International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

Performance of High Strength High Performance Steel Fiber Reinforced Concrete for use in Seismic Resistant Structures

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Abstract: ***Constructing durable seismic resistant concrete structures depends on several parameters. Proper design and detailing go part of the way to success, but even the best design is affected by the fact that crafting precise specifications of the materials is the key to obtaining durable structures. This paper presents the experimental analysis of High Strength High Performance Steel Fiber Reinforced Concrete (HPSFRC) for use in seismic resistant structures and obtaining the added benefit of improved durability. The sudden collapse in concrete structures caused by the brittleness of the structural elements during cyclic loads, so developing a High Strength HPSFRC that can provide earthquake resistance, more ductile and more energy absorption capacity to sustain the cyclic loads is required, which in turn will also reduce the brittle failure of the structures during earthquakes. Though ductility is emphasized in designing earthquake resistant structures, mechanical properties such as Compressive Strength, Flexure Strength, Split Tensile strength, MOE, Poisson's ratio and ductility parameters viz., Drying Shrinkage, Chloride Ion Penetration, Abrasion, Water & Air Permeability & curing and additives (silica fume & fibers) should be assessed for durable seismic resistant structures. Experimental investigation was done to study the mechanical properties for M80 grade of concrete. Investigation was also done to study the effect of partial replacement of cement by Silica fumes about 5% by weight of cement on mechanical properties of concrete. The steel fibers with 0%, 0.5%, 1.0%, 1.5 % & 2.0% volume fractions having aspect ratio 65 were used in concrete mixes. The test results show that the addition of steel fibers enhances performance in its mechanical properties significantly. High Strength HPSFRC with & without fibers in its fresh & hardened state is briefly described in this paper. Engineering properties such as slump, wet density, air content and setting times are investigated and described.***

Keywords: High Strength High Performance Steel Fiber Reinforced Concrete, seismic resistant concrete structures, durable structures, cyclic loads, energy absorption, performance improvers, mechanical properties, Silica Fume, steel fibers, permeability

1. Introduction

For the sustainable development, the modern society cannot do without the high performance construction material 'concrete'. A concrete system, which is adopted for performance enhancement is High Performance Concrete (HPC). It is a type of concrete with properties or attributes, which satisfy the performance criteria. High Performance Concrete is defined generally in terms of strength and durability. High performance Concrete is typified by low water/cementitious materials ratio of 0.35 or less, low permeability and high strength. Performance enhancement requirements for HPC include Enhanced mechanical properties & long life in service environment. Steel fibers are added to improve tensile strength and fracture properties of concrete besides imparting ductility to an otherwise brittle material. Steel Fiber Reinforced Concrete (SFRC) has many applications besides its suitability as an earthquake resistant construction. ACI 544.4R [1] committee reported that both laboratory tests and full-scale field trials have shown SFRC (Steel fiber reinforced concrete) has high resistance to the damage caused by the impact loads. Swamy and Al-Taan [2] reported that steel fibers significantly increase the stiffness of beams. In general, the fiber volume fractions in steel fiber reinforced concrete (SFRC) are in the range of 0.50% to 2.0%. The fundamental advantage of adding fibers is that, after matrix cracking, fibers bridge the cracks in tension zone and restrain them. In order to further deflect the structural component, additional forces and energy are required to pullout the fibers. Thus fibers act as crack arrestors. The contribution of flexural tensile stress is attributed to fibers, as the concrete is assumed to fully crack at the ultimate load. It is known phenomenon that by improving mechanical properties & durability of concrete seismic resistant structures can be achieved. The research program presented herein sets out to test a comprehensive number of High Strength HPSFRC specimens with substantially varied parameters to expand the database of test results of the developed HPSFRC. The subsequent objective is to study and quantify the material's post-cracking characteristics of SFRC specimen, to improve ductility behavior of steel fiber reinforced concrete (SFRC).

1.1 Scope of the Work

The Experimental investigation is planned by casting of specimens with M80 grade at 5% of silica fume using 0% to 2.0% steel fibers by volume of concrete to determine various engineering properties casting the specimens and test the hardened concrete at 3, 7 and 28 days of normal curing as under:

a) To obtain Mix proportions of Control concrete by IS method.
b) To conduct compressive strength test on 150mm Cubes as per IS 516
c) To conduct Flexural strength test on Beams (100x100x500mm) as per ASTM C 1609
d) Split Tensile strength test on 150mm dia. & 300mm height Cylinder as per IS 5816

e) Drying shrinkage test on (75x75x300mm) prism as per IS: 1199
f) Water permeability test on concrete cylinder (150mm dia & 150mm height) as per DIN-1048(part5)
g) Air permeability test on slabs (300x300x100mm) as per Torrent Permeability tester.

1.2 Critical properties of concrete making materials for high strength HPSFRC

To produce high strength high performance steel fiber reinforced concrete having special performance consistently by the use of conventional materials, normal mixing, placing, curing practices and more stringent quality control measures are to be adopted. To produce concrete having very low permeability, concrete mixes has to be designed using larger dosages of chemical admixtures, silica fume etc. The coarse aggregates [3] have a significant role on the performance of high strength HPSFRC. The fine aggregates should be rounded and have uniform grading with fineness modulus between 2.8 - 3.2. Improved strength and permeability of high strength HPSFRC are achieved by modification of microstructure of the transition zone [4]. The use of mineral admixtures in concrete such as silica fume improves the transition zone [5] by refinement of microstructure through the dual effects of pozzolanic reaction and mechanical effect of filler material. IS 456-2000 [6] has also incorporated the use of various mineral admixtures in concrete. A combination of mineral and chemical admixtures such as, silica fume and super plasticizers in concrete often improves high strength HPSFRC's plastic properties such as workability, pumpability, reduced bleeding and segregation and a good surface finish.

1.3 Mix proportioning and quality control of high strength HPSFRC

The basic considerations in high strength HPSFRC design are that it should consider the given constituents like cement, coarse and fine aggregates, chemical & mineral admixtures and steel fibers to achieve the specified properties of concrete at fresh and hardened states. High strength HPSFRC cannot be made by a causal approach. A strict quality control is essential during its production. As there are more ingredients (silica fume, steel fibers, etc) than normal concrete, mixing shall be continued till all the materials are uniformly distributed and a uniform colour of the entire mass is obtained and each individual particle of the coarse aggregate is fully covered with the mortar. Another critical issue for high strength HPSFRC is early water curing essential in order to avoid the rapid development of autogenous shrinkage and to control concrete's dimensional stability.

1.4 Validation of high strength HPSFRC mix

Validation of the finalized mix proportions of high strength HPSFRC for designed parameters is an important requirement of HPSFRC before its adoption. The margin for strength due to variability of batching tolerances is required to be included in target strength for achieving design strength during implementation.

2. Experimental Programme

2.1 Material used

Ordinary Portland Cement (OPC) 53 grade having specific gravity 3.10 conforming IS: 12269 were used. Local course aggregate with minimum particle size of 10 to 20 mm confirming to IS 383[7], natural sand (<4.75 mm) confirming to zone-II, Silica fumes conforming IS: 15388[8], PolyCarboxylic Ether Based HRWRA conforming IS:9103[9] have been considered. The mix design proposed by IS method was adopted. Plain and fibre reinforced concrete of M80 grade have been selected throughout the experimental investigation.

2.2 Mix proportion

Mix Design trials for w/cm ratios ranging from 0.22 to 0.28 were done & based on the trials done; five mix designs [10] in each grade of concrete were finalized for study of various parameters for high strength HPSFRC. A Mix proportion of M80 grade Control concrete designated as HSCM with 0% steel fiber content, SFRC@0.5% of steel fiber content by volume of concrete designated as HS_1, SFRC@1.0% of steel fiber content by volume of concrete designated as HS_2, SFRC@1.5% of steel fiber content by volume of concrete designated as HS_3, SFRC@2.0% of steel fiber content by volume of concrete designated as HS_4. Some adjustment is required to maintain required slump. The dose of superplasticizers is adjusted and the ratio of fine to course aggregate is adjusted upward accordingly.

Table 1: Concrete mix of control & Steel fiber reinforced concrete in percentage by weight of OPC+SF

Type of Concrete	High Strength Control Mix (M80)	SFRC@ 0.5%	SFRC@ 1.0%	SFRC@ 1.5%	SFRC@ 2.0%
Designation	HSCM	HS_1	HS_2	HS_3	HS_4
OPC + Silica Fume	1.0	1.0	1.0	1.0	1.0
W/Cm ratio	0.26	0.28	0.28	0.28	0.28
Course Aggregate	2.01	1.89	1.72	1.68	1.64
Fine Aggregate	1.34	1.20	1.05	1.02	0.98
Steel Fibre	0	0.055	0.11	0.17	0.22
HRWRA	0.015	0.015	0.015	0.024	0.024

*OPC= Ordinary Portland Cement, SFRC=Steel Fiber Reinforced Concrete & HRWRA=High Range Water Reducing Admixtures.

The laboratory conditions were maintained as per Indian Standard during casting, placing & testing of concrete specimen i.e. 27±2°C and 65±5 RH.

2.3 Engineering properties of fresh concrete

The slump of control concrete measured as 100mm. It is observed that slump decreases with the introduction of steel fibers into the mixture, affecting the workability. To maintain the required workability slump of 90-100mm, dose of HRWRA is adjusted. The air content of mixes is found to increase with introduction of steel fiber by 25 to 40%. The wet density of HSCM is 2520kg/m^3, slightly more density was observed for SFRC mix which is 2560kg/m^3.

2.4 Specimen details and test setup

Cubes of size 150 mm x 150mm x 150mm for compressive strength, Beams of size (100x100x500mm) for Flexural strength test as per ASTM C 1609, Cylinder of 150mm diameter & 300mm height Split Tensile strength test as per IS 5816, prism of size (75x75x300mm) for Drying shrinkage test as per IS: 1199, cylinder of size (150mm dia & 150mm height) for Water permeability test as per DIN-1048(part5), slabs of size (300x300x100mm) for Air permeability test as per Torrent Permeability tester incorporating 0% to 2.0% steel fibers with an increment of 0.50% have been used. All specimens were water cured for 28 days at room temperature and then tested to evaluate the mechanical properties. An average of three specimens was considered for cubes, cylinders and prism, and for beams. Table 2 shows the details of specimens used.

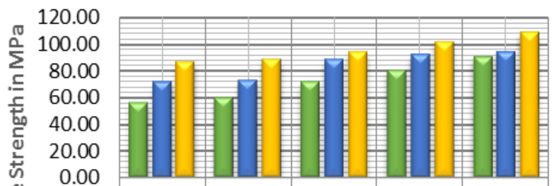
Table 2: Details of specimens

Sl. No.	Type of Test	Standards/ Codes	Type of Specimen
1	Compressive Strength	IS:516	Cube
2	Static Modulus of Elasticity & Poisson's ratio	IS:516 & ASTM C 469	Cylinder
3	Flexural Performance/ toughness	ASTM C1609	Beam
4	Flexural Toughness/ energy absorption	ASTM C 1550	Round Panel
5	Split Tensile Strength	IS:5816	Cylinder
6	Impact Strength	ACI 544	Cylinder
7	Abrasion test	ASTM C-1138	Slab
8	Water Permeability	DIN-1048 (Part 5)	Cylinder

2.5 Engineering properties of hardened concrete

2.5.1 Compressive strength

Compressive strength test was conducted on the cube specimens [11] for all the mixes at different curing periods. The compressive strength (f'_c) of the specimen was calculated by dividing the maximum load applied to the specimen by the cross-sectional area of the specimen [12]. The result of compressive strength of control and steel fiber reinforced concrete is shown in fig.1. Test results indicate that there is a substantial increase in the compressive strength of high strength HPSFRC as compared to control concrete. The compressive strength of the high strength HPSFRC is maximum at 2% steel fibers content. Improvement in Compressive Strength of high strength HPSFRC @28days over HSCM @0.5%: 3%, @1.0%: 9%, @1.5%: 18% and @2.00%: 26%

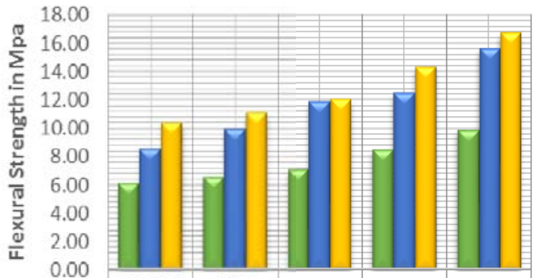


	HSC M	HS1	HS2	HS3	HS4
3Day	56.60	59.80	72.10	80.20	90.40
7Day	71.90	73.20	88.70	92.10	94.00
28Day	86.50	88.70	94.50	101.90	108.70

Figure 1: Compressive Strength

2.5.2 Flexural strength

The beams were tested under universal testing machine. The load was applied in stages and measurements were made at each stage [13]. Flexural strength of the mixes covered in the study is shown in fig- 2. From test results it is observed that there is an increase in the flexural strength with the introduction of steel fibers into the mix. Improvement in Flexural strength of high strength HPSFRC @28days over HSCM @0.5%: 7%, @1.0%: 15%, @1.5%: 37% and @2.00%: 60%



	HSCM	HS1	HS2	HS3	HS4
3Day	6.20	6.60	7.10	8.50	9.90
7Day	8.60	10.00	11.90	12.50	15.60
28Day	10.40	11.10	12.00	14.30	16.70

Figure 2: Flexural strength

Load deflection behavior, Toughness [14] of high strength HPSFRC specimens at 28days strength is discussed below:

2.5.2.1 Load-deflection behavior

The test results of high strength HPSFRC specimens as shown in fig.3 & 4, addition of steel fibers into the mix result in ductile response [15] in load deflection curve. The load-deflection response of steel fiber reinforced concrete generally starts by an initial portion that is linearly elastic up to a certain load and then deviates from its linearity. This is often identified as the onset of first cracking in the matrix. If the cement matrix is not reinforced with steel fibers, first cracking is followed by a sudden drop in the load-deflection curve, and failure occurs which is observed in case of control concrete. The addition of steel fibers influences the response of the concrete mixture after the onset of initial cracks.

Toughness shows an increasing trend with increase of steel fiber content in the mix.

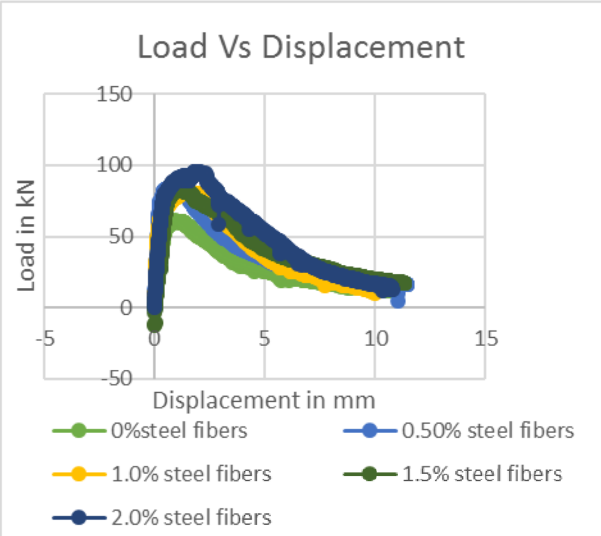


Figure 3: Load-displacement curves of SFRC Specimens

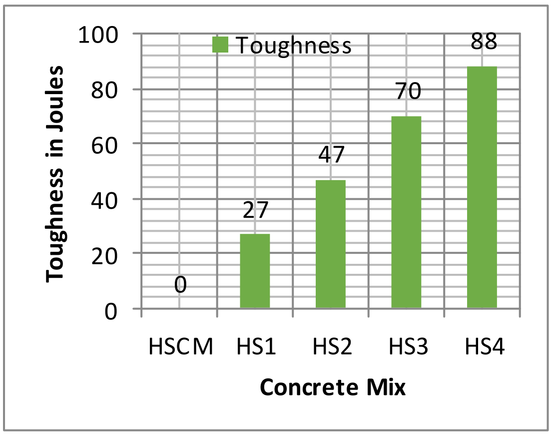


Figure 4: Toughness

2.5.3 Split tensile strength

Split tensile strength [16] of control & steel fiber reinforced concrete is shown in fig-5. Test result indicates that the tensile strength of control and steel fiber reinforced concrete specimens are almost similar. In case of SFRC, there is a substantial increase in the tensile strength compared to control mix.

Improvement in Split Tensile strength of high strength HPSFRC @ 28 days over HSCM @0.5%: 13%, @1.0%: 33%, @1.5%: 51%and @2.00%:62%

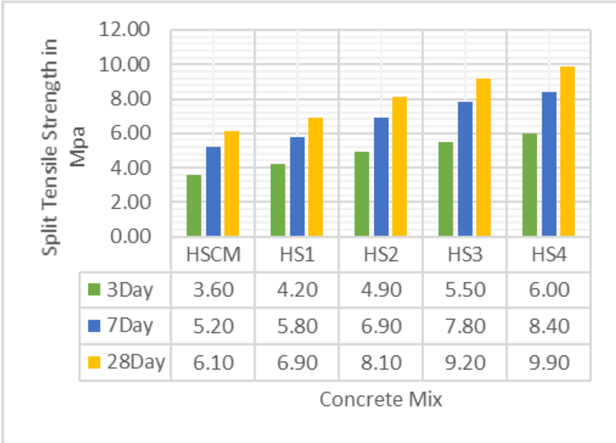


Figure 5: Split Tensile strength

2.5.4 Impact strength

Impact strength [17] of control & steel fiber reinforced concrete is shown in fig-6. Test result indicates that the Impact strength of control is much less when compared with steel fiber reinforced concrete specimens. No of blows required for HSCM is 45 blows for first crack and for SFRC no cracks visible even after 500 blows.

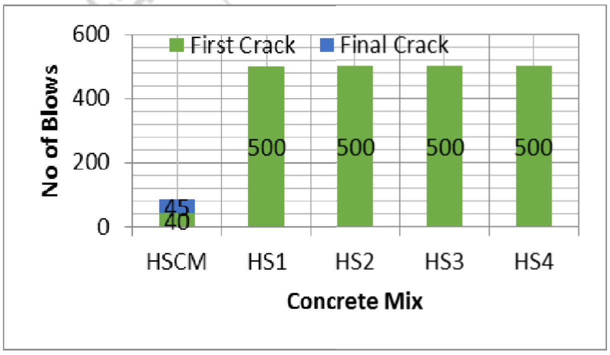


Figure 6: Impact Strength

2.5.5 MOE and Poisson's ratio

Modulus of elasticity (MOE) test was conducted on the specimens for all the mixes at different curing periods is shown in fig. 7&8. Three cylindrical specimens of size 150 mm x 300 mm were cast and tested for each age and each mix. Increase in MOE of SFRC as compared to HSCM varies from 0 to 3.28% and poisson's ratio of mixes varies from 0.212 to 0.238

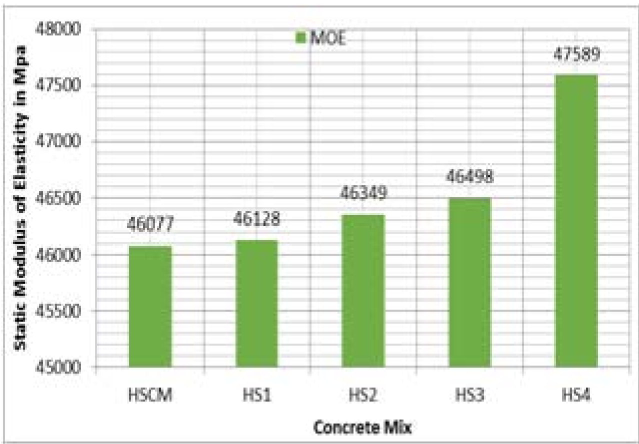


Figure 7: MOE

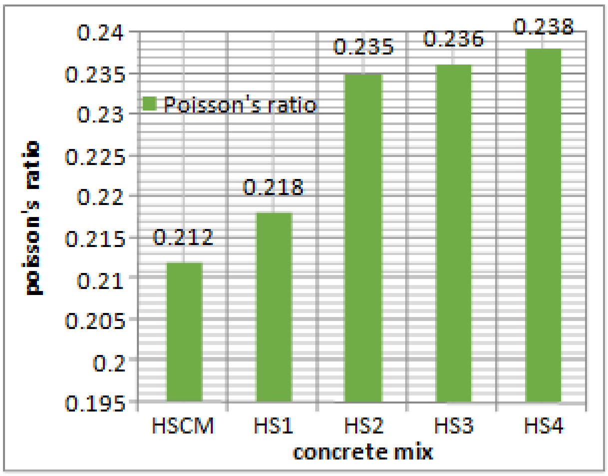
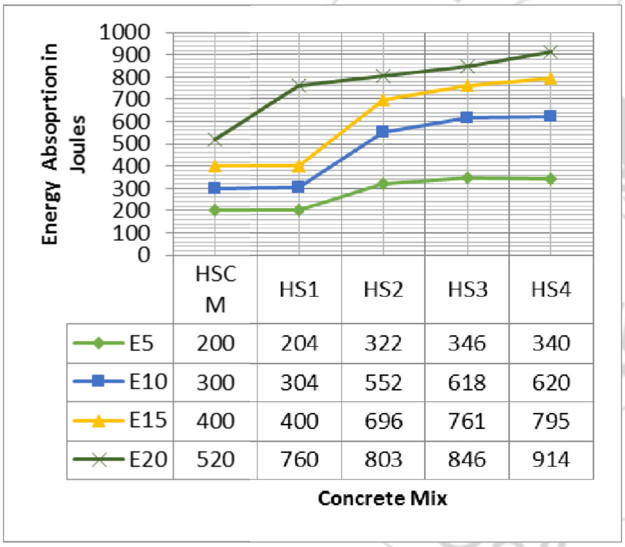


Figure 8: Poisson's ratio

2.5.6 Energy absorption

Energy absorption of control & steel fiber reinforced concrete is shown in fig-9. Test result indicates that the Energy absorption of control is much less when compared with steel fiber reinforced concrete specimens. Energy absorption also show increasing trend with increased in fiber content by volume of concrete.



	HSCM	HS1	HS2	HS3	HS4
E5	200	204	322	346	340
E10	300	304	552	618	620
E15	400	400	696	761	795
E20	520	760	803	846	914

Figure 9: Energy absorption

2.5.7 Abrasion

Abrasion loss as per ASTM C1138 from Fig.10, the inclusion of steel fibers produced an improvement in the abrasion resistance of the concrete [18]. It can be also seen that abrasion wear decreases with increase in fiber percentage.

Improvement in Abrasion resistance of high strength HPSFRC @28days over HSCM @0.5%: 26%, @1.0%: 57 %, @1.5%: 66% and @2.00%: 71%

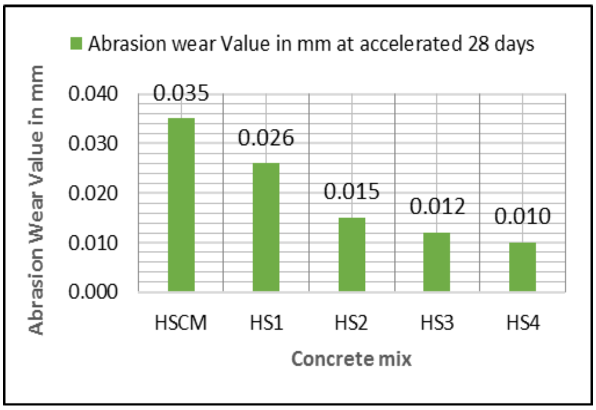


Figure 10: Abrasion wear

2.5.8 Water permeability

Concrete Samples were casted and tested for water permeability [19]. Results of the test from fig-11, indicates significant decrease in the permeability of concrete with the addition of steel fibers. The permeability decreased significantly with increasing fiber content. Improvement in Water penetration of high strength HPSFRC @ 28 days over HSCM @0.5%: 6%, @1.0%: 10 %, @1.5%: 80% and @2.00%: 90%

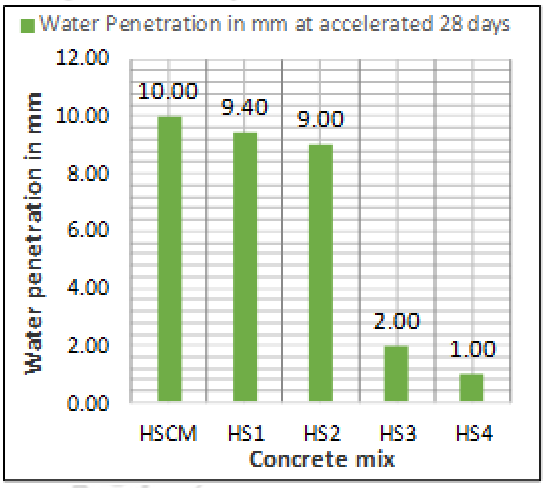


Figure 11: Water penetration

2.5.9 Air permeability

From fig-12, it is observed that the air permeability [20] coefficient (kT^-16m^2) value of SFRC specimen is less than that of control concrete. The result indicates the quality of concrete as good. The permeability coefficient decreases with increase in steel fiber percentage by volume in the mix.

Improvement in Air permeability of high strength HPSFRC @28days over HSCM @0.5%: 33%, @1.0%: 67%, @1.5%: 92% and @2.00%: 92%

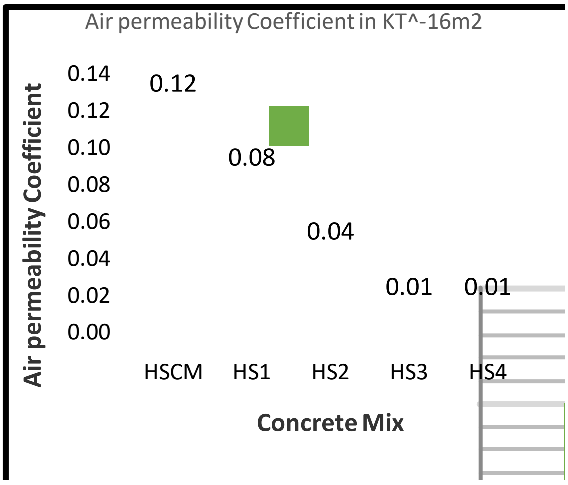


Figure 12: Air permeability

2.5.10 RCPT

Concrete Samples were casted and tested for RCPT. Results of the test from fig-13, indicates significant decrease in the chloride penetration of concrete with the addition of steel fibers. Resistance to Chloride Penetration improvement show increasing trend with increase of steel fiber content in the mix

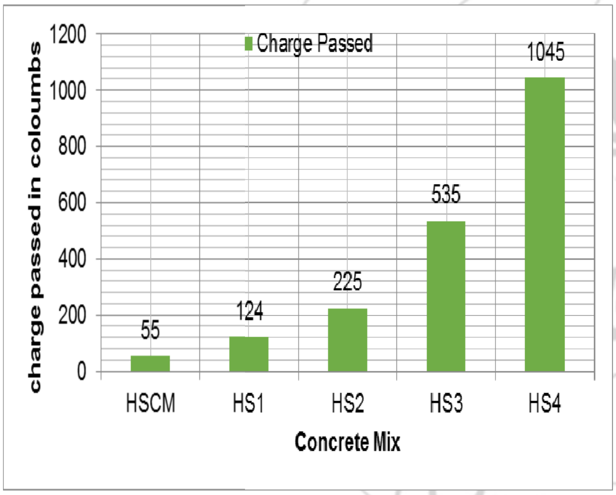


Figure 13: Resistance to Chloride Penetration

2.5.11 Drying shrinkage

The result of drying shrinkage of control & steel fiber reinforced concrete is shown in fig-14, from the figure the reduction in drying shrinkage evident in SFRC. Fibers incorporated in concrete are known to control cracking arising from drying and/or plastic shrinkage behavior occurring in the cementations matrix. The mitigation of drying shrinkage aids the concrete aesthetically and also by controlling and preventing shrinkage cracks the durability of concrete can be enhanced. Improvement in drying shrinkage show better results of steel fiber content in the mix

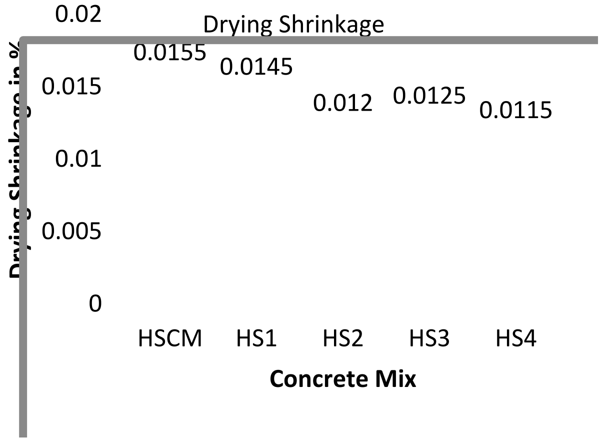


Figure 14: Drying shrinkage

3. Conclusions and Recommendations

3.1 Conclusion

In this paper, concrete samples were analyzed with the procedures laid out in IS / Euro codes. The intent of the paper was to investigate the various mechanical properties of fresh & hardened concrete samples cast from high strength HPSFRC and its suitability at seismic resistance of structures. From the above results and discussions, following conclusions can be drawn:

1) High Strength High Performance Steel Fiber Reinforced Concrete blended with 5% Silica Fume and 0.5, 1.0, 1.5 & 2.0% steel fibers in terms of mechanical properties & durability characteristics has improved enormously as compared to Control Concrete.
2) Out of the five HPSFRC mix selected for evaluation, the mix with 2.0% steel fiber content shows maximum strain hardening behaviour in the load deflection curve indicating that the specimen can absorb more energy, thus suitable for ductile structures.
3) The Toughness & energy absorption of high strength HPSFRC with 2.0% steel fiber content is highest compared to less steel fiber content concrete.
4) With the overall improvement in engineering characteristics as reported in this paper, the optimized mix incorporating 2.0% steel fibers is found suitable for application in seismic resistant structures due to ductility is of major concern.

3.2 Recommendations

Different assumptions and limitations have been considered for testing of various samples. All factors which may influence on the behavior of the structures should be considered in the further testing and analysis. Further study, till obtaining the consistent properties of the concrete the following recommendations is made:

1) As the tests were conducted for only one grade of concrete, the further investigations should be made for different grades of concrete.
2) Further investigations should be done on steel fibers with different diameter & aspect ratio, in the SFRC.
3) Medium and low grades of concrete with SFRC to be studied to establish the typical relationship between the control concrete mix verses high strength HPSFRC.

4) The testing and analysis was performed for high performance concrete materials with OPC with Silica Fume @5%. However, the performance of Silica Fume at higher dose can be tried @ 10, 15, 20% and so on.

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