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Compressive strength and pore structure of high-performance concrete after exposure to high temperature up to 800°C

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Abstract

An experimental program was carried out to study the mechanical properties and pore structure of high-performance concrete (HPC) and normal-strength concrete after exposure to high temperature. After the concrete specimens were subjected to a temperature of 800°C, their residual compressive strength was measured. The porosity and pore size distribution of the concrete were investigated by using mercury intrusion porosimetry. Test results show that HPC had higher residual strength, although the strength of HPC degenerated more sharply than the normal-strength concrete after exposure to high temperature. The changes in pore structure could be used to indicate the degradation of mechanical property of HPC subjected to high temperature. A model was developed by optimizing the parameters in the Ryshkewitch model to predict the relationship between porosity and the strength of HPC.

Keywords: High-performance concrete; High temperature; Compressive strength; Pore structure; Modeling

1. Introduction

The structure of concrete material can be approximately classified into micro- (less than 1 um), meso- (between 1 um and 1 cm), and macrolevels (greater than 1 cm) [1]. For concrete subjected to high temperature, with the increase in temperature, strength and Young's modulus decrease at macrolevel, internal structures degenerate, and microdefects develop at micro- and mesolevels. Therefore, studying the pore structure of concrete after high-temperature exposure helps to understand the mechanisms of concrete deterioration.

The addition of pozzolanic or supplementary cementing materials as partial replacements is one effective method of preparing high-performance concrete (HPC) [2–5]. In general, these blending materials enhance the performance of concrete through pozzolanic reaction, with microaggregate filling effect. Furthermore, the durability of concrete relating to ingress of aggressive ions (such as sulfate, chloride, etc.) is also improved due to the more compact microstructure of concrete, which slows down the diffusion of ions. However, the compact internal structure could probably lead to the reduction of fire resistance. In particular, there is a greater risk that HPC spalls at high temperature compared with conventional concrete [6,7]. Due to the potentially poor fire resistance of HPC, it might be recommended that the use of HPC should be limited in some cases unless future research is carried out to study and solve this problem. Thus, the investigation on performance of HPC subjected to high temperature is of great significance. There has been much research work on the change of macromechanical properties of concrete subjected to high temperatures [8–14]; however, very little work has been carried out on the change of pore structure of HPC. Rostasy et al. investigated the pore structure of two cement mortars with compressive strength of 55 MPa at both extremely low and high temperatures [15]. Chan et al. measured the pore size distribution of hardened cement paste of one normal and two high-strength concretes after exposure to a temperature of 600°C [16], and confirmed the "coarsening" effect reported previously [11,15]. In this study, more in-depth questions are discussed about the effect of high temperature up to 800°C on the re-

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Table 1
Mix design for the normal-strength and high-performance concrete (kg/m^3)

Series	Cement	Water	Sand	Coarse aggregate (mm) (10 mm)	(20 mm)	Silica fume	Fly ash	Steel fiber	Polymer fiber	Superplasticizer (mL/m^3)
NC	262.5	210.0	588.8	418.7	832.5	/	87.5	/	/	/
HPC-1	357.5	176.0	542.7	385.9	767.4	55.0	137.5	/	/	9,000
HPC-2	357.5	176.0	542.7	385.9	767.4	55.0	137.5	78.0	/	9,000
HPC-3	357.5	176.0	542.7	385.9	767.4	55.0	137.5	/	1.82	9,000

sidual strength and the corresponding pore structure in several HPCs in comparison to conventional concrete.

2. Materials and methods

The materials used in this study were: ordinary Portland cement conforming to BS12:1991, river sand, crushed granite with maximum sizes of 20 and 10 mm, superplaticizer complying to the requirement of BS5075 Part3:1985, silica fume and fly ash, and steel and polypropylene fibre. The length and aspect ratio were 25 mm and 60 for the steel fibre and 19 mm and 360 for the polymer fibre. The mix designs for conventional concrete and HPC in this study are listed in Table 1.

The specimens (100 × 100 × 100 mm in size) for compressive strength testing were demoulded 24 h after casting and then stored in a water tank. After 28 days of curing, the fully saturated specimens were put into an electric furnace with temperature elevated at a rate of 5 to 7°C. When 800°C was reached, the maximum temperature was maintained for 1 h and then the specimens were naturally cooled to room temperature (25°C) in the furnace. The samples without coarse aggregate for microstructure testing were separated from the specimens after the residual strength testing due to the limitation of sample size for the porosimeter.

The tests of pore structure of the concrete samples before and after exposure to high temperature were conducted by using a mercury intrusion porosimeter. The maximum pressure of the porosimeter was 207 MPa, covering the pore diameter range from about 0.006 to 360 um. Values of 140° and 485.0 dyn/cm were used for the contact angle and mercury surface tension. The samples were dried at about 105°C before mercury intrusion porosimeter test.

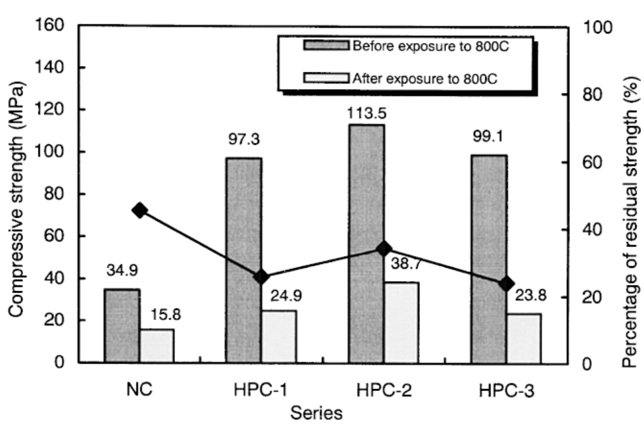

Fig. 1. The strength before and after exposure to high temperature.

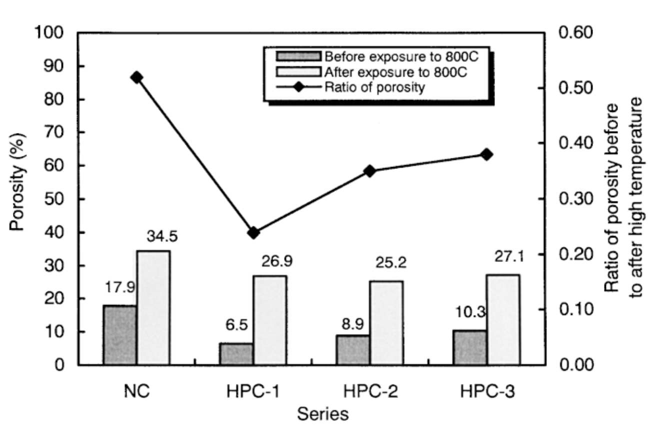

Fig. 2. The porosity before and after exposure to high temperature.

3. Results and discussion

The change of mechanical properties of concrete subjected to high temperatures are dependent on material as well as environmental factors (such as the constituents, initial strength before exposure to high temperature, moisture content, and so on) [12,17]. Particularly, for HPC exposed

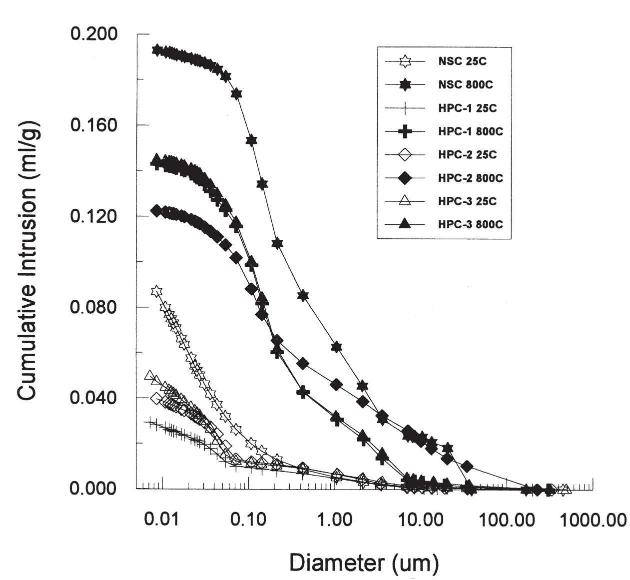

Fig. 3. Cumulative pore volume before and after exposure to high temperature.

to high temperature, moisture content in material or structure is one of the crucial factors, because spalling may occur due to the dense internal microstructure, which makes it difficult for water vapor transport and release in concrete [6,7]. The higher the moisture content, the higher the possibility and tendency of spalling for HPC. In this study, the thoroughly saturated specimens were used in the high-temperature tests to investigate the most unfavorable situation for HPC exposed to high temperatures. The residual compressive strength of the concrete is shown in Fig. 1. Each strength value is an average of three samples.

As shown in Fig. 1, with temperature elevated up to 800°C, the strength of HPC dropped more sharply (between 23.9 and 34.1%) than conventional concrete; however, the former still had higher residual strength than the latter. Among the three series of HPCs, HPC-2 (reinforced by 1% by volume steel fibre) had the smallest rate of strength loss and the largest residual compressive strength. HPC-3 (reinforced with 0.2% by volume polypropylene fibre) had almost the same residual strength as HPC-1 without fibre reinforcement, which seemed to denote that the polymer fibre did not necessarily lead to a significant reduction in strength even if it vaporized at high temperature.

Fig. 2 gives the variation of porosity for NC, HPC-1, HPC-2, and HPC-3 samples. After exposure to high temperature (up to 800°C), the porosity of both NC and the three HPCs had a great increase, in which HPC-1 had the largest increase by 314%, and the porosity of the HPC was still smaller than that of NC. Additionally, the difference between the three HPCs was reduced after exposure to high temperature.

From Fig. 3, it can be seen that:

1. Before exposure to high temperature, the major difference between the NC and the three HPCs existed in

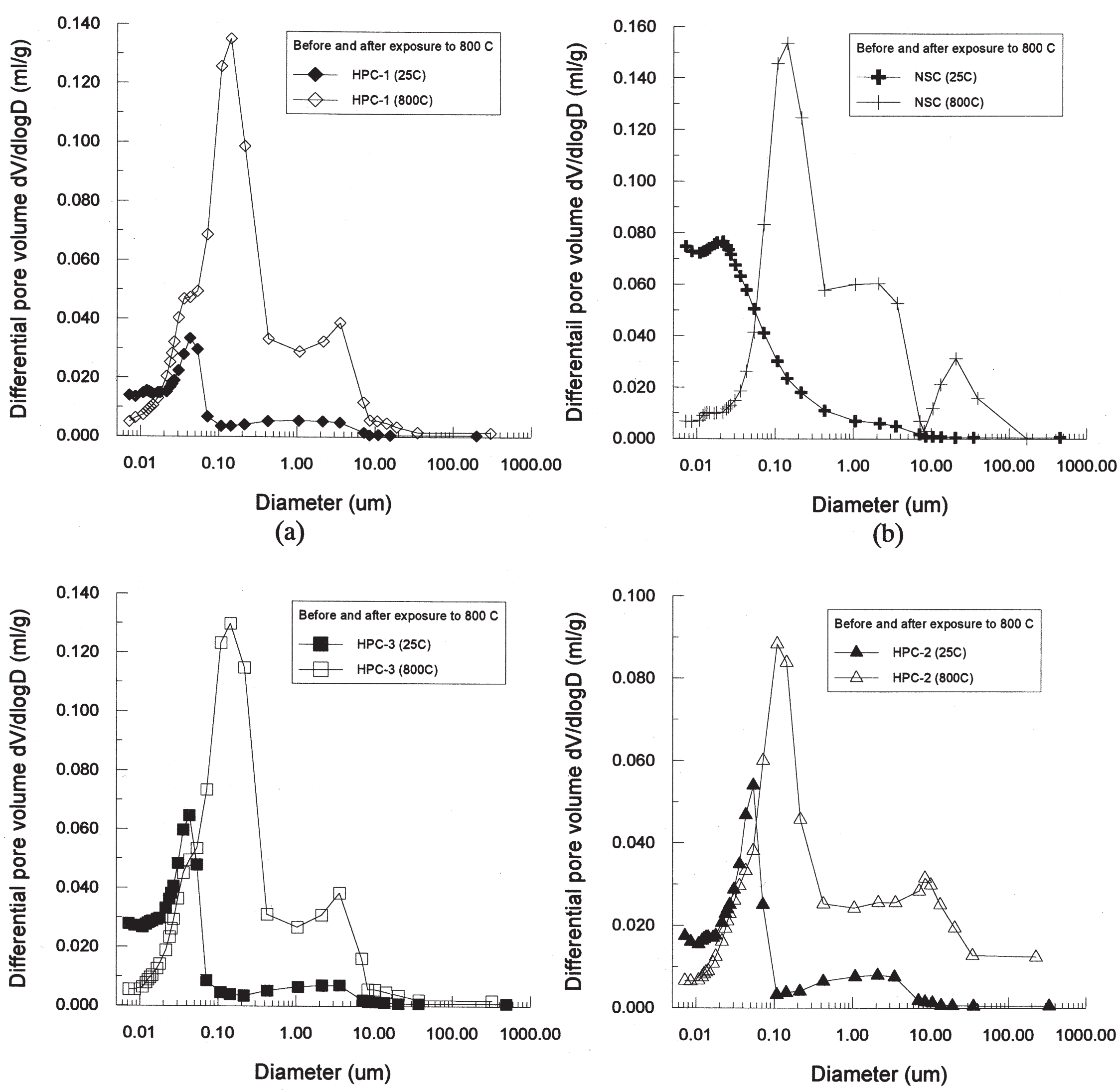

Fig. 4. Pore size distribution before and after exposure to high temperature.

the micropores with diameter smaller than around 0.40 um. Additionally, there is little difference between HPC-2 and HPC-3.
2. After being subjected to high temperature, both the NC and the three HPCs, pore sizes (from 0.01 to 1000 um) became significantly larger. The difference in the microstructure between NC and HPC also became much greater. On the other hand, the variation of both HPC-1 and HPC-3 was very similar; consequently their residual strengths were similar.

The relationship of *dV*/*d*log*D* vs. log*D* has been used to reflect the pore size distribution [1,15], in which *V* is mercury intrusion volume and *D* is pore diameter. It is accepted that the macromechanical properties of material are always closely linked to microstructure. Thus, to a certain degree, the variation of pore structure reflects the deterioration of concrete subjected to high temperature.

From Figs. 4a–d, it can be seen that the *dV*/*d*log*D* vs. log*D* curves for the three HPCs before and after high temperature had similar appearances, which were quite different from that of the conventional concrete.

After exposure to high temperature up to 800°C the peak value of *dV*/*d*log*D* of all concrete was great increased; HPC-1 had the largest increase by 309%, while HPC-2 had the smallest increase by 60%, and subsequently HPC-3 and NC increased by 100 and 95%, respectively. In addition, the subpeak of all concrete had a significant increase as well.

For both the NC and the HPC, the highest peak of *dV*/*d*log*D* occurred within a narrow range of 0.10 to 0.15 um. This meant, on the one hand, a great increment of pore size occurred here; on the other hand, the micropores within this range for both the NC and the HPC were most notably affected by high temperature up to 800°C.

Based on the experimental results, the relationship between the strength and the corresponding porosity of concrete is given in Fig. 5.

It has been revealed that the porosity is not the only parameter affecting the strength of concrete, and many other factors such as pore size distribution, microcracks, interface, and so on are also important factors that determine mechanical properties of cementitious materials [18–20]. However, porosity, which can be semiempirically and concisely used to describe the relationship between strength and microstructure of porous material, is still being studied [1,21]. In Fig. 5, a model was developed by using the test results and optimizing the parameters in the Ryshkewitch model [21]. Additionally, two other results forwarded by Bouguerra et al., using Balshin and Ryshkewitch models [21], are also given as a comparison in Fig. 5.

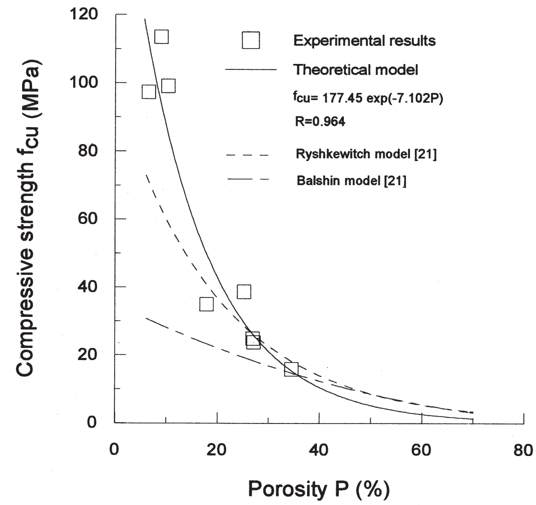

Fig. 5. Relationship between the porosity and the compressive strength.

4. Conclusions

The results and conclusions are summarized as follows:

1. Although the strength of HPC degenerated more sharply than the conventional concrete with the increase of exposed temperature, the HPC had higher residual strength.
2. The variation of pore structure, including porosity and pore size distribution, could be used to indicate the degradation of mechanical properties of HPC subjected to high temperature.
3. A model optimizing the parameters in the Ryshkewitch model was developed to predict the relationship between the porosity and the strength of HPC.

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