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Compressive strength of normal and high strength concrete with polypropylene fibers at elevated temperature

[Amjad Masood, Fatemeh Soltanzadeh, Abdul Baqi and Mohd Shariq]

***Abstract*— Experimental investigations were carried out for assessing the influence of thermal loading on the cube and cylinder compressive strength of normal and high strength concrete with and without polypropylene fibers. The tests were carried out under two phases of heating and cooling. In the first phase of heating, the specimens were subjected to single heating-cooling cycle with a hold period of 3 hours at 200^{0}C and were cooled in the furnace before testing the specimens for the residual compressive strength. Similar treatment was carried out on the specimens at 400^{0}C, 600^{0}C and 800^{0}C and their residual strength's were determined. In the second phase of heating and cooling, the specimens were subjected to successive cyclic heating-cooling regime from 200^{0}C to 800^{0}C, with an increment of 200^{0}C and a hold period of 3hrs. After subjecting the specimens to successive cycles of heating-cooling, the specimens were cooled in the furnace and tested for compressive strength. Specimens were also prepared for assessing the strengths at room temperature. It has been observed that with the increase in the thermal loading or temperature, the compressive strength experienced significant losses. The experimental results show that the strength loss is controlled by the composite action of both fiber and concrete. The polypropylene fibers show an increase in the ductility, fire resistance and enhancement of the composite material properties. The results of the present study are useful in understanding the behavior of fibrous concrete properties at elevated temperatures.**

***Keywords*— Elevated temperature; normal strength concrete; high strength concrete; polypropylene fibers; compressive strength; tensile strengths; strength ratio**

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I. Introduction

Fire is one of the natural hazards which attack building construction. The damage in buildings which is continuously exposed to fire is caused due to its high temperature. It is vital that buildings be capable of protecting people and property against the hazards of fire. High strength concrete (HSC) is being increasingly used in multi-storey building components, where structural fire safety is one of the major design considerations. Spalling under fire is one of the major concerns with HSC which is due to low water/cement ratio.

Many researchers observed the degradation in mechanical properties of concrete with different mix proportions due to exposure to high temperature. Nishida et al. [1] reported the effect of short polypropylene fibers on the spalling resistance of HSC and on their strength properties during fire. Saad et al. [2] studied the effect of temperature on physical and mechanical properties of concrete containing silica fume. Phan and Carino [3] compiled and compared the mechanical properties of HSC and NSC at elevated temperature. The differences are more pronounced in the temperature range between 25^{0}C and 400^{0}C, where HSC have higher rate of strength loss than NSC. Kodur [4] has also mentioned that HSC provides a high level of structural performance, especially in strength and durability as compared with NSC. Luo and Chan [5] discussed the effect of high temperature on the residual strength and the corresponding pore structure in several high performance concrete (HPC) in comparison to NSC. Cülfik and Özturan [6] studied the effect of high temperature (300^{0}C to 900^{0}C) on the residual modulus of elasticity, flexural and compressive strength of the high strength mortars specimens. It has been observed that the specimens that were exposed to elevated temperatures showed higher decrease in flexural strength than compressive strength. Similarly, Li et al. [7] investigated the compressive, splitting tensile and bending strength of NSC and HSC at elevated temperature. They concluded that the relative strength of concrete reduced with increase in exposure temperature. Phan and Carino [8, 9] determined the mechanical properties of concrete at elevated temperature under stressed, unstressed and unstressed residual property tests and compared the results with design standards. The investigation and review of experimental studies by Xiao and Gert [10] on the mechanical behavior of normal and high strength concrete with steel fibers at high temperature revealed that the strength, elastic modulus and peak strain degrades with increase of temperature and the degradation of tensile strength is much more as compared with compressive strength. Cheng et al. [11] revealed that the compressive strength of HSC at 400^{0}C losses significantly and

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75% strength loss has been observed at 800°C. Songa et al. [12] observed spalling and strength properties of nylon and polypropylene fiber reinforced concrete after exposure of high temperature. It has been observed that the polypropylene fibers had been reported to be a feasible method to prevent explosive spalling of HSC subjected to high temperature.

Noumowe [13] showed the significant contribution of polypropylene fiber to the spalling resistance of high strength concrete. Xiao and Falknerb [14] studied the effect of elevated temperature ranging from 20^0C to 900^0C the on high performance concrete specimens with and without PP fibers. It has been concluded that the residual compressive strength of HPC decreases with rise in temperature and the relative residual compressive strength of HPC with PP fibers was slightly greater than that of HPC without PP fibers. Kodur and Phan [15] reported that the type of fire, size and heat output has significant influence on the fire performance of a concrete structural system. Behnood and Ziari [16] investigated the effect of different amounts of silica fume (SF) and water to cement ratios (w/c) on the residual compressive strength of high-strength concrete after exposure to high temperatures. They concluded that the rates of strength loss for concrete containing SF were observed lower than the ordinary concrete at 600^0C. The effects of different pozzolans on strength behavior of concrete specimens at elevated temperature have been studied by Alidoust et al. [17]. Test results showed significant reduction in compressive strength which could be due to polypropylene fiber melting. Lourenço et al. [18] developed a fiber reinforced concrete of enhanced fire resistance (FRCEFR) and its properties. It has been concluded that the nonmetallic fibers are able of improving the concrete fire resistance, since explosive spalling was avoided. Similar research has also been done by Aydın et al. [19] investigated the effect of high temperatures on the compressive strength, flexural strength, modulus of elasticity and weight loss of the concrete specimens cured under water and autoclave cured high strength mortars. Test results indicated that the PP fiber inclusion is effective in preventing the explosive spalling behavior of high strength mortars but PP fibers caused some reduction in compressive strength under autoclave curing before high temperature exposure. Noumowe´ et al. [20] presented the experimental investigations on the effect of elevated temperature on the permeability of high-performance concrete. They concluded that the addition of 2% of polypropylene fibers (by mass) to high performance concrete did not have significant effect on the compressive and splitting tensile strength of concrete.

The ACI 216R [21] provided the information on the properties of normal strength concrete at high temperature. However, while the information on the properties of HSC with fibers at elevated temperature is scanty and thus the experimental behavior of HSC with and without fibers is required. The present study discusses the material, structural and fire characteristics that influence the performance of NSC and HSC with polypropylene fibers under different thermal loading. Also it tries comparing the fire resistance of normal and high strength concrete and offers guidelines for improving the fire resistance of HSC structural members. Thus an understanding of various factors influencing fire performance will aid in developing appropriate solutions for mitigating spalling and enhancing fire resistance of HSC members.

II. Experimental Program

A. Material Properties

Ordinary Portland Cement 43 grade (OPC 43) was used throughout the investigation. The physical properties of cement confirmed with the recommendations of IS-4031 [22]. The commercially available micro silica of grade 920 U (silica content of more than 92 percent) was used in the present investigation. 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 [23]. The commercially available polypropylene (PP) fibers with a length of 12 mm were used in the study. The potable water was used for mixing and curing which was free from injurious amount of deleterious materials as recommended by IS: 456 [24]. The commercially available superplasticizer, Glenium 51, which is based on unique carboxylic ether polymer, was used as chemical admixture for workability of concrete.

B. Mix Proportioning

Three concrete mixes were prepared as per the guidelines of IS: 10262 [25]. The normal strength concrete (NSC) mix for 20 MPa compressive strength at 28-days was prepared and high strength concrete (HSC) and high strength fibrous concrete (HSFC) mixes for 60 MPa strength at 28-day were prepared on the basis of method of trials The NSC and HSC mixes have no PP fiber, while HSFC mix prepared with 2 Kg/m^3 PP fibers. Super plasticizer with 2 percent of cement weight was used in HSFC mix for workable concrete. The details of the mix proportions are shown in Table 1.

TABLE I. CONCRETE MIX PROPORTION

Mix	Cement (Kg/m^3)	Water (liter)	CA (Kg/m^3)	FA (Kg/m^3)	SF (Kg/m^3)	Super plastisizer (litre)	PP fiber (Kg/m^3)
NSC	450	211.5	675	1350	-	-	-
HSC	600	204	624	1050	49.8	12	-
HSFC	600	204	624	1050	49.8	12	2

C. Casting and Testing Procedure

The standard cubes and cylinders were cast to determine the compressive strength of concrete at 28 days and tests were performed according to IS: 516 [26]. The coarse aggregate was first added to the mixer, followed by approximately one-third of water, to be used. Fine aggregate, cement, silica fume, and the remaining water were added to the mixer in a gradual manner. Fibers were then added gradually to the mix and the

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mixing was done for 2 minutes after the addition of PP fibers. 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 different heating-cooling regimes.

D. High Temperature Furnace

The electric furnace shown in Fig. 1 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 1000×760×510 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^{o}C with a programmable microprocessor temperature controller attached to the furnace power supply. The temperature history in the furnace is controlled by a designated fire curve, typically those of "standard fires".

Figure 1. *Details of furnace.*

E. First phase of study: specimens subjected to a single heating-cooling cycle

The specimens were heated at elevated temperatures i.e. at 200^{0}C, 400^{0}C, 600^{0}C and 800^{0}C after the curing age of 28 days. The specimens were kept from the front gate of the heating chamber. The specimens were heated for three 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 firefighters. 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. Fig. 2 shows the details of single heating-cooling cycle up to target temperature 'T'. After completion of one cycle, the specimens were tested under compression.

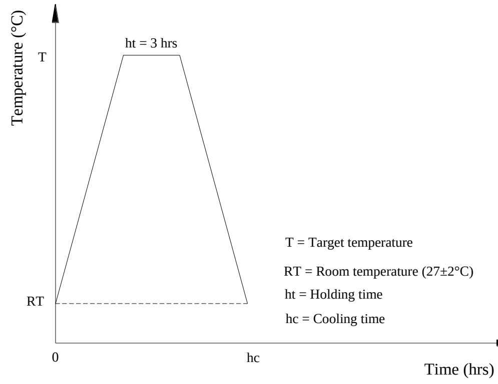

Figure 2. Single heating-cooling cycle curve.

F. Second phase of study: specimens subjected to several heating-cooling cycles

One cycle of heating and cooling is defined as the specimens being heated upon target temperature with a hold period of 3 hours and then subsequently being cooled down to room temperature. Further in the next cycles the specimens were subjected to a higher temperature with a hold period of 3 hours and then again the specimens cooled down to room temperature. Fig. 3 shows the various heating-cooling cycles. The specimens of different concretes were subjected to such heating-cooling cycle at different temperatures up to 800°C and the specimens were tested under compression.

III. Results and Discussion

The results of the compressive strength of different concrete mixes tested at room and at elevated temperatures is presented and discussed herein.

A. Effect of Single Heating-Cooling Cycle on Compressive Strength of Concrete

The behavior of all the concrete mixes at room and elevated temperatures is shown in Fig. 4 and 5.

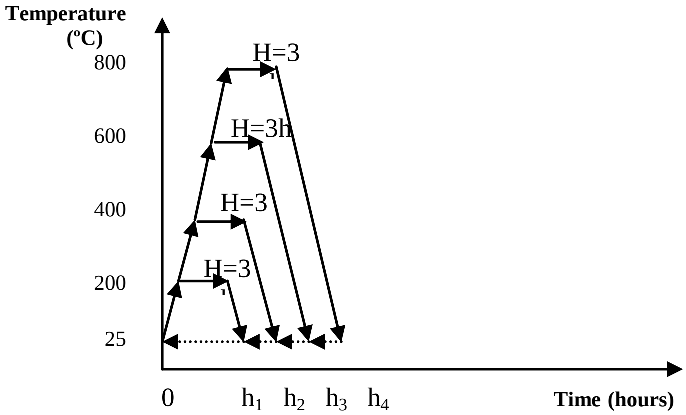

Figure 3. *Several heating-cooling cycles curve.*

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From these figures it can be seen that the compressive strengths of NSC, HSC and HSFC is decreased with increase in temperature. The figures show that NSC has shown the least strength at all temperatures. With increase in temperature a marginal loss in residual compressive strength has been observed in and the strength at high temperatures is observed to be less in cylinders in NSC specimens. Unlike NSC, HSC has shown substantial decrease of strength with increase in temperature up to 400^{0}C. The compressive strength of HSC and HSFC is close to each other from room temperature to 400^{0}C.

It has been observed that the PP fibers do not have a positive effect on the compressive strength of concrete. But they are effective for a marginal loss of residual compressive strength in HSFC up to 200^{0}C temperature. The channels which have been created due to the melting of PP fibers have made the concrete more ductile as compared to HSC up to 400^{0}C. The said phenomenon has caused a marginal loss of strength in HSFC at this temperature. At 400^{0}C temperature, the compressive strength of HSC and

HSFC is approximately the same in both cubes and cylinders. Due to formation of extensive cracks in HSC and the resulting channels in HSFC, the strengths of the both cubes and cylinders have been observed to be similar as shown in Figs. 4 and 5. After 400^{0}C temperature, though the strength of HSC has shown a higher value as compared to HSFC up to temperature of 800^{0}C. Beyond 400^{0}C, due to the cracks, which have added to the channels in HSFC, the reduction in residual strength is severe. The high temperature of 800^{0}C has its severe effect on HSFC specimens. These specimens have shown no compressive strength at all at this temperature and have collapsed without carrying any load. The compressive strength of NSC at 600^{0}C is very low in the cubes. These specimens have shown no strength after this temperature. There is no strength in NSC cylinders at 600^{0}C and beyond.

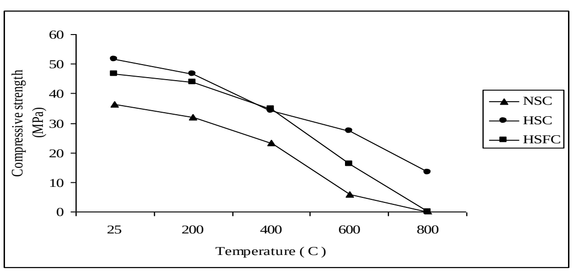

Figure 4. *Residual cube compressive strength of different concrete at elevated temperature.*

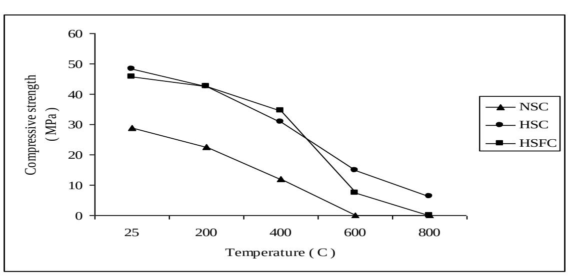

Figure 5. *Residual cylinder compressive strength of different concrete at elevated temperature.*

B. *Comparison between Cube and Cylinder Compressive Strength at Single Heating-Cooling Cycle*

The ratio of compressive strength of cube to cylinder at room and other temperatures has been shown in Fig. 6. It can be observed that this ratio increased with increase in temperature in all the concrete mixes. The ratio of compressive strength of cube-to-cylinder is higher in NSC at room temperature followed by HSC and HSFC. This ratio is about 1.25, 1.07 and 1.02 in NSC, HSC and HSFC respectively. In NSC, this ratio has its maximum value at 400^{0}C. The ratio in NSC at this temperature is about 2. The compressive strength of cube and cylinder in HSC and HSFC is approximately same at 400^{0}C. After 400^{0}C, the ratio of strength increased up to 600^{0}C. This ratio at 600^{0}C is about 1.8 in HSC and 2 in HSFC. Further this strength ratio could only be calculated in HSC up to 800^{0}C as the specimens of other mixes failed earlier. The strength of HSC cube is about 2 times of that of HSC cylinders at this temperature. Generally the strength ratio of cube-to-cylinder is nearly 1 at room temperature. Then this ratio increased with increasing temperature. In the case of HSC and HSFC this ratio is the same at 400^{0}C. NSC has its least value of this ratio at the same temperature. After the cubes and cylinders pass the last cycle, the cube-to-cylinder strength ratio for all concrete mixes is approximately equal to 2.

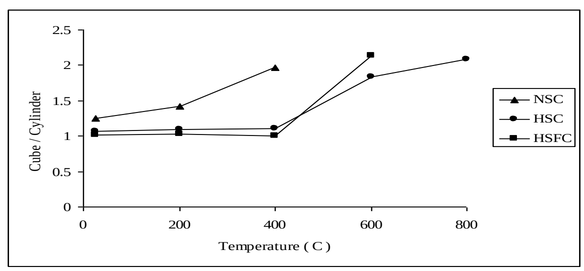

Figure 6. *Cube Cylinder and Compressive strength ratio at elevated temperature.*

The relationship between these compressive strengths at room and elevated temperature has been shown as:
Cube-to-Cylinder compressive strength ratio at room temperature: $f_c = nf_c'$ and Cube-to-Cylinder compressive strength ratio at an elevated temperature: $f_c^T = nf_c'^T$

Where: f_c and f_c^T = Cube compressive strength of concrete at room and elevated temperature respectively; f_c' and $f_c'^T$ = Cylinder compressive strength of concrete at room and elevated temperature respectively and n = Variable coefficient which is evaluated in Table 2 according to the temperature.

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TABLE II. VARIABLE COEFFICIENT 'n' AT ROOM AND ELEVATED TEMPERATURE

Temperature (^{0}C)	**Variable coefficient (n) for NSC**	**Variable coefficient (n) for HSC**	**Variable coefficient (n) for HSFC**
25	1.25	1.07	1.02
200	1.42	1.09	1.03
400	1.96	1.11	1.00
600	-	1.84	2.14
800	-	2.08	-

C. *Effect of Several Heating-Cooling Cycles on Compressive Strength of Concrete*

The second phase of study consisted of the concrete specimens which passed several thermal cycles, so it is not possible to test for the compressive strength of these specimens. For this reason after the end of each thermal cycle, non-destructive technique (NDT) has been used to determine the compressive strength of theses specimens. The compressive strength of all the concrete mixes of the second phase of study after passing of each cycle have been shown in Fig. 7 and 8. The compressive strength of the first and second phase of study at room temperature and 200^{0}C is approximately the same. Because the concrete specimens of both phases have been tested at room temperature and have not been subjected to thermal cycles they have shown the same compressive strength. As 200^{0}C is the first thermal cycle which the second phase specimens have experienced, the compressive strength of this series of specimens is the same as the specimens of the first phase of the study. But from 400^{0}C onwards, the difference between compressive strength of the concrete specimens in these phases increased. The destruction and the loss of strength has been found to be more in specimens of the second phase of study as compared to that in the first phase of study.

Although, the specimens of the second phase of study have been subjected to the cyclic heating and cooling, the trend of decrease in strength with increase in temperature is to some extent like the first phase of study. The strength of HSC has been observed to be the highest and NSC has the least value at all temperatures. Unlike the first phase of the study, the strength of HSC and HSFC is not very close at 400^{0}C. With increase in temperature, the loss of strength in NSC is sharp as compared to that of NSC in the first phase. HSC has shown very low strength at 800^{0}C, so it is not subjected to more thermal cycles. The most severe effect of temperature on HSFC is after 600^{0}C. These specimens have not shown any strength at maximum temperature of 800^{0}C. The bond of this concrete mix, between the cement paste and coarse aggregate is totally destroyed at this temperature. NSC lost its strength at 600^{0}C. In all concrete mixes of the second phase of study the loss is more severe due to thermal cycles as compared to those in the first phase of study. Like in the first phase of study, all the cylinder specimens with different mixes have shown lesser compressive strength as compared to that of the cube specimens. This difference is observed to be more after 400^{0}C.

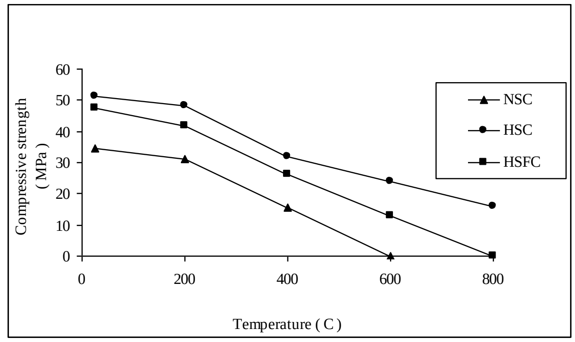

Figure 7. *Cube compressive strength of concrete at several heating-cooling cycles.*

D. *Comparison of Loss of Compressive Strength of Concrete between two Phases of Study*

The percentage of loss in compressive strength in cubes and cylinders for all concrete mixes of the second phase of study as compared to those in first phase of study with increasing temperature are shown in Figs. 9 and 10 respectively.

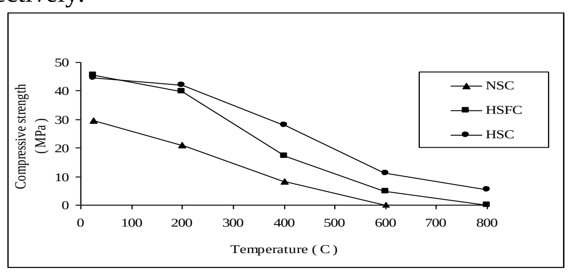

Figure 8. *Cylinder compressive strength of concrete at several heating-cooling cycles.*

At 200^{0}C there is no reduction of compressive strength in the concrete specimens of the second phase of study as compared to that in the first phase of study. At 400^{0}C, the specimens have experienced their second thermal cycle, after compressive strength of the said concrete specimens has decreased by more than that observed in the first phase of study. NSC specimens observed maximum loss of strength as compared to the other mixes at this temperature. The loss of strength in the said concrete series is more than 30% of that of NSC specimens in the first phase of study. At 400ºC, the percentage strength loss in HSFC is higher than that observed in HSC. From Figs. 13 and 14 it is also observed that at 600^{0}C, the loss in strength increased in NSC and HSC, while there is a marginal reduction in HSFC specimens. Although NSC cubes have shown some strength in the first phase of study at this temperature, but for the second phase of study, the strength of specimens has been found to be very low, thus it can be said that 100% loss of strength is observed between the two phases. Among all the mixes under study, specimens of HSC are the only mix which has shown some compressive

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strength at 800^{0}C. The percentage loss of strength of specimens in the second phase of study as compared to the first phase of study is about 4% in cubes and 18% in cylinders.

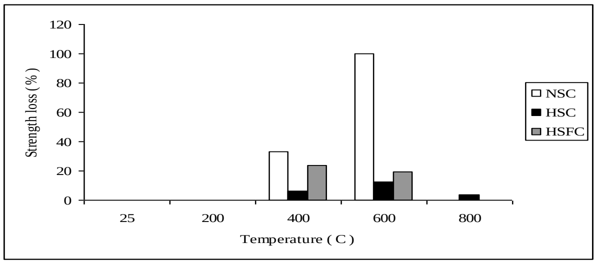

Figure 9. *Loss of cube compressive strength in the second phase of study as compared to first phase of study*

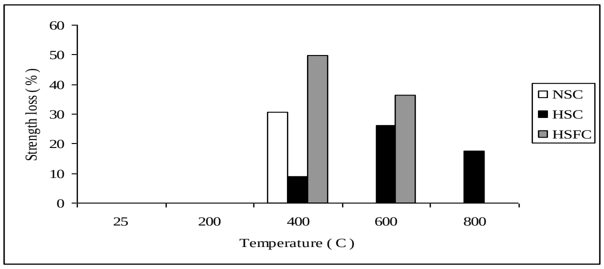

Figure 10. *Loss of cylinder compressive strength in the second phase of study as compared to first phase of study*

IV. Conclusions

Based on the results obtained in this experimental study, and within the limitations of the test parameters, the following conclusions have been drawn.

- In NSC, HSC and HSFC exposed to high temperature, compressive strength decreases with the increase of temperature. HSC, HSFC and NSC respectively have shown higher compressive strength at room as well as at elevated temperatures.
- HSC has a higher strength loss than NSC in the temperature range between 25°C to 400°C. HSC loses a significant amount of its compressive strength above 400°C and attains a strength loss of about 80% at 800°C. At 600°C loss of strength is about 85% in NSC and 63% in HSFC. The change of strength in the temperature range of 25- 400°C is marginal in all concrete mixes.
- The addition of PP fibers in HSC improves the ductility up to 200°C. Beyond this temperature the PP fibers melt and create some pores in the matrix resulting in decrease of strength of the mix reduces. PP fiber reinforced HSC exhibits better ductility characteristics than plain HSC at elevated temperatures.
- Polypropylene fibers did not modify the residual mechanical properties of the tested high strength concrete. Addition of 2% PP fibers has not shown a positive effect on the compressive strength of concrete; but they can be effective for the lesser loss of residual compressive strength up to 400°C.
- HSC can be more beneficial in the severe conditions as compared to the other mixes, due to the lesser loss of its relative compressive strength at 400°C and beyond in both phases of study.
- The compressive strength of cube/cylinder ratio is observed to be near to 1.0 at room temperature, and it increased with higher temperatures.
- The reduction in relative residual compressive strength has been marginal up to 600°C whereas it is substantial beyond this temperature.
- The residual strength stabilization has been observed in HSFC and NSC at 600°C in the first phase and beyond that in both phases.

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