Pergamon

Cement and Concrete Research 30 (2000) 379–383

CEMENT AND CONCRETE RESEARCH

Effect of heating and cooling regimes on residual strength and microstructure of normal strength and high-performance concrete

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Received 9 July 1999; accepted 13 December 1999

Abstract

A research program was carried out to investigate the residual compressive strength of high-performance concrete (HPC) and normal strength concrete (NSC) after they were exposed to high temperatures, 800°C and 1100°C, and two cooling regimes. Test results obtained showed that compared with the strength at room temperature, the residual strength of both HPC and NSC dropped sharply after exposure to high temperatures. Water cooling, which resulted in a significant thermal shock, caused a bit more severe deterioration in strength compared to furnace cooling. Thermal shock was not necessarily the primary cause for spalling in HPC. Mercury intrusion porosimetry tests were carried out to measure variation in the pore structure of concrete. Significant changes in the cumulative pore volume curves before and after high temperatures in both NSC and HPC were observed. The cumulative pore volume of HPC increased more remarkably than that of NSC. The difference between the effects of the two cooling regimes on mechanical property as well as the microstructure decreased at 1100°C when compared 800°C.

Keywords: High-performance concrete; High temperature; Compressive strength; Microstructure

1. Introduction

High-performance concrete (HPC), with high strength, high toughness or increased resistance against physical and chemical damage, is increasingly replacing normal strength concrete (NSC), especially in applications with exposure to severe environments. It has been revealed that these advantages in HPC result from the improvement of internal microstructure of the material as compared with NSC [1,2]. Dense microstructure in HPC often ensures a high strength and a very low permeability, which is essential to obtain good durability in severe conditions where there are harmful agents such as chloride, sulfates, and so on. However, in some situation where HPC is subjected to fire attack, the dense microstructure of HPC seems to become a disadvantage. Recent research results indicate that there is a big difference between the behaviors of HPC and NSC when subjected to high temperatures [3,4]. It was also observed that some HPC—especially high strength concrete (HSC)—are quite susceptible to spalling, or even explosive spalling when exposed to speedy temperature rise in case of fire [5]. Experimental studies have shown that spalling of HPC is influenced or governed by a lot of complicated factors such as rate of temperature elevation, mineral constituents of aggregates, thermally induced stress, density of concrete, moisture content, and so on. Although the failure mechanisms for HPC spalling has not been sufficiently revealed, there are two mechanisms that are considered as the direct causes of spalling in HPC. One is the thermal stress induced by the rapid temperature rise or thermal shock [6]; the other is water vapor pressure that may cause large pore vapor pressure [7]. There are many works in literature that deal with the influence of different heating rates on the behaviors of concrete material [8–11]. However, there is little research about the effect of cooling regimes, which might be important in such a situation when a fire is being extinguished by using water in a real situation. In a previous study [12], the residual strength and the corresponding variations of pore structure of ordinary concrete and HPC after being subjected to 800°C and furnace cooling were investigated. In this paper, both NSC and HPC were further tested after exposure to temperatures up to 1100°C and to

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0008-8846/00/$ – see front matter
PII: S0008-8846(99)00264-1

different cooling regimes. The variation in the pore structures of HPC and NSC were also measured by means of mercury intrusion porosimetry (MIP).

2. Materials and test methods

Ordinary Portland cement, river sand, superplasticizer of naphthalene sulphonates and pulverized fly ash (PFA) in accordance with BS12: 1991, BS882, BS5075 Part 3: 1985, and BS3892 Part 1: 1982, respectively; silica fume, crushed granite with maximum size of 20 and 10 mm, steel, and polypropylene fiber were adopted in this study. The chemical compositions and physical properties of cement, silica fume, and fly ash are given in Table 1. The length and aspect ratio are 25 mm and 60, respectively, for the steel fibers and 19 mm and 360, respectively, for the polypropylene fibers. The mix proportions are summarized in Table 2.

The specimens exposed to high temperatures were cubes with dimensions of 100 × 100 × 100 mm. After 24-h moisture curing in moulds, the concrete specimens were demoulded and stored in freshwater at 20 ± 5°C. After 90-day curing, the saturated specimens were taken out of the water and immediately put into a computer-controlled electric furnace for high temperature tests. The temperature in the furnace was elevated at a rate of 5–7°C/min. Two maximum temperatures (800°C and 1100°C) were chosen. After the peak temperatures were reached, 1-h maintenance was conducted and then the specimens were allowed to cool down. Two cooling regimes were chosen. One was furnace cooling, i.e., specimens underwent natural cooling in the furnace to room temperature at a rate of about 2–3°C/min. The other was water cooling, i.e., the hot specimens at peak temperature (800°C or 1100°C) were taken out of the furnace and immediately immersed in a freshwater tank with water temperature at 20 ± 5°C. The compressive strength of the concrete samples—including control samples that were not exposed to high temperature and those that were subjected to high temperature—were tested according to BS 1881 Part 116: 1983. The samples for MIP test were prepared from the cored specimens and cautions were taken to ensure that no coarse aggregates were included. In the MIP test, the maximum pressure of the porosimeter was 207 MPa, covering the pore diameter ranging from 6.0×10^{-9} to 3.6×10^{-4} m. Values of 140° and 0.485 N/m were used for the contact angle and mercury surface tension, respectively. The samples were dried at 105°C before the MIP test. Each strength or porosity value was the average of the three specimens.

Table 1
Chemical analysis (percentage by mass) and some properties of cement, silica fume, and PFA

Items	Cement	Silica fume	PFA
SiO_2	20.7	94.0	44.9
CaO	64.4	0.3	5.7
Al_2O_3	5.4	0.3	35.4
Fe_2O_3	2.3	0.8	4.9
MgO	0.9	0.4	1.2
Na_2O	0.13	1.0	1.0
K_2O	0.4	–	1.0
SO_3	2.4	0.2	0.7
LOI	0.97	2.8	5.6
Specific gravity	3.1	2.2	2.1
Specific surface (m^2/kg)	355	2.0×10^4	528

Table 2
The mix proportions for NSC and HPC (kg/m^3)

Series	NP	HS	HF1S	HF2S
Cement	262.5	357.5	357.5	357.5
Water	210.0	176.0	176.0	176.0
Sand	588.8	542.7	542.7	542.7
Coarse (10 mm)	418.7	385.9	385.9	385.9
Aggregate (20 mm)	823.5	767.4	767.4	767.4
Silica fume	–	55.0	55.0	55.0
PFA	87.5	137.5	137.5	137.5
Steel fiber	–	–	78.0	–
Polypropylene fiber	–	–	–	1.82
Superplasticizer (ml/m^3)	–	9×10^3	9×10^3	9×10^3

Note: Series of NP were NSC; series of HS, HF1S and HF2S were HPC.

3. Test results and discussion

The residual strength percentage was the ratio of the strength of samples that were exposed to high temperature to that of the relative control samples. The residual strength and relative change of pore structure of NSC and HPC after being subjected to 800°C and furnace cooling were given in a previous study [12]. The compressive strength of HPC decreased more sharply than that of NSC, as shown in Fig. 1.

After exposure to 800°C, the residual strength percentage of the three series of HPC was 24.0–34.1% for furnace cooling, and 21.4–28.4% for water cooling. When

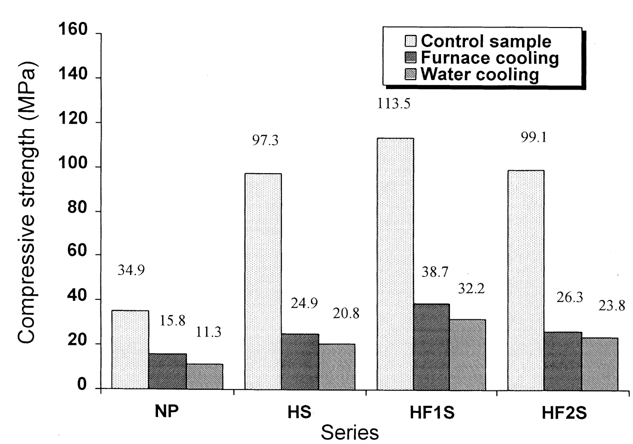

Fig. 1. The compressive strength before and after exposure to 800°C.

temperature reached 1100°C, the residual strength percentage of HPC was 8.1–12.2% for furnace cooling and 8.4–10.4% for water cooling, as shown in Fig. 2. It is obvious that the cooling regimes had just a slight effect on the residual compressive strength. Moreover, the effect of cooling rate was less pronounced for concrete exposed to higher peak temperature. The addition of steel fiber was aimed to constrain the volume change of concrete due to the rapid temperature variation (elevating or cooling) so as to reduce the initiation and propagation of micro-defects in concrete material. Recent studies showed that steel fiber performed well in concrete when exposed to high temperature [13,14]. For example, after 800°C and furnace cooling, HS (without steel fiber) had the residual strength percentage of 25.6%, while HF1S (with steel fiber) had the residual percentage of 34.1%. At room temperature, the compressive strength of HF1S was 16.6% higher than that of HS; after 800°C and furnace cooling, the residual strength of the former was 55.4% higher than that of the latter. Thus, to a certain extent, steel fiber could reduce the deterioration of concrete when subjected to high temperatures. Besides, the addition of polypropylene fiber did not cause a significant decrease in residual strength compared to the case when they are not added.

Spalling—especially explosive spalling—when subjected to fire or sudden temperature rise, is a major disadvantage of HPC. There are still many problems about HPC spalling, which needs to be further investigated due to its complexity. For example, spalling does not occur in all specimens in replicate test specimens under identical conditions. Despite this inconsistency, it is believed that spalling occurs under the combination of certain test conditions. From the viewpoint of mechanics, spalling results from the non-uniformity of stress distribution in a material. As mentioned above, there are two major reasons that directly contribute to the non-uniform stress distribution: (i) one is temperature stress due to thermal gradients, and (ii) the other is water vapor pressure due to the dense microstructure and low permeability of HPC. However, in this study, no

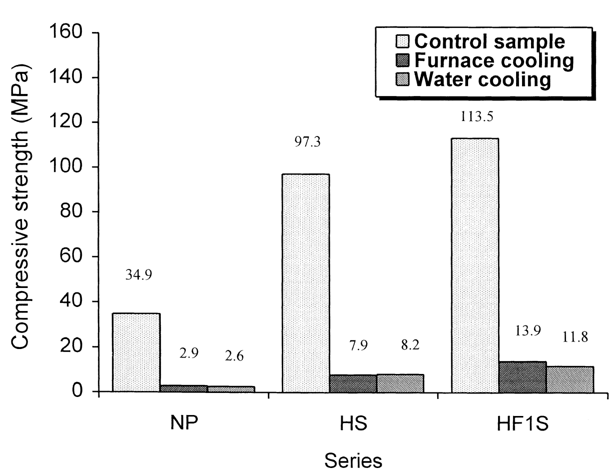

Fig. 2. The compressive strength before and after exposure to 1100°C.

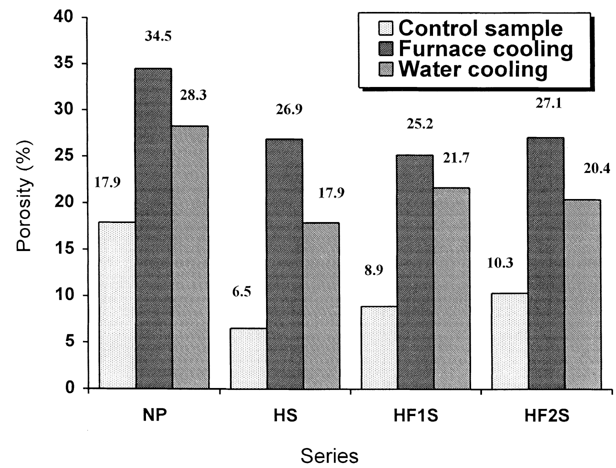

Fig. 3. The porosity before and after subjected to 800°C.

spalling was observed after HPC was subjected to water cooling at peak temperatures of 800°C or 1100°C, which indicated that thermal gradients or thermal shock was not the primary reason for spalling in HPC. Besides, thermal shock seemed to have a little effect on the residual strength of HPC.

In Figs. 3 and 4, the variation of porosity of NSC and HPC after 800°C and 1100°C are shown. It shows that HPC had a greater ratio of increase in pore volume than NSC. This was an important factor deemed to be responsible for greater strength deterioration in HPC compared with NSC. Water cooling caused a denser microstructure than furnace cooling due in part to the re-hydration of the components, which resulted from the decomposition of hardened cement mortar in concrete at high temperatures. After exposure to peak temperature of 800°C, compared with the original porosity, the porosity of HPC increased by 163.1–313.8% for furnace cooling and 98.1–175.4% for water cooling; after 1100°C, HPC increased by 52.8–187.7% for furnace-cooling and 56.2–184.6% for water cooling.

Fig. 5 gives the variations of cumulative pore volume and its distribution as influenced by different heating and

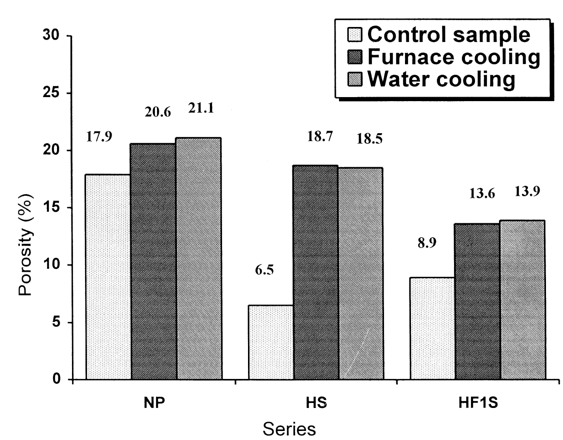

Fig. 4. The porosity before and after subjected to 1100°C.

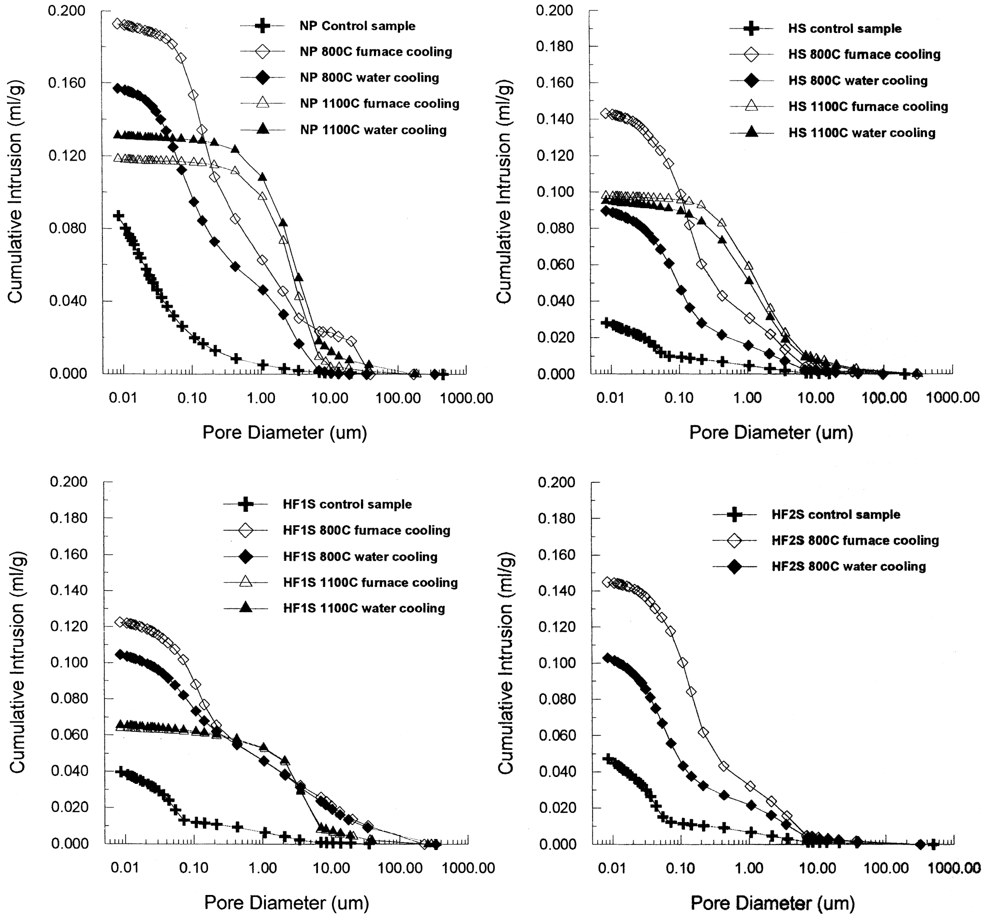

Fig. 5. Cumulative pore volume before and after exposure to high temperatures.

cooling regimes. Comparing exposure at 1100°C with that at 800°C, cumulative pore volume with pore diameters smaller than around 0.1 μm decreased while that with pore diameters greater than 0.1 μm increased. Difference between the effect of two cooling regimes on pore structure reduced at 1100°C as compared with that at 800°C. This was attributed to the fact that, at very high temperature (1100°C), sinter was the primary factor affecting the microstructure of concrete.

In the previous research [12], a model was proposed to predict the relationship between compressive strength and porosity of concrete. In Fig. 6, the test results of concrete obtained at room temperature, after 800°C, and different cooling regimes are shown. The modified model, which is based on the previously proposed model by considering more test results in this study, is given in Fig. 6. The Balshin and Ryshkewitch models [15] are also provided as a comparison.

The test results of the concrete specimens at 1100°C are not included in Fig. 6, because, at such a very high temperature (1100°C), components in the hardened concrete material decomposed. Besides, sintering of cementitious material occurred and changes in terms of new phases and microstructure formed. Porosity was not the predominant factor governing the strength of concrete.

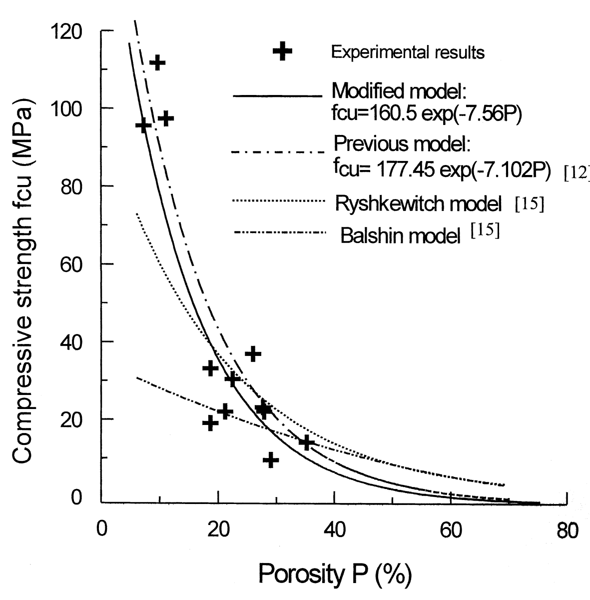

Fig. 6. Relation between compressive strength and porosity.

Thus, it is not adequate to use the model in Fig. 6 to predict the strength of concrete subjected to 1100°C by means of porosity.

4. Conclusions

When exposed to high temperatures, the residual compressive strength of HPC decreased: it dropped to about 25–35% of the original strength after 800°C, and about 8–12% after 1100°C. To an extent, steel fiber could reduce the deterioration of concrete when it is subjected to high temperature. Polypropylene fiber did not cause significant decrease in residual strength compared with the case when it was not added. Cooling regimes had some effect on the residual compressive strength. Water cooling caused only a bit more deterioration in strength than in the case of furnace cooling. However, the effect of cooling rate was less pronounced when concrete was exposed to higher peak temperature. Test results also show that thermal gradient or thermal shock was not the primary reason for the spalling of HPC. HPC had a greater ratio of increase in pore volume than NSC had, which is an important factor deemed to be responsible for the more severe strength deterioration for HPC. A significant change of the cumulative pore volume and its distribution was observed and the difference between the effects of two cooling regimes on the pore structure reduced at 1100°C as compared with that at 800°C. A modified model based on the previous study was developed to predict the relationship between the strength and porosity of concrete.

Acknowledgments

The Hong Kong Polytechnic University CRG project S610 for supporting the experimental work is gratefully acknowledged. This research is also a part of a key project supported by National Nature Science Foundation Grant No. 59938170.

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