International Journal of Civil Engineering

Structure
Concrete

Technical Note

Impact characteristics of high-performance steel fiber reinforced concrete under repeated dynamic loading

P. Ramadoss[1],*, K. Nagamani[2]

Received: April 2013, Revised: October 2013, Accepted: December 2013

Abstract

An experimental study on the impact performance of silica fume concrete and steel fiber reinforced concrete at 28 days and 56 days under the action of repeated dynamic loading was carried out. In this experimental investigation, w/cm ratios of 0.4 and 0.3, silica fume replacement at 10% and 15% and crimped steel fibers with an aspect ratio of 80 were used. Results indicated that addition of fibers in high-performance concrete (HPC) can effectively restrain the initiation and propagation of cracks under stress, and enhance the impact strengths, toughness and ductility of HPC. Pulse velocity test was carried out for quality measurements of high-performance steel fiber reinforced concrete. Steel fibers were observed to have significant effect on flexural strength of concrete. The maximum first crack strength and ultimate failure strength at 28 days were 1.51 times and 1.78 times, respectively at 1.5% volume fraction to that of HPC. Based on the experimental data, failure resistance prediction model was developed with correlation coefficient (R) = 0.96 and absolute variation determined is 1.82%.

Keywords: *Silica fume, High-performance concrete, Steel fiber reinforcement, Mechanical properties, Pulse velocity, Impact resistance, Toughness.*

1. Introduction

The improved toughness in compression imparted by fibers is useful in preventing sudden and explosive failure under static loading, and in absorption of energy under dynamic loading [1]. The acceptance rests primarily on the impact resistance [2]. Concrete materials are subjected to impact loading in various fields of application, including airfield pavements, pile driving, hydraulic structures, protective shelters and industrial floors. Under impact loading plain concrete exhibits extensive cracking and undergoes brittle failure, and has a relatively low energy absorption capacity. The addition of fibers in concrete and mortar can enhance many of the engineering properties such as flexural strength, toughness, resistance to fatigue, impact and thermal shock as well as failure mode of concrete [2, 3, 4].

In the production of high-performance concrete (HPC), silica fume plays a vital role because of the characteristics and micro structure of interfacial zone are significantly improved.

The adoption of HPC in the design of structural components reduces the section size and increases the capacity of structures; used in the economical design of earthquake resistance structures, but it suffers from the high brittleness. The addition of discrete fibers of small diameter in the concrete matrix has shown to improve ductility of NSC and HSC, particularly concrete containing silica fume [5], and can effectively restrain the initiation and propagation of cracks under stress, and improve the toughness of HSC [6]. Yan et al. (1999) [7] have observed that silica fume effectively improved the structure of the interfacial zone, reduced the number and size of cracks, and enhanced the ability of steel fibers to resist the cracking and restrain damage. The impact resistance is assessed through different types of test procedures, such as drop weight test, explosive test, projectile impact test, constant strain rate test, etc. The measured performance can be used to design the structural elements that should withstand certain kinds of impact loads. However, the results from these tests should be interpreted very carefully as they depend on a number of factors, such as fiber types, aggregate types, disc geometries, concrete mixes, degree of compaction, etc. [8, 9].

Several researchers (refer Table 1) [6- 38] have evaluated the impact strength characteristics of HSC/ FRC/ cement fiber composites and that the repeated impact (ACI drop-weight) test has been extensively used to evaluate the impact strength, because of its simple technique**.** Rather, the method is designed to assess the relative performance

---

** Corresponding author: dosspr@gmail.com*

1 Associate Professor, Department of Civil Engineering, Pondicherry Engineering College, Puducherry - 605014, India

2 Professor, Structural Engineering Division, Anna University, Chennai - 600025, India

of plain concrete matrix and fiber reinforced concrete. Moreover, from the literature review (refer Table 1), it is observed that the impact performance of high-performance steel fiber reinforced concrete (HPSFRC) is rarely investigated in the statistical sense and most of the studies reported merely on NSC/ HSC and SFRC.

Table 1 Impact resistance measurement for fiber reinforced concrete- An overview

Sl. No.	Test method	Type of fiber	Reference
1	Drop weight impact	Steel	[6, 7, 8, 9,12, 13, 14, 19, 20, 21], [30, 31, 35, 36].
		Polypropylene (PP)	[10, 11,16, 24, 32]
		Polyethylene	[11]
		Nylon	[10]
		Jute	[26, 28]
		Coir	[26, 28]
2	Modified drop weight impact	PP/ Steel	[16]
3	Projectile impact(low/ high velocity	Steel	[28]
4	Instrumented impact	PP	[8, 17, 22, 23, 37, 38]
		Steel	[15, 17, 37, 38]
5	Explosive impact	PP	[25]
6	Pendulum impact (Charpy/ Izod)	Steel	[29]
7	Modified pendulum impact	Steel	[18, 34]

This paper mainly deals with (i) the impact characteristics of silica fume concrete (HPC) under repeated dynamic loading with the addition of crimped fibers at different volume fractions, and (ii) the development of failure impact strength prediction model. To study the quality and uniformity of composite including fiber distribution, ultrasonic pulse velocity test was conducted.

Research significance

Information on the influence of steel fibers in HPC on impact performance is insufficient since most of studies reported mere on HSC with limited data. The work reported herein studies the influence of crimped steel fibers in enhancing the impact characteristics/ performance of HPC and development of empirical expression on prediction of impact strength at ultimate failure at 28 days. Quality and uniformity of composite including fiber distribution was studied using ultrasonic pulse velocity test.

2. Experimental Program

2.1. Materials, mixture proportions, and preparation of specimens

Ordinary Portland cement- 53 grade having 28-day compressive strength of 56.5 MPa and fineness by specific surface area of 265 m^2/kg complying with IS: 12269-1987, and condensed silica fume having fineness by specific surface area of 23000 m^2/kg and specific gravity of 2.25 complying with ASTM C1240-1999 were used. Chemical composition of cementitious materials is listed in Table 2. Fine aggregate of river sand conforming to grading zone-II of IS: 383-1978, has a fineness modulus of 2.65 and a specific gravity of 2.63. Coarse aggregate of crushed granite stones with maximum size of 12.5mm, conforming to IS: 383-1978 was used. The characteristics of coarse aggregates are: specific gravity (SSD) = 2.70; fineness modulus = 6.0; dry rodded unit weight = 1600 kg/m^3; crushing strength = 14.47%; impact strength = 11.8%; abrasion value = 12.5%. Super-plasticizer of sulphonated naphthalene formaldehyde condensate as high range water reducing admixture conforming to ASTM C 494 (Type F) was used. Crimped steel fibers (conforming to ASTM A 820-2001) of length = 36 mm, diameter = 0.45 mm and aspect ratio = 80, having an ultimate tensile strength (f_u) = 910 MPa and Young's modulus = 210 GPa was used.

Table 2 Chemical Composition of Cementitious materials (in percentage)

Chemical composition	CaO	SiO_2	AlO_3	Fe_2O_3	MgO	K_2O	SO_3	P_2O_5	C	LOI	LSF
Ordinary Portland cement	64.26	21.07	5.54	5.16	0.86	0.37	0.72	0.33	-	1.54	0.925
Silica fume	3.10	88.70	0.60	0.28	0.30	-	0.25	-	0.90	1.80	-

- = not measured items

Mixtures were proportioned using guidelines and specifications given in ACI 211.4R-1993 [39], and recommended guidelines of ACI 544.3R-1993 [4]. Mixture proportions used in this test programme are summarized in Table 3. For each water-cementitious materials ratio, two HPC mixes with 5% &10% SF replacement and three fibrous concrete mixes at each SF replacement level having fiber volume fractions (V_f) of 0.5, 1.0 and 1.5% by volume of concrete (39, 78 and 117.5 kg/m^3, respectively) were prepared. Super-plasticizer with dosage range of 1.75 to 2.5% has been used to maintain the adequate workability of concrete mixes. Sixteen series of high-performance steel fiber reinforced concrete mixes with w/cm ratios of 0.4 and 0.3 were used in this investigation. For each mix at least six 150Ø x 64 mm discs, three 150 mm Ø cylinders, three 150 mm side cubes and three 100 x 100 x 500 mm prisms were produced. Specimens were cast and cured in water until the testing age of 28 days and 56 days.

Table 3 Mix proportions and static mechanical properties of HPSFRC

Mix Designation	W/Cm	Cement Kg/m^3	Silica fume Kg/m^3	Sand ratio (%)	Steel fiber V_f (%)	SP Kg/m^3	compressive strength(MPa)		Flexural strength (MPa)
							f_{cf}	f'_{cf}	
FC1-0	0.4	394.2	43.8	38.8	0	7.66	61.03	52.56	6.21
FC1-0.5	0.4	394.2	43.8	38.8	0.5	7.66	64.75	54.77	7.15
FC1-1	0.4	394.2	43.8	38.8	1	7.66	66.85	56.01	7.73
FC1-1.5	0.4	394.2	43.8	38.8	1.5	7.66	67.38	57.40	8.19
FC1*-0	0.4	372.3	65.7	38.8	0	7.66	65.73	55.70	6.84
FC1*-0.5	0.4	372.3	65.7	38.8	0.5	7.66	69.71	58.67	7.69
FC1*-1	0.4	372.3	65.7	38.8	1	7.66	71.58	60.21	8.64
FC1*-1.5	0.4	372.3	65.7	38.8	1.5	7.66	72.15	61.17	9.28
FC2-0	0.3	495	55	36.4	0	13.75	72.75	63.86	7.40
FC2-0.5	0.3	495	55	36.4	0.5	13.75	75.87	67.12	8.76
FC2-1	0.3	495	55	36.4	1	13.75	76.96	68.91	9.32
FC2-1.5	0.3	495	55	36.4	1.5	13.75	77.29	69.67	10.13
FC2*-0	0.3	467.5	82.5	36.4	0	13.75	77.81	64.27	8.16
RC2*-0.5	0.3	467.5	82.5	36.4	0.5	13.75	81.98	67.78	9.23
FC2*-1	0.3	467.5	82.5	36.4	1	13.75	82.42	69.74	10.32
FC2*-1.5	0.3	467.5	82.5	36.4	1.5	13.75	82.87	70.31	11.08

In mix designation FC1 to FC2 and FC1* to FC2*, silica fume replacement is 10 percent and 15 percent respectively by weight of cementitious materials, after hyphen denotes fiber volume fraction in percent.

Water required for w/cm = 0.4 is 175 kg/m^3 and for w/cm = 0.3 is 165 kg/m^3.

V_f (%) = steel fiber volume fraction (%) in total volume of concrete.

f_{cf} = cube compressive strength; f'_{cf} = cylinder compressive strength.

(1 lb = 0.445 kg; 1 MPa = 1 N/mm^2 = 145 psi; 1 lb/ft^3 = 15.723 kg/m^3)

2.2. Test methods

2.2.1. Compressive and flexural strengths

The compressive strength tests were performed according to IS: 516-1981 standards using 150 mm side cubes and ASTM C39-1992 using 150 mm diameter cylinder specimens. The tests were conducted in a hydraulically operated compression testing machine. Three samples were used for computing the mean compressive strength.

The flexural strength (modulus of rupture) tests were conducted as per the specification of ASTM C 78-1994 using 100 x 100 x 500 mm prisms under third- point loading on a simply supported span of 400 mm. The tests were conducted in a 100 kN closed loop hydraulically operated Universal testing machine. Samples were tested at a deformation rate of 0.1 mm/min. Three samples were used for computing the mean strength.

2.2.2. Ultrasonic pulse velocity

Ultrasonic pulse velocity test was performed for a qualitative measurement of HPSFRC mixes. A suitable apparatus and a standard procedure are described in ASTM C 597-1991/ IS: 13311(Part 1)-1992 [40]. Pulse velocity is measured using Ultra sonic concrete tester. The variation in pulse velocity was marginal indicating the uniformity of the composites. Visual observation of the surface of the discs indicated the uniform distribution of fibers in the mixes. Pulse velocity of SFRC increases marginally with the increase in fiber content. Average pulse velocity is reported in Table 4. From the UPV measurements, it is found that all the concrete specimens can be classified under good quality.

Table 4 28-day impact resistance and UPV test results, and predicted failure strengths for high-performance steel fiber reinforced concrete

Mix Designation	V_f	Aver- age thick	Ultrasonic Pulse velocity (UPV)		Impact resistance Number of blows		PINPB	T	Predicted by Eq.(1)
	(%)	(mm)	Transient time (µs)	Wave velocity (m/sec)	at first crack (N_1)	at failure (N_2)		(Nm)	N_2
FC1-0	0	64	14.44	4433	101	112	10.95	2269	-
FC1-0.5	0.5	64.5	14.80	4358	128	162	26.76	3301	152
FC1-1	1	64	14.46	4527	140	181	29.06	3683	169
FC1-1.5	1.5	64	15.65	4090	152	199	30.54	4044	185
FC1*-0	0	64.5	15.26	4226	115	128	11.28	2610	-
FC1*-0.5	0.5	64.5	15.35	4203	143	176	23.04	3586	173
FC1*-1	1	64	15.28	4189	156	194	24.20	3942	191
FC1*-1.5	1.5	64.5	15.65	4122	172	214	24.60	4354	213
FC2-0	0	64	14.34	4464	123	137	11.61	2788	-
FC2-0.5	0.5	64.5	14.31	4508	152	182	19.70	3708	185
FC2-1	1	64	14.60	4383	160	198	23.82	4019	196
FC2-1.5	1.5	64	15.04	4255	171	214	24.85	4344	212
FC2*-0	0	64.5	14.75	4372	134	147	9.72	2986	-
RC2*-0.5	0.5	64	14.90	4296	168	199	18.63	4049	207
FC2*-1	1	64.5	15.15	4257	176	213	21.51	4339	218
FC2*-1.5	1.5	64.5	15.49	4165	183	223	22.16	4542	228

1µs= 10^{-6} seconds; impact toughness (T) in Nm or Joules; predicted N2= predicted failure strength at 28 days in number of blows. (1 in = 25.4 mm; 1 ft. lb = 1.356 Nm; 1 ft/sec = 0.3048 m/sec; % = percentage)

2.2.3. Impact resistance

The impact resistance (strength) test was carried out by using drop weight method recommended by ACI Committee 544-1989) [41]. The drop-weight test equipment was fabricated according to ASTM standards and the view of the impact test set-up is shown in Fig. 1.

Fig. 1 Disc specimen under drop weight impact test

The 150 Ø x 64 mm [5.91 x 2.52 in.] thick disc specimens were cast for this testing. The mass and drop height of the manually operated falling hammer are 4.54 kg and 457 mm (ASTM D1557), respectively. The number of blows to the first visible cracks on the top surface of the disc is defined as the first-crack strength, while the number of blows to generate the 3-lug toughing action of the disc is the failure strength. Figs. 2(a) and (b) show the failure pattern of disc specimens after ultimate failure. The impact performance is expressed by four indices: (1) the number of blows at first crack (N_1), (2) the number of blows at ultimate failure (N_2), (3) percentage increase in the number of post-first crack blows (PINPB), and (4) the impact toughness (T).

Fig. 2a Non-fibrous (silica fume) concrete disc specimens after failure

Fig. 2b Steel fibrous concrete disc specimens after failure

3. Results and Discussion

3.1. Mechanical properties

The average 28-day compressive and flexural strengths obtained are given in Table 3. The 28-day compressive strength of HPSFRC obtained is varying from 60-83 MPa depending upon the w/cm ratio, silica fume replacement and steel fiber content. Compressive strength gain of silica fume concrete (HPC) obtained at 10% and 15% SF replacement are 16.65% and 25.63%, respectively to that of plain concrete [12]. This strength improvement reveals that SF can be effectively used to enhance the performance characteristics of concrete. Maximum increase in strength obtained is about 13% at 1.5% fiber volume fraction. Cube compressive strength of HPSFRC at 56 days obtained is presented in Table 5. The improvement in flexural strength with increasing the fiber content from 0 to 1.5% in concrete matrix varies from 16 to 38% of that of reference concrete. It is observed from the test results that there is a significant improvement in flexural strength due to fiber-matrix bond in tension.

Table 5 56-day compressive strength and impact resistance, PINPB and toughness of high-performance steel fiber reinforced concrete

Mix Designation	V_f (%)	f_{cf} MPa	Impact resistance		PINPB	T
			Number of blows			
			at first crack, N_1	at failure, N_2		(Nm)
FC1-0	0	66.74	109	117	7.34	2381
FC1-0.5	0.5	71.81	140	165	17.86	3357
FC1-1	1	74.46	156	184	17.95	3744
FC1-1.5	1.5	75.28	167	204	22.16	4151
FC1*-0	0	71.58	124	131	5.65	2665
FC1*-0.5	0.5	77.29	157	176	12.10	3581
FC1*-1	1	79.88	173	202	16.76	4110
FC1*-1.5	1.5	84.09	190	225	18.42	4578
FC2-0	0	79.63	130	138	6.15	2808
FC2-0.5	0.5	85.36	163	182	11.66	3703
FC2-1	1	86.84	175	205	17.14	4171
FC2-1.5	1.5	87.79	188	227	20.74	4619
FC2*-0	0	83.80	142	149	4.93	3032
RC2*-0.5	0.5	90.62	178	200	12.36	4069
FC2*-1	1	92.32	189	216	14.29	4395
FC2*-1.5	1.5	92.98	198	234	18.18	4761

1µs= 10^{-6} seconds; impact toughness (T) in Nm or Joules; (1 in = 25.4 mm;
1MPa = 145 psi ; 1 ft. lb = 1.356 Nm; 1 blow = 20.347 Nm or Joules)

3.2. Impact resistance

The impact resistance performance of silica fume concrete (HPC), steel fiber reinforced concrete (SFRC), percentage increase in the number of post-first crack blows (PINPB) and impact toughness at 28 days and 56 days are presented in Tables 4 and 5, respectively. It is found that the behavior indices of HPSFRC with addition of crimped fibers (V_f = 0.5 to 1.5%) are higher compared to silica fume concrete (HPC). The variation in number of blows at first crack and number of blows at ultimate failure at different fiber volume fractions of HPSFRC are shown in Figs. 3 & 5 and Figs. 4 & 6, respectively. The initiation and propagation of cracks during the dynamic loading were restrained by the effect of steel fibers. At the crack tip, the extension of the crack is restrained; extent of stress concentration has reduced and delayed the growth rate of crack. HPSFRC can still withstand impact stress and absorb higher energy without leading to damage after first cracking due to ductility effect and bonding of fibers with matrix. The final failure (damage) pattern of SFRC is observed to be multiple cracking without complete rupture. A statistical analysis of the generated test data was also conducted for the effects of fibers on the impact resistance of concrete, considering the variations obtained in the test results, and revealed that fibers at V_f = 0.5-1.5% significantly improved the impact resistance of concrete; a positive interaction was also found between the fibers and pozzolan.

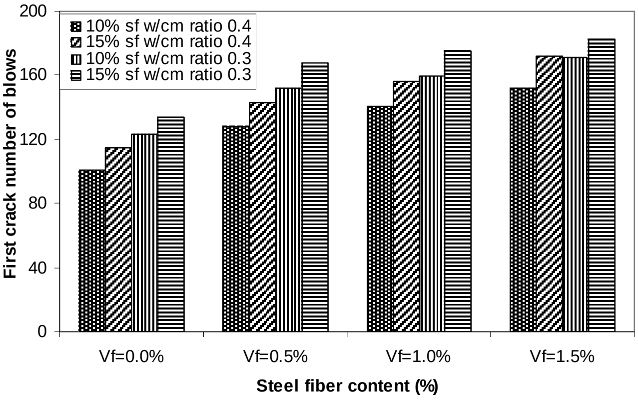

Fig. 3 Impact (first crack) characteristics at 28 days of HPSFRC (w/cm = 0.4 & 0.3)

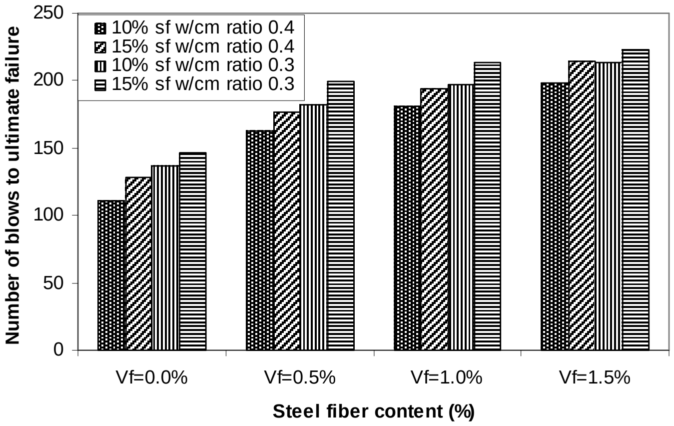

Fig. 4 Impact (ultimate failure) characteristics at 28days of HPSFRC (w/cm = 0.4 & 0.3)

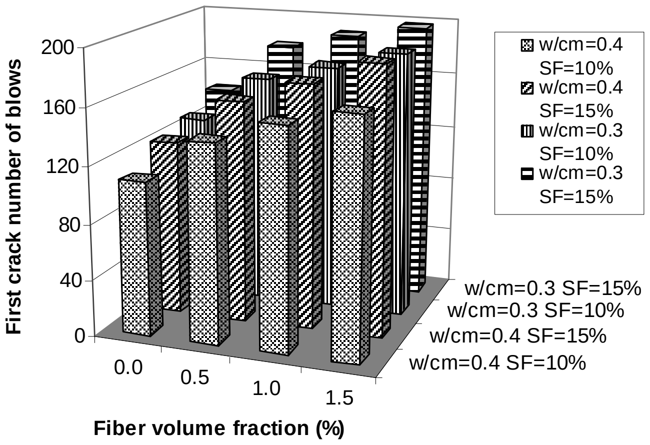

Fig. 5 Impact (first crack) characteristics at 56 days of HPSFRC (w/cm = 0.4& 0.3)

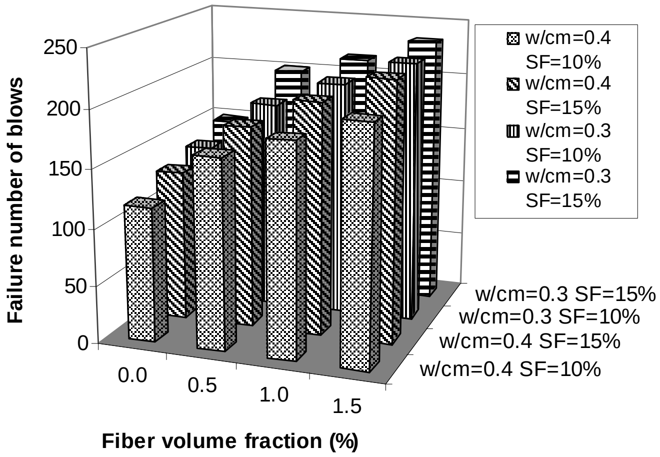

Fig. 6 Impact (ultimate failure) characteristics at 56 days of HPSFRC (w/cm = 0.4& 0.3)

The maximum first crack strength at 28 days of the V_f=1% and 1.5% concrete (HPSFRC) at 10% SF replacement for w/cm = 0.4 was about 1.39 times and 1.51 times, respectively to that of silica fume concrete (HPC) and of V_f = 1% and 1.5% concrete at 15% SF replacement was about 1.36 times and 1.49 times following mean values of the impact strength given in Table 4. The ultimate failure strength of V_f = 1% and 1.5% concrete at 10% SF replacement for w/cm = 0.4 was approximately 1.62 times and 1.78 times, respectively to that of HPC and of V_f = 1% and 1.5% concrete at 15% SF replacement was about 1.51 times and 1.67 times following mean values of the impact strength given in Table 4. This is because of steel fibers provided three-dimensional reinforcement, and fiber-matrix bond which assisted the discs in absorbing the impact energy of repeated blows.

The maximum first crack strength at 56 days of the V_f=1% and 1.5% concrete at 10% SF replacement for w/cm = 0.4 was about 1.43 times and 1.53 times, respectively to that of HPC and of V_f = 1% and 1.5% concrete at 15% SF replacement was about 1.39 times and 1.53 times following mean values of impact strength given in Table 5. The ultimate failure strength at 56 days of V_f = 1% and 1.5% concrete at 10% SF replacement for w/cm= 0.4 was approximately 1.57 times and 1.74 times to that of HPC and of V_f = 1% and 1.5% concrete at 15% SF replacement was about 1.54 times and 1.72 times following mean values of impact strength given in Table 5. This is because of pozzolanic reaction after 28 days and steel fibers provided three-dimensional reinforcement.

The substantial improvement in the impact resistance in the form of energy absorption after the initiation of first crack and up to the ultimate failure was observed for all the SFRC specimens at higher fiber content. However, the residual impact strength ratio (I_{rs}) was found to be different. Residual impact strength ratio (I_{rs}) (defined as the ratio of energy at ultimate failure to the energy at first crack) for the SFRC is about 1.3 (varies from 1.11 to 1.31) and Crack resistance factor (C_r) (defined as the ratio of kinetic energy at ultimate failure to the compressive strength of reference concrete) for SFRC is about 71.2 (varies from 43.17 to 71.2), are observed for concrete mix with V_f = 1.5%. Where, Energy at first-crack = 20.347 N_1, Nm or Joules; Energy at ultimate failure = 20.347 N_2, Nm or Joules; Energy for 1 blow = 20.347 Joules.

3.3. Percentage increase in the number of post-first crack blows (PINPB)

PINPB describes the potential of a crack-bearing as it retains the residual impact withstanding capacity. Compared to silica fume concrete (HPC), the maximum PINPB (at 28 days) of HPSFRC has increased by 144 %, 165 % and 179 %, respectively for V_f = 0.5, 1 and 1.5% at 10% SF content, and the maximum PINPB (at 56 days) has increased by 151%, 179% and 258%, respectively for V_f = 0.5, 1 and 1.5% at 15% SF content. Variations in other results such as thickness of discs, transit times, and pulse velocity are marginal and within the acceptable limits. Substantial improvement in the impact characteristics after the initiation of first cracks and up to the ultimate failure was observed for all the SFRC discs at V_f = 1.5%. The residual impact strength (PINPB) at 28 days is varying from 18.6 to 30.54, which could be attributed to the increase of steel fiber content (Table 4). The PINPB value of 10 for SFRC (with cylinder compressive strength = 76MPa at V_f = 1.0% and SF = 5%) was obtained by Song et al. 2005 [9] and the PINPB value of 30 obtained with cube compressive strength of 50.7 MPa at V_f = 1%) by Nataraja et al. 2005 [14], are comparable with the maximum PINPB value of 30.54 obtained in the present investigation, and is 2.84 times that of silica fume concrete (reference concrete). This improvement reveals that there is a significant effect on impact resistance performance of HPSFRC.

3.4. Failure impact strength prediction

Based on the experimental results, using least-squares regression analysis, the relationship between 28-day ultimate failure resistance and first crack strength of HPSFRC with correlation coefficient (R) = 0.96 obtained, is given as:

$$N_2 = 1.086 N_1 + 24.312 \tag{1}$$

where, N_1= number of blows at first crack at 28 days and N_2 = predicted number of blows at ultimate failure at 28 days [kinetic energy for1 blow = 20.35 Nm or Joules or 15.02 ft.lb].

The linear relationship between the two strengths was remarkably strong with R = 0.96. The absolute variation for the estimated failure strength was found to be 1.82%, which shows higher accuracy in the relationship obtained. The failure to first crack resistance relation for HPC was also remarkably strong. In order to further evaluate the deviation between experimental data points and predicted values, integral absolute error (IAE) is assessed, which is written as:

$$IAE = \frac{\Sigma(Q-P)}{\Sigma Q} x 100\ \% \tag{2}$$

Where, Q is the ultimate failure resistance (UFR) in number of blows and P is the predicted value in number of blows. The model is validated with the test data of previous researchers [6, 7, 9, 13, 14, 16], in which the integral absolute error (IAE) obtained is 10.49 indicating that the prediction model performs very well with the data of earlier researchers.

4. Conclusions

Based on the experimental study, the following conclusions are drawn.

1. Addition of steel fibers to silica fume concrete significantly enhances modulus of rupture and toughness, and resists cracking in high-performance concrete, and restrains damage during the process of impact by complemental mechanisms.
2. The maximum first crack impact strength of HPSFRC at 28 days was about 1.51 times that of silica fume concrete, the failure strength about 1.78 times, PINPB about 1.79 times. The impact indices of HPSFRC could be increased by about two times compared with those of HPC.
3. The empirical expression for the prediction of ultimate failure strength of HPSFRC was developed and the absolute variation obtained is less than 2%, which shows higher accuracy in the relationship obtained, and the model was validated with the experimental data of previous researchers.
4. Residual impact strength ratio and crack resistance factor of HPSFRC at 28-day obtained are about 1.3 and 71.2, respectively, and at 56-day the values are 1.2 and 55, respectively.
5. Silica fume and steel fibers have the synergistic effect that brings the combined effect of both the materials into play in concrete matrix. Therefore, every performance is enhanced considerably.

Acknowledgement: The author would like to record his thanks to the Structural Engineering Division of Anna University, Chennai for the facility extended to partly carry out the research work.

Notations

HPC= high-performance concrete (reference concrete)

HPSFRC= high-performance steel fiber reinforced concrete

f_{cf} = cube compressive strength of HPSFRC, MPa or N/mm^2

f'_{cf} = cylinder compressive strength of HPSFRC, MPa or N/mm^2

f_{rf} = flexural strength (modulus of rupture) of HPSFRC, MPa or N/mm^2

V_f = volume fraction of fiber, percent

l/d = aspect ratio of fiber

RI = fiber reinforcing index

T = impact toughness, Nm or Joules

I_{rs} = residual impact strength ratio

C_r = crack resistance factor

PINPB = percentage increase in the number of post-first crack blows

IAE = integral absolute error

References

[1] ACI 544.4R- 89, Design considerations for steel fiber reinforced concrete, American Concrete Institute, Detroit, 2006.

[2] Balaguru N, Sha SP. Fiber Reinforced Concrete Composites, McGraw Hill international edition, New York, 1992.

[3] ACI 544.1R- 96, State-of-the-art report on fiber reinforced concrete, American Concrete Institute, Detroit, 2006.

[4] ACI 544.3R- 93, Guide for specifying, mixing, placing and finishing steel fiber reinforced concrete, American Concrete Institute, Detroit, 2006.

[5] Ezeldin AS, Balaguru PN. Bond behavior of Normal and high strength fiber reinforced concrete, ACI Materials Journal, 1989, No. 5, Vol. 86, pp. 515-523.

[6] Song PS, Hwang S, Sheu BC. Statistical evaluation for impact resistance of steel fiber reinforced concrete, Magazine of Concrete Research, 2004, No. 8, Vol. 56, pp. 437-442.

[7] Yan H, Sun W, Chen H. The effect of silica fume and steel fibers on the dynamic mechanical performance of high-strength concrete, Cement and Concrete Research, 1999, Vol. 29, pp. 423-426.

[8] Gopalaratnan VS, Shah SP. Properties of fiber reinforced concrete subjected to impact loading, ACI Journal, 1986, No. 1, Vol. 83, pp. 117-126.

[9] Song PS, Wu JC, Sheu BC. Assessment of statistical variations in impact resistance of high-strength concrete and high-strength steel fiber reinforced concrete, Cement and Concrete Research, 2005, No. 2, Vol. 35, pp. 393-399.

[10] Song PS, Hwang S, Sheu BC. Strength properties of nylon and polypropylene fiber reinforced concrete, Cement and Concrete Research, 2005, Vol. 35, pp. 1546-1550.

[11] Soroushian P, Khan A, Hsu J. Mechanical properties of concrete materials reinforced with polypropylene or polyethylene fibers, ACI Materials Journal, 1992, No. 6, Vol. 89, pp. 535- 540.

[12] Ramadoss P. Studies on high-performance steel fiber reinforced concrete under static and impact loads, Ph.D. Dissertation, Anna University-Chennai, Chennai, India, 2008.

[13] Nataraja MC, Dhang N, Gupta AP. Statistical variations in impact resistance of steel fiber reinforced concrete subjected to drop weight test, Cement and Concrete Research, 1999, No. 7, Vol. 29, pp. 989-995.

[14] Nataraja MC, Nagaraj TS, Basvaraja SB. Reproportioning of steel fiber reinforced concrete mixes and their impact resistance, Cement and Concrete Research, 2005, Vol. 35, pp. 2350-2359.

[15] Wang N, Mindess S, Ko K. Fiber reinforced concrete beams under impact loading, Cement and Concrete Research, 1996, No. 3, Vol. 26, pp. 363-376.

[16] Badr A, Ashour AP. Modified ACI drop weight impact test for concrete, ACI Materials Journal, 2005, No. 4, Vol. 102, pp. 249-255.

[17] Mindess S, Yan C. Perforation of plain and fiber reinforced concrete subjected to low-velocity impact loading, Cement and Concrete Research, 1993, Vol. 23, pp. 83-92.

[18] Gopalaratnan VS, Shah SP, John RA. Modified instrumental charpy test for cement based composites, Experimental mechanics, 1989, No. 2, Vol. 24, pp. 102-111.

[19] Balasubramanian K, Barathkumar BH, Gopalakrishnan S, Parameswaran VS. Impact resistance of steel fiber reinforced concrete, Indian Concrete Journal, 1996, Vol. 9, pp. 256-262.

[20] Ramakrishnan V, Coyal WV, Kulandaisamy V. Performance characteristics of fiber reinforced concrete with low fiber contents, ACI Materials Journal, 1981, No. 5, Vol. 78, pp. 388-394.

[21] Balaguru N, Ramakrishnan V. Mechanical properties of super plasticized fiber reinforced concrete developed for bridge decks and highway pavements-Concrete in transportation, SP-93, ACI, Detroit, 1986, pp. 563-584.

[22] Banthia NP, Mindess S. Impact behavior of concrete beams, RILEM, Materials Structure, 1987, Vol. 20, pp. 293-302.

[23] Mindess S,Vondran S. Properties of concrete reinforced with polypropylene fibers under impact loading, Cement and Concrete Research, 1988, Vol. 8, pp. 109-1215.

[24] Hippert AP, Hannant DJ. Impact resistance of fiber concrete, Trans. of road research lab, UK, DEDT Suppl, Rep, 1981, pp. 625-54.

[25] Robins PJ, Calderwood RW. Explosive testing of fiber reinforced concrete, Concrete, 1978, No. 1, Vol. 12, pp. 26-38.

[26] Sridhara S, Kumar S, Sinare MA. Fiber reinforced concrete, Indian Concrete Journal, 1971, Vol. 10, pp. 428-430.

[27] Luo Xin. Characteristics of high performance fiber reinforced concrete subject to high velocity impact, Cement and Concrete Research, 2000, Vol. 30, pp. 907-914.

[28] Ramasamy HS, Ahuja BM, Krishnamoorthy S. Behavior of concrete reinforced with jute, coir, and bamboo fibers, Int, Journal of cement compos Light Weight concrete, 1983, No. 1, Vol. 5, pp. 3-13.

[29] Kankam CM. Impact resistance of palm kernel fiber reinforced concrete pavement slab, Journal of Ferrocement, 1999, No. 4, Vol. 29, pp. 279-286.

[30] Suaris W, Shah SP. Properties of concrete subjected to impact, ASCE, Journal of Structural Engineering, 1983, No. 7, Vol. 109, pp. 1727-1741.

[31] Huges BP, Nourbakhsh F. Impact resistance of reinforced concrete beams with fiber reinforced in FRC-86: Developments of fiber reinforced cement and concrete, In: Swamy RN. et al, editors, RILEM Symposium, 2, paper No. 8.12, 1986.

[32] Alhozaimy AM, Soroushian A, Mirza F. Mechanical properties of polypropylene fiber reinforced concrete and the effect of pozzolanic materials, Cement and Concrete Composites, 1996, Vol. 18, pp. 85-92.

[33] Savastano Jr. H. The use of coir fibers as reinforcement to Portland cement mortars, In. Sobral H, editor, Proceedings of Second International Symposium on Vegetable plants and their fibers as Building materials, Salvodor Brazil, Sep. 17-21, London, Chapman and Hall, 1990, pp. 150-158.

[34] Shah SP, Gopalarathnan VS. Impact measurement for fiber cement composites in FRC-87: developments in fiber reinforced cement and concrete. In: Swamy RN, et al, editors, RILEM Symp, 1, paper No. 3.9, 1987.

[35] Wang ZL, Shi Z, Wang JG. On the strength and toughness properties of steel fiber reinforced concrete under static and dynamic compression, Composites Part B: Engineering, 2011, No. 53, Vol. 42, pp. 1285-1290.

[36] Tara R, Behnam K, Mohammad S. Statistical and experimental analysis on the behavior of fiber reinforced concrete subjected to drop weight test, Construction Build. Materials, 2011, Vol. 31, pp. 360-369.

[37] Bindiganavile V, N. Banthia N. Polymer and steel fiber reinforced cementitious composites under impact loading -part 2: Flexural toughness, ACI Materials Journal, 2001, No. 1, Vol. 98, pp. 17-24.

[38] Deng Z, Li J. Mechanical properties of concrete combined with steel and synthetic macro-fibers, Computers and Concrete, 2007, No. 3, Vol. 4, pp. 207-220.

[39] ACI 211.4R- 93, Guide for selecting proportions for High strength concrete with Portland cement and Fly ash, ACI Manual of concrete practice, 1999.

[40] IS: 13311 (Part 1). Methods of non-destructive testing of concrete: Part-1 Ultrasonic pulse velocity, Bureau of Indian standards, New Delhi, India, 1992.

[41] ACI 544.2R-89. Measurement of properties of fiber reinforced concrete, American Concrete Institute, Detroit, 2006.