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An Experimental Investigation on Mechanical Properties of High Performance Slurry Infiltrated Fibrous Concrete (HPSIFCON)

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Abstract

The technology is giving impetus to research driven towards new materials for more efficient and reliable construction. Slurry Infiltrated Fibrous Concrete has proven to be useful for specialized applications encountering high stresses and reversal of stresses. Applications such as post tensioning can benefit from High Performance Fiber Reinforced Cement based Composites that can also offer early strength gain. The present study focuses on an extensive experimental program to develop and evaluate structural properties of High Performance Slurry Infiltrated Fibrous Concrete (HPSIFCON) that incorporates this high performance characteristic and also high strength into SIFCON. High cementitious content of the typical SIFCON has also been reduced by the use of alternate binders incorporating industrial wastes. Both end hooked steel fibers of aspect ratio 80 varying in 4, 5, 5.5, 6 and 7% content and slurry incorporating micro particles of ultrafine microsilica, fly ash and alccofine were used. The high performance concrete has the desirable properties of early strength gain and high strength above 100MPa. Under compressive, tensile and flexural loading, fibers were observed to provide crack bridging effect in HPSIFCON. No brittle failure is observed. Considerable enhancement has been observed in the flexural and tensile strength. The optimum steel fiber volume fraction of 5.5% led to improvement in the mechanical properties. Fine binder materials with their properties such as high surface area, small size, and pozzolanic activity develop a denser microstructure and improved pore structure in comparison to conventional concrete mixes which results in a ductile material with improved load bearing capacity. HPSIFCON provides a sustainable, low carbon and efficient concrete for the specialized application

Keywords: High Performance Slurry Infiltrated Fibrous Concrete, Mechanical properties, Steel fiber, Alccofine, Ultrafine Microsilica, Fly ash

1.0 Introduction

Technology driven world has not left the construction sector unmarked. The focus of various researchers is to explore new materials, techniques and methodologies that can make the sector more reliable and efficient. Concrete is a widely used construction material on account of its strength, durability and ability to be formed into desired shapes. Conventional concrete is designed for a desired compressive strength but such design does not address the particular application and performance requirements. High Performance Concrete (HPC) can address these requirements [1] by controlled material selection, mixing, placing and curing procedure. Fiber Reinforced Concrete (FRC) utilize discrete fibers acting as discontinuous reinforcement which are distributed randomly or in certain placement patterns in the concrete to achieve the desired

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strength characteristics. It has proven to enhance the structural performance of members in terms of parameters such as shear strength, energy absorption capacity, ductility and damage tolerance due to the crack bridging role of the fibers [1]. High performance for FRC composites is related to their tensile behaviour characterized by multiple cracking after the first cracking and strain going to relatively higher levels called the strain hardening behaviour [2]. These class of composites are called High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) that are suitable for application in structural members having large demands of deformation.

Slurry Infiltrated Fibrous Concrete (SIFCON) falls in this class of new generation concrete. Its origin goes back to 1979 as a result of the research done by Prof. Lankard wherein he illustrated that increase in the percentage of fibers (from the conventional 1-2% in FRC) included in the cement matrix could result in a material with high values of mechanical properties. SIFCON includes high percentage of steel fibers ranging from 4 - 30 percent by volume that are placed into the formwork and then a flowable fine slurry made of sand, mineral admixture and binders is infiltrated through the fibers. SIFCON is characterized by high cementitious concentration and no coarse aggregates [15]. High-range water-reducing plasticizers are also used. Researchers in the past have achieved high mechanical properties with SIFCON i.e. compressive strength above 60-90 MPa; tensile strength 15-48 MPa; flexural strength 31-34 MPa; toughness index 6 - 8 times, ductility 2 - 4 times, energy absorption capacity 3 - 6 times the conventional concrete, better flexural and shear response [3-15]. Table 1 shows the typical constituents and their proportions used by them for SIFCON.

Table 1: Typical SIFCON Design Mix [3-15]

Constituent		**Quantity (*)**
Binders	Cement	850-1000 kg/m^3
	Fly Ash	279-480 kg/m^3
	Silica Fume	80-186 kg/m^3
	GGBS	400 kg/m^3
Fine Aggregate		759-1000 kg/m^3
Water binder Ratio		0.27-0.5
Superplasticizer		0.8-1.9% by weight of binder
**The quantity of respective constituent varied as per the combination of constituents used in the particular mix to achieve the desired compressive strength of 60-90 MPa.*		

SIFCON has proven to be useful to deal with specialized applications encountering high stresses and reversal of stresses. It is also notable that its use does not need to extend to the entire structure. Rather the parts where its properties are desirable, can be constructed with SIFCON [5].

The current study aimed at developing a new material HPSIFCON i.e. High Performance Slurry Infiltrated Fibrous Concrete that incorporates the characteristics of HPC and HSC into SIFCON. Different steel fiber content were utilized along with slurry using alternate binders incorporating industrial wastes such as fly ash, silica and glass slag to reduce cement content. Ultra high strength above 100 MPa and early strength gain are the high performance characteristics achieved. This can prove useful for applications such as post-tensioning requiring early strength gain for the purpose of post tensioning. Further, the mechanical properties of HPSIFCON i.e. Modulus of elasticity, Poisson's ratio, uniaxial compressive, direct tensile, splitting tensile and flexural strength are determined.

2.0 Experimental Program

The experimental program consisted of preparation of HPSIFCON slurry mix and casting and testing of 150 mm cubes for compressive strength, 150 x 300 mm cylinders for Modulus of Elasticity and Poisson's Ratio, dog bone briquettes for direct tensile, 100 x 200 mm standard cylinders for split tensile and 100 x 100 x 500 mm beams for flexural strength.

2.1 Raw Materials

The desirable mechanical properties of HPSIFCON were achieved by ensuring minimization of voids or pores in the concrete developed using the principle of maximum density wherein pores created by packing of a constituent material were filled by particles of a much finer mix constituent. Slurry was designed to partially replace cement by micro fillers based on industrial wastes to lower the cement content and achieve high strength. Elimination of coarse aggregates, incorporation of various micro-fillers helped in achieving fine microstructure of the slurry.

2.1.1 Cement

Ordinary Portland Cement 53 Grade procured from Ultratech Cement conforming to IS: 269-2015 [16] was used to develop HPSIFCON. The specific gravity was 3.15 and fineness was 304 m^2/kg.

2.1.2 Fine Aggregate

Locally available crushed sand and only passing 1.18 mm sieve conforming to Zone II requirements of IS: 383-2016 [17] was used to ensure maximum packing density of the slurry. The specific gravity was found to be 2.63 and bulk density was 1760 kg/m^3.

2.1.3 Alccofine

Alccofine 1203 is a new-generation low-calcium ultrafine silicate mineral admixture made out of slag having high glass content. Its controlled granulation process imparts it high reactivity. It has been developed by Ambuja Cements in association with Counto Microfine Products Pvt Ltd. The fineness was 1200 m^2/kg, average particle size of 4-6 micron, specific gravity of 2.86 and bulk density of 700 kg/m^3.

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2.1.4 Ultrafine Microsilica

Ultrafine Microsilica ® 920 ASTM was provided by Ultrafine Mineral. It is a dry silica fume powder conforming to IS 9103[18] and IS 15388[19] for silica fume specification. The fineness was 15000 m^2/kg, specific gravity of 2.44 and bulk density of 623.6 kg/m^3.

2.1.5 Fly Ash

Fly Ash confirming to IS: 3812, Part 1-2013 [20] was used. The specific gravity was found to be 2.15 and fineness was 340 m^2/kg.

2.1.6 Superplasticizer

High range water reducing, poly-carboxylic ether based super-plasticizer MasterGlenium Sky 8866 provided by Master Builders Solutions was used for the study. The properties are listed in Table 2 and are conforming to [18].

Table 2: Technical Data of MasterGlenium Sky 8866

Parameter	Description
Physical state	Light to Dark Reddish Brown Liquid
Relative density at 25 °C	1.11
pH	6.9
Chloride ion content (%)	0.0016
Dry Material Content	45.09

2.1.7 Water

The water utilized for the experimental work for the purpose mixing and for curing was potable water confirming to requirements of IS 456 – 2000 [21]. It was ensured that water was clean and did not contain any substances which could jeopardize the concrete properties.

2.1.8 Steel Fibers

SHAKTIMAN® MSH 7560 both ends hooked end steel fibers (Figure 1) conforming to ASTM A-820M [22] Type I were used. The fibers had a length of 60mm, diameter 0.75 mm, aspect ratio 80, tensile strength greater than 1250 MPa and strain at failure less than 0.04. This aspect ratio was found to have higher working capacity as compared to other fibers due to its slenderness ratio [23, 24] and its capacity to achieve higher strength in SIFCON [14, 25].

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Figure 1: Both ends hooked steel fibers

2.2 Mix Proportioning and Specimen Preparation

Series of trial mixes were prepared to finalize the proportion of various binder content as replacement of cement and the optimum dosage of superplasticizer to achieve the required high strength and flow able slurry without bleeding or segregation. The mix preparation was done by dry mixing the required quantity of dry ingredients i.e. cement, alccofine, microsilica, fly ash and fine sand in a pan mixer for 5-10 minutes till the color of mix was uniform and without any clusters of material. About half of the required water was added then. Next superplasticizer was introduced to the mix. Remaining water was then added in last stage. Mixing time of about 40 minutes resulted in a slurry that was sufficiently flow able (slump flow of 810 mm determined using flow table as per IS 1199 (Part 6): 2018 [26]). Small amount of viscosity modifying agent was added in the middle of mixing due to a long duration of mixing. After determining the flow value, the slurry was immediately poured in moulds with required quantity of fibers randomly pre placed for casting. Tamping rod and light form of external vibration were used as required to compact large quantity of fibers in the mould until no more air bubbles are seen to ensure uniform slurry infiltration through the mould depth. The design mix for HPSIFCON slurry is presented in Table 3.

Table 3: HPSIFCON Slurry Mix Proportions

Cement (kg/m^3)	Alccofine (kg/m^3)	Microsilica (kg/m^3)	Fly ash (kg/m^3)	Sand (kg/m^3)	Super plasticizer (%)	Water/ Binder (w/b)
807	83	104	84	1036	1.3	0.23

The specimen casting started by first greasing the sides and the base of all the respective type of moulds. After filling of the moulds, the top surface was made flush using a trowel to remove excess material. The compacted specimens were left in vibration free position at 27±2°C. De-moulding was done after 24 hours. Next step was curing of samples in controlled conditions as per required time before testing and taken out only prior to testing. Various types of specimens were casted in many batches of each fiber percentage based on the test to be performed. Figure 2 shows the casting and specimen preparation procedure. Specimens were casted for each fiber percentage of 0, 4, 5, 5.5, 6 and 7% (by volume of mould) respectively. Previous research by Ali et.al [14] reported 4-10% as the practical fiber content and also found improvement in mechanical properties with increase in fiber percentage up to 7.5% only in SIFCON. For the current study, fibers beyond 7% could not be practically placed in moulds for preparation of HPSIFCON specimens. The unit weight of slurry without fibers was 2264 kg/m^3 while that of HPSIFCON with 4, 5, 5.5, 6 and 7% fibers were 2409, 2507, 2524, 2563 and 2620 kg/m^3 respectively.

Figure 2: HPSIFCON Specimen Preparation

2.3 HPSIFCON Testing

Compressive and split tensile strength of HPSIFCON were determined as per test method IS 516 (Part 1/Sec 1): 2021 [27]. The load was uniformly increased at a rate of 1.2 mm/min [7, 11, 25] in the displacement based loading, Servo Controlled Compression Testing Machine with a capacity of 3000 kN. The test was carried till the load carrying capacity decreased by about 80% of the peak strength. Elastic range mechanical parameters of HPSIFCON at various fiber content i.e. Poisson's Ratio and Modulus of Elasticity were determined with reference to IS 516 (Part 8/Sec 1): 2020 [28]. Similar work done by other researchers [7, 25, 29-30] and ASTM standards [31-32] were also referred to finalize the test details. The strain in the specimen during testing were recorded using Data Acquisition System, Data Taker (DT85) of AIMIL connected to two concrete strain gauges, surface application type CGC fixed on the face of cylinder horizontally and vertically. Universal Testing Machine with load capacity of 1000 kN was used to perform the four point flexural strength test as per [24] and direct tensile test. The load was applied at the rate of 1 kN/sec without any shock till the specimen failed. No standardized test exists in India for tensile behaviour determination of ultra-high strength concrete. Dog bone specimens (Figure

3) were used to determine direct uniaxial tension failure based on studies [7, 25, 33] done by various researchers and guidelines of standard ASTM codes of practice [34-37]. The loading was done till failure i.e. elongation in the neck region. Tensile strength was determined using the peak load as indicated by the UTM and neck area of the briquette. Figure 4 shows the test set up and instrumentation used for the study. Three samples of each specimen were casted and the testing values were reported as the average. Rebound Hammer N-Type of Schmidt, Proceq was used to conduct the non-destructive test on HPSIFCON 150 mm cubes as per IS 516 (Part 5/Sec 4): 2020 [38]. Rebound number indicates the impact energy transferred to the material through the surface which can then be correlated to the compressive strength for a particular set of samples. The equipment for of Proceq make was used to conduct the non-destructive test of Ultrasonic Pulse Velocity on HPSIFCON cylinders 150 x 300 mm and cubes 150 mm surface as per IS 516 (Part 5/Sec 1): 2018 [39] and to calculate dynamic Young's modulus of elasticity using Equation (1) [37]. The velocity of the longitudinal ultrasonic pulse in km/s (v) travelling through the elastic solid material is dependent on the elastic properties of the material such as density in kg/m3 (ρ), elastic modulus (E) and Poisson's Ratio (μ). These non-destructive testing techniques are popular and reliable methods for estimation of concrete quality.

$$\mathrm{E} = \rho v^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \qquad (1)$$

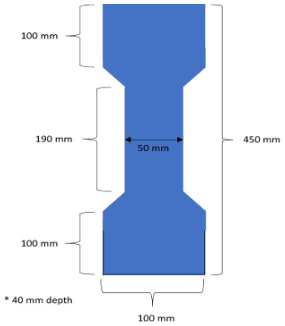

Figure 3: Schematic Representation of Dog Bone Briquette

Figure 4: Test setup and instrumentation (top left to bottom right): Compressive test, Modulus of elasticity and Poisson's Ratio, split tensile, direct tensile test and flexural test.

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3.0 Results and Discussion

3.1 Failure Pattern

HPSIFCON developed has shown ductile behaviour which is a desirable property to avoid brittle failure of concrete which is seen in non-fibrous control specimens. Under various kinds of loading, fiber crack bridging effect is seen at ultimate failure load where localization of deformation occurred. This then governs the load carrying capacity. The overall specimen remains as a complete unit. Figure 5 shows the HPSIFCON failure patterns in compression. HPSIFCON cubes exhibit an intact core as per [24]. This confirms the tight packing of slurry in case of non-fibrous specimen and bonding of steel fibers with the cementitious slurry matrix in case of fibers specimens of 4, 5, 5.5, 6 and 7%. The fibers present in the HPSIFCON lead to a microstructural bonding between the matrix and the fibers that helps in holding the cube specimens together even at ultimate failure. 4% specimen failed mainly due to formation of vertical cracks. Multiple vertical cracking is observed in higher fiber volumes of 5% and above. Inclusion of fibers transformed the spalling lateral sides into columnar cracks. Similar failure characteristics were observed in similar test conducted by Fang et. al. [41].

Figure 5: Failure Mechanism of HPSIFCON in Compression

HPSIFCON failure mechanism in flexure can be seen in Figure 6. Specimens without fiber underwent an extremely brittle failure with loss of ultimate strength. Flexural cracks are seen to extend from bottom to side face similar to findings of Abbas et. al. [15] who developed SIFCON using hooked steel fibers and Fang et. al. [41] who studied ultra-high performance concrete incorporating fibers. The role that the fibers play in acting as micro reinforcement is well evident. They slow down the unstable crack propagation and transmit the stress by bridging the gap [42]. The top compressive face of beams at 4% fiber content show minor cracking between the two loading positions. The bottom tensile face shows cracking along with fiber crack bridging which prevents the collapse of the specimen. Similar behaviour is seen in 5 and 5.5% fibers beams. For high fiber content of 6 and 7% fiber crack bridging prevents the loss of structural element and wider cracks at much higher loads exhibit highly ductile behaviour even at much higher loads leading to enhancement of capacity.

Figure 6: Failure Mechanism of HPSIFCON in Flexure

HPSIFCON failure mechanism in indirect tension is shown in Figure 7. 4% specimen shows minor cracking at the flat faces of the cylinder and along the cylinder length for almost double the load sustained by control specimen. The 5% fiber specimen exhibits further cracking but at a higher load. The bonding effect of fibers prevent development of major cracks in this case. Fibers play a major role in stitching of major cracks at higher loads which is visible in 5.5, 6 and 7% specimens. Specimen failure was mainly due to local strain maximization in cracks extending from top face to the sides [41]. Similar failure was observed by Abbas et. al. [15] in indirect tension.

Figure 7: Failure Mechanism of HPSIFCON in Indirect Tension

Figure 8 depicts the failure mechanism of HPSIFCON in direct tension. Brittle failure was seen in non-fibrous specimen. In the case of fibrous specimens, micro cracks combine to form a macro crack which can be seen as a single localized crack at the weakest section. Similar observations were made by Fang et. al. [41]. The crack developed in neck region of 4% specimen did not cut through the depth of the web region and there is fiber crack bridging is seen at the other end of the depth. The specimen sustained an ultimate load almost double the control specimen without any brittle response. This implies enhanced load carrying capacity. 5% specimen did not have wide crack but only minor cracks stitched by fibers bonding. 5.5% specimen had an ultimate load of 3 times the control specimen with minor small cracks. 6 and 7% specimens did not see any cracking/damage/deterioration in the web region. Pull out response was seen in the flanges region. The shifting of failure region towards the flange with increasing fiber volume was also reported by Fang et. al. [41]. This response can be attributed to fiber content in high volume in the web region wherein the fibers placement is as a close interwoven network in low depth specimen.

Figure 8: Failure Mechanism of HPSIFCON in Direct Tension

3.2 HPSIFCON Strength

The HPSIFCON mechanical strength values are listed for both 7 days strength and for 28 days strength along the percentage in values for various fiber specimens of 4, 5, 5.5, 6 and 7% with respect to the control non-fibrous specimen in Figure 9 and Table 4-5. It can be seen that fibers play a more significant role in flexural and tensile strength enhancement than in compression. The fibers bond with the matrix and also undergo fiber lock as a mechanical and frictional interlock [14]. Also early strength gain more than 85% of the 28 day strength is seen at 7 days which is much higher than conventional concrete. The early strength gain has been achieved due

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to ultrafine binders; alccofine and ultrafine silica used along with cement and fly ash. This leads to the hydration process taking place at an early stage.

Figure 9 shows that the slurry itself is of high compressive strength. Fibers lead to a compressive strength enhancement of 2 – 12 % from the control specimen. The limited effect of fibres on compressive strength has been observed by other researchers as well [14, 41]. The strength increases for 4, 5 and 5.5 % fiber content after which there is a slight decrease for 6 and 7% fiber content which may be attributed to dense fiber network posing slight difficulty in uniform in depth slurry infiltration. Lowering of mechanical properties with rise in steel fiber ratio leading to their lesser orientation in the casting direction was also discussed by Ali et. al. [14]. The authors also concluded lower strength at 7.5% fiber content as a result of segregation of concrete and voids produced at this high fiber volume.

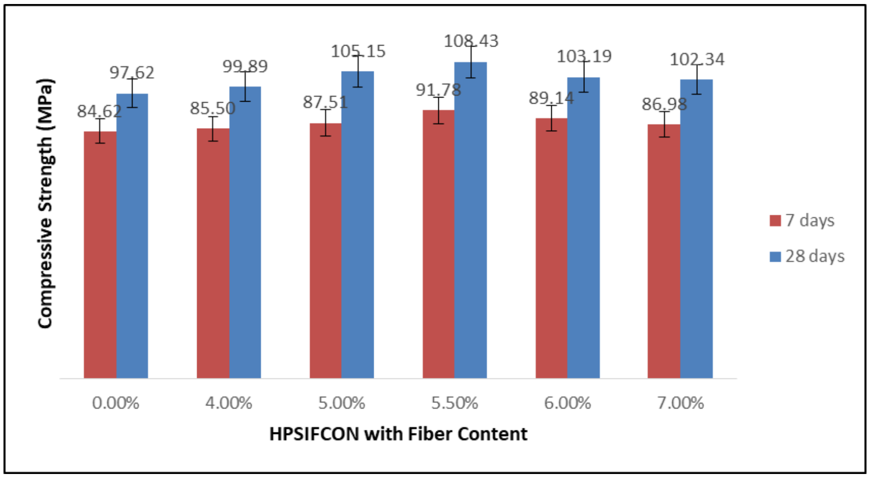

Figure 9: Bar Chart for HPSIFCON Compressive Strength

The HPSIFCON developed has shown excellent flexural strength i.e. modulus of rupture (59.72 to 80.16 MPa) with inclusion of fibers (Table 4). Gain in flexural strength is 2.5 to 3.8 times the non-fibrous control specimen. Fiber packing of high fiber percentages used contributes to these high values since they aid in transfer of large internal tensile forces. The rich binder cementitious matrix act as struts carrying compressive forces and fibers as connections forming an internal web like structure resembling a space truss [15]. High flexural strength provides the flexibility to the member to bend without cracks and there is improvement of the compression zone of the prisms under bending. This provides higher flexural capacity. Similar conclusions were made by Ali et. al. [14] and Abbas et. al. [15]. The gain in flexural strength is seen to be highest at 5.5% fiber content which is 2.2 times that of the direct tensile strength obtained. This is attributed to involvement of more fibers in the bridging effect during cracks development in flexural behaviour. Higher flexural improvement with inclusion of fibers was also observed by Fang et. al. [41].

Table 4: HPSIFCON Flexural Strength Results

Fiber (%)	Flexural Strength (MPa)			
	7 days	% change	28 days	% change
0	11.12	0	16.8	0
4	55.89	403	59.72	255
5	70.95	538	71.405	325
5.5	79.87	618	80.16	377
6	76.54	588	76.96	358
7	71.23	541	71.715	327

The tensile strength of HPSIFCON is considerably high as compared to conventional concrete. The values are 21% as seen in indirect split tensile and 32% in direct tensile results (Table 5). The impact of volumetric ratio of steel fibers on tensile strength of concrete can be seen. The split tensile strength increase is 1.88 to 2.41 times the non – fibrous control specimen.

In case of direct tensile, the overall increase in strength over control specimen ranges from 73-314% indicating a synergistic impact of micro fillers as they improve the packing efficiency and interfacial adhesion with concrete matrix. Hooked fibers further develop the bond between the fibers and the matrix which leads to enhancement of mechanical characteristics of HPSIFCON. Similar strength enhancement was observed by Ali et. al. [14]. HPSIFCON with 5.5% fiber content exhibits the highest tensile strength. The split tensile and direct tensile values are seen to be similar as observed by Fang et. al. [41] in their study as well. 5.5% HPSIFCON exhibited highest tensile strength.

Table 5: HPSIFCON Split and Direct Tensile Strength Results

Fiber (%)	Split Tensile Strength (MPa)				Direct Tensile Strength (MPa)			
	7 days	% change	28 days	% change	7 days	% change	28 days	% change
0	9.23	0	9.92	0	8.14	0	8.56	0
4	19.87	115	20.21	104	18.75	130	19.38	126
5	20.91	127	21.04	112	23.01	183	23.19	171
5.5	22.72	146	23.89	141	34.78	327	35.45	314
6	18.07	96	18.7	89	20.90	157	21.12	147
7	16.29	76	18.62	88	12.88	58	14.8	73

3.3 Modulus of Elasticity and Poisson’s Ratio

Table 6 shows Modulus of Elasticity results obtained from experimental testing of HPSIFCON cylinders for compressive test and dog bone briquettes for direct tensile test. Addition of fibers has led to improvement in the initial stiffness in comparison to the control slurry samples with no fibers. An approximate increase of 13, 16, 17, 25 and 33% is seen in elastic modulus values for fiber percentages of 4, 5, 5.5, 6 and 7% respectively. The increase at fiber percentages till 5.5% is lesser as compared to a higher increase seen in the other higher fiber content. Similar observations for lower fiber content were made by Fang et.al. [41]. Values of modulus of elasticity obtained by UPV are higher by 4 - 29% of those obtained by experimental tests. This can be attributed to the fact these are indirect methods whereas the results obtained experimentally are through direct test. The UPV gives elastic modulus values based on the pulse velocity and there is an increasing trend with addition of fibers. The enhancement in value of elastic modulus and hence the stiffness of HPSIFCON is of great significance for its structural performance and durability. This indicates an increased ability of composite to withstand external forces and maintain its integrity over time. The improvement in elastic modulus values highlight the positive influence of fine cementitious materials and fibers in enhancing the stiffness and resistance to deformation of matrix.

Table 6: HPSIFCON Modulus of Elasticity obtained from Compressive and Tensile Tests and UPV

Fiber content (%)	Modulus of Elasticity (GPa)		Compressive Modulus of Elasticity from UPV (GPa)	Poisson's Ratio
	Compressive	Tensile		
0	26.25	28.49	30.62	0.194
4	29.87	29.03	31.40	0.220
5	30.50	31.84	31.85	0.210
5.5	30.64	32.65	35.98	0.225
6	32.97	31.97	39.53	0.230
7	35.13	29.75	38.47	0.227

Poisson's Ratio of HPSIFCON can be seen to vary from 0.19 to 0.23. Similar values were obtained by Fang et. al. [41] and Ali et. al. [14]. Addition of fibers leads to increase in the value as compared to cementitious matrix with no fibers. This indicates that inclusion of fibers improves the Poisson's ratio and hence the ability of HPSIFCON to undergo deformations under compressive loads.

3.4 Rebound Hammer and Ultrasonic Pulse Velocity Results

The values of Rebound Number as an average of the nine readings taken for each specimen of HPSIFCON at various fiber content are tabulated in Table 7. They indicate the range of very good hard layer on the surface indicative of the high strength of HPSIFCON. The values of compressive strength estimated from rebound hammer results are in close proximity with those obtained by direct test.

Table 7: Rebound Number Values of HPSIFCON

Fiber content (%)	Rebound Number	Estimated Compressive Strength (MPa)
0	61.5	97.0
4	61.7	98.3
5	62.7	104.8
5.5	63.1	107.5
6	62.4	102.8
7	62.2	101.5

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UPV tests results for various samples are listed in Table 8.

Table 8: Values of Ultrasonic Pulse Velocity for HPSIFCON

Fiber content (%)	Cube Specimens		Cylinder Specimens	
	UPV (m/s)	Grading - Concrete Quality	UPV (m/s)	Grading - Concrete Quality
0	4237	Good	4172	Good
4	4298	Good	4209	Good
5	4360	Good	4231	Good
5.5	4491	Excellent	4495	Excellent
6	4425	Excellent	4484	Excellent
7	4392	Good	4292	Good

The values of rebound hammer and ultrasonic pulse velocity are increasing as the fiber content increases except for a slight decrease for 7% specimens. This may be attributed to difficulty in slurry infiltration for this high fiber volume as compared to others. Similar observations were made by Ali et. al. [14].

The results of the experimental investigations undertaken in this study are in agreement with those obtained by previous researchers [7, 14, 30, 40-41] and indicate that the various binding materials and micro fillers such as cement, micro silica, alccofine and fly ash that have been used along with crushed sand have developed a uniform heterogeneous mixture and the material matrix is well dispersed within the casted samples filling up the voids created by dense network of steel fibers. Pore structure improvement due to optimized particle distribution and ultra-fineness micro fillers give dense packing to the matrix. The distribution of fibers in the matrix also plays a role in the strength of HPSIFCON.

4.0 Conclusions

The study presented development of HPSIFCON and experimental investigations to determine its mechanical properties. The following conclusions can be drawn based on the results obtained within the limits of this study parameter.

A new material, HPSIFCON has been developed that possesses the combined characteristics of high performance and high strength incorporated into SIFCON. High performance characteristics of early strength gain, high strength above 100 MPa and enhanced ductility have been achieved by using higher fiber content and slurry incorporating micro particles.

HPSIFCON also utilizes alternate binders incorporating industrial wastes such as fly ash, silica and glass slag to reduce the cement content of the cementitious slurry and presents a concrete with lower carbon than the conventional concrete.

In the present study, the optimum steel fiber volume fraction of 5.5% led to improvement in mechanical properties of HPSIFCON.

Fine binder materials such as micro silica, alccofine and fly ash with their properties such as high surface area, small size, and pozzolanic activity develop a denser microstructure and improved pore structure in comparison to conventional concrete mixes. The enhanced packing and better inter-particle bonding in HPSIFCON slurry results is a stiffer material with improved load bearing capacity.

Under compressive, tensile and flexural loading, fibers were observed to provide crack bridging effect on account of the fiber lock mechanism in HPSIFCON.

Early strength of more than 85% of 28 day strength achieved at 7 days can play a vital role in important construction projects where high and early strength gain are important in completing the project in lesser time and saving money as well. This can also prove useful applications such as prestressed concrete where the prestressing force can be applied only after concrete achieves sufficient strength.

The enhancement in flexural strength of 2.5 to 3.8 times and in tensile strength of 2.4 times the non-fibrous control specimen imparts desirable properties for application in high stressed and seismic resistant structures.

Addition of fibers has led to improvement in the modulus of elasticity and Poissons's ratio.

Rebound Hammer Test on HPSIFCON specimens indicates material having very good hard layer on the surface. Ultrasonic pulse velocity values are in the range 4172 m/s to 4495 m/s indicating the concrete grading quality as good to excellent.

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