Stress-Strain Curves for High Strength Concrete at Elevated Temperatures

Fu-Ping Cheng[1]; V. K. R. Kodur[2]; and Tien-Chih Wang[3]

Abstract: The effects of high temperature on the strength and stress-strain relationship of high strength concrete (HSC) were investigated. Stress-strain curve tests were conducted at various temperatures (20, 100, 200, 400, 600, and 800°C) for four types of HSC. The variables considered in the experimental study included concrete strength, type of aggregate, and the addition of steel fibers. Results from stress-strain curve tests show that plain HSC exhibits brittle properties below 600°C, and ductility above 600°C. HSC with steel fibers exhibits ductility for temperatures over 400°C. The compressive strength of HSC decreases by about a quarter of its room temperature strength within the range of 100–400°C. The strength further decreases with the increase of temperature and reaches about a quarter of its initial strength at 800°C. The strain at peak loading increases with temperature, from 0.003 at room temperature to 0.02 at 800°C. Further, the increase in strains for carbonate aggregate HSC is larger than that for siliceous aggregate HSC.

DOI: 10.1061/(ASCE)0899-1561(2004)16:1(84)

CE Database subject headings: Stress strain curves; Fire resistance; High strength concretes; Temperature.

Introduction

In recent years, high strength concrete (HSC) is becoming an attractive alternative to traditional normal strength concrete (NSC). Concretes of strength in excess of 70 MPa are often used in a wide range of applications. With the increased use of HSC, concern has developed regarding the behavior of such concrete in fire.

The high strength in HSC is often obtained, by reducing the amount of water, through the use of special admixtures that also improve the workability. However, the lower water-cement ratio leads to lower porosity that makes HSC more brittle and makes it have less fire endurance at elevated temperatures as compared to NSC. Hence, one of the main concerns for the usage of HSC in fire resistance applications is its performance in fire conditions. Preliminary studies (Fukujiro et al. 1993; Hsu and Hsu 1994; Khoury 1992; Lankard et al. 1971) have shown that there are well-defined differences between the properties of HSC and NSC at elevated temperatures.

In order to understand and eventually predict the performance of HSC structural members, the material properties that determine the behavior of the member at elevated temperatures must be known. The behavior of a structural member exposed to fire is dependent, in part, on the thermal and mechanical properties of the material of which the member is composed (Castillo and Durrani 1990; Fukujiro et al. 1993).

In the past, the fire resistance of structural members could be determined only by testing. In recent years, however, the use of numerical methods for the calculation of the fire resistance of various structural members is gaining wide acceptance. These calculation methods are far less costly and time consuming. However, for the use of these calculation methods, the material properties at elevated temperatures are required. One of the basic mechanical properties that is required for the prediction of structural performance under fire conditions is the stress-strain relationship.

For developing stress-strain curves of HSC at elevated temperature, a joint research project between National Chiao Tung University (NCTU), Taiwan, and the National Research Council Canada (NRCC) is currently in progress. As part of this project, detailed experimental studies were undertaken on four different types of HSC.

Both plain HSC and steel fiber reinforced concrete HSC were considered in the study. This is because the addition of steel fibers enhances the mechanical behavior of HSC at elevated temperature and significantly improves the ductility of concrete (Diederichs et al. 1989; Hsu and Hsu 1994; Lie and Kodur 1996). Also, two types of commonly used aggregates, siliceous and carbonate, were considered in the tests since the type of aggregate influences the fire performance and the shape of the stress-strain curves. Detailed results from the experimental study are presented in this paper.

Research Significance

Fire represents one of the more severe exposure conditions and hence provisions of appropriate fire resistance for structural members are major safety requirements in building design. The fire resistance of structural members is dependent on the thermal and mechanical properties, at elevated temperatures, of the materials of which the members are composed.

[1]Associate Professor, Dept. of Civil Engineering, National Chiao Tung Univ., HsinChu, Taiwan.

[2]Senior Research Officer, Institute for Research in Construction, National Research Council, Ottawa ON, Canada K1A 0R6.

[3]PhD Student, Dept. of Civil Engineering, National Chiao Tung Univ., HsinChu, Taiwan.

Note. Associate Editor: Zhishen Wu. Discussion open until July 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 28, 2001; approved on June 11, 2003. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 16, No. 1, February 1, 2004. ©ASCE, ISSN 0899-1561/2004/1-84–90/$18.00.

One of the key properties needed for the assessment of the overall response of structures under fire conditions is the stress-strain relationships. Whereas the stress-strain curves at elevated temperatures have been established for various types of NSC, this is not the case with HSC, specifically HSC with steel fibers (Lie and Kodur 1996).

Temperature is one of the main factors that influence the strength, as well as the stress-strain relationships, of concrete. The present study was undertaken to investigate the effect of high temperature on the strength and stress-strain relationship for HSC. The variables considered in the experimental study included concrete strength, type of aggregate, and the addition of steel fibers, since these variables have been shown to be of significant influence in the fire endurance of high strength concrete (Kodur 2000). Stress-strain curve tests were conducted at various temperatures (20, 100, 200, 400, 600 and 800°C) for two types of HSC; plain HSC and steel-fiber-reinforced HSC, made with siliceous and carbonate aggregate. Concrete strengths in the range of 75–84 MPa were considered.

The data on mechanical properties presented in this paper can be used to develop stress-strain relationships, as a function of temperature, for HSC. These relationships can be used as input to numerical models, which in turn can be used to determine the behavior of HSC structural members at high temperatures. The development of computer programs for the calculation of the fire resistance of HSC columns is in progress at NRCC (Kodur 2000).

Experimental Program

Test Specimens

Four types of HSC specimens were investigated, namely specimens made with siliceous and carbonate aggregate concrete; with and without steel fiber reinforcement. The 100 mm diameter×200 mm height specimens were prepared by NRCC, and made in four batches: TWN1, TWN2, TWN3, and TWN4. Each batch consists of one mix proportion. The TWN1 was made of siliceous aggregate and the TWN2 was made of carbonate aggregate. The TWN3 and TWN4 were the counterpart of TWN1 and TWN2, but with the addition of steel fibers. The strength of the specimens at 28 days was in the range 75 MPa to 84 MPa. Granite was used for siliceous aggregate and limestone was used for carbonate aggregate.

In all batches, general purpose Portland cement for construction of concrete structures was used. The fine aggregate for all four batches consisted of silica-based sand. In order to improve workability, superplasticizer and retarding admixture were added to all four batches of concrete mix.

Steel fibers of typical corrugated type were used as reinforcement in TWN3 and TWN4 batches of concrete mix. The steel fiber is a mild carbonaceous steel with tensile strength of approximately 960 MPa. A typical steel fiber is shown in Fig. 1. The corrugated shape of these fibers provided a strong mechanical bond to the concrete to resist shear stress. The fibers, which were 50 mm in length with a 0.9 mm equivalent diameter, had an aspect ratio of 57.

Superplasticizer was added to the concrete, half in the plant and half at the site before the fabrication of specimens, to improve workability. The mix proportions of four batches are given in Table 1.

From each batch of concrete, the following specimens were made:

- 40 small cylinders of 100 mm diameter and 200 mm length.

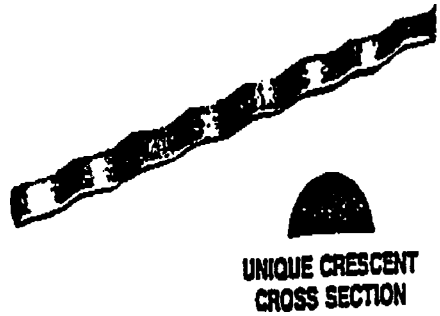

Fig. 1. Typical steel fiber

- 10 large cylinders of 150 mm diameter and 300 mm length.

To measure representative temperature, thermocouples were installed in two small cylinders (100×200 mm) from each batch of concrete. Two thermocouples were installed at mid-height of the cylinder; one on the center axis and the other at quarter depth (25 mm from surface) of the cylinder, as shown in Fig. 2.

The specimens were demolded one day after casting, then soaked under water for seven days and, subsequently, cured in a climate room at 50% relative humidity and 20°C temperature. The compression tests were conducted on large cylinders (150×300 mm) at 7 days, 28 days, and 91 days, respectively, for each type of concrete. The compressive strengths of concrete are given in Table 1.

Afterwards, 100 mm diameter cylinders of each concrete type were shipped to NCTU, Taiwan, for undertaking experimental studies. These specimens were stored in the NCTU laboratory in an atmosphere of approximately 50% relative humidity at 20°C.

Test Apparatus

The tests were performed in a closed-loop servo-control 220 Kip (985 kN) hydraulic pump actuator with a loading frame and an electric furnace. Fig. 3 shows the test apparatus (loading frame with furnace), while Fig. 4 shows the schematic of the test setup. Two special cylindrical nickel-based alloy attachments were used in the top and bottom of the specimen to transmit load from the actuator to the specimen at high temperature. One concrete cylinder of 150 mm diameter and 300 mm height, made of high strength concrete, was placed on the top of the alloy attachment as a heat insulator to protect the test equipment from extreme temperature. Two blankets were welded to the bottom of the upper attachment and the other two were welded on the top of the bottom attachment, respectively, for setting up the linear variable differential transducer (LVDT) to measure the relative deformation of the specimen. Two half-spherical disks were attached on the bottom of the lower attachment and the top of the concrete heat insulator for a uniform load distribution. The clearance between the alloy attachment and the furnace was filled with a ceramic fiber insulator to limit the loss of heat through air circulation. The specimens were encased in a wire mesh, made of nickel-based alloy, to protect the interior of the furnace from explosive spalling of HSC.

To account for the effect of deformation from the attachments and the test equipment, the deformation of the specimen and the displacements of the actuator were calculated by averaging the difference of two pairs of LVDT. The average deformation, Δ_{avg}, was calculated as follows (see Fig. 4):

$$\Delta_{ave} = \frac{(\Delta_{up1} - \Delta_{low1}) + (\Delta_{up2} - \Delta_{low2})}{2}$$

J. Mater. Civ. Eng. 2004.16:84-90.

Table 1. Mix Proportions of High Strength Concrete Specimens

Concrete mix	Batch 1	Batch 2	Batch 3	Batch 4
Specimen	TWN 1	TWN 2	TWN 3	TWN 4
Cement (kg/cu m)	501	499.5	496.5	505
Coarse aggregate (kg/cu m)	1100	1118.5	1100	1100.5
Fine aggregate (kg/cu m)	700	700	700	700
Silica fume (kg/cu m)	45.4	45.4	45.4	45.4
Water (kg/cu m)	123	109.5	114.5	120
Steel fiber (kg/cu m)	0	0	42	42
Water reducing/retarding admixture (ml)	1453	1453	1453	1453
Superplasticizer (L)	9.4	9.4	9.4	11.75
Water-binder ratio	0.25	0.22	0.23	0.25
Compressive strength (MPa)				
7 days	67.8	60.5	64.3	72.1
28 days	75.5	74.5	74.4	83.9
91 days	79	78.3	81.4	85.5

The load was applied, at a constant displacement rate, using an automated computer controlled system. The load and deformation of specimens were recorded continuously for the duration of each test.

Experimental Procedure

For each type of concrete and target test temperature, three specimens were tested and the average of these results was used as the final result. The target test temperatures were determined to be 20 (room temperature), 100, 200, 400, 600 and 800°C, respectively. All tests were conducted under ''hot conditions'' and no residual strength tests were carried out.

Before undertaking stress-strain curve tests, the temperature of the furnace was calibrated against the specimen temperatures. To facilitate this, the concrete cylinders, with thermocouples, were heated in the furnace and the furnace temperatures were measured when the center of the specimens reached the specified target temperature. These temperatures were used as the representative highest furnace temperature for the following stress-strain tests.

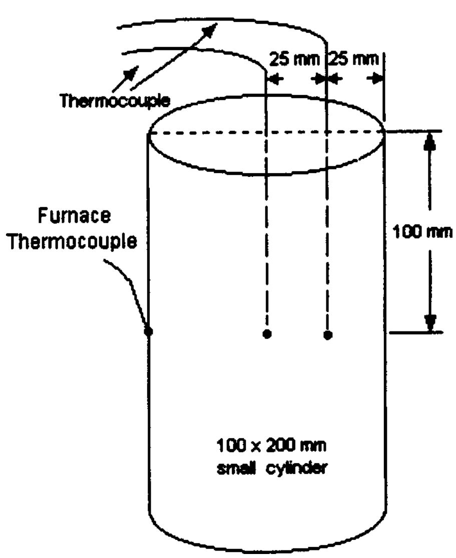

Fig. 2. Typical test specimen with thermocouples

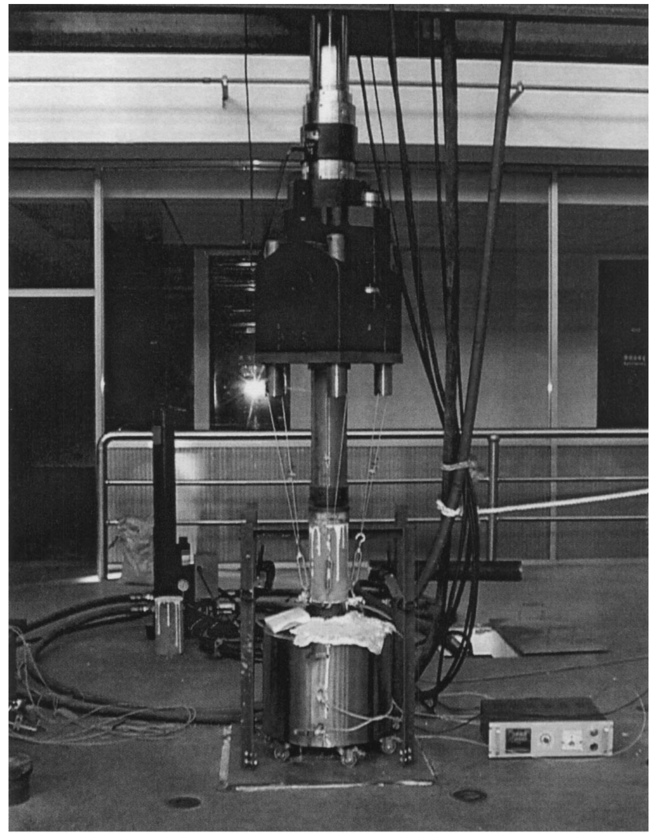

Fig. 3. Test equipment—loading frame with furnace

The cylindrical specimens were heated, without any load, at a constant heating rate of 2°C/min in the furnace chamber until the temperature at the center of the specimen reaches the target temperature. Then the furnace temperature was dropped to the desired target temperature and was kept constant for 60 min to attain a steady state at the center of the specimen (Fig. 5). From the calibration of the furnace, the conservative time needed to reach the desired target temperature at the center of the specimen was found to be 70, 135, 230, 325 and 435 min, corresponding to 100, 200, 400, 600 and 800°C, respectively. See Table 2. During the heating period, moisture in the test specimens was allowed to escape freely.

For generating data in the descending part of the stress-strain curve of concrete, a strain control technique was adopted. After the specimen reached the steady state, it was loaded under uniaxial compression at a rate of (machine crosshead movement) 0.05%/min (0.1 mm/min) until the specimen could no longer sustain the axial load.

During the tests, load and displacement of specimens were measured. The load was measured from the MTS system and the displacement was measured from the average of two pairs of LVDT.

Results and Discussion

Compressive Strength

The variation of the compressive strength ratio with temperature is shown in Fig. 6 for four types of HSC. The compressive strength ratio is defined as the ratio of the max-

J. Mater. Civ. Eng. 2004.16:84-90.

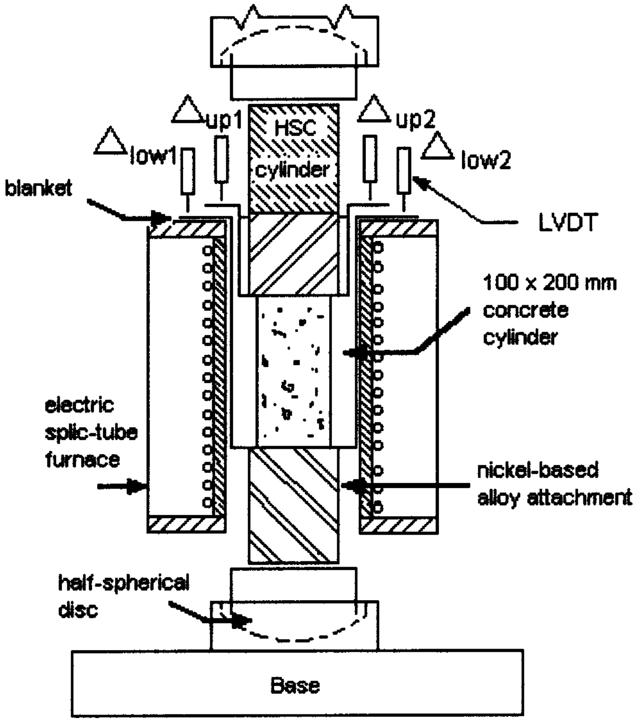

Fig. 4. Schematic of test setup for stress-strain curve tests

imum compressive strength, at a specified temperature, to the maximum compressive strength at room temperature (original strength). The compressive strength was calculated as the average of three cylinder tests. In all four types of HSC, compressive strength decreases with temperature. Initially, as the temperature increased to 100°C, the strength decreased compared to the original strength (Khoury 1992). With a further increase in temperature, the specimens recovered part of its strength at 200°C. The strength at 200°C is about 80% of the original strength (at 20°C). In the temperature range of 400 to 800°C, the strength drops sharply, reaching to a low level of 45 and 20%, of initial strength, at 600 and 800°C, respectively.

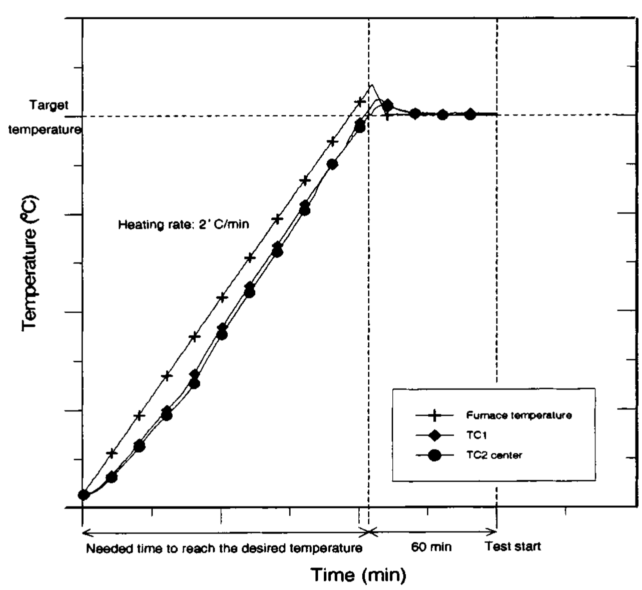

Fig. 5. Sketch map for typical heating process

Table 2. Calibration of Furnace Temperatures with Specimen Temperatures

	Time (min) to attain target temperature				
	Temperature (°C)				
Specimen type	100	200	400	600	800
TWN1	70	131	227	322	420
TWN2	64	125	224	324	433
TWN3	67	130	224	319	415
TWN4	64	135	226	322	432

The moisture content has a significant bearing on the strength of concrete in the temperature range from 20 to 200°C. It is believed that water in concrete softens the cement gel, or attenuates the surface forces between gel particles, thus reducing the strength (Lankard et al. 1971).

The slight increase in concrete strength associated with a further increase in temperature (between 100 and 200°C) is attributed to the general stiffening of the cement gel, or 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 four types of HSC 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.

The presence of steel fiber has little influence on compressive strength. The HSC without steel fiber has a slightly higher compressive strength below 400°C for both aggregate types. However, the ductility of HSC with steel fibers increases at temperatures above 400°C.

Overall, HSC at elevated temperatures loses a significant amount of its compressive strength above 400°C and attains a

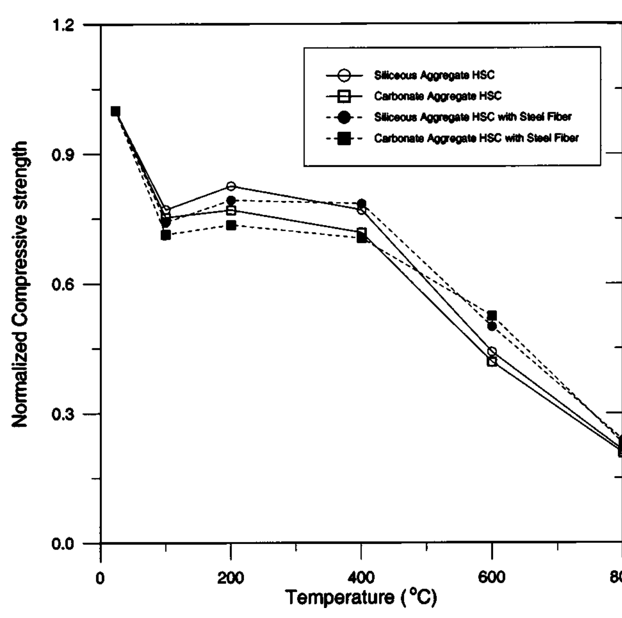

Fig. 6. Normalized compressive strength of high strength concrete (HSC) as a function of temperature

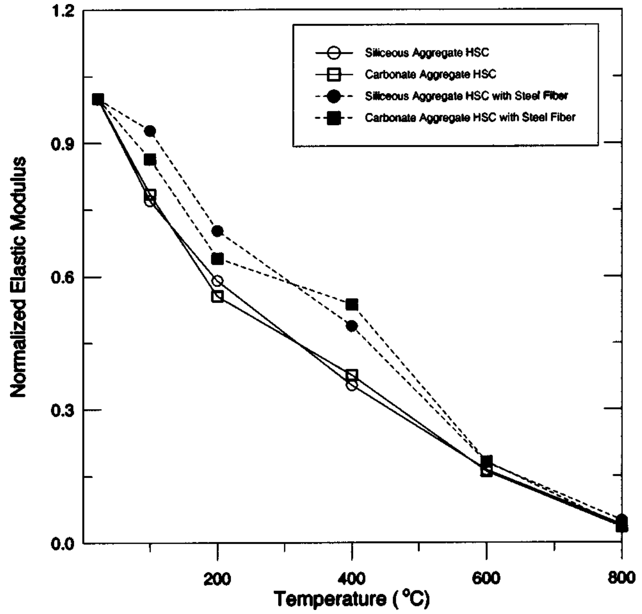

Fig. 7. Normalized elastic modulus of high strength concrete (HSC) as a function of temperature

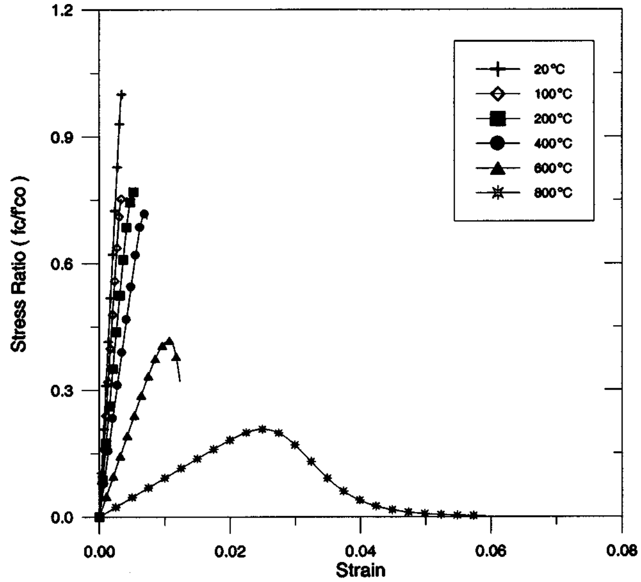

Fig. 9. Stress-strain curves for carbonate aggregate high strength concrete without steel fiber

strength loss of about 75% at 800°C. The loss of strength in the temperature range of 20–200°C is marginal and 200–400°C is minimal, but slightly higher than that in normal strength concrete (Lie 1992).

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. 7 as a function of temperature. Up to about 400°C the elastic modulus of all four types of HSC decreases in a similar fashion, reaching to about 50% of its initial values. The extent of decrease in the elastic modulus of steel fiber reinforced HSC is much higher than that of plain HSC in the 400–600°C range. But, the aggregate type does not influence the variation of modulus of elasticity of HSC with temperature.

Stress-Strain Relationship

The stress-strain plots for HSC, made from siliceous aggregate and carbonate aggregate, at elevated temperatures are shown in Figs. 8 and 9, respectively. The stress ratio, defined as the ratio of the compressive strength at specified temperature (f_c) to the compressive strength at room temperature (f'_{c0}). The stress-strain curves for their counterparts with steel fiber reinforcement are shown in Figs. 10 and 11, respectively.

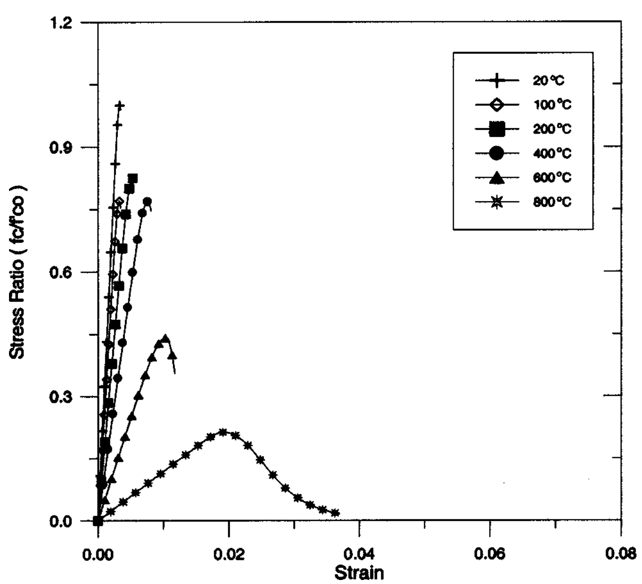

Fig. 8. Stress-strain curves for siliceous aggregate high strength concrete without steel fiber

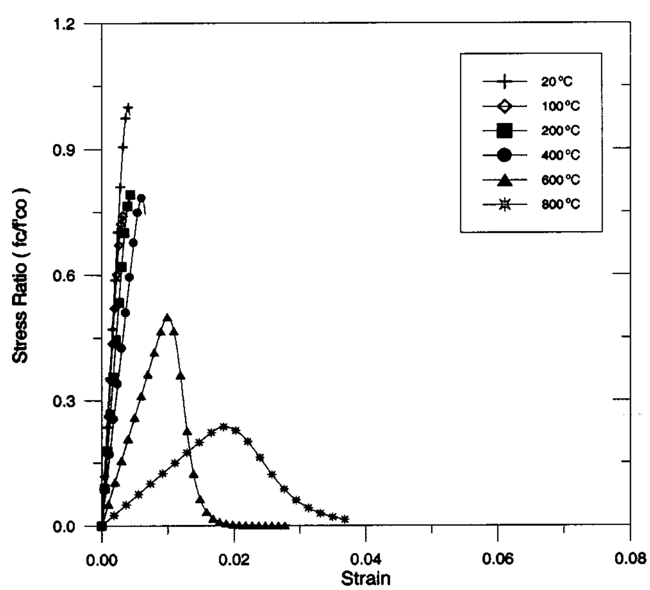

Fig. 10. Stress-strain curves for siliceous aggregate high strength concrete with steel fiber

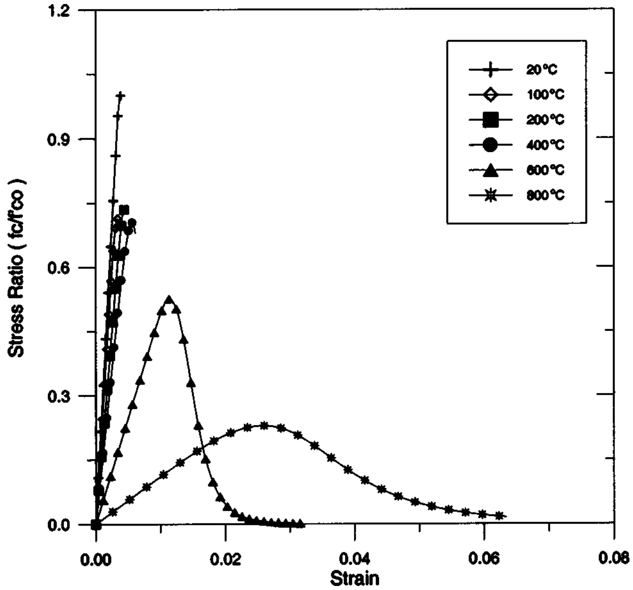

Fig. 11. Stress-strain curves for carbonate aggregate high strength concrete with steel fiber

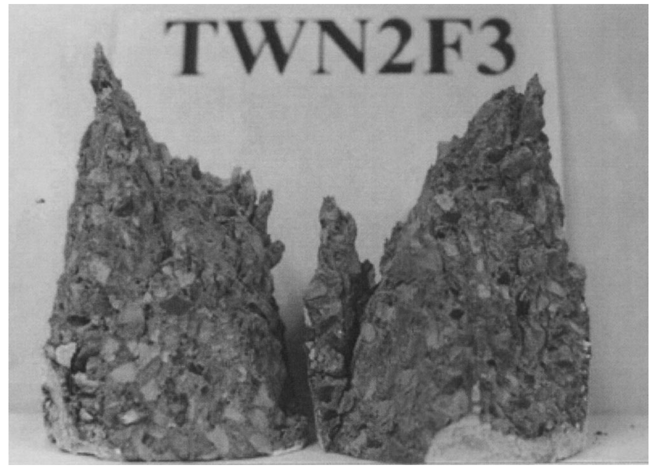

Fig. 13. Failure mode of typical high strength concrete specimen (without steel fiber) at 800°C

The strain corresponding to peak strength did not significantly change up to about 400°C for all four types of HSC. Above this temperature the strains, corresponding to peak strength, increased considerably. The strains attained, corresponding to peak strength at 600°C and 800°C, were twice and seven times the strain at room temperature. For all four types of HSC the strain corresponding to peak strength is almost the same up to about 600°C. These results suggest that the steel fiber reinforced HSC exhibits better ductility characteristics than plain HSC at elevated temperatures.

It can be seen from Figs. 8 and 9 that the aggregate type has an effect on the ultimate strain attained in HSC at elevated temperatures. The strain attained, corresponding to peak strength, in HSC specimens with carbonate aggregate, was 40% larger than those made from siliceous aggregate. It can be seen in Figs. 10 and 11, that a similar trend exists for steel fiber reinforced HSC.

Failure Mode

HSC specimens without steel fiber showed a very brittle type of failure at temperatures less than 600°C. It was impossible to define the complete stress-strain curves, especially in the descending portion. The specimens failed soon after reaching their peak strength. The failure surfaces are "neat surfaces" and pass through the "broken aggregate." The end portion of the failed specimens resembled "double-cone pattern" (at the top and bottom), as can be seen in Fig. 12. When exposed to a temperature of 800°C, concrete specimens without steel fibers exhibited a gradual failure and complete stress-strain curves could be defined. These specimens failed in an irregular pattern (Fig. 13).

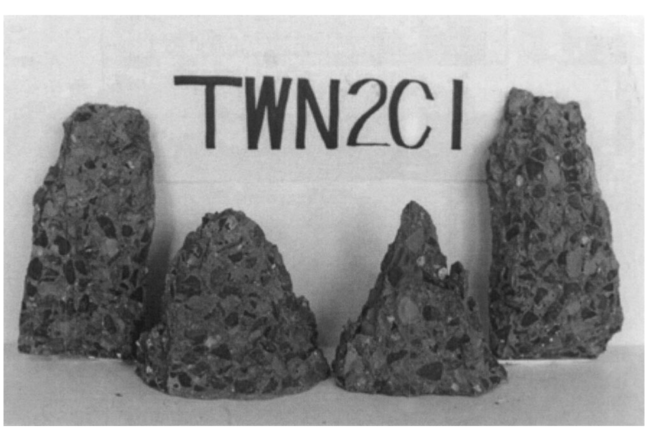

Fig. 12. Failure mode of typical high strength concrete specimen (without steel fiber) at 100°C

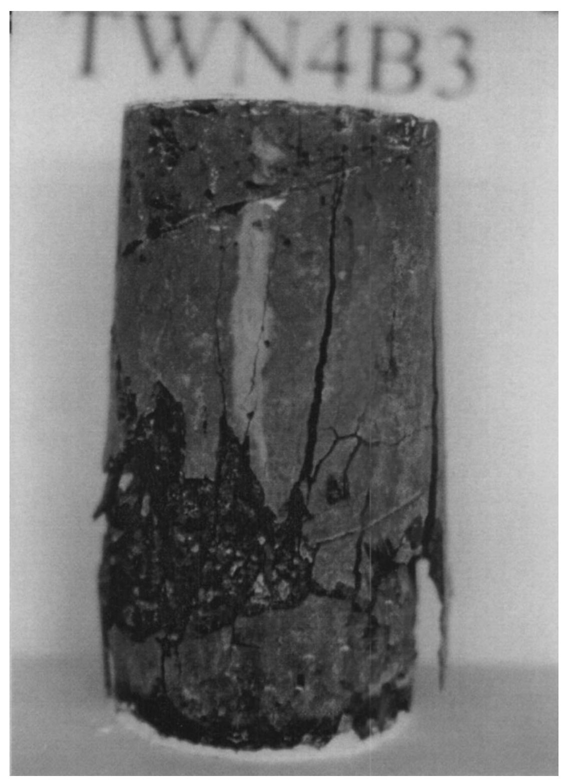

Fig. 14. Failure mode of typical specimen (with steel fiber) at 100°C

J. Mater. Civ. Eng. 2004.16:84-90.

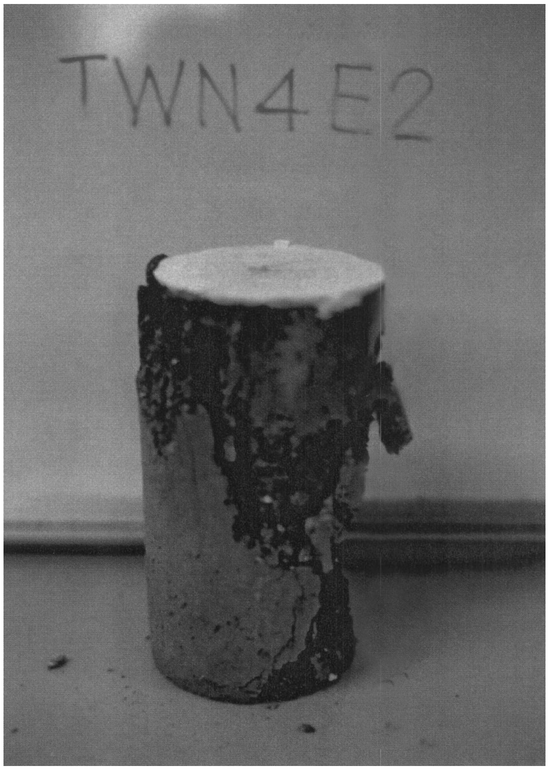

Fig. 15. Failure mode of typical specimen (with steel fiber) at 800°C

The specimens with and without steel fibers exhibited similar failure mode, up to about 400°C. Due to bonding, vertical cracks that appeared in the broken specimens were held together by steel fibers (Fig. 14). With a further increase of temperature, the specimens failed gradually. In these specimens, the tests could be easily carried out (to trace the descending portion of the stress-strain curve) above 600°C (Fig. 15).

Since HSC is a brittle material, it fails soon after crack propagation is initiated. If the number of voids is increased, the propagation of cracks occurs more gradually, resulting in less brittle failure. When temperature increases, the pore water is removed and more voids appear. The ductility of specimens increased with increased temperatures.

Conclusions

Based on the results obtained in this study, and within the limitations of the test parameters, the following conclusions can be drawn:

1. HSC loses a significant amount of its compressive strength above 400°C and attains a strength loss of about 75% at 800°C. The change of strength in the temperature range of 100–400°C is marginal.
2. The addition of steel fibers in HSC improves the ductility at elevated temperature. Steel fiber reinforced HSC exhibits better ductility characteristics than plain HSC at elevated temperatures.
3. The presence of steel fiber has little influence on the variation of modulus of elasticity with temperature. The type of aggregate has moderate influence on the variation of the elastic modulus with temperature.
4. The aggregate type has an effect on the ultimate strain attained in HSC exposed to elevated temperatures; with carbonate aggregate HSC attaining larger strain as compared to siliceous aggregate HSC.

References

Castillo, C., and Durrani, A. J. (1990). ''Effect of transient high temperature on high-strength concrete.'' *ACI Mater. J.*, 35(1), 47–53.

Diederichs, U., Jumppanen, U. M., and Penttala, V. (1989). ''Behavior of high strength concrete at high temperatures.'' *Rep. No. 92*, Helsinki University of Technology, Helsinki, Finland, p. 76.

Fukujiro, F., Takeo, A., and Yasuji, S. (1993). ''Mechanical properties of high strength concrete at high temperatures.'' *Report of Research Laboratory of Engineering Materials*, Tokyo Institute of Technology, Japan.

Hsu, L. S., and Hsu, C. T. (1994). ''Stress-strain behavior of steel-fiber high-strength concrete under compression.'' *ACI Struct. J.*, 91(4), 448–457.

Khoury, G. A. (1992). ''Compressive strength of concrete at high temperatures.'' *Mag. Concr. Res.*, 291–306.

Kodur, V. K. R. (2000). ''Spalling in high strength concrete exposed to fire—Concerns, causes, critical parameters and cures.'' *Proc., ASCE Structures Congress*, Reston, Va., 1–8.

Lankard, D. R., Birkimer, D. L., Fondfriest, F. F., and Synder, M. J. (1971). ''Effects of moisture content on the structure properties of Portland cement concrete exposed to temperatures up to 500°F.'' *Temperature and Concrete, SP-25*, American Concrete Institute, Detroit, 59–102.

Lie, T. T., ed. (1992). ''Structural fire protection: Manual of practice.'' *ASCE Manuals and Reports on Engineering Practice No. 78*, American Society of Civil Engineers, New York, p. 241.

Lie, T. T., and Kodur, V. K. R. (1996). ''Thermal and mechanical properties of steel-fiber-reinforced concrete at elevated temperatures.'' *Can. J. Civ. Eng.*, 23, 511–517.

J. Mater. Civ. Eng. 2004.16:84-90.