil furnace is used in this study. Its temperature–time curve is close to standard curve, which conforms to Chinese standard GB/T 9978-1999. After being heated to temperatures of 200, 400, 600, 800, and 1000 °C, respectively, the mechanical properties of HSC were tested. The influence of temperature, water content, specimen size, strength grade, and temperature profiles on mechanical properties of HSC are discussed.

Keywords: High-strength concrete; Fire; Mechanical properties

1. Introduction

The fire resistance capacity of concrete is very complicated because not only is concrete a composite material with components having different thermal characteristics, it also has properties that depend on moisture and porosity [1]. Various performances of normal-strength concrete (NSC) after fire have been researched exhaustively. Although the thermal parameters of high-strength concrete (HSC) components are similar to those of NSC, such as specific heat, diffusivity, thermal conductivity, and coefficient of thermal expansion, some studies have shown that HSC has such disadvantages as poor fire resistance [2,3], being more prone to explosive spalling due to their low permeability and high brittleness [4,5] compared to NSC. With the growth of engineering structure towards large span, higher rise, and ultra-high rise, the applications of HSC are increasing day by day. Therefore, questions about the performance of HPC at elevated temperature need to be examined.

2. Research methods

2.1. Specimen making

The materials used in this study were Portland cement conforming to 42.5 P II according to Chinese standard GB175-1999, river sand with fineness modulus of 2.50, crushed basalt with sizes of approximately 5–10 mm and approximately 10–20 mm, fly ash with grade I according to Chinese standard GB1596-91, and high-range water-reducing agent. The mix proportions are listed in Table 1.

The average values of compressive strength of C40, C60, and C70 after curing for 28 days are 42.5, 68.0, and 76.0 MPa, respectively. The sizes of specimens include $100 \times 100 \times 100$, $150 \times 150 \times 150$, and $100 \times 100 \times 415$ mm. After curing for 28 days at 20 °C and 90% RH, the specimens were tested. The strength was tested according to Chinese standard GBJ 81-85.

2.2. The oil-burning furnace and temperature–time curve

The oil-burning furnace is designed according to Chinese standard GB/T 9978-1999. The size of the furnace is $580 \times 400 \times 450$ mm, and the furnace temperature is tested by Pt–Rh–Pt thermocouple. The furnace is illustrated in Fig. 1. According to GB/T 9978-1999, the standard temperature–time curve is required as

$$T - T_0 = 345 lg(8t + 1) \quad (1)$$

In this formula, T is the mean furnace temperature (°C) at t time; T_0 is the initial furnace temperature (°C); t is the time that specimens experienced fire.

The temperature–time curves are given in Fig. 2. Curve 1 is the temperature–time curve of Chinese standard GB/T 9978-1999, and Curve 2 is the temperature–time curve of oil-

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Table 1
Mix proportion of concrete (1-m^3 concrete)

Series	Cement (kg)	Fly ash (kg)	Sand (kg)	Coarse aggregate (kg)		Water (kg)	High-range water-reducing agents (m^3)
				Approximately 5–10mm	Approximately 10–20mm		
C40	368	0	656	466	699	196	0
C60	487	86	679	405	607	172	9.17×10^{-3}
C70	410	150	628	335	781	146	12.44×10^{-3}

burning furnace achieved in this research. Curve 3 is the temperature–time curve by electric oven from Ref. [6].

When the temperature inside the furnace reaches 200, 400, 600, 800, and 1000 °C, respectively, heating is stopped immediately. At this time, the temperature on the surface is considered to be 200, 400, 600, 800, and 1000 °C, respectively, while the temperature at the center of the specimens is lower. Specimens are cooled to room temperature in the furnace and then taken out for testing.

3. Results and discussion

3.1. Compressive strength

The concrete compressive strength after fire is given in Fig. 3. The dashed line used for comparison is test results from Ref. [6].

3.1.1. Influence of temperature and temperature profile

Fig. 3 shows that the compressive strength of concrete drops with temperature starting from 200 °C in this research. With the example of C70, the compressive strength after 200 °C is retained at 82.3%. The retained compressive strength after 400 °C is 63.2% compared to the unfired strength, while after 600 °C, the strength is 58.1%. The compressive strength value drops sharply to 21.3% compared to that of specimens unfired after 1000 °C. For concrete subjected to 200 °C, color does not change, while straw yellow, off-white, and red appear when the concrete are exposed to temperature of 400, 800, and 1000 °C, respectively. Therefore, by combining changes in rules of strength, color, and temperature during fire, the retained compressive strength can be inferred primarily. This will provide some reference for structure in practice. The reduction in compressive strength and the change in color of concrete result from the change in structure and composition of concrete during firing. Some complicated processes of shrinkage, decomposition, expansion, and crystal destruction occur during fire. According to Ref. [7], crystal shape transformation of SiO_2 results in the increase of volume up to 0.85%. Dehydration, followed by the hydroscopic process of $Ca(OH)_2$, also makes volume expansive. Moreover, expansion caused by temperature rise and shrinkage caused by dehydration of cement paste ultimately results in a volume change of 0.5% [7].

The test results reported in Fig. 3 are different from that in Ref. [6]. The difference between two test results is caused by different temperature profiles. In Ref. [6], an electric furnace with a low heating rate is used to make concrete heat homogeneously, while in this study, an oil burner furnace is used to achieve a high heating rate speed that is much prone to actual fire condition. Test results from the experiment with electric furnace cannot reflect real situations of fire before 400 °C.

3.1.2. Effect of strength grade

From Fig. 3, it can be seen that the strength loss of HSC (C60 and C70) surpasses that of NSC (C40) in this

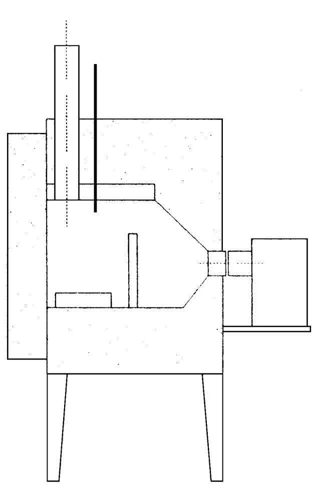

Fig. 1. Illustration of oil-burning furnace.

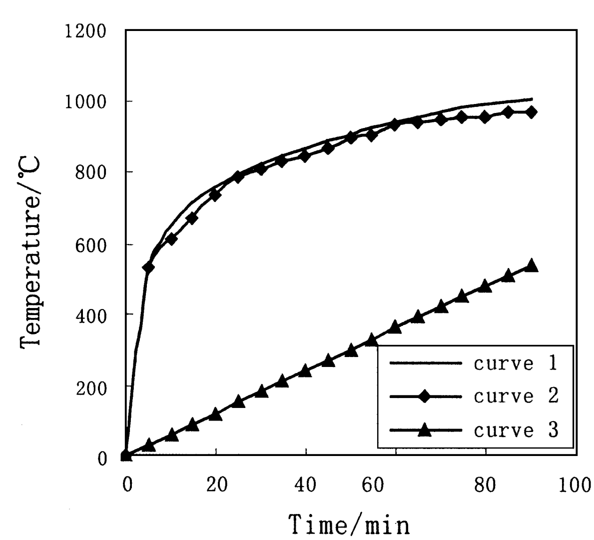

Fig. 2. Temperature–time curve of furnace.

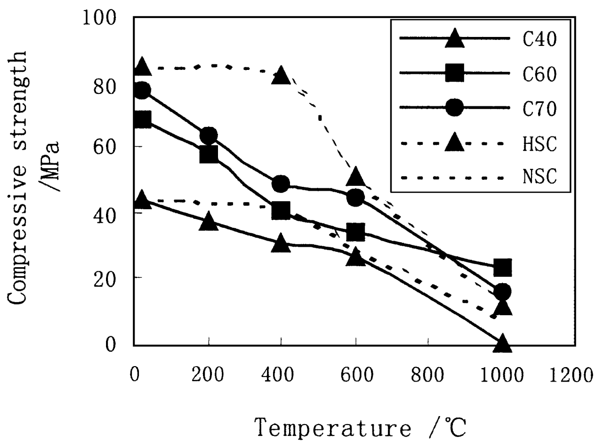

Fig. 3. Compressive strength of concrete after high temperature.

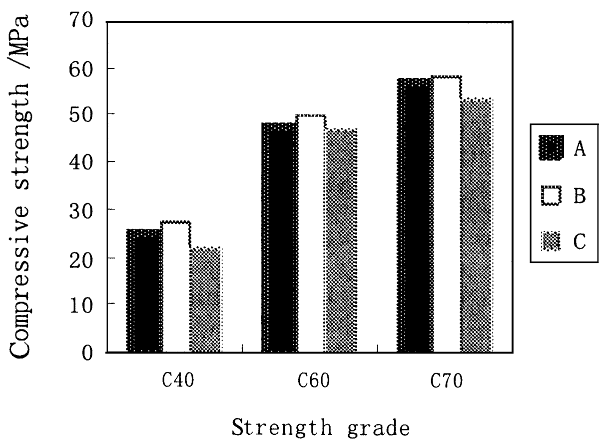

Fig. 4. Effect of water content to compressive strength after heated to 800 °C.

research. This difference is noteworthy, especially at the range of 25–400 °C. For compressive strength grade of C70, the retained compressive strength at 400 °C is 63.2%, while for compressive strength grade of C40, the value is 71.2%. Inasmuch as the strength grade is higher, the internal structure is denser. According to Ref. [4], HSC will produce explosive crack at about 400 °C because of its dense structure.

3.1.3. Effect of water content

The compressive strength of concrete after it was heated to 800 °C is given in Fig. 4. Label A refers to the specimens heated to constant weight at 105 °C before fire. Label B refers

Table 2
Water content of specimens

Series	A			B			C		
Strength grade	C40	C60	C70	C40	C60	C70	C40	C60	C70
Water content (%)	0	0	0	1.8	1.2	2.1	3.7	1.4	2.6

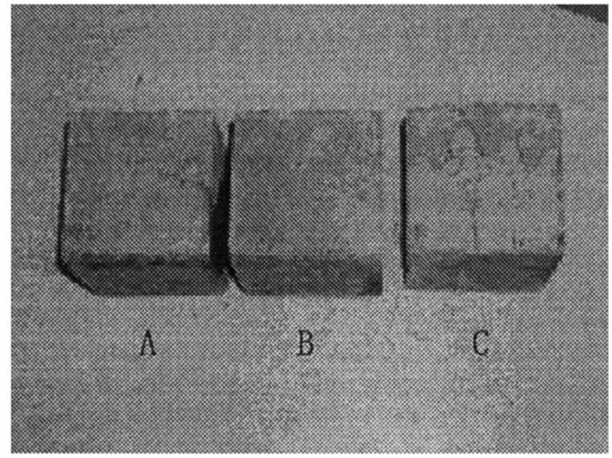

Fig. 5. Surface character of C70 after heated to 800 °C.

to the ordinary specimens. Label C refers to the specimens immerged into water for 48 h before fire. The water content values of specimens are listed in Table 2, in which each value represents the average of three similar specimens.

Fig. 4 shows that different water content brings about different concrete compressive strength after high temperature. Because of dense internal structure of HSC, it is difficult for vapor to be discharged at high temperature. The vapor pressure, which causes cracks on concrete surface, comes into being. Subsequently, concrete properties are aggravated.

Fig. 5 shows the surface character of C70 at three different water contents, as indicated by Samples A, B, and C, after high temperature. After 800 °C, many surface cracks occur on Sample C. However, few cracks happen on Sample B. The reason is that free water has been transgressed a great deal at 105 °C, then cement particles combine more tightly, and vapor transgress more difficultly. Further research on water content will be carried out for specimens heated to 400 °C, that is, before $Ca(OH)_2$ decomposes.

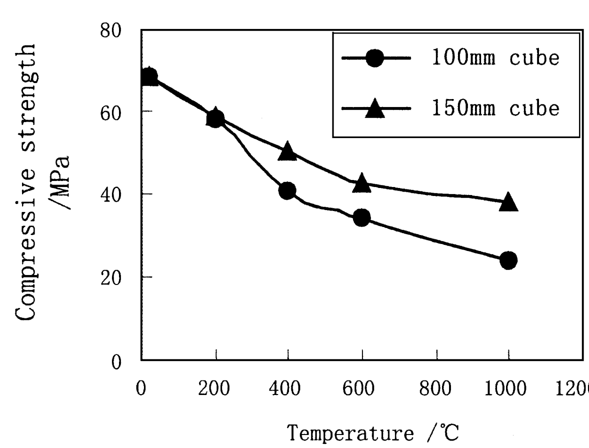

Fig. 6. Effect of specimen size on compressive strength after high temperature.

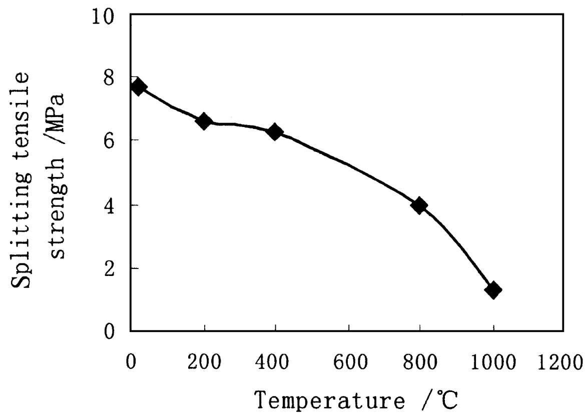

Fig. 7. Splitting tensile strength after fire.

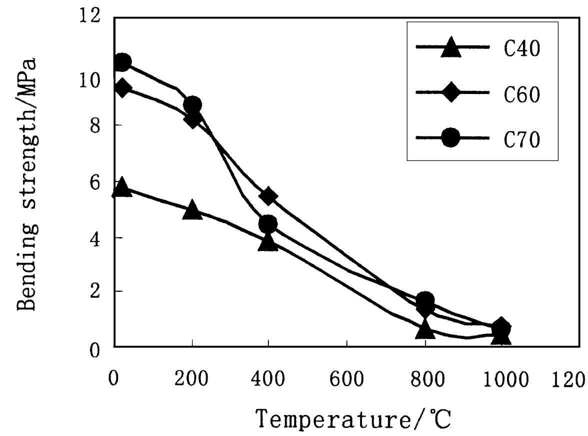

Fig. 8. Bending strength after fire.

3.1.4. Effect of specimen size

Fig. 6 shows the comparison of compressive strength loss of C60 with two specimen sizes of 100 × 100 × 100 and 150 × 150 × 150 mm. It can be seen that the compressive strength is affected by specimen size after high temperature. The larger the specimen size is, the lesser the strength loss becomes. Concrete is poor in heat conduction; therefore, there exists a temperature distribution field inside concrete specimens during heating. Consequently, the temperature in the center of the concrete is much lower than that on the exposed surface. Therefore, under the same condition, the compressive strength loss of the concrete specimen with a larger cross-section is smaller.

In short, the mechanical properties of HSC after high temperature affected by many factors, such as temperature, strength grade, water content, specimen size, and temperature, elevated speed.

3.2. Splitting tensile strength

The specimens used in this research are concrete cubes (100 mm) with a strength grade of C70. These specimens are fired up to the temperature of 200, 400, 800, and 1000 °C, respectively. The test results are given in Fig. 7.

From Fig. 7, it can be seen that splitting tensile strength is reduced after elevated temperature. After 1000 °C, the retained splitting tensile strength is only 16.9% compared to the unfired. For the C70 concrete, the dense structure induces thermal stress that results in many microcracks and even a few macrocracks. The decompositions of $Ca(OH)_2$ and other ingredients also induce the appearance of cracks. On one hand, the existence of cracks reduces a valid area of cross-sections. On the other hand, the existence of tensile stress makes cracks expand. Therefore, the effect of crack on the splitting tensile strength is more obvious than on the compressive strength. Table 3 shows the retained splitting tensile strength, the compressive strength, and the bending strength with the strength grade of C70 after fire compared to that at 25 °C.

Table 3
Retained splitting tensile strength, compressive strength, and bending strength after fire compared to that at 25 °C

Temperature (°C)	25	200	400	600	800	1000
Retained splitting tensile strength (%)	100	85.7	81.8	–	51.9	16.9
Retained compressive strength (%)	100	82.3	63.2	58.1	–	27.3
Retained bending strength (%)	100	84.5	43.7	–	16.3	7.4

3.3. Bending strength

Bending strength tests are carried out by the specimen of C40, C60, and C70 with the size of 100 × 100 × 415 mm. Test results are given in Fig. 8.

Bending strength is reduced with the temperature elevated. The retained bending strength is listed in Table 3. Bending strength of C70 is reduced to 16.3% after 800 °C. However, after 1000 °C, only 7.4% is retained; that is, the reduction of bending strength is much higher than that of compressive strength and splitting tensile strength. Fig. 8 shows that the bending strength of HSC (C60 and C70) drops more sharply than that of NSC (C40), especially within the range of 200–400 °C.

4. Conclusions

1. Compared to the test results from the experiment with an electric furnace, different test results are obtained in this study by oil furnace; that is, the strength reduction starts from temperature elevating and not after 400 °C, as stated in the research by electric furnace. Therefore, electric furnace cannot reflect real situations of fire before 400 °C because its temperature elevation speed is very slow.
2. After the temperature inside the furnace reached 200, 400, 600, and 1000 °C, the compressive strength of the specimens with a strength grade of C70 was retained at 82.3%, 63.2%, 58.1%, and 27.3%, respectively. After the temperature inside the furnace reached 200, 400,

800, and 1000 °C, the splitting tensile strength was retained at 85.7%, 81.8%, 51.9%, and 16.4%, respectively, and the bending strength was retained 84.5%, 43.7%, 16.3%, and 7.4%, respectively.

3. The larger the specimen size is, the lesser the strength loss becomes. Larger size specimens remain to be investigated for fire resistance.
4. The effect of water content on the compressive strength after 800 °C is not remarkable. The effect of water content around 500 °C, that is, before decomposition of $Ca(OH)_2$, will be investigated further.

Acknowledgements

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