Effect of hybrid fibres on the mechanical properties of high performance concrete

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Abstract. Fibre reinforcement is a technique used to provide toughness and ductility to brittle cementitious matrices. Reinforcement of concrete using a single type of fibre could improve the properties to a limited level. A hybrid composite refers to two or more types of fibres that are rationally combined to produce a composite that stems benefits from each of the individual fibres and exhibits a synergetic response. This study intends to illustrate and quantify the mechanical properties of Hybrid Fibre Reinforced Concrete. For this purpose, a reference High Performance Concrete (HPC) of grade M65 with water-binder ratio of 0.34 was used. Specimens of plain concrete mix, HPC with silica fume, Steel Fibre Reinforced High Performance Concrete (SFRHPC) containing only steel fibres, and Hybrid Fibre Reinforced High Performance Concrete (HFRHPC) containing steel fibres and carbon fibres were prepared. Optimum amount of silica fume was taken as 12.5%. The crimped steel fibre was added initially at 0.25%, 0.5%, 0.75%, 1% and 1.25% by weight of concrete and its optimum percentage was found out. Once the optimum dosage of crimped steel fibre was obtained, carbon fibre was used to replace the optimum steel fibre dosage at 25%, 50%, 75% and 100% by volume fraction. Thus an optimum hybrid fibre dosage was obtained. The mechanical properties of the HFRHPC like compressive strength, flexural strength, splitting tensile strength, modulus of elasticity and impact resistance were studied and compared with HPC mix. The results revealed that the addition of steel fibre improved all the mechanical properties of concrete.

1. Introduction
Concrete is the most widely used construction material made by mixing Portland cement with sand, coarse aggregate and water. Inherently, concrete is a brittle material and reinforcement in terms of continuous rebars or short discrete fibres are often used to improve this brittle behavior. When short discrete fibres are used, the corresponding material will then be termed as Fibre Reinforced Concrete (FRC), which is defined by ACI Committee 544 as a concrete made of hydraulic cements comprising of fine or fine and coarse aggregates and discontinuous discrete fibres. FRC is often regarded as a composite material with two phases in which concrete represents the matrix phase and the fibre constitutes the inclusion phase. Even though, properties and volume fractions of individual phases

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affect the composite behavior, those pertaining to fibres are often more important, which include its volume fraction, geometry and mechanical properties. Depending on these factors, reinforcement of concrete with a single type of fibre will improve the properties of the composite to a limited level. However, using the concept of hybridization, a rational combination of two or more types of fibres, more attractive engineering properties of the composite could be achieved from a possible synergetic response of the different fibres.

Studies on the influence of the combination of steel and carbon fibres on concrete properties are limited. Yao et al. [1] have studied the effects of fiber hybridization on the mechanical properties of concrete and concluded that a composite with superior mechanical characteristics can be obtained through combined use of fibers with different properties. Bentur and Mindess [2] described the advantages of hybrid fiber systems and elucidated that the presence of the durable fiber can increase the strength and/or toughness relation after age. Khalil [3] investigated mechanical properties of high performance fibre reinforced concrete. The addition of steel fibres caused a slight increase in compressive strength of HPC as fibre volume fraction increases. Khalil and Abdulrazaq [4] carried out research to find the mechanical properties of high performance carbon fibre concrete. The results showed that the addition of carbon fibres improved the mechanical properties of HPC. Nili and Afroughsabet [5] studied the combined effect of silica fume and steel fibres on the impact resistance and mechanical properties of concrete and concluded that incorporation of steel fibres improved the strength performance of concrete. Soutsos et al. [6] investigated the ductility of concrete made with commercially available steel and synthetic fibres. Yakhlaf et al. [7] studied the effects of discrete pitch-based carbon fibres on the fresh properties of self-consolidating concrete.

The objective of this study is initially develop a hybrid fibre reinforced concrete (HFRC) composites and then to characterize and quantify the benefits obtained by the concept of hybridization. Moreover, an attempt will be made to compare the mechanical properties of these composites.

2. Methodology
The main investigation of this study was to develop HFRHPC with steel and carbon fibres. The optimum amount of silica fume required for making the HPC was found out from previous studies (12.5% of cement). In order to find the optimum percentage of steel fibre, varying percentages of fibres were added such as 0.25, 0.50, 0.75, 1.00 and 1.25. The optimum percentage of fibre was found out by studying mechanical properties of concrete reinforced with steel fibre. After that HFRHPC was made by replacing optimum amount of steel fibre with carbon fibre in order to study the properties and to identify the optimum percentage of hybrid fibres.

2.1 Materials
The ingredients used for the present study includes cement, fine aggregate, coarse aggregate, water, silica fume, steel fibre and carbon fibre. The properties of these materials were studied for designing the mix for target strength of 65MPa. Tests are conducted as per IS codes.

Cement is the most important constituent in a concrete mixture. The function of cement is first, to bind the sand and the coarse aggregates together and second, to fill the voids in between sand and coarse aggregates particles to form a compact mass. Fineness affects water requirements for consistency. In this study, Ordinary Portland Cement (OPC) conforming to IS: 12269 (53 Grade) was used. Table 1 shows the material properties of cement.

| Table 1. Material properties of cement |
|--------------------------------------|
| Particulars | Specific gravity | Fineness (%) | Standard consistency (%) | Initial setting time (min) | Final setting time (min) |
| Values | 3.13 | 4.00 | 29.50 | 98.00 | 253.00 |
Locally available good quality Manufactured sand (M sand) was used for Fine aggregate. Laboratory tests were conducted to determine the different physical properties as per IS: 383 (Part III)-1970. Table 2 shows the properties of fine aggregate.

Table 2. Material properties of fine aggregate

| Particulars | Type  | Specific gravity | Fineness modulus(%) | Water absorption (%) |
|-------------|-------|------------------|---------------------|---------------------|
| Values      | M sand| 2.58             | 2.9                 | 1.12                |

The size of aggregate between 20 mm and 4.75 mm was considered as coarse aggregate. Laboratory tests were conducted on coarse aggregates to determine the different physical properties as per IS: 383 (Part III)-1970. Properties of coarse aggregate are shown in table 3.

Table 3. Material properties of coarse aggregate

| Particulars | Specific gravity | Fineness modulus(%) | Water Absorption (%) |
|-------------|------------------|---------------------|---------------------|
| Values      | 2.70             | 7.084               | 0.085               |

Water is used with cement to cause hydration of the cement. Water in additional of that required for hydration acts as a lubricant between coarse and fine aggregates and produces a workable and economical concrete. Water used should be free from impurities.

Silica fume is a light-to-dark grey cementitious material composed of at least 85% ultra-fine, amorphous non-crystalline (glassy) spherical silicon dioxide (SiO$_2$) particles. It is produced as a by-product during the manufacture of silicon metal or ferrosilicon alloys. The extremely fine particle size, large surface area and high content of highly reactive amorphous SiO$_2$ give silica fume the super pozzolanic properties. Various properties of silica fume used for the study are given in the table 4.

Table 4. Material properties of Silica fume

| Particulars | SiO$_2$ (%) | Specific gravity | LOI (%) | Moisture (%) | Pozzolanic activity index(%) | Specific surface area (m$^2$/g) | Bulk density (kg/m$^3$) | $+45$ microns (%) |
|-------------|-------------|------------------|---------|--------------|-----------------------------|-------------------------------|------------------------|------------------|
| Values      | 92.3        | 2.2              | 2.7     | 0.2          | 137.0                       | 22.0                          | 603.0                  | 0.2              |

Steel fibre is one of the widely used fibre. Generally round fibres of diameters from 0.25 to 0.75 mm are used. The steel fibre has the possibility to get rusted and lose some of its strengths. But research has shown that the rusting of the fibres takes place only at the surface. Usage of steel fibre in concrete makes noteworthy improvements in flexural, impact and fatigue strength of concrete. The properties of steel fibre used are given in the table 5. For this study, crimped type of steel fibres were used as depicted in figure 1.

Table 5. Material properties of crimped steel fibres

| Particulars | Type  | Diameter (mm) | Length (mm) | Aspect ratio | Density |
|-------------|-------|---------------|-------------|--------------|---------|
| Values      | Crimped| 0.45          | 25.00       | 55.00        | 7.85g/cc|
Carbon fibres are a type of high-performance fibre having high tensile strength and strength for their size. It has high elastic modulus and fatigue strength than those of glass fibres. They are also exceedingly chemically resistant and have high temperature tolerance with low thermal expansion and corrosion resistance. Carbon fibres are twice as stiff as steel and five times as strong as steel. The most significant factors determining the physical properties of carbon fibre are degree of carbonization (carbon content, usually more than 92% by weight) and orientation of the layered carbon planes (the ribbons). Mainly carbon fibres are available in two types: Pan type and Pitch type and are shown in figure 2. For this study Carbon fibre of Pan type was used. Properties of Carbon fibre used are given in the table 6.

**Table 6. Material properties of Carbon fibres**

| Particulars | Type   | Diameter (mm) | Length (mm) | Aspect ratio | Density (g/cc) |
|-------------|--------|---------------|-------------|--------------|----------------|
| Values      | Pan    | 7 micron      | 10.00       | 1428.57      | 1.85           |

2.2 Mix Proportions
The modified ACI method proposed by P.C. Aitcin [8], which is based on ACI: 211.1-91 guidelines, was followed for designing the HPC mix of M65 grade. To obtain sufficient consistency in fibre reinforced mixes naphthalene formaldehyde based superplasticizer was used. Using the above mentioned ingredients, a common concrete matrix was prepared and used for all mixtures. For this study mix proportions of the plain concrete mix were used as 1: 1.99: 2.55 with water binder ratio 0.34.

2.3 Mixes Developed
Specimens of plain concrete mix M65 grade control mix (CM), HPC with silica fume, SFRHPC containing only crimped steel fibres and HFRHPC containing crimped steel fibres and carbon fibres were prepared. Crimped steel fibres were added in to the HPC mix with a volume fraction of 0.25%,
0.50%, 0.75%, 1% and 1.25%. HFRHPC mixes were developed after finding out the optimum crimped steel fibre dosage such that the optimum steel fibre dosage was replaced by carbon fibres. In the first hybrid mix, 25% of optimum crimped steel fibre was replaced by carbon fibre, 50% of optimum crimped steel fibre was replaced by carbon fibre in the second, 75% of optimum crimped steel fibre was replaced by carbon fibre in the third sample and in the fourth sample steel fibre was fully replaced by carbon fibre. The mix designation of SFRHPC and HFRHPC are shown in table 7 and 8 respectively.

| Table 7. Mix designation of SFRHPC mixes |
|------------------------------------------|
| Mix designation | S25 | S50 | S75 | S100 | S125 |
| % of crimped steel fibre | 0.25 | 0.5 | 0.75 | 1.0 | 1.25 |

| Table 8. Mix designation of HFRHPC mixes |
|------------------------------------------|
| Mix designation | S75C25 | S50C50 | S25C75 | S0C100 |
| Crimped steel fibre (% of optimum steel fibre) | 75 | 50 | 25 | 0 |
| Carbon fibre (% of optimum carbon fibre) | 25 | 50 | 75 | 100 |

3. Experimental program
The experimental investigation for the study involves the preparation and testing of the concrete specimens with various mixes according to the Indian Standards.

3.1 Specimen preparation
Using a tilting drum mixer, the concrete mixes were prepared. For preparing aggregates, cement and mineral admixtures were mixed in the tilting drum mixer. After proper mixing, mixture of water and superplasticizer was added. The final mixing stage involved the addition of steel fibre. A number of specimens were prepared to study the mechanical properties of concrete. Standard moulds were used for casting. 150mm×150mm×150mm cube specimens, 150mm×300mm cylinders, 150mm×50mm discs and 100mm×100mm×500mm beam specimens were cast. Specimens were demolded after one day and then placed in the curing room with 90 ± 5% relative humidity and 20 ± 1°C temperature until testing day. After demoulding the specimens, they were continuously cured by water. Compressive strength was taken for 3, 7 and 28 days while rests of the specimen were cured for 28 days. After the completion of curing period, specimens were air dried for few hours and then tested.

3.2 Test Procedures
To determine the various mechanical properties, the following tests were conducted on the concrete specimens.

A. Tests conducted on fresh concrete
   a) Workability test
B. Tests conducted on hardened concrete
   a) Compressive strength test  
   b) Flexural strength test  
   c) Modulus of elasticity  
   d) Splitting tensile strength  
   e) Impact resistance test

Compacting factor test of fresh concrete is done to determine the workability of fresh concrete. The apparatus used is compacting factor apparatus. Compressive Strength Test is the test which is widely used on hardened concrete. This test was carried out on cubical specimen in a compression testing machine of capacity 3000 kN, at a loading rate of 14 N/mm² per minute as per IS: 516-1959 specification. Flexural strength of plain concrete was obtained by two-point loading. The plain concrete beam specimen was used for the test as per IS: 516-1959. The maximum load at which the
specimen fails under flexure was noted. The modulus of elasticity was determined by subjecting cylindrical specimen uniaxial compression as per IS: 516-1959 specification. The instrument used is deflection controlled UTM. Splitting Tensile Test is a well-known indirect test used for determining the tensile strength of concrete. Test was carried out on cylindrical specimen as per IS: 5816-1999 specification. The load at failure was recorded. The tensile strength of concrete is measured by flexural test to estimate the load under which cracking will develop. Impact resistance can be carried out using drop weight test or the repeated impact test. According to this test, impact resistance is characterized by a measure of the number of blows in a repeated impact test to achieve a prescribed level of distress.

4. Results and discussions

4.1 Test results of SFRHPC
Table 9 summarizes the results of all tests that are performed to characterize the mechanical properties of SFRHPC. Addition of steel fibre reduces the workability. To find optimum steel fibre dosage, steel fibre was added at 0.25%, 0.50%, 0.75%, 1%, and 1.25% by volume fraction of concrete into the HPC mix. Comparing the results of compressive strength of all the mixes on the basis of fibre volume added in the concrete mixes and it was found that highest compressive strength was achieved in S100. Addition of fibre increases compressive strength till 1% after that strength decreases due to balling effect of fibres. Maximum increase in compressive strength for crimped steel fibre with HPC was 10.86% for 28th day.

Table 9. Measured Properties of SFRHPC

| Mix desg. | Compacting factor | 28th day Cube compressive strength (N/mm²) | 28th day Flexural strength (N/mm²) | 28th day Modulus of elasticity (GPa) | 28th day Splitting tensile strength (N/mm²) | Impact resistance (No. of blows) |
|-----------|-------------------|------------------------------------------|-----------------------------------|-------------------------------|--------------------------------------------|--------------------------------|
| CM        | 0.89              | 66.40                                    | 5.80                              | 39.74                         | 3.54                                       | 30                             |
| HPC       | 0.87              | 68.25                                    | 6.05                              | 41.14                         | 3.67                                       | 15                             |
| S25       | 0.86              | 70.44                                    | 6.34                              | 41.83                         | 3.84                                       | 44                             |
| S50       | 0.85              | 72.68                                    | 6.96                              | 42.26                         | 4.23                                       | 59                             |
| S75       | 0.84              | 73.54                                    | 7.23                              | 42.88                         | 4.91                                       | 64                             |
| S100      | 0.82              | 75.66                                    | 7.96                              | 43.80                         | 5.76                                       | 104                            |
| S125      | 0.80              | 72.81                                    | 7.52                              | 42.66                         | 4.22                                       | 87                             |

Beam specimens were tested for determining the flexural strength. SFRHPC mix exhibited increasing flexural strength with increasing in crimped steel fibres compared with reference control mix and HPC mix. The increase in 28th day flexural strength on addition of crimped steel fibres was 4.79%, 15.04%, 19.50%, 31.57% and 24.3% with respect to HPC mix. This increase in flexural strength is due to the presence of steel fibres which will bridge across the cracks preventing it from spreading. The above results show that the flexural strength of normal HPC concrete was very poor, (31.57% rise with addition of 1% volume of steel fibre). It was found that 1.25% volume of crimped steel fibre at 28th day reduces flexural strength due to balling effect of fibres.

The Young’s modulus values are obtained from stress-strain diagram obtained by carrying out the test on cylinder specimens. With addition of crimped steel fibre, modulus of elasticity increases till 1% fibre volume fraction. For 1% volume fraction the increment observed for 28th day was 6.47% compared with the HPC mix. The percentage increase in modulus of elasticity was 1.68, 2.72, 4.23 and 3.69 for S25, S50, S75 and S125 respectively, when compared to HPC. For splitting tensile
strength, cylinders were cast and tested for 28\textsuperscript{th} days. An enhancement of 3.67\% was observed by the replacement of cement with 12.5\% silica fume. Addition of crimped steel fibre to HPC mix increases the splitting tensile strength. For 1\% and 1.25\% volume fraction the increment observed was 56.94\% and 14.98\%. So the splitting tensile strength exhibited a significant increase after a curing age of 28 days till 1\% fibre volume is reached.

Impact test was conducted to determine the number of blows to achieve a prescribed level of distress of the specimen. The main drawback of HPC is its brittleness. To remove the brittleness fibres are added in it. So the addition of silica fume increases the brittleness. Replacement of cement by weight using 12.5\% silica fume showed an increase in brittleness of 100\%. The addition of crimped steel fibre to HPC mix increases the impact resistance and decreases the brittleness. The addition of steel fibres to HPC leads to an increase in the impact resistance of HPC, but it decreased at 1.25\% steel fibre volume fraction. A remarkable improvement was observed in impact resistance and the percentage increment in number of blows for first crack and at failure was 593.33\% and 738.88\% respectively in comparison with the HPC and it was for 28\textsuperscript{th} day.

4.2 Test results of HFRHPC

Table 10 summarizes the results of all tests that are performed to characterize the mechanical properties of HFRHPC.

| Mix desg. | Comp acting factor | 28\textsuperscript{th} day Cube compressive strength (N/mm\textsuperscript{2}) | 28\textsuperscript{th} day Flexural strength (N/mm\textsuperscript{2}) | 28\textsuperscript{th} day Modulus of elasticity (GPa) | 28\textsuperscript{th} day Splitting tensile strength (N/mm\textsuperscript{2}) | Impact resistance (No. of blows) |
|-----------|--------------------|---------------------------------------------|----------------------------------------|---------------------------------------------|----------------------------------------|----------------------------------|
| S100C0    | 0.84               | 75.66                                        | 7.96                                     | 43.80                                       | 5.76                                     | 104                              |
| S75C25    | 0.82               | 80.18                                        | 8.94                                     | 44.89                                       | 6.56                                     | 149                              |
| S50C50    | 0.80               | 71.50                                        | 8.13                                     | 42.30                                       | 4.77                                     | 211                              |
| S25C75    | 0.79               | 65.41                                        | 7.25                                     | 41.50                                       | 3.64                                     | 244                              |
| S0C100    | 0.77               | 55.66                                        | 6.83                                     | 39.13                                       | 3.17                                     | 202                              |

Comparing the results of compressive strength of all the mixes on the basis of fibre volume added in the concrete mixes, it was found that highest compressive strength was achieved in S75C25. Maximum increase in compressive strength for S75C25 with crimped steel fibre was 5.97\% for 28\textsuperscript{th} day. It has been observed that with further increasing carbon fibre replacement, the compressive strength started to show a declining trend. Flexural strength was obtained by loading the beam specimen under two-point loading setup. The results obtained show that the increase in 28 day’s flexural strength was 12.31\% for S75C25, compared to S100C0 and further flexural strength decreases with increasing carbon content.

The modulus of elasticity values was obtained from stress-strain diagram obtained by carrying out the test on cylinders’ samples. On analyzing the strength values it can be observed that the modulus of elasticity increased slightly for S75C25 mix when comparing to S100C0 mix. An increment of 2.49\% can be noted for S75C25 mix when compared to S100C0 mix. It can be seen that the modulus of elasticity showed a slightly declining trend for hybrid fibre combination. The values for splitting tensile strength for HFRHPC mixes are determined. The results obtained shows that the increase in 28 days’ splitting tensile strength was 13.89\% for S75C25, compared to S100C0. When compared to S100C0, the splitting tensile strength showed a declining trend for S50C50, S25C75 and S0C100. To determine the impact resistance of concrete the first crack and ultimate failure of specimens were determined. The results obtained from the experimental investigation shows that S25C75 mix had
better impact resistance. For S25C75 mix the number of blows for first crack was 134.62% increment and for ultimate failure was 90.73% increment at 28th day compared with the optimum of crimped steel fibre.

5. Conclusion
Fibre reinforcement is commonly used to provide toughness and ductility to brittle cementitious matrices. The objective of this study was to develop a hybrid fibre reinforced concrete; to illustrate and quantify the benefits obtained by the concept of hybridization thereby determining the mechanical properties of these composites. After reviewing the obtained results, following conclusions could be drawn as a result of this experimental study.

- Addition of crimped steel fibres into the mix increased all the mechanical properties such as compressive strength, splitting tensile strength, modulus of elasticity, flexural strength and impact resistance.
- S100 mix exhibited maximum compressive strength, hence HPC with 1% crimped steel fibre was selected as the optimum percentage.
- The addition of steel fibre resulted in improved mechanical properties.
- From the experimental results it was clear that in hybrid steel and carbon fibre combinations, S75C25 combination showed a slight increase incompressive strength and modulus of elasticity, but they increase the flexural strength and Splitting tensile strength as compared to SFRHPC.
- Impact resistance increases with the addition of carbon fibre.
- The workability reduced further with carbon fibre replacement.

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