Effect of Harsh Temperature Environment on Strength and Durability of Normal and High Strength Concrete

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ABSTRACT: Concrete is a material which is likely to expose at high temperature during fire. The mechanical properties such as strength, modulus of elasticity, volume stability etc are severely affected at the time of such exposure. In the present experimental study, the effect of elevated temperatures on split and flexural tensile strengths of normal and high strength concrete have been investigated. Test samples were subjected to temperatures varying from 100 - 800 degree Celsius. The split tensile strength and flexural tensile strength of normal and high strength concrete is determined by testing cylinders of 100 mm x 300 mm size and prisms of 100 mm x 100 mm x 500 mm respectively. The specimens were subjected to a heating-cooling cycle at 100 degree Celsius with a hold period of 3 hours. The specimens were cooled in the furnace before testing it for tensile strengths. Similar type of harsh conditions was provided to the specimens at 100˚C, 200˚C, 400˚C, 600˚C and 800˚C and their residual strengths were determined. Specimens were also prepared for determining the tensile strengths at ambient temperature environment. It has been observed that the significant losses occur with the increase in temperature for both normal and high strength concrete. High strength concrete (HSC) experienced lesser amount of loss in comparison to normal strength concrete (NSC). Flexural tensile strength was observed to experience a sharp loss at high temperatures but however, split tensile strength experienced a gradual loss, with the increase in temperature. The test results revealed that the effect of high temperature is more severe on flexural tensile strength as compared to split tensile strength. A regression analysis has been performed to model a mathematical relation of normalized strength with surrounding temperature in terms of characteristic strength of concrete.

1. INTRODUCTION

Fire is classified as one of the most severe exposure condition for the civil structures. For the sake of safety, a proper structural design meeting the requirements of fire resistance has been a need in the modern era. The fire resistance of structural member has put its dependencies on the thermal and mechanical characteristics of building material and of course on severity of thermal exposure. Temperatures are one of the different factors that provide key role for making influence on strengths and elastic-plastic properties, especially that for concrete. For finding the structural fire response, the evaluation of prime thermo-mechanical characteristics of material has been done by plotting stress-strain curves. In recent times, the use of high strength concrete (HSC) in construction industries has been boosted as compared with that of normal strength concrete (NSC). It is important to model the behavior of HSC for elevated temperatures conditions. According to codal provisions, the HSC pertain the cube compressive strength of equal or more than 60MPa whereas on the other hand, NSC acquires less than 60MPa. The HSC mix is often prepared by reducing the water-cement ratios and mixing admixtures for purpose of increasing workability. One of the major concerns in using HSC is the lesser reluctance against the fire caused due to increased brittleness as a result of less porosity developed using lower w/c ratios relative to NSC. Preliminary studies showed in various reported researches show significant variations in characteristics of HSC and NSC. Kodur et al. investigated the stress-strain behavior of plain and steel fiber reinforced HSC having compressive strength of specimens ranging between 75MPa to 84MPa at temperature of 20˚C, 100˚C, 200˚C, 400˚C, 600˚C and 800˚C (Kodur 1998). Another study studied by Noumowe on mechanical properties of concrete revealed no significant effects while mixing polypropylene fibers at elevated temperatures (Noumowe 2005). While in another reported study, substantial reductions in value of Young's modulus of elasticity, split tensile strength as well as compressive strength have been found in HSC specimens with increment in temperatures when elevated to 200˚C (Suhaendi 2009). Recently, the durability of sustainable concrete subjected to elevated thermal conditions has been reported (Memon 2019). The study revealed the silica fumes and metakaolin based high strength concrete lose durability at a faster rate when compared to fly ash and GGBS concrete. Further it is concluded that the inclusion of propylene had negative effects on post fire durability of concrete. The losses in durability are due to irreversible physical and chemical transformations that take place due to exposure in fire. Another reported study investigating residual properties of concrete subjected to elevated temperatures revealed 80% loss in elastic modulus and 50% loss in tensile strength in NSC when exposed to 600˚C temperature (Rafi et al. 2019). The loss in compressive strength of NSC was also found near to 70% at 800˚C. The high strength concrete due to its lower permeability results into explosive failure in higher elevated temperatures. The explosion results due to pore water vapor pressure exerted inside the concrete due to inability of gas escaping. This erratic behavior provides difficulties in obtaining the mechanical characteristics of HSC at elevated temperatures.

The literature revealed the research gap in finding the comparative behavior of fire resistance on to the behavior of tensile and flexural strengths of concrete materials. In the present paper, the model for split tensile and flexural strength has been made on the basis of experimental investigations carried out on NSC and HSC specimens at elevated temperatures of up to 800˚C. The novelty aspect includes the study done in finding the comparison of mechanical properties of HSC with NSC under the fire environment.

2. EXPERIMENTAL PROGRAM

2.1 Material Properties

Ordinary Portland Cement 43 grade (OPC 43) was used throughout the experimental investigation. The physical properties of cement confirmed with the recommendations of IS-4031. Locally available river sand with fineness modulus of 2.43 was used as fine aggregate and locally available crushed granite stone of maximum size aggregate of 20 mm was used as coarse aggregate. The specific gravity of the aggregate was 2.65 g/cm^3. Washed aggregate was used throughout the study. The physical properties of fine and coarse aggregate confirmed with IS-383. The potable water was used for mixing and curing which was free from injurious amount of deleterious materials as recommended by IS: 456. The commercially available super plasticizer was used as chemical admixture for enhancing the strength and workability of concrete.

Table 1. Physical properties of Ordinary Portland Cement

Characteristics	Experimental Results	Recommended values
Specific Gravity	3.15	3.15
Normal Consistency (% by weight of cement)	32	-
Setting time (minutes) (i) Initial (ii) Final	 65 600	 30 (min.) 600 (max.)
Soundness of cement (mm)	5	<10
Compressive strength (MPa) (i) 3-days (ii) 7-days (iii) 28-days	 23.5 28.6 43.5	 22 28 43

Table 2. Physical properties of Fine Aggregate & Coarse Aggregate

Fine Aggregate

Characteristics	Observed Test Values
Grading zone	II
Fineness modulus	2.95
Specific Gravity	2.30
Water Absorption (%)	1.01

Coarse Aggregate

Characteristics	Observed Test Values
Fineness modulus	6.95
Specific Gravity	2.75
Water Absorption (%)	0.8

2.2 Proportioning of specimen mixes

Three concrete mixes were prepared as per the guidelines of IS: 10262 at an ambient temperature of 20^0C and relative humidity of 60%. The normal strength concrete (NSC) mix for 20MPa compressive strength of concrete at 28-days and trial mixes were conducted for HSC to obtain the target strength about 60MPa at 28-day. Super plasticizer with 2 percent of cement weight was used in HFC mix for workable concrete. The details of the mix proportions are shown in Table 1.

2.3 Casting and Testing Procedure

The standard prisms of size 100 mm × 100 mm × 500 mm and cylinders of size 150 mm × 300 mm were cast to determine the flexural and spilt tensile strength of concrete at 28 days and tests were performed according to IS: 516 and IS: 5816 respectively (see Figure 1b and Figure 1c). One thermocouple per specimen was inserted just after casting the specimens into moulds. The specimens were demoulded after 24 hours and cured under water for the period of 28 days. After 28 days of curing, the specimens were prepared for testing at room and at elevated temperatures for single heating-cooling regimes.

2.4 High Temperature Furnace

The electric furnace was fabricated for testing of cubes and cylinders at different thermal loading. The heating elements were fixed at the two opposite sides and on the top side of the furnace, with refractory lining on all six faces. The internal dimensions of the furnace are 1000 mm × 760 mm × 510 mm (length × width × height). A 40 mm diameter hole was provided in front of the furnace for the release of fumes and used for placing thermocouples in the furnace. The electric furnace has the rating of 1150˚C with a programmable microprocessor temperature controller attached to the furnace power supply (see Figure 1a). The temperature history in the furnace is controlled by a designated fire curve, typically those of "standard fires". Usually, furnaces are equipped with devices to measure temperatures, and deformations, and to load test specimens.

The specimens were heated at elevated temperatures i.e. at 100˚C, 200˚C, 400˚C, 600˚C and 800˚C after the curing age of 28 days. The specimens were heated for two hours holding time keeping in view that concrete must have a fire test rating of at least two hours in order to insure that structural damage will not result in a collapse, before buildings are evacuated, and for safety of fire fighters. Public life-safety codes do not allow structures to be built unless they have two hours fire ratings and insurances companies will not insure structures that have less than two hours fire rating. The furnace was completely closed during heating and cooling process. After completion of one cycle, the specimens were tested for split and flexural tensile strength.

(a) **(b)**

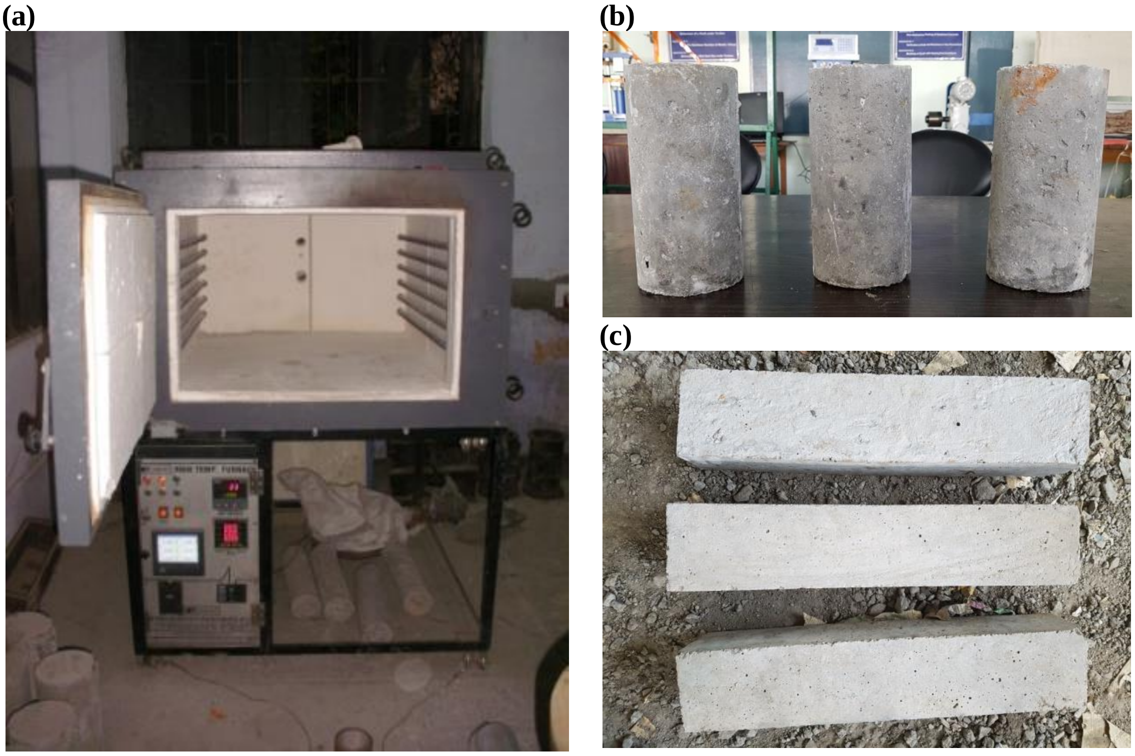

Figure 1. **(a)** Electrical furnace having temperature rating of 1150˚C, **(b)** Cylindrical concrete specimens of grade M20 and M60 for split tensile test, and **(c)** Concrete prism specimens of grade M20 and M60 casted for performing flexural strength test.

3. OBSERVATIONS

Two separate experimental investigations were carried out to evaluate the split tensile strength and flexural strength of NSC and HSC for six different temperature conditions. Three specimens for each data set have been tested to estimate the mean strength for NSC and HSC so as to get precise results with minimum errors. It is observed that with increase in testing temperature, both the split tensile strength as well as flexural strength decreases. The plots for variation of split tensile and flexural strengths for both NSC as well as HSC are depicted in Figure 2. The behavior of respective strengths with elevated temperatures has been evaluated by considering the parabolic curves. These expressions are shown in equation (1), (2), (3), and (4).

For split tensile strength,

$$S_F = 4E\text{-}06T^2 - 0.007T + 3.848 \quad \text{for NSC} \quad (1)$$

$$S_T = 4E\text{-}06T^2 - 0.008T + 5.115 \quad \text{for HSC} \quad (2)$$

For flexural strength,

$$S_F = 8E\text{-}06T^2 - 0.011T + 4.148 \quad \text{for NSC} \quad (3)$$

$$S_T = 6E\text{-}06T^2 - 0.011T + 5.394 \quad \text{for HSC} \quad (4)$$

Where, 'S_T', 'S_F' and 'T' are residual split tensile strength in MPa, flexural strength in MPa, and the surrounding temperature in ˚C.

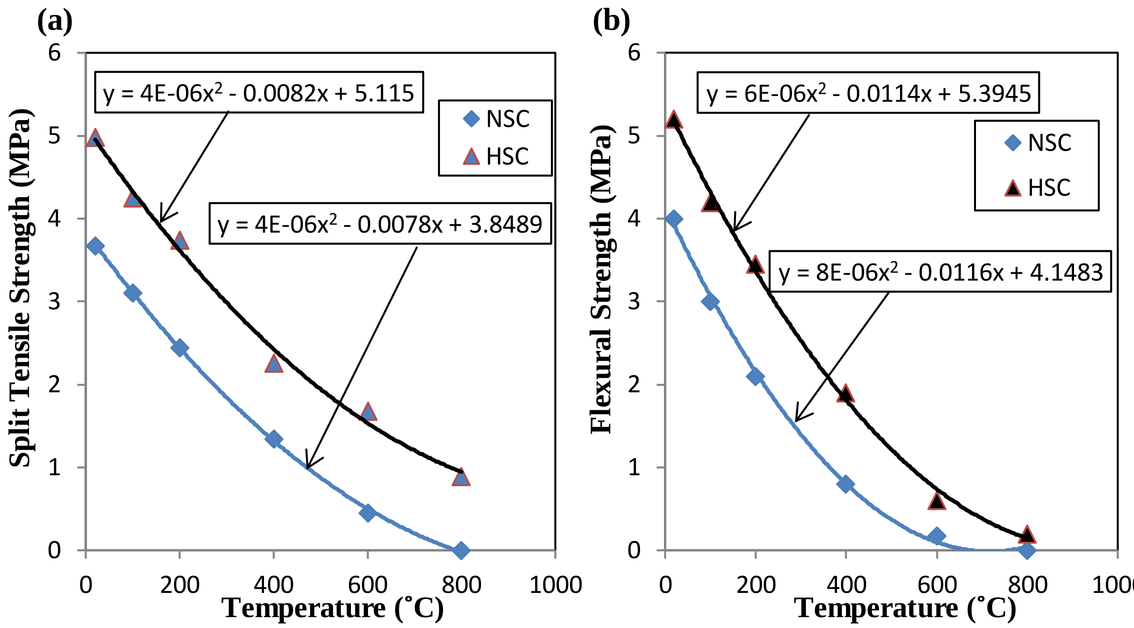

Figure 2. Variation of **(a)** Split tensile strength, and **(b)** Flexural Strength, for normal strength concrete (NSC) and high strength concrete (HSC) with elevated temperatures (Range 20˚C-800˚C).

The equations for residual strengths of both NSC and HSC were modeled with confidence level of more than 99% in temperature range of 20˚C - 800˚C. These equations will help the future researcher in evaluating the performances of M20 and M60 grade concrete for a better prediction of split tensile and flexural strengths. To obtain a better understanding in degradation of considered strengths, the bar graphs evaluating the percentage losses in strengths of NSC and HSC with increasing temperatures are plotted shown in Figure 3. It has been observed that losses were higher in flexural strength values when compared to losses in split tensile strength on increasing the surrounding temperature up to 800˚C.

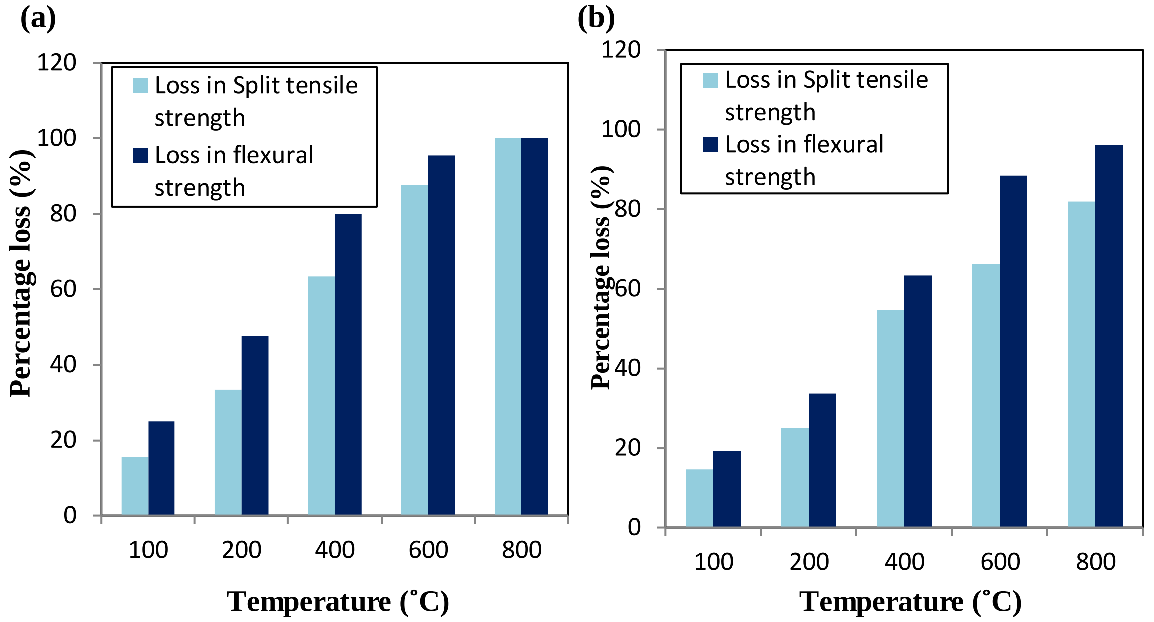

Figure 3.Variation of percentage loss in **(a)** NSC, and **(b)** HSC, with increase in surrounding temperature ranging between 20˚C - 800˚C.

Also, on visualizing Figure 3, it is observed that the losses in strengths are more for normal strength concrete (NSC) specimens with increase in temperatures when compared to that of high strength concrete (HSC) specimens. The losses in NSC are about 1.5 times higher than that of HSC at respective temperatures. For the purpose of standardizing and modeling the results, the variation of normalized residual strength has plotted against normalized temperatures shown in Figure 4.

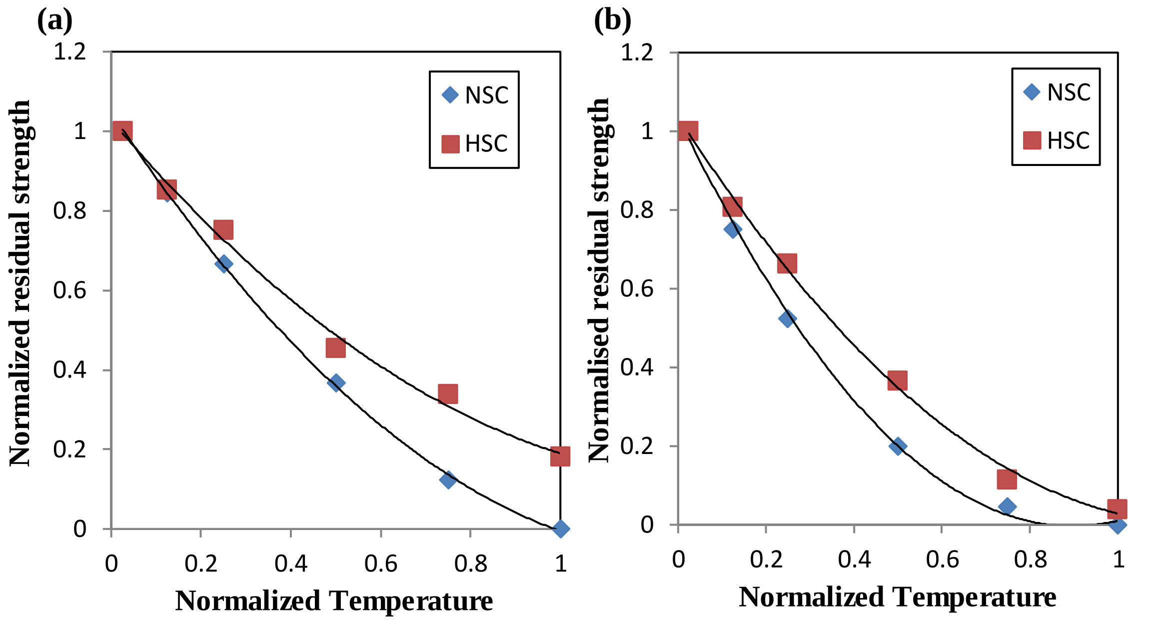

Figure 4. Variation of normalized **(a)** Residual split tensile strength, and **(b)** Residual flexural strength, for normal strength concrete (NSC) and high strength concrete (HSC) with elevated temperatures (Range 20˚C-800˚C).

The equation modeled depicting the retarding behavior of split tensile and flexural strengths with elevated temperatures are shown in equation (5) and (6) respectively.

For split tensile strength,

$$S_T = \left\{(-4f_{ck} + 722)\left(\frac{T}{T_f}\right)^2 + (9f_{ck} - 1882)\frac{T}{T_f} - 0.513f_{ck} + 1057.75\right\} \times 10^{-3} \quad (5)$$

For flexural strength,

$$S_F = \left\{(-13f_{ck} + 1572)\left(\frac{T}{T_f}\right)^2 + (14f_{ck} - 2606)\frac{T}{T_f} + 1037\right\} \times 10^{-3} \quad (6)$$

Where, 'S_T' , S_F', 'T', 'T_f' and ' f_{ck}' are normalized residual split tensile strength, normalized residual flexural strength, test temperature, temperature at failure and characteristic compressive strength of concrete respectively.

4. CONCLUSIONS

The present study successfully investigates the retarding behavior of tensile and flexural strength in normal and high strength concrete specimen. It has been shown that significant losses in strengths occurred with the increase in surrounding temperature which was consecutively modeled in terms of parabolic expressions. High strength concrete (HSC) experienced lesser amount of loss in comparison to normal strength concrete (NSC). Flexural tensile strength was observed to experience a sharp loss at high temperatures but however, split tensile strength experienced a gradual loss, with the increase in temperature. The test results revealed that the effect of high temperature is more severe on flexural tensile strength as compared to split tensile strength. A regression analysis has been carried out successfully for modeling a mathematical relation of normalized residual strength in terms of surrounding temperature and characteristic strength of concrete. The expression derived helps the future researchers in developing better alarming system by predicting more precise residual strengths.

5. REFERENCES

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