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Mechanical properties of high-strength concrete subjected to high temperature by stressed test

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Abstract: Recently, the effects of high temperature on compressive strength and elastic modulus of high strength concrete were experimentally investigated. The present study is aimed to study the effect of elevated temperatures ranging from 20 °C to 700 °C on the material mechanical properties of high-strength concrete of 40, 60 and 80 MPa grade. During the strength test, the specimens are subjected to a 25% of ultimate compressive strength at room temperature and sustained during heating, and when the target temperature is reached, the specimens are loaded to failure. The tests were conducted at various temperatures (20-700 °C) for concretes made with W/B ratios of 46%, 32% and 25%, respectively. The results show that the relative values of compressive strength and elastic modulus decrease with increasing compressive strength grade of specimen.

Key words: high-strength concrete; stressed test; high temperature

1 Introduction

Concrete is a widely used construction material in all the modern concrete structures because of its high compressive strength, good durability and plasticity. High-strength concrete can be achieved by using state-of-art additives such as mineral and chemical admixtures, which can reduce the water requirement and also improve the workability.

In recent years, for that reason the use of high-strength concrete has become increasingly popular. It feasibles technically and economically to produce ready-mixed high-strength concrete using conventional methods and materials. Concretes of strength in excess of 40 MPa are typically obtained by using special admixtures, which can reduce the water requirement and also improve the workability. The limit of 40 MPa is, therefore, well accepted as a reasonable value to differentiate high-strength concrete from normal strength concrete [1-2].

As the use of high-strength concrete becomes common, the risk of exposing it to high temperatures also increases. The behavior of high-strength concrete under elevated temperatures differs from that of normal-strength concrete. The two main differences between high-strength concrete and normal-strength concrete are the relative strength loss in the temperature range from 100 °C to 400 °C and the occurrence of explosive spalling in high-strength concrete specimens in the temperature range from 500 °C to 700 °C. To be able to predict the response of structures employing high-strength concrete during and after exposure to high temperature, it is essential that the strength and deformation properties of high-strength concrete subjected to high temperatures should be clearly understood[3-6]. The present paper, which focuses on the strength and deformation properties of high-strength concrete, is a part of major research program of the Chungnam National University in Korea that aims to study the mechanical properties of high-strength concrete under elevated temperature.

Three types of test are commonly used to study the effect of transient high temperature on the stress-strain properties of concrete under axial compression. 1) Stressed test where a fraction of the ultimate compressive strength at room temperature is applied and sustained during heating and, when the target temperature is reached, the specimens are loaded to failure; 2) Unstressed test where the specimens are heated under no

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initial stress and loaded to failure at the desired elevated temperature; 3) Unstressed residual strength test where the specimens are heated without any preload, cooled down to room temperature, and then loaded to failure[1-2].

In the present study, the specimens were heated under 25% of the ultimate compressive strength at room temperature and loaded to failure in hot state after the desired heat treatment[7].

2 Research significance and objective

With the increasing application of high-strength concrete in different concrete structures of high-rise, the risk of exposing it to elevated temperatures increases significantly. In order to assess the structural safety of such structures after a fire, it is important that the effect of exposure to high temperature on strength and deformation characteristics of high-strength concrete should be well understood. This paper provides a part of an ongoing study on the mechanical properties of (ultra) high-strength concrete under utmost temperature conditions.

The main objective of the present study is to compare the variation of stress-strain relationship of high-strength concrete with temperature. The test specimens that are cylinders with 100 mm in diameter and 200 mm in height were subjected to temperatures ranging from 100 $^{\circ}$ C to 700 $^{\circ}$ C at 100 $^{\circ}$ C increments, and their mechanical properties were compared with those obtained at room temperature (23–25 $^{\circ}$ C).

3 Experimental program

To study the effect of transient high temperature on the strength and deformation characteristics of highstrength concrete, the test specimens of high-strength concrete with nominal strength of 40, 60 and 80 MPa were subjected to temperatures up to 700 $^{\circ}$ C and loaded to failure under axial compression. For each type of concrete, the specimens were tested under stressed conditions. In stress tests, the specimens were preloaded to 25% of their ultimate compressive strength at room temperature.

High-strength concrete were made from type I Portland cement, natural sea sand, and crushed granitic

Table 2 Mix proportion of concrete

gravel. Owing to the low W/C ratio adopted, the superplasticizer was used to increase the workability. A commercially available sulfonated naphthalene formaldehyde-type superplasticizer was used in Mix I and Mix II, and the polycarboxylic-acid type superplasticizer was used in Mix III to obtain high-strength concrete. The properties of the used materials and the mix proportion are given in Tables 1 and 2, respectively.

Table 1 Properties of materials

1	
Material	Physical property
Cement	OPC, density: 3.15 g/cm ³
Fine aggregate	Sea sand, density: 2.61g/cm ³ , absorption: 0.97%
Coarse aggregate (W/B46, 32%)	Crushed granitic aggregate, size: 25 mm, Density: 2.67 g/cm ³ , absorption: 0.9%
Coarse aggregate (W/B 25%)	Crushed granitic aggregate, size: 20 mm, Density: 2.64 g/cm ³ , absorption: 0.9%
Fly ash	Density: 2.2 g/cm ³ , brain: 3 090 cm ² /g
Silica fume	Density: 2.2 g/cm ³ , brain: 230 000 cm ² /g

The specimens, as shown in Fig. 1, were demolded one day after casting, then soaked under water for 7-day and, subsequently, cured in a climate room at relative humidity of 50% and temperature of 20 °C for a period of 113–150 days; the specimens for 28-day compressive strength test were soaked under water for 28-day and, subsequently, then the compressive strength test were conducted[8–10].

3.1 Test setup and temperature control

The tests were performed in a closed-loop servocontrolled 4 600 kN hydraulic testing machine equipped with an electric furnace, as shown in Fig.2. Special cylindrical carbon-based alloy attachments were designed to transmit load from the frame to the specimen at high temperature. A continuously circulation water-cooling system was used to protect the instrumentation and to avoid heating the testing frame. The specimens were encased in heat transmission jig made with stainless-steel to heat the whole specimen and to restrain the explosive failure of high-strength concrete specimen, as shown in Fig.3. During the tests, the load and displacement of specimens were measured. The load

No	(W/B)/	FA rep./	SF rep./ %	(s/a)/ %	Water/ (kg·m ⁻³)	Unit content/(kg·m ⁻³)					AD/%CW
INO.	%	%				С	FA	SF	S	G	SP.
Mix I	46	10	_	46.4	176	344	38	_	793	919	0.6
Mix II	32	15	-	40.0	170	452	80	-	634	955	1.4
MixIII	25	15	7	36.0	165	515	99	46	537	972	2.0



Fig.1 Experimental program





Fig.2 Loading and heating machine



Fig.3 Heat transmission jig

was measured by the MTS system and the displacement was measured by the average of two pairs of LVDT [11-13].

It required a total of three specimens for each test at a given temperature and on average of the test results. To measure representative temperature and to control furnace temperature, three Type-K Chromel-alumel thermocouples, 0.91 mm thick, were installed in all testing specimens. Two thermocouples were installed at top-bottom height (10 mm from top and bottom) of the cylinder and one thermocouple was installed at mid-height; all the thermocouples were installed at 5 mm in depth from surface of the cylinder, as shown in Fig.4. The heating temperature of furnace was controlled from electric heater by voltage feedback-type thyristor regulator system.

3.2 Testing procedure

For each set of tests at a given temperature, three specimens from the same batch were also tested at room temperature. The target temperatures varied from 100 °C to 700 °C at 100 °C increment. As shown in Fig.5, the rate of heating for all specimens carry out 0.77 °C/min, 30 min sustenance per 50 °C increased by RELEM TC 129-MHT and preceding experiment[8, 12]. In the stress tests, 25% of the ultimate compressive strength at room temperature was applied to the specimens and sustained during the heating period. After the temperature reached the steady state, the load was increased at the prescribed

rate until the specimen failed. The specimens from the all batch of mixed concrete were tested under the stressed condition. However, three specimens of each batch for thermal strain and SEM test were tested under the unstressed condition. The control specimens were tested at room temperature in unstressed state on the day of the high temperature tests. The average compressive strength of the control specimens was 49.3 MPa for Mix I at 113 days, 78.8 MPa for Mix II at 139 days, and 99.3MPa for Mix III at 140 days, as shown in Table 3.



Fig.4 Location and numbering of thermocouples in specimen



Fig.5 Testing method used in this study (heating velocity: 0.77 °C/min, heating cycle: 50 °C/cycle)

4 Results and discussion

4.1 Effect of temperature on compressive strength The variation of the compressive strength ratio with



temperature is shown in Figs.6 and 7 for three types of high-strength concrete. Each point in the figure represents an average of the maximum compressive strength of three specimens normalized with respect to the average maximum compressive strength at room temperature. The change in the strength of high-strength concrete specimens appears to follow a common trend. Initially, as the temperature increased to 100 °C, the strength decreased compared with the room-temperature strength. The strength at 100 °C is about 80% of the room-temperature strength. With further increase in temperature, the specimens recovered the strength loss and of 90%–110% of the room-temperature strength. In the temperature range from 400 °C to 700 °C, the strength drops sharply, reaching to a low level of 60%



Fig.6 Variation of compressive strength with temperature





No.	f _{ck} /MPa	Compresiive strength of 28 days/MPa	Curing - time/d -	Av				
				Genera	1 U.T.M	Load and heat machine	Water	
				Water curing	Dry air curing	Dry air curing	content/70	
Mix I	40	40.5	113	49.3	42.0	41.0	2.0	
Mix II	60	68.4	139	81.2	78.8	76.0	2.1	
Mix III	80	82.2	140	98.7	99.3	93.9	2.0	

and 45% of initial strength, at 600 $^\circ\!\! C$ and 700 $^\circ\!\! C$, respectively.

The moisture content has a significant bearing on the strength of concrete in the temperature range from 20 $^{\circ}$ C to 200 $^{\circ}$ C. It is believed that water in concrete softens the cement gel, or attenuates the surface forces between gel particles, thus reducing the strength[14–18].

The slight increase in concrete strength associated with a further increase of temperature (between 100 $^{\circ}$ C and 200 $^{\circ}$ C) is attributed to the general stiffening of the cement gel and the increase in surface forces between gel particles, due to the removal of absorbed moisture. The temperature at which absorbed water is removed and the strength begins to increase depends on the porosity of the concrete.

Above 400 °C, all three types of high-strength concrete lose their strength at a faster rate. At these temperatures, the dehydration of the cement paste results in its gradual disintegration. Since the paste tends to shrink and aggregate expands at high temperature (differential thermal expansion at temperatures above 100 °C), the bond between the aggregate and the paste is weakened, thus reducing the strength of the concrete. SEM analysis of 40 MPa strength is shown in Fig.8.



Fig.8 SEM analysis of Mix I : (a) Cracks of cement paste at 100 $^{\circ}$ C; (b) Production of hydrate at 300 $^{\circ}$ C

4.2 Elastic modulus of high strength concrete under high temperature

The elastic modulus, defined as the ratio of the elastic modulus (taken as the tangent to the stress-strain curve at the origin) at a specified temperature to that at room temperature, is shown in Fig.9 as a function of

temperature. As the temperature increased to 100 $^{\circ}$ C, the elastic modulus decreased compared with the roomtemperature elastic modulus. The elastic modulus at 100 °C is about 80%–90% of the room-temperature strength. With further increase in temperature, the specimens recover the elastic modulus loss and are 85%-100% of room temperature elastic modulus. Up to about 600 °C the elastic modulus of all three types of high-strength concrete decreased in a similar fashion, reaching to about 50% of its initial values. In the temperature range of 100-400 °C, as the dehydration progressed and the bond between materials was gradually lost, the modulus of elasticity decreased to about 20%-35% of the value at room temperature. The effect of high temperature on the load-deformation behavior of high-strength concretes is shown in Fig.10.



Fig.9 Variation of elastic modulus with increase in temperature

5 Conclusions

1) When exposing at 100 $^{\circ}$ C, the high-strength concrete showed a 20% loss of compressive strength. As the strength of concrete increased, the loss of strength from exposure to high temperature also increased.

2) After an initial loss of strength, the high-strength concrete recovered its strength between 200 and 300 $^{\circ}$ C, reaching a maximum value of 8%–13% above the room temperature strength. As the strength of concrete increased, the recovery point of strength from exposure to high temperature also increased.

3) The high-strength concrete loses a significant amount of its compressive strength above 400 $^{\circ}$ C and attains a strength loss of about 55% at 700 $^{\circ}$ C. The change of strength in the temperature range of 100–400 $^{\circ}$ C is marginal.

4) The elastic modulus of the high-strength concrete decreased by 10%-20% when exposing in the temperature range of 100-300 °C. At 700 °C, the elastic modulus was only 45%-50% of the value at room temperature.



Fig.10 Compressive-strain behavior of high-strength concrete at high temperature: (a) Compressive-strain behavior of Mix I ; (b) Compressive-strain behavior of Mix II ; (c) Compressivestrain behavior of Mix III

References

- POTHA RAJU M, SRINICASA RAO K, RAJU P S N. Compressive strength of heated high-strength concrete [J]. Magazine of Concrete Research, 2007, 59(2): 79–85.
- [2] CASTILLO C, DURRANI A J. Effect of transient high temperature on high-strength concrete [J]. ACI Material Journal, 1990, 87(1): 47–53.

- [3] AVE T, FURUMURA F, TOMATSURI K, KUROHA K KOKUBO I. Mechanical properties of high strength concrete at high temperatures [J]. AIJ The Journal of Asian Architecture and Building Engineering, 1999, 515: 163–168.
- [4] AVE T, OHTSUKA T, KOBAYASHI Y, MICHIKOSHI S. Mechanical properties of moderate strength concrete at high temperatures [J]. AIJ The Journal of Asian Architecture and Building Engineering, 2007, 615: 7–13.
- [5] KODUR V K R, CHENG F P, WANG T C, SULTAN M A. Effect of strength and fiber reinforcement on fire resistance of high-strength concrete columns [R]. NRCC-45005, National Research Council, Canada, 2003.
- [6] CHENG F P, KODUR V K R, WANG T C. Stress-strain curves for high strength concrete at elevated temperatures [J]. Journal of Materials in Civil Engineering, 2004, 16(9): 84–90.
- [7] LONG T P, NICHOLAS J C. Fire performance of high strength concrete, research Needs [C]// Proceeding of ASCE/SEI Structures Congress 2000. Philadelphia: NIST, 2000.
- [8] RIREM129-MHT. Methods for mechanical properties of concrete at high temperatures (Part 3. Compressive strength for service and accident conditions) [J]. Materials and Structures, 1995: 410–414.
- [9] HIRASHIMA T, TOYODA K, YAMASHITA H, TOKOYODA M, UESUGI H. Compression tests of high-strength concrete cylinders at elevated temperature [C]// International Workshop, fib, 2007. Coimbra, Portugal: fib, 2007.
- [10] KODUR V K R, CHENG F P, WANG T C, SULTAN M A. Effect of strength and fiber reinforcement on fire resistance of high-strength concrete columns [J]. Journal of Structural Engineering, 2003, 129(2): 253–259.
- [11] HIRASHIMA T, TOKOYODA M, TOYODA K, YAMASHITA H, SHINOHARA K, UESUGI H. Experimental study on mechanical properties of concrete at elevated temperature [C]// Summaries of Technical Papers of Annual Meeting AIJ. Tokai, Japan, 2003: 135–137.
- [12] KIM G Y, KIM M H, KIM Y S, PARK C G, Test method for mechanical properties of heated concrete by heat transfer method [C]// Proceedings of the Japan Concrete Institute, 2007: 759–764.
- [13] YAMASHITA H, SHINOHARA K, TOYODA K, HIRASHIMA T, UESUGI H. Experimental study on mechanical property of super high strength concrete at high temperatures (Part 4. Transient strain of super high strength concrete) [C]// Summaries of Technical Papers of Annual Meeting AIJ. Hokkaido, Japan, 2004: 75–76.
- [14] LANKARD D R, BIRKIMER D L, FONDFRIEST F F, SNYDER M J. Effects of moisture content on the structural properties of portland cement concrete exposed to temperatures up to 500F [C]// Temperature and Concrete, Sp-25. Detroit: American Concrete Institute, 1971: 59–102.
- [15] SCHNEIDER U. Behavior of concrete under thermal steady state and non-steady state conditions [J]. Fire and Materials, 1976, 1: 103–115.
- [16] DAVIS H S. Effects of high temperature exposure on concrete [J]. Materials Research and Standards, ASTM International, 1967, 7(10): 452–459.
- [17] MENZEL C A. Tests of the fire resistance and thermal properties of solid concrete slabs and their significance [J]. Proc Am Soc Testing Mater, 1943, 43: 1099–1153.
- [18] BENJAMIN I A. Fire resistance of reinforced concrete [C]// Symposium on Fire Resistance of Concrete, SP-5. Detroit: American Concrete Institute, 1962: 25–39.

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