ELSEVIER

Cement and Concrete Composites 21 (1999) 23–27

Cement & Concrete Composites

Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures

Y. N. Chan*, G. F. Peng, M. Anson

Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Received 20 November 1997; accepted 27 July 1998

Abstract

Based on normal strength concrete (NSC) and high-strength concrete (HSC), with compressive strengths of 39, 76, and 94 MPa respectively, damage to concrete under high temperatures was identified. After exposure to temperatures up to 1200°C, compressive strength and tensile splitting strength were determined. The pore structure in HSC and in NSC was also investigated. Results show that HSC lost its mechanical strength in a manner similar to that of NSC. The range between 400 and 800°C was critical to the strength loss. High temperatures have a coarsening effect on the microstructure of both HSC and NSC. On the whole HSC and NSC suffered damage to almost the same degree, although HSC appeared to suffer a greater worsening of the permeability-related durability.

Keywords: High-strength concrete; High temperatures; Residual strength; Microstructure coarsening

1. Introduction

Fire remains one of the serious potential risks to most buildings and structures. The extensive use of concrete as a structural material has led to the need to fully understand the effects of fire on concrete. Generally concrete is thought to have good fire resistance [1–3]. With the further development and use of high-strength concrete (HSC), however, some doubt about its fire resistance emerged [4].

Since Lea and Stradling [5,6], the pioneers who investigated the factors influencing concrete strength at high temperatures in the 1920s, a number of researches have been carried out relating to the fire resistance of concrete. Due to the variety of high temperature conditions tested and the variety of constituent materials of concrete used in these researches, and the differences in the available experimental equipment, many explanations for the behavior of concrete subjected to high temperature have been proposed. It is now commonly recognized that the actual behavior of concrete subjected to high temperatures is a result of many factors, including both environmental factors and constituent materials factors. Among the environmental factors, heating rate and peak temperature are the two main factors which have a significant influence on concrete properties. Under certain heating conditions, the dehydration of C–S–H gel, the thermal incompatibility between the aggregate and cement paste and the pore pressure within the cement paste are the main detrimental factors.

As HSC is a relatively new type of concrete, knowledge about the performance of HSC subjected to fire is small compared with that of normal strength concrete (NSC). Only in recent years, have a small number of researches been carried out on HSC subjected to fire or high temperature. From these researches HSC has been found to be prone to spalling under high temperature in some cases [4,7]. The possible reason might be that the dense hardened cement paste (HCP) keeps the moisture vapor from escaping under high temperatures. Considerable pore pressure is therefore established. Furthermore, a thermal incompatibility between the HCP and aggregate and between the outer and inner part of concrete is produced. Naturally, the spalling problem brought about the suspicion regarding the behavior of HSC in fire conditions. To ensure that HSC can be used safely in buildings it is also important to know whether, apart from spalling, HSC suffers from fire damage to a greater degree than NSC.

*Corresponding author.

0958-9465/99/$ — see front matter
PII: S0958-9465(98)00034-1

Although concrete is generally thought to have good fire resistance [1,3], concrete does lose its original properties when subjected to high temperatures. Field survey showed that the fire damage of concrete included mechanical strength reduction, spalling and cracking [8, 9]. Nevertheless, exposure to high temperatures may also cause a change in pore structure of concrete, i.e. "pore-structure coarsening" [10–12]. Generally the pore-structure coarsening means an increase in concrete permeability and a worsening of the permeability-related durability.

HSC and NSC of three strength grades were prepared for the damage investigation reported in this paper. Compressive strength and splitting tensile strength have been determined and samples were also selected to determine the pore size distributions in their HCP.

2. Experimental details

100 mm cube specimens were prepared for three grades of concrete named NSC, HSC-1, and HSC-2 respectively, using ordinary Portland cement (OPC), crushed granite of sizes 10 and 20 mm, sand and superplasticizer. The OPC complied with the requirements of BS12:1991. The mix proportions and the 28-day compressive strength are given in Table 1. NSC of a water/cement ratio (w/c) of 0.60 was used here for comparison with HSC to help understand the behavior of HSC.

After demolding at one day, the specimens were cured in water at 20°C until 28-day age and then cured in an environmental chamber with a controlled temperature of 20°C and 75% R.H.

At 90 days three specimens from each batch were heated in an electric furnace to temperatures of 400, 600, 800, 1000 and 1200°C respectively. The peak temperature was maintained for 1 h. The time–temperature curve for the furnace is given in Fig. 1 and compared with the standard curve recommended in BS476:Part20:1987.

After the specimens had been allowed to cool naturally to room temperature, the residual compressive strength and splitting tensile strength were determined according to BS1881:Part120:1983 and BS1881:Part 117:1983 respectively.

The pore size distribution was determined using a mercury intrusion porosimeter, which has a measuring pressure range from 1.02×10^{-2} to 2.04×10^{2} MPa. The contact angle selected was 141°, so the measurable pore size range was from 0.007 to 144 μm. The samples in the form of pellets of about 5 mm in size, consisted of HCP collected from the concrete specimens.

3. Results and discussion

The behavior of concrete exposed to high temperature is influenced by many factors. Generally, for mature concrete an increase in exposed temperature causes concrete to gradually lose its mechanical strength.

The residual compressive strength results after exposure to 400, 600, 800, 1000 and 1200°C temperatures are given in Fig. 2. The relationship between compressive strength and exposure temperature was found to be similar to that reported previously [7,13]. From the viewpoint of strength loss, there are three temperature ranges, 20 to 400°C, 400 to 800°C and 800–1200°C. The strength loss was markedly different among each of the three temperature ranges. Up to 400°C, only a small part of the original strength was lost, between 1 and 10% for HSC and 15% for NSC. The severe compressive strength loss occurred mainly within the 400–800°C range. This may be regarded as a common feature for HSC and NSC as long as the cement used is OPC, because in this case the HCP, which is the main source of the concrete strength, is bound to undergo dehydration of the C–S–H gel and lose its cementing ability [2,10,14]. Therefore the temperature range between 400 and 800°C may be regarded as critical to the strength loss of concrete. For this temperature range, HSC maintained a higher percentage value of residual strength than NSC, as shown in Fig. 3. Aggregates of 10 and 20 mm used in this experiment are granite, a kind of siliceous aggregate that is thermally less stable than some other aggregates such as carbonate aggregates [13,15] . Therefore it would be possible to obtain a HSC which

Table 1
Mix proportion and compressive strength of three strength grade concretes

Type	w/c	Mix proportions (kg/m^3)					Compressive strength (MPa)	
		Cement	Aggregate		Sand	Water	28-day age	90-day age
			20 mm	10 mm				
NSC	0.60	350	835	420	440	210	39	47
HSC-1	0.35	550	785	393	478	190	76	84
HSC-2	0.28	550	872	436	433	152	94	118

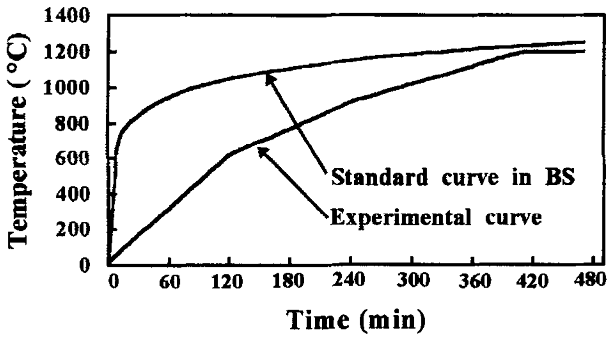

Fig. 1. Experimental temperature–time curve and standard curve recommended in BS476:Part20:1987.

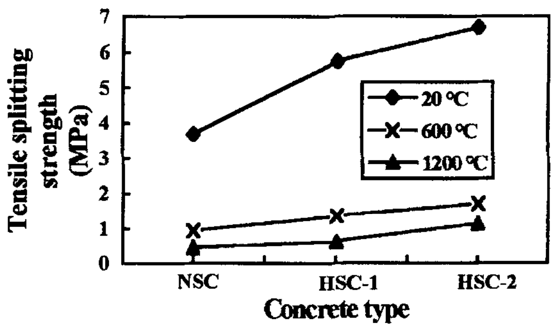

Fig. 4. Tensile splitting strength of three grades of concrete subjected to different temperatures.

can maintain a higher residual strength when exposed to, say, 600°C by using thermally stable aggregates.

Above 800°C, only a small part of the original compressive strength was left at about 9–20%. At these levels, both HSC and NSC were structurally damaged. Some products of sintering reaction between HCP and aggregate has been reported [16,17] and these were also found in the present experimental study within some HSC and NSC specimens after exposure to 1200°C. Nevertheless the residual compressive strength for 1200°C was only slightly increased compared to that for 1000°C as shown in Figs 2 and 3 by such sintering reaction.

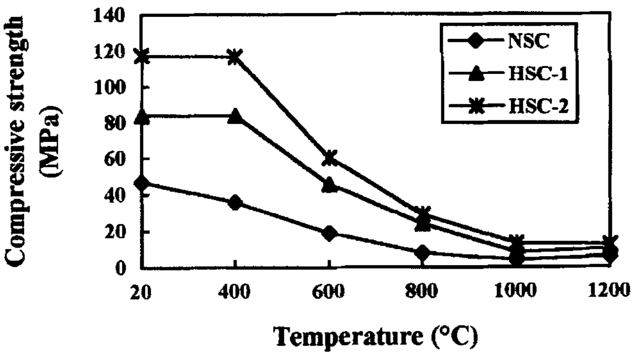

Fig. 2. Compressive strength of three grades of concrete subjected to different peak temperatures.

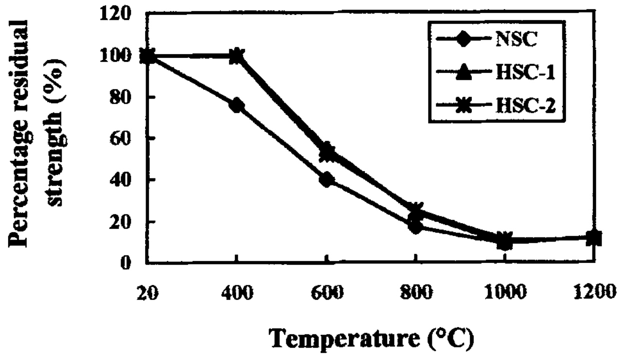

Fig. 3. Percentage of residual compressive strength of three grades of concrete subjected to different peak temperatures to the original compressive strength at 20°C.

The results of tensile splitting strength are shown in Fig. 4. The sharp loss of tensile splitting strength for both HSC and NSC subjected to high temperatures is clearly different from the more gradual loss of compressive strength. This is because many micro- or macro-cracks were produced in the specimens due to the thermal incompatibility [2,17,18] within the concrete. Generally tensile strength is more sensitive to such cracks than compressive strength [2,15].

In this experimental investigation, some specimens of HSC and NSC encountered spalling damage during heating. Spalling occurred within a temperature range 400–500°C, different from the reported 320–360°C range [7].It might be due to the difference in the pore-structure of concrete, moisture content, heating rate and specimen configuration etc. which are believed to be the governing factors of spalling [4,19,20]. The spalling of 100 mm cube specimens was explosive, causing specimens to break into pieces. As high moisture content of concrete is one of the reasons for spalling, the specimens with spalling might have moisture contents higher than those of the other specimens in the same batch but without spalling. Great attention should be paid to spalling as a severe damage to concrete. Research on the topic of concrete spalling is in progress and will be reported later.

The HCP pore size distribution in NSC, HSC-1 and HSC-2 was determined using a mercury intrusion porosimeter. The results given in Fig. 5(a–c), confirm the coarsening effect of high temperatures on the pore structure reported previously [8,11,12].

The cumulative volume of pores in the range greater than 1.3 μm, which should be responsible for the permeability of HCP [20], increased after exposure to 600°C as shown in Fig. 6. Therefore, high temperatures have reduced the permeability-related durability of HSC and NSC as well as their mechanical strength.

For comparison between HSC and NSC, two worsening indexes $d_{1,600}$ and $d_{2,600}$ are introduced, among which $d_{1,600}$ is the worsening index of mechanical strength in terms of the mean percentage loss of compressive strength and tensile splitting strength, and $d_{2,600}$ is the worsening index of the permeability-related durability in terms of the parameter $(1-\alpha)$, where α is the ratio of cumulative volume of pores larger than 1.3 μm before and after the exposure to 600°C temperature. These indexes have a value from 0 (no worsening) to 1 (full worsening). The subscript 600 indicates that the case of a 600°C temperature is being considered. The calculated value of $d_{1,600}$ and $d_{2,600}$ is given in Table 2.

The $d_{1,600}$ value of HSC is lower than that of NSC whereas the $d_{2,600}$ value of HSC is higher than that of NSC. This means that HSC suffered a smaller worsening of its mechanical strength but a greater worsening of the permeability-related durability.

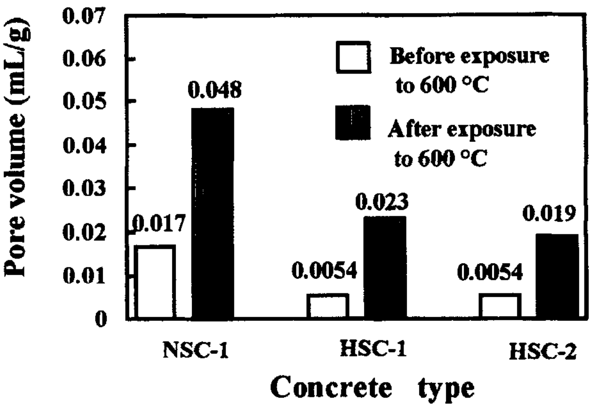

Fig. 6. Cumulative pore volume of three types of concrete before and after exposure to 600°C.

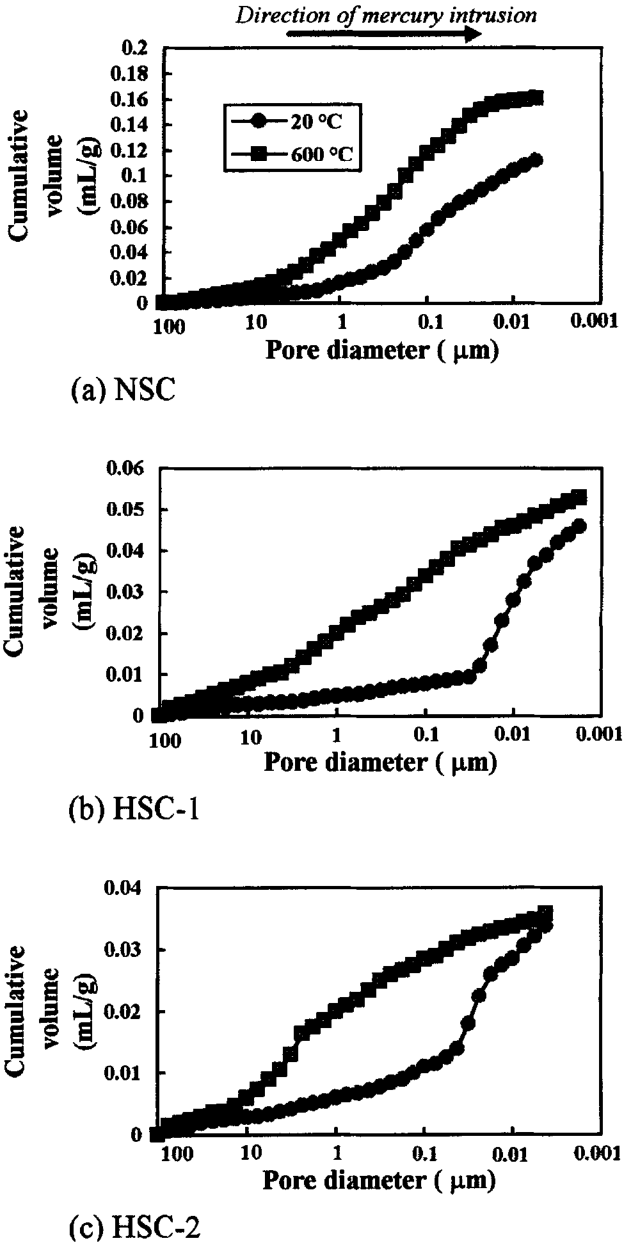

Fig. 5. Pore size distribution of HCP in three grades of concrete before and after exposure to 600°C.

4. Conclusions

The mechanical strength of HSC decreased in a similar manner to that of NSC when subjected to high temperatures up to 1200°C. With electrical heating, there was no special danger of spalling for HSC although the HCP within it was much denser than that within NSC.

High temperatures can be divided into three ranges in terms of effect on concrete strength loss, namely 20–400°C, 400–800°C and above 800°C. In the range 20–400°C, HSC by and large, unlike NSC, maintained its original strength. In the range 400–800°C, both HSC and NSC lost most of their original strength, especially at temperatures above 600°C. This range, within which the unavoidable dehydration of C–S–H gel in OPC paste occurs to a greater degree than within 20-400°C, may be regarded as the critical temperature range for the strength loss of concrete. Above 800°C, only a small portion of the original strength was left for both HSC and NSC. Therefore it is only within the range 400–800°C that research efforts should be made to reduce the strength loss and improve the thermal behavior of concrete. Like NSC, HSC lost its tensile splitting strength more sharply than its compressive strength at a temperature of 600°C.

Table 2
Calculated value of worsening indices, $d_{1,600}$ and $d_{2,600}$

Concrete type	$d_{1,600}$	$d_{2,600}$
NSC	0.682	0.652
HSC-1	0.608	0.764
HSC-2	0.615	0.716

Under high temperatures, HSC and NSC experienced the change of pore structure, known as the 'microstructure coarsening effect'. The effect is believed to be one of the reasons for the strength loss at temperatures below 600°C. This effect also reduces the permeability-related durability for concrete exposed to high temperatures. HSC suffered a marginally smaller loss of mechanical strength but a greater worsening of the permeability-related durability than NSC.

The mechanism of concrete spalling under high temperatures remains unclear in the present investigation and needs more investigation.

References

[1] Lea FM. The Chemistry of Cement and Concrete. Edward Arnold (Publishers) Ltd, London, 1983.

[2] Mehta PK, Monteiro PJM. Concrete: Structure, Properties, and Materials. Prentice-Hall, Englewood Cliffs, NJ, 1993.

[3] Curwell S, March C, Venables R. Buildings and Health. RIBA Publishers Ltd, London, 1990.

[4] Jahren PA. Fire resistance of high strength/dense concrete with particular references to the use of condensed silica fume — a review. In Proceedings of the Third International Conference, Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, ACI SP-114, Detroit, USA, 1989, pp. 1013–1049.

[5] Lea FC. The effect of temperature on some of the properties of materials. Engineering 1920;110:293–298.

[6] Lea FC, Stradling R. The resistance to fire of concrete and reinforced concrete. Engineering 1922;114(2929):341–344, 380–382.

[7] Castillo C, Durrani AJ. Effect of transient high temperature on high-strength concrete. ACI Materials Journal 1990;Jan–Feb:47–53.

[8] Neves IC, Branco FA, Valente JC. Effects of formwork fires in bridge construction. Concrete International 1997;March:41–46.

[9] Al-Mutairi NM, Al-Shaleh MS. Assessment of fire-damaged Kuwaiti structures. Journal of Materials in Civil Engineering ASCE 1997;Feb:7–14.

[10] Crook DN, Murray MJ. Regain of strength after firing of concrete. Magazine of Concrete Research 1970;22(72):149–154.

[11] Woods H. Durability of Concrete Construction. ACI and The Iowa State University Press, USA, 1968.

[12] Rostasy RS, Weiss R, Wiedemann G. Changes of pore structure of cement mortars due to temperatures. Cement and Concrete Research 1980;10:157–164.

[13] Sarshar R, Khoury GA. Material and environmental factors influencing the compressive strength of unsealed cement paste and concrete at high temperatures. Magazine of Concrete Research 1993;45(162):51–61.

[14] Mindess S, Young JF. Concrete. Prentice-Hall Inc., Englewood Cliffs, NJ, 1981.

[15] Li Wei, Guo Zhen-hai. Experimental research on the strength and deformation properties of concrete exposed to high temperature. Journal of Building Structure (China) 1993;14(1):8–16.

[16] Lydon FD. Development in Concrete Technology — I. Applied Science Publishers Ltd, London, 1991.

[17] Khoury GA. Compressive strength of concrete at high temperatures: reassessment. Magazine of Concrete Research 1992;44(161):291–309.

[18] Tanaka H, Totani Y, Seito H. Properties after being heated and re-hydration of hardened cement paste. Cement and Concrete (Japan) 1983;Apr:34–40.

[19] Motoo H. Physical properties of high strength and high quality concrete using high-range water reducing agents — Part 2. Cement and Concrete (Japan) 1992;549:9–18.

[20] Neville AM. Properties of Concrete. Pitman Publishing Ltd, London, 1981.