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An Insight into High Strength Concrete with Steel Fibre Reinforcement under Cyclic Loading

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Abstract : Concrete which is very comfortable under compression is also expected to behave ductile under tension for various structural applications. High strength concrete which has more potential for higher compressive strengths more than 100 MPa is prone to brittle mode of failure at service loads. To overcome this deficit of brittle behaviour and to achieve ductility in high strength concrete, discrete micro-reinforcements in the form of hooked end steel fibre having tensile strengths of 1100 MPa are dispersed in the concrete randomly to instigate the inherent tensile properties within the concrete matrix. The experimental programme consisted of casting of six high strength concrete beams prepared by the addition of 8% silica fume as mineral admixture at a constant water-cement ratio of 0.36 with a tension reinforcement designed for 1% and reinforced with steel fibre in volume fractions of 0.5%, 1.0% and 1.5 %. In addition to this, two high strength concrete beams without steel fibres are casted. Further to achieve more flexural strength, the concept of confinement shear reinforcement is implemented by varying stirrup spacing at 100 and 200mm c/c combinations. The beams are tested under cyclic loading and the test results were compared between beams with and without steel fibre to analyze the effect of ductility in concrete. The test result shows satisfactory performance in deformation and ductility characteristics with the incorporation of steel fibre and improvement in flexural strength due to confinement of shear reinforcement. The experimental results are compared with analytical results obtained by predicted regression values.
Keywords: high strength concrete, steel fibre, hooked end fibre, fibre volume fraction, mineral admixture, silica fume, shear confinement.

1. Introduction

Advanced cement based materials and improved concrete construction techniques provide opportunities for the design of structures to resist severe loads resulting from earthquakes, impact, fatigue, and blast environments. Conventional concrete cracks easily. When concrete is reinforced with random dispersed fibres, we get favourable behaviour for repeated loads. Fibres prevent micro cracks from widening. Addition of fibres makes components ductile and tough[1].

Research carried out in various parts of the world has established that addition of fibres improves the static flexural strength, fatigue, ductility, and fracture toughness of the material. Recent investigations have also given rise to highly reinforced SFRC containing up to 20 % volume of steel fibres.[2] The recent developments are due to the introduction of a new generation of additives such as superplasticizers and microsilicas, which allow the use of high volume of steel fibres and high-strength concrete[12-25].

Lakshmipathy and Santhakumar (1987)[3] conducted an experimental analytical investigation on two span continuous beams with steel fibres. The important characteristics such as cracking behaviour, ductility and energy absorption were ascertained from experimental investigation and compared with analytical results. The fibrous concrete beams served to be superior than conventional concrete.

Heffernan and Erki (2004) [4] studied the fatigue behaviour of RC beams. The authors concluded that an increase of 2% to 6% in the tensile stress of the reinforcing bars that was attributed to softening of concrete occurred in beams subjected to cyclic load. The authors further concluded that the lowest average stress range on reinforcing steel that causes fatigue failure was 165 MPa.

Ramakrishnan (2008)[5] evaluated the performance of synthetic fibre reinforced concrete for transportation structures. The non-metallic polyolefin fibres (50 mm long and 0.63 mm diameter) and dramix steel fibres (60 mm long and 0.8 mm diameter) were used in the construction of bridge deck overlays, pavements, barriers and white-topping. Different quantities of polyolefin fibres 11.9 and 14.8 kg/m3 were used. The authors reported that addition of fibres at 14.8 kg/m3 enhanced the structural properties of concrete. The author also reported that there was a slight increase in flexural strength and toughness, impact, fatigue, endurance limit and post-crack load-carrying capacity and this improvement was same or in some cases (such as impact) better than the enhancement achieved with the addition of 39.1 kg/m3 of steel fibres.

Aoude (2012)[6] performed a series of full-scale SFRC beam tests with and without minimum conventional shear reinforcement. The beams tested had a depth of 250 mm to 500 mm. The concrete matrix consisted of low strength concrete with hooked-end fibres having an aspect ratio of 55. The author reported that the beams without shear reinforcement benefited significantly from the addition of steel fibres; a 1.0% fibre addition increased the peak load by more than 50% and considerably improved the ductility. In some cases, 1.0% fibre content was sufficient in altering the failure mode from shear to flexure; however, the load carrying capacity of these fibrous beams was only 81% of the capacity reached by the beams with minimum stirrups. For beams reinforced with minimum shear reinforcement, flexural failures occurred as expected. The addition of fibres in these flexural-critical beams introduced significantly less benefits and did not lead to increases in the load-carrying capacity.

2. Experimental Programmes.

Concrete Mix Proportions

In this study, concrete of grade M60 was used and it was designed as per the ACI and BIS standards.[7,8&9] The mix was designed with a water-cement ratio (w/c) of 0.36. The concrete mix proportions used in the test program is presented in the Table 1. In order to increase the strength of the concrete mineral admixture Silica fume was added at 8% by weight of cement and to achieve workability Hyperplasticizer was added at 1% by weight of cement.[10&11] Steel fibre was added in volume fractions of 0.5%, 1% & 1.5% by weight of cement.

Table 1. Composition of Concrete Mix Design

Grade of concrete	Cement	FA	CA	Water	Silica Fume	Hyperplasticizer	Steel Fibre
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	$litre/m^3$	kg/m^3
M60	450	750	10mm=450	160	36	4.5	0.5% = 2.25
							1.0%= 4.5
			20mm=680 1130kg				1.5%= 6.75

The experimental programme was performed to study the flexural performance of the steel fibre reinforced concrete beams in conjunction with the conventional RC beam. The research work consisted of casting a total of 8 rectangular beams of cross-section 150mm x 250mm and 3m long. The beams were made of concrete of strength 68.72Mpa and provided with HYSD bars of yield strength 445.63Mpa. All the beams were designed for the under-reinforced condition with percentage of steel, Pt=1.14%. The variables considered for the study include the steel fibre volume fraction and stirrup spacing. For all the test beams, the study parameters included ultimate load, yield load, service load, mid span deflection, crack width, ductility and failure modes. The details of the beam are furnished in Table 2 and the arrangement of reinforcement is furnished in Fig. 1.

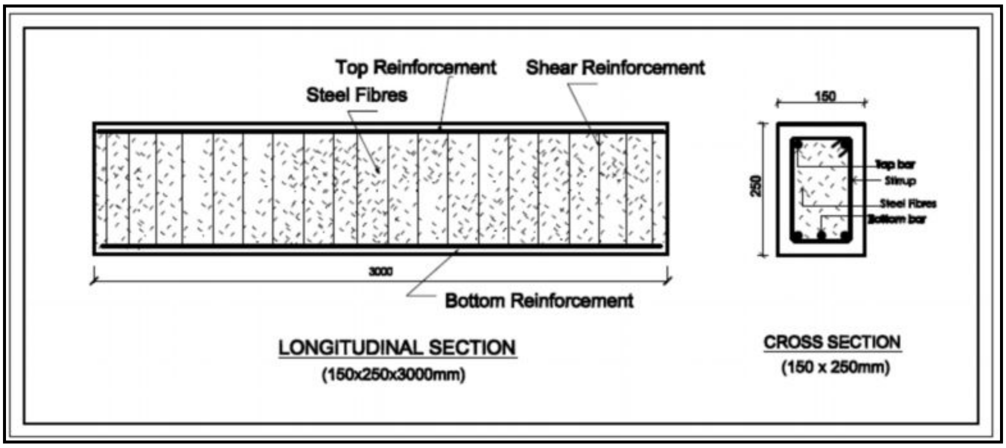

Fig.1. Reinforcement Details of Test Beam

Table 2. Details of Tested Beams

Beam ID	**Characteristic Strength of Concrete 'fck'**	**Steel fibre volume fraction**	**Bottom Bar**	**Top Bar**	**2L-8dia Stirrup**
	N/mm^2	%			mm c/c
HSC-P1	67.11	0	3-12#	2-10#	100
HSC-P2	67.56	0	3-12#	2-10#	200
HSF-P1	68.44	0.5	3-12#	2-10#	100
HSF-P2	68.00	0.5	3-12#	2-10#	200
HSF-Q1	69.78	1.0	3-12#	2-10#	100
HSF-Q2	68.88	1.0	3-12#	2-10#	200
HSF-R1	70.67	1.5	3-12#	2-10#	100
HSF-R2	69.33	1.5	3-12#	2-10#	200

Cyclic Test Procedure

The beams were tested under cyclic loading in a push pull jack operated by a hydraulic pump of 280 kg/cm^2 capacity. The eight beam specimens were tested under four point-bending in a loading frame of 50 Tons capacity in dynamic. The details of cyclic load test set-up are in shown in Fig. 2. The beams were simply supported at the ends with one end hinged and roller at the other end. The beams were supported with 100mm bearing at the ends, resulting in a test span of 2.8m. Two-point loading was applied through a spreader beam. The deflection at each cycle was recorded. Crack widths, crack spacing, number of cracks and corresponding cycles were periodically measured during cyclic loading. The crack widths were measured using a crack detection microscope with a least count of 0.02mm. The cracks were made to see in magnification using a magnifying lens to facilitate identification and measurement of crack widths. Crack propagation was continuously monitored during the process of testing. All the above measurements were taken until the failure stage of the beam.

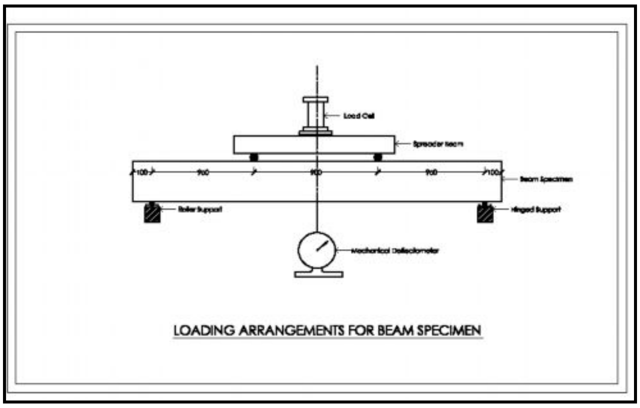

Fig. 2 Beam Test Setup Showing Details of Instrumentation

Fig. 3 Beams under cyclic load testing

3. Test Results and Discussions

The influence of cyclic loading on the behaviour of high strength fibre reinforced concrete beams with varying fibre volume fraction and shear reinforcement spacing was investigated. Adequate data's were obtained and presented in Table 3 with regard to number of cycles, deflection, stiffness, crack width, number of cracks, average spacing of cracks, energy absorption and failure characteristics of high strength fibre reinforced concrete beams with different fibre volume fractions (0.5%, 1.0%, and 1.5%).

Table 3. Cyclic Test Results of Beams

Beam ID	Ultimate Load	No. of Cycles	Deflection	Stiffness	Energy Absorption	Number of Cracks	Average Spacing of Cracks	Average Crack Width
	kN	Nos	mm	kN/mm	kNmm	No's	mm	mm
HSC-P1	87.9	9	4.5	19.53	158.19	18	84	0.14
HSC-P2	84.6	9	4.5	18.8	152.39	20	67	0.16
HSF-P1	65.1	9	4.5	14.47	145.73	16	82	0.14
HSF-P2	65.1	9	4.5	14.47	151.56	18	80	0.16
HSF-Q1	68.3	10	5	13.66	141.05	14	72	0.13
HSF-Q2	61.8	10	5	12.36	183.6	16	78	0.15
HSF-R1	61.8	8	4	15.45	113.12	14	81	0.12
HSF-R2	58.6	8	4	14.65	119.2	12	84	0.12

Effect on Cyclic Test Parameters

In beams with fibre volume fraction, Vf=0.5% and with stirrup spacing's of 100mm and 200mm, the maximum number of cycles went up to 9, the values of deflection and stiffness were obtained as 4.5mm and 14.47 kN/mm. Whereas the energy absorption decreased by 3.84% in beams with 100mm stirrup spacing when compared to beams with 200mm stirrup spacing.

In beams with fibre volume fraction, Vf=1.0% and with stirrup spacing's of 100mm and 200mm, the maximum number of cycles went up to 10, the values of deflection and stiffness were obtained as 5.0mm and 13.66&12.36 kN/mm. Whereas the energy absorption decreased by 23.17% in beams with 100mm stirrup spacing when compared to beams with 200mm stirrup spacing.

In beams with fibre volume fraction, Vf=1.5% and with stirrup spacing's of 100mm and 200mm, the maximum number of cycles went up to 8, the value of deflection was obtained as 4mm and the values of stiffness were obtained as 15.45 and 14.65 kN/mm. The stiffness increased by 5.46% in beams with 200mm stirrup spacing when compared to beams with 100mm stirrup spacing. The energy absorption decreased by 5.10% in beams with 100mm stirrup spacing when compared to beams with 200mm stirrup spacing.

The load Vs deflection behavior of all the beams under cyclic loading is shown in Fig. 4(a) to 4(h). The deflection Vs numbers of cycles for beams with 100 and 200mm stirrup spacing are presented in Fig-5 & Fig-6. The stiffness Vs number of cycles for beams with 100 and 200mm stirrup spacing's are presented in Fig-7 & Fig-8. The energy absorption Vs number of cycles for beams with 100 and 200mm stirrup spacing's are presented in Fig-9 & Fig-10.

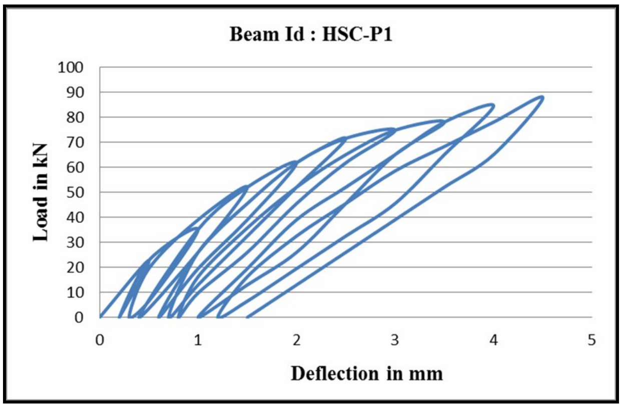

Fig. 4(a) Cyclic Response of HSC-P1 Beam

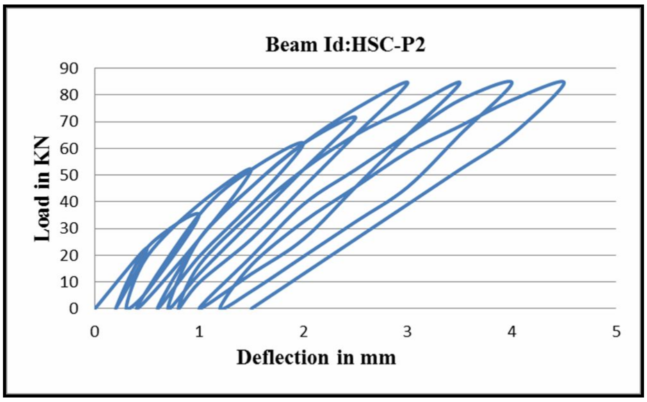

Fig. 4(b) Cyclic Response of HSC-P2 Beam

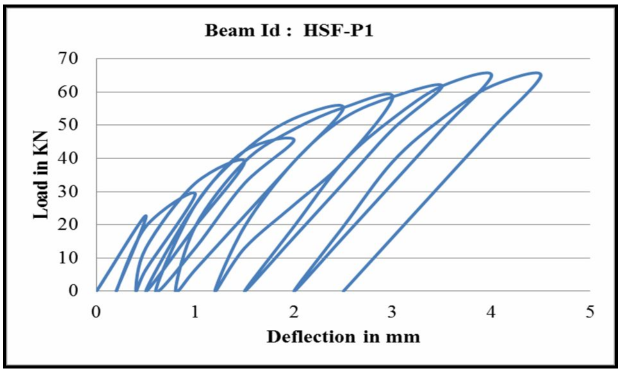

Fig. 4(c) Cyclic Response of HSF-P1 Beam

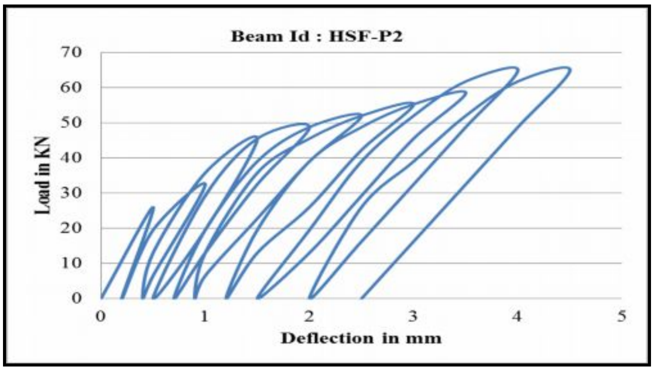

Fig. 4(d) Cyclic Response of HSF-P2 Beam

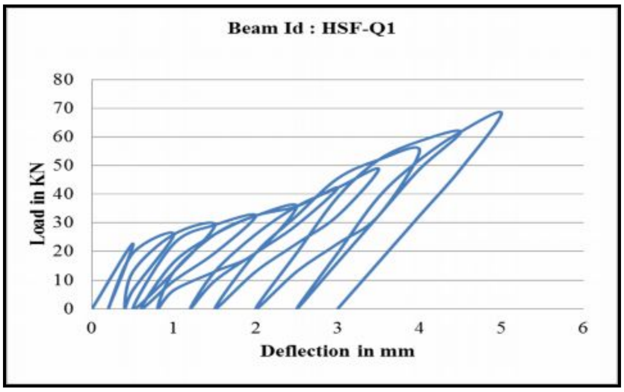

Fig. 4(e) Cyclic Response of HSF-Q1 Beam

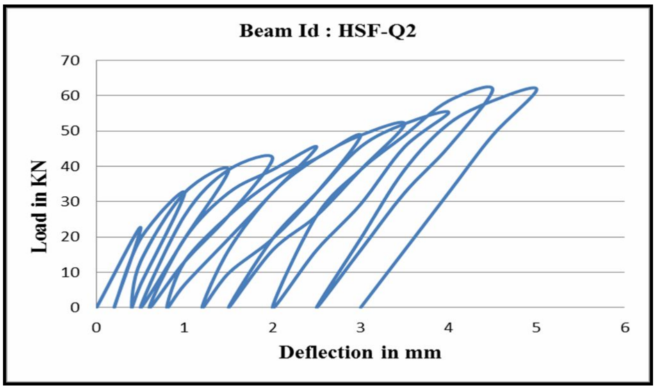

Fig. 4(f) Cyclic Response of HSF-Q2 Beam

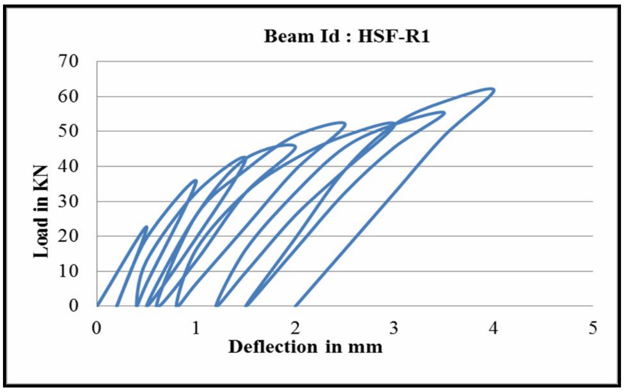

Fig. 4(g) Cyclic Response of HSF-R1 Beam

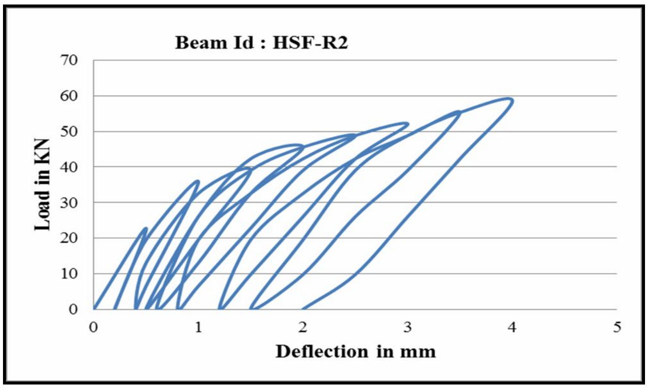

Fig. 4(h) Cyclic Response of HSF-R2 Beam

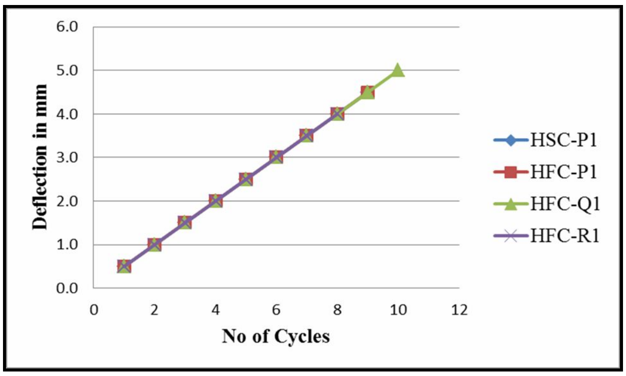

Fig. 5 Deflection Vs No. of Cycles -100mm stirrup spacing

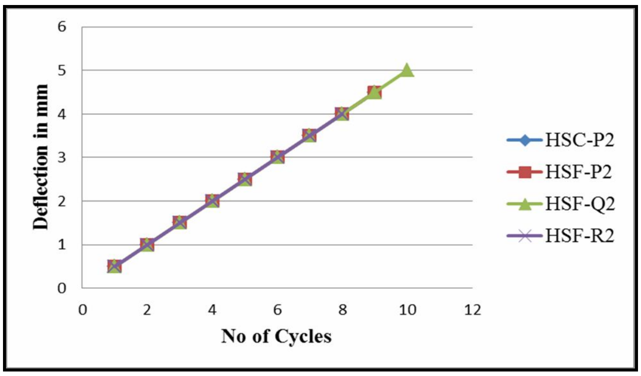

Fig. 6 Deflection Vs No. of Cycles -200mm stirrup spacing

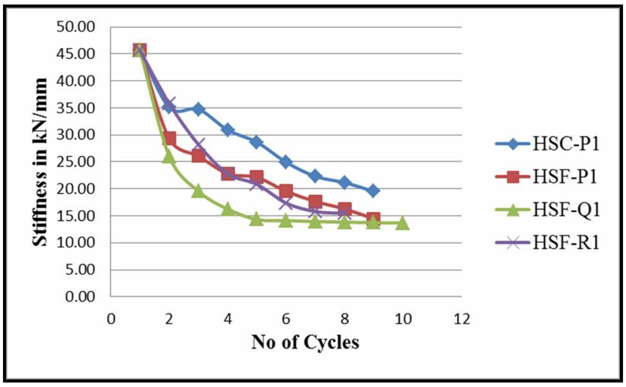

Fig.7 Stiffness Vs No. of Cycles -100mm stirrup spacing

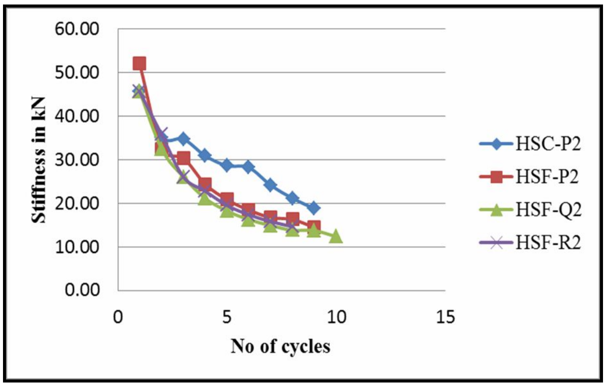

Fig.8 Stiffness Vs No. of Cycles -200mm stirrup spacing

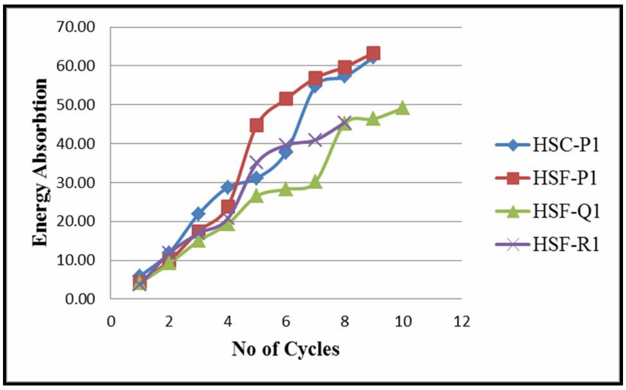

Fig.9 Energy Absorption Vs No.of Cycles-100mm stirrup

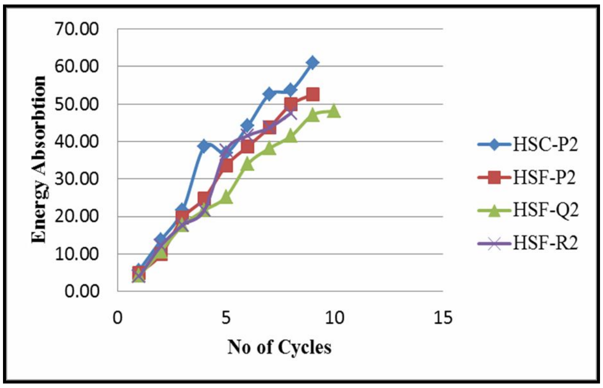

Fig.10 Energy Absorption Vs No. of Cycles-200mm stirrup

Effect on Crack Width

In beams with 0.5% fibre volume fraction, the crack width of 100mm shear reinforcement spacing decreased by 12.5 % when compared to 200mm spacing, whereas the crack width varied by 0 % when compared to control beams.

In beams with 1.0% fibre volume fraction, the crack width of 100mm shear reinforcement spacing decreased by 13.33 % when compared to 200mm spacing, whereas the crack width decreased by7.14% and 6.25 % when compared to control beams.

In beams with1.5% fibre volume fraction, the crack width of 100mm shear reinforcement spacing varied by 0% when compared to 200mm spacing, whereas the crack width decreased by 14.28% and 25% when compared to control beams.

The variations in crack width with respect to Vf and stirrup spacing are shown in Fig.11.

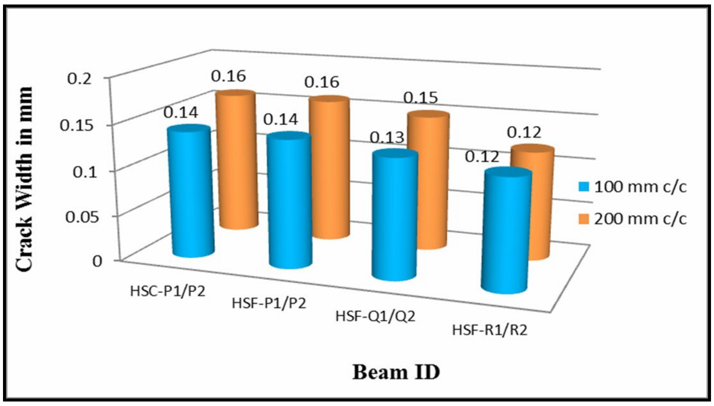

Fig.11 Crack Width at Ultimate Stage

4. Analytical Prediction

Regression Analysis and Modeling

Regression analysis is performed to predict or estimate one variable (dependent) in terms of the other variable (s) (independent). In regression analysis, the nature (or form) of actual relationship if it is exists between two or more variable is studied by determining the mathematical equation between the variables. The development of a mathematical equation to represent real time parameters is required for predicting the behaviour of systems. The procedure involves assuming a suitable initial form for the equation with a number of unknown co-efficients, called regression co-efficients which approximately resembles the form of relationship between the independent and dependent parameters.

Minitab 16 Statistical Software is a Windows statistical software package developed and published by Minitab, Inc. It is used for different statistical analysis and data management.

The regression equations have been proposed for predicting the study parameters. Regression equations for tested beams are presented in Table 4. Predictions from the regression equations were compared against experimental results and are presented in Table 5 and Figs. 12 to 17.

Table 4. Regression Equation for Tested Beams – Cyclic Load

Parameter	Regression Equation	RMS Error	Fitness
Total No.of Cycle	-25.4 - 1.33 (Vf) + 0.508 (fck) + 0.00283 (Sv)	0.915912	0.713
Ultimate Load	37 - 16.9 (Vf) + 0.71 (fck) - 0.0285 (Sv)	7.24591	0.945
Ultimate Deflection	-12.7 - 0.663 (Vf) + 0.254 (fck) + 0.00142 (Sv)	0.457956	0.713
Ultimate Stiffness	60 - 1.66 (Vf) - 0.61 (fck) - 0.0105 (Sv)	2.38588	0.738
Total Energy absorbtion	335 - 15.6 (Vf) - 2.8 (fck) + 0.106 (Sv)	2.27909	0.844
Crack width at Ultimate load	1.11 - 0.0099 (pt) - 0.0136 (fck) - 0.000112 (sv)	0.030287	0.588

Table 5. Percentage variation between Experimental and Predicted Results on Beams

Sl.No	Parameter	Unit	Beam ID	Experimental	Predicted	% Variation
1	Total No of Cycle	No	HSC-P1	9	8.97	-0.28
			HSF-P1	9	8.99	-0.16
			HSF-Q1	10	9.00	-9.99
			HSF-R1	8	8.79	9.85
			HSC-P2	9	9.49	5.41
			HSF-P2	9	9.05	0.50
			HSF-Q2	10	8.83	-11.73
			HSF-R2	8	8.39	4.88
2	Ultimate Load	kN	HSC-P1	87.9	81.80	-6.94
			HSF-P1	65.1	74.29	14.12
			HSF-Q1	68.3	66.79	-2.21
			HSF-R1	61.8	58.98	-4.57
			HSC-P2	84.6	79.27	-6.30
			HSF-P2	65.1	71.13	9.26
			HSF-Q2	61.8	63.30	2.43
			HSF-R2	58.6	55.17	-5.85

3	Ultimate Deflection	mm	HSC-P1	4.5	4.49	-0.27
			HSF-P1	4.5	4.49	-0.13
			HSF-Q1	5	4.50	-9.94
			HSF-R1	4	4.40	9.94
			HSC-P2	4.5	4.74	5.43
			HSF-P2	4.5	4.52	0.54
			HSF-Q2	5	4.42	-11.67
			HSF-R2	4	4.20	4.98
4	Ultimate Stiffness	Kn/mm	HSC-P1	19.53	18.01	-7.77
			HSF-P1	14.47	16.37	13.14
			HSF-Q1	13.66	14.72	7.79
			HSF-R1	15.45	13.35	-13.58
			HSC-P2	18.8	16.69	-11.23
			HSF-P2	14.47	15.59	7.74
			HSF-Q2	12.36	14.22	15.07
			HSF-R2	14.65	13.12	-10.45
5	Total Energy Absorption	kNmm	HSC-A1	158.19	157.69	-0.31
			HSF-A1	152.39	167.03	9.61
			HSF-B1	145.73	146.17	0.30
			HSF-C1	151.56	158.00	4.25
			HSC-A2	141.05	134.62	-4.56
			HSF-A2	183.60	147.74	-19.53
			HSF-B2	113.12	124.32	9.90
			HSF-C2	119.20	138.68	16.34
6	Crack Width at Ultimate Load	mm	HSC-A1	0.14	0.19	32.93
			HSF-A1	0.14	0.16	16.48
			HSF-B1	0.13	0.14	7.61
			HSF-C1	0.12	0.12	2.37
			HSC-A2	0.16	0.17	5.49
			HSF-A2	0.16	0.16	-1.34
			HSF-B2	0.15	0.14	-6.05
			HSF-C2	0.12	0.13	8.22

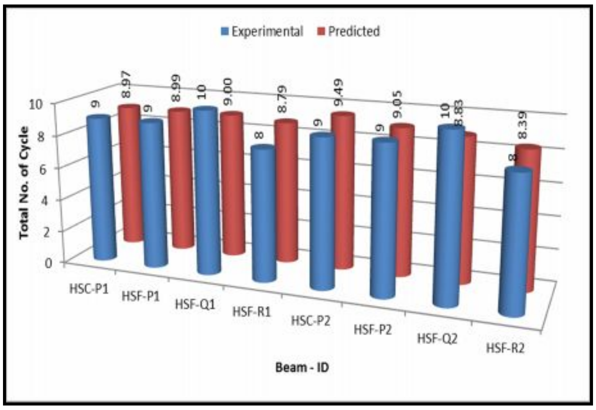

Fig.12 Total Number of Cycles - Experimental Vs Predicted

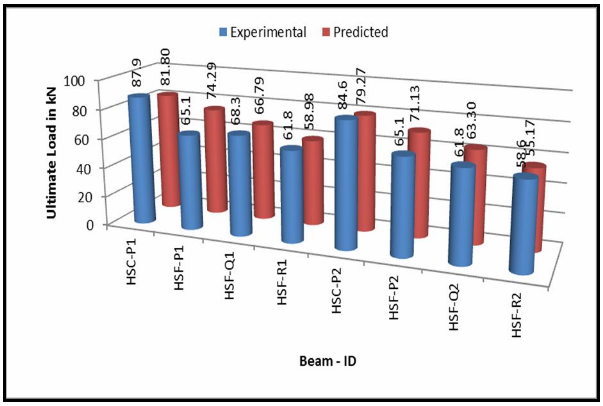

Fig. 13 Ultimate Load - Experimental Vs Predicted

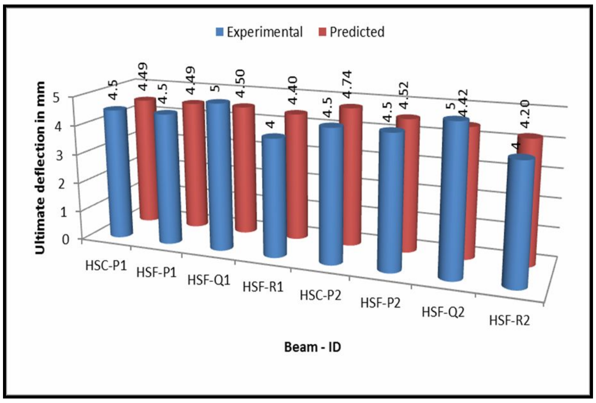

Fig. 14 Ultimate Deflection - Experimental Vs Predicted

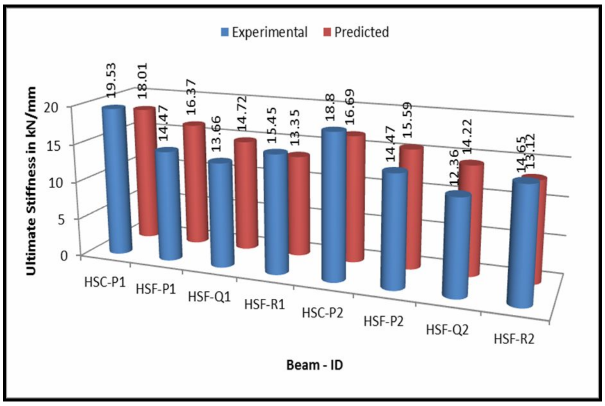

Fig. 15 Ultimate Stiffness - Experimental Vs Predicted

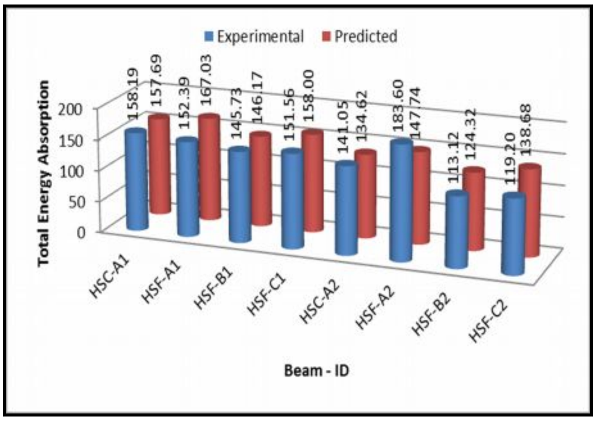

Fig. 16 Total Energy Absorption -Experimental Vs Predicted

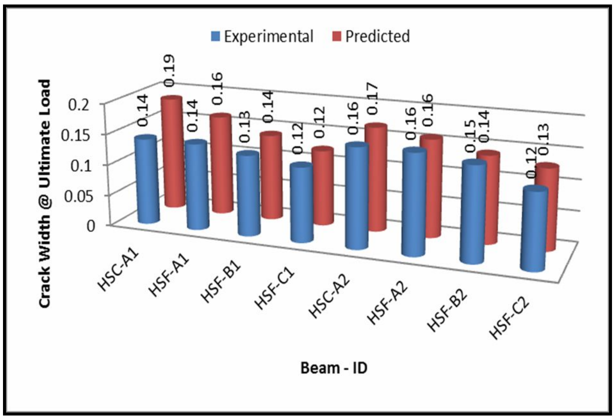

Fig.17 Crack Width at Ultimate Load-Experimental Vs Predicted

5. Conclusions

1. The beams with steel fibers displayed inelastic and ductile behavior near the failure, and higher ultimate flexural strength than the beam without fibers.
2. The steel fibers in concrete controlled the propagation of cracks and the crack width.
3. The addition of fibers with steel bars can be possible method to overcome the low ductility.
4. Concrete strength and fibre volume fraction have significant influence on the overall performance of the steel fibre reinforced high strength concrete beams.
5. The measure of fitness of regression shows that the multivariate linear regression can estimate the prediction values with reasonable levels of accuracy for number of cycles for steel fibre reinforced high strength concrete beams subjected to cyclic loading.

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