Effect of high temperature on high strength RC confined columns with steel fibers

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This paper presents the experimental investigations on the unstressed residual properties of confined and unconfined normal and high strength concrete with and without steel fibers subjected to single heating-cooling cycle of temperatures in the range of 200°C to 800°C with an increment of 200°C. Spalling in HSC columns has been observed at elevated temperatures in both the concretes has been identified and discussed. The ultrasonic pulse velocities of normal and high strength concrete is also determined and discussed. The results presented will generate data on the resistance of high strength RC columns at single heating-cooling cycle of temperature and contribute to identifying the characteristic of behavior of HSC and NSC concretes.

INTRODUCTION

The use of high strength concrete (HSC) is advantageous in columns and shear walls in high-rise buildings, long span pre-stressed concrete bridges and the consideration of durability in construction. One of the major safety requirements in building design is the provision of appropriate fire safety measures for HSC structural members. Past studies [1-15] identified that the spalling in HSC columns at elevated temperature is of major concern. Results from the fire resistance tests show that strength of concrete has significant influence on fire performance of concrete members. The higher the strength, the higher will be the probability of spalling. In majority of the studies, the spalling was quite significant in the HSC columns as compared to NSC columns. Studies also show that the addition of steel fibers was found to be beneficial in enhancing fire endurance of HSC column. The presence of steel fibers increases the tensile strength of concrete, at high temperatures, and thus reduces spalling and enhances fire resistance. Hence, spalling in HSC at elevated temperature is a critical issue and must be realistically assessed and discussed.

Therefore, in the present research paper some aspects related to the spalling and residual properties of concrete at ambient and after single heating-cooling cycle have been covered.

RESEARCH SIGNIFICANCE

The present study discusses the materials residual strength that influences the performance of unconfined NSC, and HSC and corresponding confined specimens after subjected to single heating-cooling cycle of elevated temperature. The work resulted in developing behavior of normal and high strength concrete subjected to single heating-cooling cycle upto 800°C.

OBJECTIVES

The objectives of the present investigation are:

- To develop trial mixes for normal and high-strength concretes designated as NSC and HSC and re-proportioning them by adding steel fibers designated as NSFC and HSFC.
- To determine the residual properties of confined and unconfined concrete of all mixes at ambient and after single heating-cooling cycle.

EXPERIMENTAL PROGRAM

Material properties

Ordinary Portland Cement 43 grade (OPC 43) was used throughout the investigation. The physical properties of cement satisfied the requirements of IS 4031 [16]. The commercially available micro silica of grade 920 U (silica content of more than 92 percent) was used in the present

Table 1. Physical and chemical properties of silica fume

Characteristics	Value obtained
Blaine's fineness (cm^2/gm)	22000
Specific gravity	2.2
Silicon dioxide, SiO_2, (percent by mass)	95.1
$SiO_2+Al_2O_3+Fe_2O_3$, percent by mass	95.1
Loss on ignition, percent by mass	2.79

investigation. The physical and chemical properties of silica fume are given in Table 1. Locally available river sand of Zone-III with fineness modulus of 2.43 and specific gravity of 2.63 and the locally available crushed stone of maximum size of 20 mm with fineness modulus of 2.43 and specific gravity of 2.63 were used as fine and coarse aggregate respectively. The physical properties of fine and coarse aggregate were determined as per IS 383 [17]. The water used for mixing and curing of concrete conformed to IS 456 [18].

The commercially available superplasticizer based on unique carboxylic ether polymer, was used as chemical admixture. Commercially available steel fibers 25 mm in length were used at a dosage of 1% volume fraction (39.25 kg/m^3). The density of fibers used was 7.85 g/cc and were crimped in section as shown in Figure 1. Thermo mechanical treated (TMT) steel bars of 6 mm nominal diameter were used as reinforcement columns and lateral ties. The steel reinforcement confirmed to IS 1786 [19].

Confinement

The confinement of NSC columns carried out in the following manner;

1. NSC column using 25 mm crimped steel fiber reinforcement (NSC+F)
2. NSC column specimens by reinforcing steel with lateral ties (NSC+S)

Figure 1. Crimped carbon steel fiber with crescent shaped cross section

3. NSC column using both reinforcing steel with lateral ties and crimped steel fiber (NSC+F+S). Similarly, the confinement of HSC columns carried out as:
4. HSC column specimens by reinforcing steel with lateral ties (HSC+S)
5. HSC column using 25 mm crimped steel fiber reinforcement (HSC+F)
6. HSC column using both reinforcing steel with lateral ties and crimped steel fiber (HSC+F+S).

Mix proportions

In the present study, The NSC mix was prepared according to the guidelines of IS 10262 [20] and the HSC concrete mix was selected based on method of trials. Quantities of ingredients for one cubic meter of concrete were calculated by using the absolute volume method. The normal and high strength concrete mixes used in the present study are shown in Table 2.

Table 2. Concrete mix proportion

Mix	Cement (kg/m^3)	Silica fume (kg/m^3)	Fibers (% Vol. fraction)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water-cement ratio	Super plasticizer (% by wt of cement)	Slump (mm)
NSC	338	-	-	624.9	1160	0.55	-	75
NSFC	338	-	1.0	624.9	1160	0.55	-	72
HSC	600	49.8	-	624	1050	0.34	2.0	30
HSFC	600	49.8	1.0	624	1050	0.34	2.0	28

Casting of specimens

The cast iron cylinders of 150mm×300mm were used for measuring the compressive strength of concrete with and without fibers at ambient and after heating at elevated temperature. Special cylindrical moulds of column of 100mm×450mm were fabricated for determining the behavior of the unconfined and confined normal and the high strength concrete at ambient and after heating at elevated temperature. The RC columns were cast to find the behavior under compression at ambient and at elevated temperature. The columns reinforced with 6 # 6 mm diameter bars as longitudinal reinforcement and 6 mm circular lateral ties. After 28 days of curing, the samples were prepared for testing at different elevated temperatures for heating duration of 3 hrs. The total numbers of cylinders tested were 12 (standard cylinder) X 5 (25±2°C to 800°C) + 18 (special cylinders) X 5 (25±2°C to 800°C) = 150.

High temperature furnace

The electric furnace used in the present experimental work consists of front opening and three sides were fixed not to open. The internal dimensions of the furnace are 1000×760×510 mm (length × width × height). The electric furnace has the rating of 1150°C with a programmable microprocessor temperature controller attached to the furnace power supply. The specimens kept in it were heated for three hours holding time keeping in view that the public life-safety codes do not allow structures to be built unless they have 2 hr fire ratings and insurances companies will not insure structures that have less than 2 hr fire rating.

Testing of cylinders and RC columns after single heating-cooling cycle of temperature

For single heating-cooling cycle, the specimens were heated to elevated temperature ranging 200°C to 800°C at an average rate of 3°C/min. The specimens were then held at the desired temperature for approximately 3 hours. Figure 2 shows the single heating-cooling cycle upto target temperature 'T'. After one cycle of heating and cooling, the ultrasonic pulse velocities have been measured as per IS: 13311 [21] and specimens were tested for the unstressed residual compressive strength. For each mix, the reading of an average of 3 specimens has been reported.

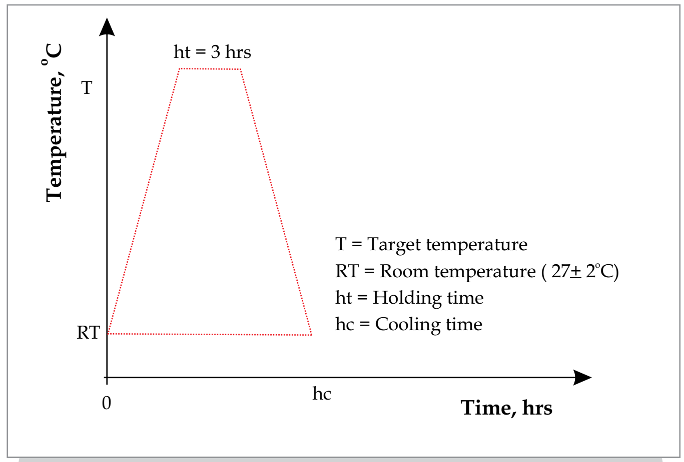

Figure 2. Single heating-cooling cycle curve

RESULTS AND DISCUSSION

Spalling in columns at elevated temperature

The spalling in RC columns subjected to single heating-cooling cycle is discussed in the following:

i. The NSC and HSC columns without confinement collapsed at higher temperature (800°C) temperature and could not be tested for its residual strength under compression, as shown in Figure 3.

ii. The confinement provided by the fibers only is observed to be inadequate at elevated temperature.

Figure 3. Failure in columns without confinement after single heating-cooling cycle at elevated temperatures

Figure 4. Confined column with fibers with extensive cracks before spalling at 800°C

The cover of high strength columns confined with fibers spalled at higher temperature (beyond 600°C) as shown in Figure 4, whereas the performance of high strength column confined with steel reinforcement (HSC+S) is observed to be better at higher temperature

Figure 5. Spalling in columns confined with steel reinforcement at elevated temperature

Figure 6. Behavior of columns confined with fibers and steel reinforcement after single heating-cooling cycle at elevated temperature

as shown in Figure 5. It can be due to the heating of fibers, which did not act as crack arrestors and accelerated the process of spalling of cover concrete due to fibers loosing bond at higher temperatures.

iii. The spalling of concrete was more prominent in HSF+S+F as compared to other HSC column specimens as shown in Figure 6. The reason of spalling in HSC columns may be attributed due to the lower permeability, which will cause escape of water from pores at higher temperature resulting build up of pore pressure within cement matrix.

Ultrasonic pulse velocity after single heating-cooling cycle

The results of the experiment generated on ultrasonic pulse velocity of concrete after single heating-cooling cycle and related quality of concrete as shown in Tables 3 and 4 respectively is discussed as follows:

i. As expected, the pulse velocity of different concrete mixes at different temperatures decreases with increase in temperature.

Table 3. Ultrasonic pulse velocities of concrete after single heating-cooling cycle of elevated temperature (Km/sec)

Temperature (°C)	NSC	HSC	NSFC	HSFC
25	4.01	4.60	4.51	4.40
200	3.50	4.30	3.71	4.00
400	2.01	3.67	3.01	3.80
600	-	3.47	2.68	-

Table 4. Quality of concrete mixes after single heating-cooling cycle of elevated temperature

Temperature (ºC)	NSC	HSC	NSFC	HSFC
25	Good	Excellent	Excellent	Good
200	Good	Good	Good	Good
400	Poor	Good	Medium	Good
600	-	Medium	Poor	-

Table 5. Residual compressive strength of concrete after single heating-cooling cycle of elevated temperature (MPa)

Temperature (°C)	NSC	HSC	NSFC	HSFC
25	24.38	44.61	28.02	53.31
200	18.37	39.34	29.02	46.83
400	10.00	34.21	24.19	35.15
600	3.00	27.12	12.20	26.90

ii. After 200ºC, the pulse velocity has decreased sharply in NSC and NSC+F due to increase in crack propagation in all concrete specimens when subjected to elevated temperature and decrease in strength of concrete.

iii. The HSC has shown a higher pulse velocity as compared to that in NSC and HSC+F at ambient temperature to about 400ºC. The pulse velocity of HSC and HSC+F is close at 400ºC. At 400ºC, cracks are visible on the surface of all concrete specimens and it was not possible to record the pulse velocity.

iv. The quality of HSC at ambient temperature, which has been found to be excellent, but the quality of NSC, NSC+F and HSC+F is found to be good up to 200ºC. At 400ºC and beyond, the quality of all concrete mixes has been found to poor. The pulse velocity could not be recorded at 800ºC.

Effect of elevated temperature on compressive strength of NSC and HSC

The residual compressive strength of all the concrete mixes at ambient and elevated temperatures is shown in Table 5 and discussed as follows:

i. There is a substantial reduction in strength of NSC with increase in temperature, but the strength reduction in HSC is lower as compared with NSC. It can be due to the low w/c ratio and lesser porosity of HSC as compared to that of NSC.

ii. On addition of these fibers, the compressive strength of NSFC increases with increase in temperature as compared to NSC and similar trend is observed in HSFC up to 400°C, but at 600°C there is a reduction in strength of HSFC as compared to HSC due to melting of fibers beyond 600°C.

iii. The residual compressive strength of all concrete mixes could not be recorded at 800°C, because the concrete specimens collapsed during heating at elevated temperature (800°C).

Effect of elevated temperature on behavior of normal and high strength RC columns under compression

The residual strength of RC columns at ambient and after single heating-cooling cycle discussed in the following:

i. As expected, the residual compressive strength of all RC columns decreases with increase in temperature as shown in Table 6.

ii. There is substantial decrease in strength in NSC+F, NSC+F+S with increase in temperature as compared to NSC+S. It can be due to the failure of bond between the fibers and concrete. It has also been observed

Table 6. Residual compressive strength of RC column after single heating-cooling cycle of elevated temperature (MPa)

Temperature (ºC)	NSC+F	NSC+S	NSC+F+S	HSC+F	HSC+S	HSC+F+S
25	30.12	48.00	50.27	55.76	73.00	75.13
200	19.19	47.57	42.13	48.00	68.00	62.47
400	10.73	39.50	12.00	35.30	58.00	25.28
600	2.59	20.20	-	25.00	46.90	-

that the rate of reduction in strength, with increase in temperature in NSC+S is lesser as compared to other concretes. The residual compressive strength in NSC+S is found to be greater than NSC+F+S and NSC+F at all temperatures. The specimens of all the above concretes, collapsed at 800°C, and thus could not be tested for its residual compressive strength.

iii. The values of residual compressive strength are higher in HSC+S at all temperatures as compared to other concretes. Substantial reduction of residual compressive strength is observed in HSC+S and HSC+F at 600°C temperature. The residual compressive strength at 600°C, could not be measured for HSC+F+S as the concrete specimens started deteriorating.

The reason of above observations is bond failure between concrete and fibers and concrete with steel and fibers due to melting of fibers at elevated temperature. Another reason may be due to higher cement content which leads to higher content of $Ca(OH)_2$ in concrete. However, the free $Ca(OH)_2$ may react with the siliceous material and contribute to strength of concrete.

CONCLUSIONS

From the present experimental investigation, the following conclusions have been recorded:

- Residual compressive strength of NSC and HSC concrete cylinders decreased with increase from 25 to 600°C.
- Steel fiber reinforced HSC exhibits better ductility characteristics than plain HSC at elevated temperatures and addition of steel fibers modifies the residual compressive strength of the both the concretes. Therefore, HSC with fiber can be more beneficial in the severe conditions as compared to the other concrete mixes.
- The reduction in residual compressive strength is marginal in HSC and HSC+F at higher range of temperature whereas large variation in strength is observed in NSC and NSC+F at all temperatures. NSC+S specimens performed better at all temperatures as compared to NSC and NSC+F
- Percentage reduction in residual compressive strength is found to be higher in NSC+F as compared to HSC+F. Percent reduction in compressive strength is higher in NSC+F as compared to NSC+F+S and NSC+S.
- Considerable reduction in residual strength was observed in NSC+F+S and HSC+F+S specimens at 400°C and beyond this can be due to the overheating of steel fibers and subsequent loss of bond.
- Beyond 600°C a reduction in strength was observed in all specimens and at 800 °C cracks covered the entire body of specimens and concrete spalled on being tested under load.
- The ultrasonic pulse velocity decreases with increasing temperature and could not be recorded at 400°C for NSC and after 600°C for the other mixes. Based on the pulse velocity, the quality of NSC has been categorized as good up to 200°C. Similarly on the above basis HSC and HSFC can be categorized as good up to 400°C.

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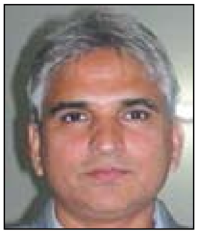

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