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# Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures

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**Abstract**

An experimental investigation was conducted on the effect of thermal shock during cooling on residual mechanical properties of fiber concrete exposed to elevated temperatures from 200 to 800 °C. Various cooling regimes were used including natural cooling, spraying water for a series of durations from 5 to 60 min, and quenching in water. The temperature determination results prove that the rapid cooling regimes such as quenching in water, or water spraying for 30 min or more, caused an action of "thermal shock" to concrete under elevated temperature, characterized by a high temperature decreasing rate ranged from 25 to 44 min/°C. The experimental results indicate that, compared with natural cooling, thermal shock induced by water quenching and spraying water caused more severe damage to concrete, in terms of greater losses in compressive strength, tensile splitting strength, and fracture energy. The fact that the impact of spraying water for 30 min or more on mechanical properties was almost the same as that of water quenching, indicates that spraying water for 30 min or more could cause thermal shock to a similar degree to water quenching, which is in good agreement with the results of the temperature determination. Hybrid fiber (steel fiber and polypropylene fiber) can enhance residual strength and fracture energy of concrete subjected to thermal shock induced by rapid cooling from high temperatures up to 800 °C to room temperature.


*Keywords:* High temperature; Thermal shock; Mechanical properties; Fiber reinforcement; High-performance concrete; Fire; Rapid cooling

## 1. Introduction

As a considerable shortcoming of high-strength concrete/high-performance concrete (HSC/HPC), thermally induced explosive spalling has attracted lots of research attention during the past two decades [1,2]. It has been proved that, among a couple of factors influencing occurrence of explosive spalling of HSC/HPC, internal vapor pressure which is associated with both internal moisture content and dense microstructure of concrete, is a main factor governing spalling occurrence [3,4]. In light of this point, using polypropylene fiber (PP fiber) becomes a common approach for alleviating or even avoiding explosive spalling of HSC/HPC [5,6].

In general, if concrete has been well prepared for inhibiting explosive spalling, the main damage to concrete caused by fire or elevated temperatures should be loss in mechanical properties. Experimental results [7,8] confirmed that compressive strength can be broadly maintained within a range of temperature from 20 to 400 °C. Considerable loss in compressive strength occurs between 400 and 600 °C, and most of the original compressive strength before heating may be lost from 600 to 800 °C. Compared with compressive strength, tensile splitting strength suffers a more severe loss under identical temperature, as the latter is more sensitive to thermally induced cracking [7].

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Nevertheless, most research data of residual strength after exposure to high temperature were obtained under conditions of natural cooling [1,2,7,8], which should differ obviously from cooling regimes in a real fire, where water spraying is usually used for fire extinguishing and consequently thermal shock is induced to concrete. It has been reported that water cooling caused more severe decrease in strength compared to natural cooling [9–11]. Therefore, the effect of cooling regimes on mechanical properties of concrete is of great concern, especially after a fire case was reported [12,13], which happened in the city of Hengyang, Hunan Province, China, November 3rd, 2003. In this case, an 8-storey reinforced concrete building collapsed catastrophically during fire extinguishing and twenty fire fighters died from the building collapse. Furthermore, apart from these reports on the effect of cooling on plain concrete with no fiber [9–13], there is little literature on properties of fiber concrete subjected to various cooling regimes.

As it has been found in a preceding investigation by the authors [14] that using hybrid fiber (steel fiber and polypropylene fiber) is an optimum approach for enhancing fire resistance of HSC/HPC, this paper presents an investigation on the effect of cooling regimes, including natural cooling, spraying water for a series of durations from 5 to 60 min, and quenching in water, on residual mechanical properties of high-performance concrete incorporating hybrid fiber after exposure to high temperatures from 200 to 800 °C.

## 2. Experimental details

### 2.1. Raw materials

Cement: ordinary Portland cement, strength grade 42.5 MPa (which was compressive strength at 28 days, determined on mortar specimens at a mix proportion of cement:sand:water = 1:3:0.5 by mass, according to Chinese Standard GB/T 17671-1999 [15]). Fine aggregate: medium sand, with the modulus of fineness of 2.5. Coarse aggregate: crushed limestone, particle size between 5 and 25 mm. High-range water reducing agent, at a dosage from 1.0% to 2.5% of cement contents to maintain slump of mixtures from 100 to 150 mm. The diameter of the polypropylene fiber (PP fiber) was 20 μm, while the diameter of steel fiber was 2 mm, as given in Table 1.

### 2.2. Experimental procedure

Five types of concretes were prepared, of which mix proportions and compressive strength at 3 days and 28 days are given in Table 2. Cube specimens of 100 mm size were used for strength determination, and beams of 100 mm height, 100 mm width and 400 mm length, were used for fracture energy determination. After demolding, the specimens were cure in water at 20 °C till 58 days.

At 58 days, the specimens were taken from curing water, and dried under temperature of 105 °C in order to avoid undesirable explosive spalling of concrete when exposed to high temperature. The specimens were exposed to high temperatures in an electric furnace, 200, 400, 600, and 800 °C, respectively. The time–temperature curve of the furnace is given in Fig. 1. The ISO 834 curve in Fig. 1 is a standard time–temperature curve for fire resistance testing recommended in ISO standard, ISO 834. For each exposure to high temperature, the target temperature was maintained for 1 h. After exposure to high temperatures, the specimens were subjected to various cooling regimes as given in Table 3. Under each cooling regime, six cubes (three cubes a batch for compressive strength, and the other three cubes a batch for tensile splitting strength determinations, respectively) and two beams (for fracture energy determination) were used for each type of concrete. After the specimens cooled down to room temperature, compressive strength, tensile splitting strength, and fracture energy were measured respectively.

Table 1
Characteristics of fibers

| Type | Density (g/cm$^3$) | Diameter | Length (mm) | Aspect ratio | Tensile strength (MPa) | Elastic modulus (GPa) |
|---|---|---|---|---|---|---|
| PP fiber | 0.91 | 20 μm | 20 | 1000 | 560–770 | 3.5 |
| Steel fiber | 7.80 | 2 mm | 30 | 15 | 650–800 | 200 |

Table 2
Mix proportions and compressive strength of concretes prepared[a]

| Type of concrete | $W/B$ | Quantity (kg/m$^3$) | | | | | | | Compressive strength (MPa) at 28 days |
|---|---|---|---|---|---|---|---|---|---|
| | | C | W | S | G | SF | PP-F | S-F | |
| 26C | 0.26 | 535 | 156 | 597 | 1153 | 64 | 0 | 0 | 83.5 |
| 26P1 | 0.26 | 519 | 151 | 579 | 1122 | 62 | 0.91 | 0 | 88.6 |
| 26P2 | 0.26 | 515 | 150 | 575 | 1112 | 62 | 2.73 | 0 | 83.4 |
| 26H1 | 0.26 | 527 | 154 | 588 | 1139 | 63 | 0.60 | 80 | 87.2 |
| 26H2 | 0.26 | 528 | 154 | 589 | 1139 | 63 | 1.82 | 70 | 89.3 |

[a] $W/B$ for water/binder ratio (mass), C for ordinary Portland cement (OPC), SF for silica fume, S for sand, G for coarse aggregate, W for water, PP–F for 20 μm polypropylene fiber (PP fiber), and S-F for steel fiber respectively.