Computers and Concrete, *Vol. 13, No. 2 (2014) 255-270*
DOI: http://dx.doi.org/10.12989/cac.2014.13.2.255

Performance and modeling of high-performance steel fiber reinforced concrete under impact loads

Ramadoss Perumal*

Department of Civil Engineering, Pondicherry Engineering College, Puducherry- 605014, India

(*Received March 17, 2013, Revised September 11, 2013, Accepted October 26, 2013*)

Abstract. Impact performance of high-performance concrete (HPC) and SFRC at 28-day and 56-day under the action of repeated dynamic loading was studied. Silica fume replacement at 10% and 15% by mass and crimped steel fiber (V_f = 0.5%- 1.5%) with aspect ratios of 80 and 53 were used in the concrete mixes. Results indicated that addition of fibers in HPC can effectively restrain the initiation and propagation of cracks under stress, and enhance the impact strengths and toughness of HPC. Variation of fiber aspect ratio has minor effect on improvement in impact strength. Based on the experimental data, failure resistance prediction models were developed with correlation coefficient (R) = 0.96 and the estimated absolute variation is 1.82% and on validation, the integral absolute error (IAE) determined is 10.49%. On analyzing the data collected, linear relationship for the prediction of failure resistance with R= 0.99 was obtained. IAE value of 10.26% for the model indicates better the reliability of model. Multiple linear regression model was developed to predict the ultimate failure resistance with multiple R= 0.96 and absolute variation obtained is 4.9%.

Keywords: fiber reinforcement; high-performance steel fiber reinforced concrete; mechanical properties; impact resistance; toughness; modeling

1. Introduction

Steel fiber reinforced concrete (SFRC) has gained popularity in various applications, namely industrial floors, bridge decks, pavement and overlays, marine structures, nuclear vessels, repair and rehabilitation works, blast and penetration resistance structures (Balaguru and Shah 1992, ACI Committee 544-96, ACI Committee 544-93). The acceptance rests primarily on the impact resistance (Balaguru and Shah 1992). 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 (Balaguru and Shah 1992, ACI Committee 544-89).

The adoption of high-performance concrete in the design of structural components reduces the

*Corresponding author, Associate Professor, E-mail: dosspr@gmail.com.

http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

section size and increases the capacity of 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 and energy absorption capacity of NSC and HSC, particularly concrete containing silica fume (Ezeldin and Balaguru 1989, Ramdoss and Nagamani 2013, Farhad Aslani and Natoori 2013), and can effectively restrain the cracks under stress, and improve the toughness of HSC (Song *et al*. 2004). Yan *et al*. (1999) have observed that silica fume effectively improved the structure of the interfacial zone, reduced the width of cracks, and enhanced the ability of steel fibers to 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. (Gopalaratnan and Shah 1986, Song *et al*. 2005).

Several researchers 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 (Song *et al*. 2004, Yan *et al*. 1999, Gopalaratnan and Shah 1986, Song *et al*. 2005, Song *et al*. 2005, Soroushian *et al*. 1992, Ramadoss 2008, Nataraja *et al*. 1999, Nataraja *et al*. 2005, Wang *et al*. 1996, Badr and Ashour 2005, Mindess and Yan 1993, Gopalaratnan *et al*. 1984, Balasubramanian *et al*. 1996, Ramakrishnan *et al*. 1981, Balaguru and Ramakrishnan 1986, Banthia and Mindess 1987, Mindess and Vondran 1988, Hippert and Hannant 1981, Robins and Calderwood 1978, Sridhara *et al*. 1971, Luo Xin 2000, Ramasamy *et al*. 1983, Kankam 1999, Huges and Nourbakhsh 1986, Alhozaimy *et al*. 1996, Savastano Jr 1990, Shah and Gopalaratnan 1987, Suaris and shah 1983, Bindiganavile and Banthia 2001, Deng and Li 2007, Mohammadi *et al*. 2009, Mahmoud Nili and Afroughsabet 2010, Tara *et al*. 2011, Wang *et al*. 2011). Rather, the method is designed to assess the relative performance of plain concrete matrix and fiber reinforced concrete. Moreover, from the literature review, 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 mere on NSC/ HSC and SFRC.

The main aim of this paper is (i) to study the impact performance of silica fume concrete (HPC) under dynamic (repeated impact) loading with the addition of crimped fibers at different volume fractions with aspect ratios of 80 and 53, (ii) to develop the empirical relation on correlation of data for failure impact resistance, (iii) to develop multiple linear regression (MLR) model for the assessment of ultimate failure resistance as function of influencing variables (V_f %, SF% and w/cm). To study the quality and uniformity of composite including fiber distribution, ultrasonic pulse velocity (UPV) test was conducted.

2. Research significance

Information on the influence of steel fibers in HPC on impact performance is insufficient, since most of the studies reported mere on HSC. The work reported herein, studies the influence of crimped steel fibers with varying aspect ratios in enhancing the impact performance of HPC and development of empirical expression on prediction of impact strength at ultimate failure at 28 days and 56 days, and to confirm the necessity to develop empirical relationship on the correlation of data of researchers for ultimate failure resistance. Multiple linear regression (MLR) model for the assessment of ultimate failure resistance of HPSFRC as function of three influencing variables (V_f%, SF% and w/cm) has been developed.

3. Experimental details

3.1 Materials and mixture proportions

Ordinary Portland cement - 53 grade having 28-day compressive strength of 56.5 MPa complying with IS: 12269-1987, and condensed silica fume having a specific gravity of 2.25 complying with ASTM C1240-1999 were used. Chemical composition of cementitious materials is

Table 1 Chemical composition of cementitious materials (in percentage)

Chemical composition	Ca O	SiO_2	AlO_3	Fe_2O_3	Mg O	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

Table 2 Mix proportions and static mechanical properties of HPSFRC

Mix Designation	W/Cm	Cement	Silica fume	Sand ratio	Steel fiber	SP	Compressive strength (MPa)		Flexural strength
		Kg/m^3	Kg/m^3	(%)	V_f(%)	Kg/m^3	f_{cf}	f'_{cf}	(MPa)
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, the value after hyphen indicates fiber volume fraction (%). 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(%) denotes Steel fiber volume fraction in percent 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)
listed in Table 1. Fine aggregate of river sand conforming to grading zone-II of IS: 383-1978, has a specific gravity of 2.63. Coarse aggregate of crushed granite stones with maximum size of 12.5 mm 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 Impact strength = 11.8%; Crushing strength = 14.47%; and Abrasion value = 12.5%. Super-plasticizer of sulphonated naphthalene formaldehyde condensate as high range water reducing admixture conforming to ASTM Type F (ASTM C494) was used. Crimped steel fibers of length = 36 & 24 mm, diameter = 0.45 mm and aspect ratio = 80 & 53, having an ultimate tensile strength (f_u) = 910 MPa was used.

Mixtures were proportioned using guidelines and specifications given in ACI Committee 211-93, and recommended guidelines of ACI Committee 544-93. Mixture proportions used in this test programme are summarized in Table 2. For each water-cementitious materials ratio, 3 fibrous concrete mixes were prepared, 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). Super-plasticizer with dosage range of 1.75 to 2.5% has been used in the concrete mixes. Sixteen series of HPSFRC mixes with two w/cm ratios were used in this investigation. For each mix at least six 150Ø × 64 mm [5.91 × 2.52 in.] discs, three 150Ø [5.91 in.] cylinders, three 150 mm [5.91 in.] side cubes and three 100 × 100 × 500 mm [3.94 × 3.94 × 19.69 in.] prisms were produced. Specimens were cast and cured at 27 ± 2^{o}C in water until the testing age of 28 days and 56 days.

3.1 Test methods

3.1.1 Compressive strength

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.

3.1.2 Flexural strength

The flexural strength (modulus of rupture) tests were conducted as per the specifications of ASTM C 78-1994 using 100 × 100 × 500 mm prisms under third- point loading on a simply supported span of 400 mm The tests were conducted in a 100 kN [22.48 kpi] 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 flexural tensile strength.

3.1.3 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 IS: 13311(Part 1)-1992. Pulse velocity is measured using Ultrasonic concrete tester. The variation in pulse velocity is marginal, which indicates the uniformity of the composites (Table 3). 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 3. From the UPV measurements, it is found that all the concrete specimens can be classified under good quality.

Table 3 28-day impact resistance, UPV test results, PINPB values and toughness, and predicted failure strength for high-performance steel fiber reinforced concrete

Mix designation	V_f	Average thick	Ultrasonic Pulse velocity (UPV)		Impact resistance Number of blows		I_{rs}	C_r	PINPB	T	Predicted by Eq. (3)
	(%)	(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	1.11	43.17	10.95	2269	-
FC1-0.5	0.5	64.5	14.80	4358	128	162	1.27	60.27	26.76	3301	152
FC1-1	1	64	14.46	4527	140	181	1.29	65.66	29.06	3683	169
FC1-1.5	1.5	64	15.65	4090	152	199	1.31	70.45	30.54	4044	185
FC1*-0	0	64.5	15.26	4226	115	128	1.13	46.84	11.28	2610	-
FC1*-0.5	0.5	64.5	15.35	4203	143	176	1.23	61.12	23.04	3586	173
FC1*-1	1	64	15.28	4189	156	194	1.24	65.47	24.20	3942	191
FC1*-1.5	1.5	64.5	15.65	4122	172	214	1.25	71.18	24.60	4354	213
FC2-0	0	64	14.34	4464	123	137	1.20	46.66	11.61	2788	-
FC2-0.5	0.5	64.5	14.31	4508	152	182	1.21	55.24	19.70	3708	185
FC2-1	1	64	14.60	4383	160	198	1.24	58.32	23.82	4019	196
FC2-1.5	1.5	64	15.04	4255	171	214	1.25	62.35	24.85	4344	212
FC2*-0	0	64.5	14.75	4372	134	147	1.10	46.46	9.72	2986	-
RC2*-0.5	0.5	64	14.90	4296	168	199	1.18	59.74	18.63	4049	207
FC2*-1	1	64.5	15.15	4257	176	213	1.20	62.22	21.51	4339	218
FC2*-1.5	1.5	64.5	15.49	4165	183	223	1.22	64.59	22.16	4542	228

1μs= 10^{-6} seconds; impact toughness (T) in Nm or Joules; predicted N_2= 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)

3.1.4 Impact resistance

The impact resistance (strength) test was carried out by using drop weight method recommended by ACI Committee 544-89 (ACI 544.2R-1989). 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. The mass and drop height of the manually operated falling hammer are 4.54 kg and 457 mm, respectively. The 150Ø × 64 mm thick disc specimens were cast for this testing. 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. Fig. 2 shows 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. 1(a) Close-up view of the impact test set up

Fig. 1(b) Disc specimen under drop weight impact test

Fig. 2(a) Silica fume concrete (HPC) disc specimens after failure

Fig. 2(b) steel fibrous concrete disc specimens after failure

4. Results and discussion

4.1 Mechanical properties

The average 28-day cube/ cylinder compressive and flexural strengths obtained are given in Table 2. 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 (Ramadoss 2008). This strength improvement reveals that SF can be effectively used to enhance the performance characteristics of concrete. Maximum increase in 28-day cube compressive strength obtained is about 13% at 1.5% fiber volume fraction. The improvement in flexural strength with increasing the fiber content from 0.5% 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 or fiber pullout effect. The 28-day cylinder compressive strength of HPSFRC (with fiber aspect ratio = 53) obtained is varying from 52.6-70.8 MPa, and is presented in Table 4. Cube compressive strength of HPSFRC at 56 days obtained is presented in Table 5.

Table 4 28-day compressive (150 mm Ø cylinder) strength and impact resistance of HPSFRC – fiber aspect ratio = 53

Mix designation	w/cm	V_f	RI (Reinforcing index)	150dia × 300 mm cylinder	Impact resistance	
				Experimental value	at first crack	at failure
		%	l/d = 53	f_c, MPa	N_1	N_2
FC1-0	0.4	0	0	52.56	101	112
FC1-0.5	0.4	0.5	0.86	55.21	132	168
FC1-1	0.4	1	1.71	55.75	144	189
FC1-1.5	0.4	1.5	2.57	58.46	156	211
FC1*-0	0.4	0	0	55.7	115	128
FC1*-0.5	0.4	0.5	1.71	60.83	146	183
FC1*-1	0.4	1	2.57	61.85	161	200
FC1*-1.5	0.3	1.5	0	63.87	177	221
FC2-0	0.3	0	0.86	63.86	123	137
FC2-1	0.3	1	1.71	65.4	164	206
FC2-1.5	0.3	1.5	2.57	67.09	176	222
FC2*-0	0.3	0	0	64.27	134	147
FC2*-1	0.3	1	1.71	67.95	181	220
FC2*-1.5	0.3	1.5	2.57	70.83	188	231

Table 5 56-day compressive strength, impact resistance results and toughness, and predicted failure strength for high-performance steel fiber reinforced concrete

Mix designa-tion	V_f	f_{cf}	Impact resistance		I_{rs}	C_r	PINP B	T	Predicted by eq.(4)	Error
			Number of blows							
	(%)	(MPa)	at first crack, N_1	at failure, N_2				(Nm)	N_2	(%)
FC1-0	0	66.74	109	117	1.07	35.68	7.34	2381	-	-
FC1-0.5	0.5	71.81	140	165	1.18	46.75	17.86	3357	167.02	1.22
FC1-1	1	74.46	156	184	1.18	50.28	17.95	3744	184.03	0.02
FC1-1.5	1.5	75.28	167	204	1.22	55.14	22.16	4151	195.72	-4.06
FC1*-0	0	71.58	124	131	1.06	37.23	5.65	2665	-	-
FC1*-0.5	0.5	77.29	157	176	1.12	46.33	12.10	3581	185.09	5.17
FC1*-1	1	79.88	173	202	1.17	51.45	16.76	4110	202.10	0.05
FC1*-1.5	1.5	84.09	190	225	1.18	54.44	18.42	4578	220.17	-2.15
FC2-0	0	79.63	130	138	1.06	35.26	6.15	2808	-	-
FC2-0.5	0.5	85.36	163	182	1.12	43.38	11.66	3703	191.47	5.20
FC2-1	1	86.84	175	205	1.17	48.03	17.14	4171	204.23	-0.38
FC2-1.5	1.5	87.79	188	227	1.21	52.61	20.74	4619	218.04	-3.95
FC2*-0	0	83.80	142	149	1.05	36.18	4.93	3032	-	-
RC2*-0.5	0.5	90.62	178	200	1.12	44.90	12.36	4069	207.41	3.71
FC2*-1	1	92.32	189	216	1.14	47.61	14.29	4395	219.11	1.44
FC2*-1.5	1.5	92.98	198	234	1.18	51.20	18.18	4761	228.67	-2.28

f_{cf} = cube compressive strength at 56 days, MPa

1μs = 10^{-6} seconds; impact toughness (T) in Nm or Joules; predicted N_2= predicted failure strength at 56 days in number of blows.

(1 in = 25.4 mm; 1MPa = 145 psi ; 1 ft. lb = 1.356 Nm; %= percentage; 1 blow = 20.347 Nm or Joules)

4.2 Impact resistance

The impact resistance performance of silica fume concrete (HPC) and steel fiber reinforced concrete (impact resistance, percentage increase in the number of post-first crack blows (PINPB) and impact toughness (*T*)) at 28 days and 56 days are presented in Tables 3 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 reference silica fume concrete. The difference between N_2 and N_1 was increased by 47 at 28 days and 39 at 56 days for HPSFRC, indicating greater ability of HPSFRC to attain higher impact toughness. 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 and 4, 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 was restrained; extent of stress concentration has reduced and delayed the growth rate of crack. This indicates that HPSFRC could absorb high 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. It is revealed that the failure mode of concrete considerably changes from fragile to ductile with the increase of steel fibers.

The impact strength results of drop-weight tests found to exhibit moderate variability with different type of mixes and fiber volume fractions. Previous researchers (Song *et al*. 2004, Yan *et al*. 1999, Gopalaratnan and Shah 1986, Song *et al*. 2005, Song *et al*. 2005, Nataraja *et al*. 1999, Badr and Ashour 2005, Balasubramanian *et al.* 1996) have also observed the results exhibit variability. A statistical analysis of the generated test data was also conducted. Analysis of variance of the data revealed that steel fibers at V_f= 0.5%, 1.0% and 1.5% significantly improved the first crack and failure impact resistance of concrete at 95% (or higher) confidence level; a positive interaction was also found between the fibers and pozzolan.

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 that of silica fume concrete (HPC) and of V_f = 1% and1.5% concrete at 15% SF replacement was about 1.36 times and 1.49 times following mean values of the strength given in Table 3. 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 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 3. 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. There was a marginal improvement in impact strength both at first crack (N_1) and ultimate failure (N_2) for HPSFRC with fiber aspect ratio of 53 compared to that with fiber aspect ratio of 80. This improvement in impact strength is mainly attributed to the improvement in compressive strength of fibrous concrete with fiber aspect ratio = 53. This is because of number of fibers in the same volume fraction of concrete is increased considerable as aspect ratio (l/d) decreases from 80 to 53 when the disc is subjected to dynamic compression. The difference between N_2 and N_1 for both the fibrous concretes having aspect ratio of 80 and 53 is closer to each other. Therefore, it is observed that variation in (l/d) has little effect in improving the impact performance of HPSFRC.

The ultimate failure strength at 56 days of HPSFRC with 10% and 15% SF replacement for w/cm = 0.4 and 0.3 is given in Table 5. 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 V_f = 1% and 1.5% concrete at 15% SF replacement was about 1.39 times and 1.53 times following mean values of the strength given in Table 5. This improvement in impact strength is due to pozzolanic reaction after 28 days.

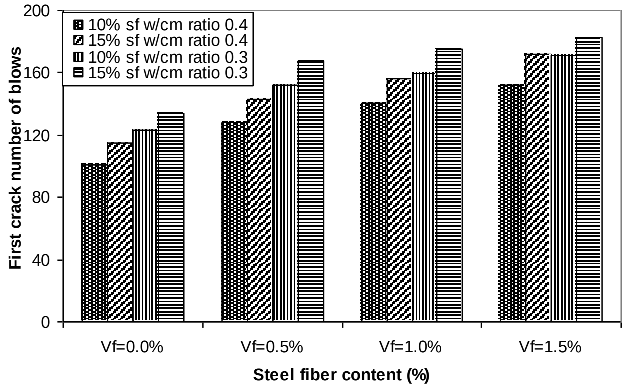

Fig. 3 Impact (first crack) characteristics at 28 days of HPSFRC (w/cm = 0.4 & 0.3)

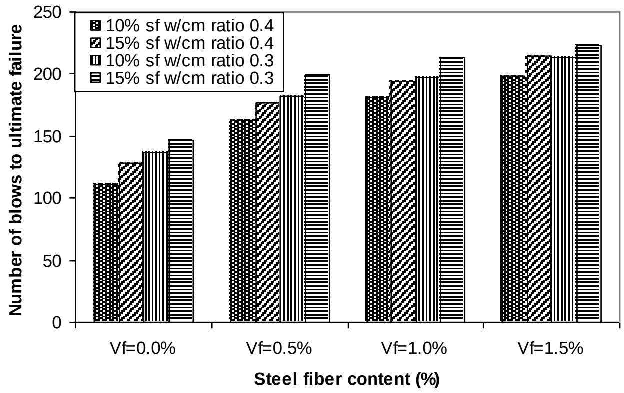

Fig. 4 Impact (ultimate failure) characteristics at 28days of HPSFRC (w/cm = 0.4 & 0.3)

4.3 Residual impact strength ratio and crack resistance factor

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 in Eq. (1) for the HPSFRC is about 1.3, and Crack resistance factor (C_r) defined as in Eq. (2) for SFRC is about 71.2, are observed for concrete mix with 1.5% fiber volume fraction.

$$\text{Residual impact strength ratio}\,(I_{rs}) = \frac{\text{Energy at ultimate failure}}{\text{Energy at first crack}} \tag{1}$$

$$\text{Crack resistance factor}\,(C_r) = \frac{\text{Kinetic energy at ultimate failure}}{\text{Compressive strength of reference concrete}} \tag{2}$$

where, Energy at first-crack = 20.347N_1, Nm or Joules; Energy at ultimate failure = 20.347 N_2, Nm or Joules; $N_1$and N_2 are the first-crack and failure-crack number of blows, respectively.

4.4 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. 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 18.5 to 30.54, which could be attributed to the increase of steel fiber content. The PINPB value of 10 for SFRC (with cylinder compressive strength = 76 MPa at V_f = 1%) was obtained by Song *et al*. (2005) and the value of 35 obtained (with cube compressive strength of 50.7 MPa at V_f = 1%) by Nataraja *et al*. (2005), are comparable with the maximum PINPB value of 31 at V_f = 1% obtained by the authors in the present study, and is 2.84 times that of the silica fume concrete (reference concrete) which is comparable with the value of 2.5 obtained by Nataraja *et al*. (2005). This improvement reveals that there is significant effects on impact resistance performance of HPSFRC as silica fume (SF = 10%) in concrete strengthen the transition zone by pozzolanic reaction and filler effect.

4.5 Failure impact strength prediction

Based on the experimental results, using least-squares regression analysis, the relationship between the 28-day ultimate failure resistance and first crack strength of HPSFRC with correlation coefficient (R) = 0.96 obtained (refer Fig. 5), is given as

$$N_2 = 1.086 N_1 + 24.312 \tag{3}$$

where, N_2 = predicted number of blows at ultimate failure at 28 days and N_1= number of blows at first crack at 28 days [kinetic energy for1 blow = 20.35 Nm. or Joules; 1 blow = 15.02 ft.lb].

The absolute variation for the estimated failure strength was found to be 1.82%, which shows higher accuracy in the relationship obtained. In order to further evaluate the deviation between experimental data points and predicted values, integral absolute error (IAE) is assessed, which is written as

$$IAE = \frac{\Sigma(Q-P)}{\Sigma Q} x 100 \ \% \tag{4}$$

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 experimental data of previous researchers (Song *et al*. 2004, Yan *et al*. 1999, Song *et al*. 2005, Nataraja *et al*. 1999, Nataraja *et al*. 2005, Badr and Ashour 2005, Song *et al*. 2005), in which the integral absolute error obtained is 10.49 indicating that the prediction model performs very well with the data of earlier researchers.

Based on the experimental results, using least-squares regression analysis, the relationship

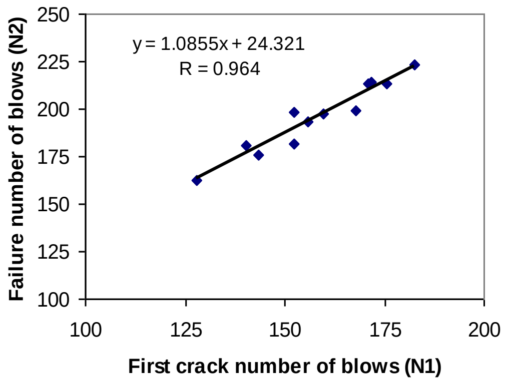

Fig. 5 Relationship between 28-day ultimate failure strength (N_2) and first crack strength (N_1)

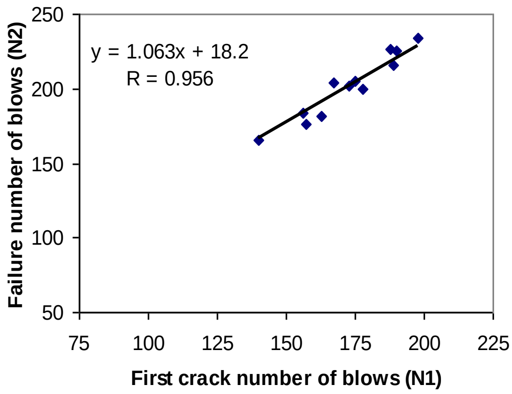

Fig. 6 Relationship between 56-day ultimate failure strength (N_2)) and first crack strength (N_1)

between 56-day ultimate failure resistance and first crack strength of SFRC with correlation coefficient (R) = 0.96 obtained (refer Fig. 6), is given as

$$N_2 = 1.063N_1 + 18.201 \tag{5}$$

where, N_2 = predicted number of blows at ultimate failure at 56 days; N_1= number of blows at first crack at 56 days.

The absolute variation for the estimated failure strength was found to be 2.47%, which shows good accuracy in the relationship obtained.

4.6 Correlation of first crack resistance and ultimate failure resistance of HPSFRC

Correlation between first crack resistance (N_1) and ultimate failure resistance (N_2) of SFRC on the experimental data (162 data points) of researchers (Song *et al*. 2004, Yan *et al*. 1999, Song *et al*. 2005, Nataraja *et al*. 1999, Nataraja *et al*. 2005, Badr and Ashour 2005, Song *et al*. 2005) and Authors, is analyzed by regression analysis, which is shown in Fig. 7, and the empirical relation obtained can be expressed as

$$N_2 = 1.1297N_1 + 49.76 \tag{6}$$

The developed model established the likely trends of failure impact strength through the measured first-crack strength. Coefficient of determination (R^2) of this relation (Eq. (6)) is 0.98 (coefficient of correlation, R = 0.99), indicating a strong correlation between the two resistance properties, and manifesting that the equation captured almost 100% of the experimentally observed (data set) failure resistance variability. IAE value calculated is 10.26%, which indicates that the variability of this proposed equation is low and the reliability of the model is good. This linear regression result is in good agreement with the empirical expression for 28-day failure resistance suggested by the authors for which the calculated IAE value is 10.49%.

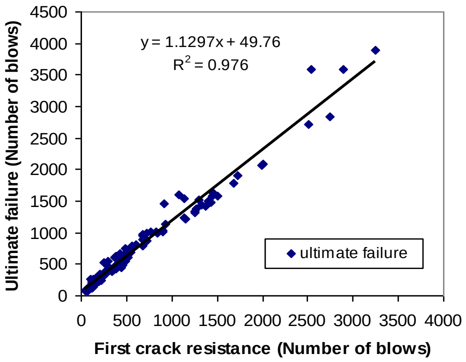

Fig. 7 Proposed correlation relation between ultimate failure resistance (N_2) and first-crack resistance (N_1)

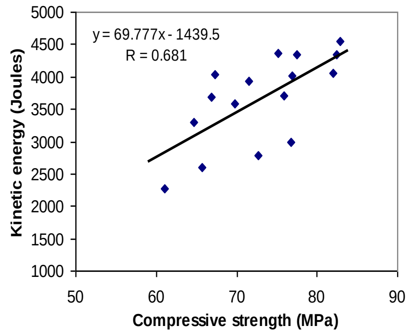

Fig. 8 Relation between kinetic energy (impact toughness) (joules) and 28-day compressive strength (MPa) of HPSFRC

4.7 Relation between impact toughness and 28-day compressive strength of HPSFRC

The linear relation between the failure impact strength (impact toughness) and 28-day cylinder compressive strength (MPa) of high-performance steel fiber reinforced concrete with correlation coefficient (R) = 0.681 has been obtained through regression analysis on test results as:

$$IT = 69.777\, f'_{cf} - 1439.5 \tag{7}$$

Table 6 Ratio of failure impact strength to 28-day compressive strength of HPSFRC

Mix designation	w/cm ratio	Silica fume replacement (%)	fiber content V_f (%)	Failure impact strength/ 28-day compressive strength (f'_{cf}) ratio	
				joules/ MPa	No. of blows/ MPa
FC1-0.0	0.40	10	0.0	37.17	1.83
FC1-0.5	0.40	10	0.5	50.99	2.51
FC1-1	0.40	10	1.0	55.09	2.71
FC1-1.5	0.40	10	1.5	60.02	2.95
FC1*-0	0.40	15	0.0	39.70	1.95
FC1*-0.5	0.40	15	0.5	51.41	2.53
FC1*-1	0.40	15	1.0	55.07	2.71
FC1*-1.5	0.40	15	1.5	57.94	2.85
FC2-0	0.3	10	0.0	38.32	1.88
FC2-0.5	0.3	10	0.5	48.88	2.40
FC2-1	0.3	10	1.0	52.22	2.57
FC2-1.5	0.3	10	1.5	56.06	2.76
FC2*-0	0.3	15	0.0	38.88	1.91
RC2*-0.5	0.3	15	0.5	49.39	2.43
FC2*-1	0.3	15	1.0	52.64	2.59
FC2*-1.5	0.3	15	1.5	54.81	2.69

f'_{cf} = cylinder compressive strength at 28 days
Statistical parameter for HPSFRC (with fiber only): Mean = 2.640; Standard deviation = 0.1665; coefficient of variation (CV) = 2.77%.
where, IT is the impact toughness (failure resistance) in joules and f'_{cf} = 28-day compressive strength in MPa. The empirical model developed (Eq. (7)) as shown in Fig. 8, can be used for the prediction of failure resistance as a function of 28-day cylinder compressive strength of HPSFRC.

Table 6 shows the ratio of failure impact strength to 28-day compressive strength (MPa) of HPSFRC. It is observed from the Table 6 that the two strength ratio values of steel fiber reinforced concrete at all fiber volume fractions (V_f = 0.5, 1.0, and 1.5%) are almost closure and impact strength is proportionate with compressive strength of HPSFRC; revealing similar trend with marginal variation of strength ratios with varying fiber content, as both the strengths, one is impact under dynamic compression and the other is compressive strength under static compression are related to each other. The statistical parameters obtained for the strength ratios of fibrous concrete are: Mean = 2.64; standard deviation = 0.1665; coefficient of variation (CV) = 2.77%.

4.8 Multiple linear regression model for the prediction of ultimate failure resistance

Multiple linear regression (MLR) model for the assessment of ultimate failure resistance (failure impact strength) (in joules) as function of three influencing variables (ie., V_f %, *SF*% and w/cm) is given as

$$FIS = f\left(V_f\,\%, SF\%, w/cm\right) \tag{8}$$

where, *FIS* is the failure impact strength in joules.

Multiple linear regression model was developed on analyzing the test data sets containing three parameters by using statistical methods as

$$FIS = 3465.9843 + 1061.8591\,(V_f\,\%) + 56.3358\,(SF\%) - 3732.403\,(w/cm) \tag{9}$$

The predicted values were also analyzed at significance level of 0.05 and absolute error range obtained is within ±5. The standard error of the estimate and absolute variation in percent obtained for the proposed MLR model are 19.13 and 4.93, respectively. It was found that the predictions provided by the proposed model are in good agreement with the experimental values and observed that MLR model predicts the values quite accurately.

5. Conclusions

1. Addition of steel fibers to silica fume concrete with 10% *SF* replacement significantly enhances the 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 with v_f = 1.5% and 10% SF replacement was about 1.51 times that of silica fume concrete, the failure strength about 1.78 times, PINPB about 1.79 times. Variation of aspect ratio of fiber has shown to have minor improvement on impact resistance.
3. The empirical expressions enabled the interval estimates for the number of blows to ultimate failure in the HPSFRC and the absolute variation is within 2.5%, which shows higher accuracy in the relationship obtained, and the model is validated with the experimental data of

previous researchers and the IAE value obtained is 10.49%.

4. Crack resistance factor of HPSFRC with 10% SF replacement and 1.5% fiber volume fraction at 28 days and 56 days were about 70.5 and 55, respectively.

5. Addition of Steel fibers in HPC improved the impact toughness significantly at 95% confidence level. On the average the addition of 0.5%, 1.0% and 1.5% volume fraction of fibers in HPC increased the impact toughness by 37%, 51% and 67%, respectively.

6. For HPSFRC, strong correlation was found between first crack resistance and failure resistance, where R and IAE values are 0.99 and 10.26, respectively.

7. The proposed MLR model is found to provide results in good correlation with the experimental results, where 95% of the estimated values are within ± 5% of the actual values.

References

ACI Committee 211- 93 (1999), Guide for selecting proportions for High strength concrete with Portland cement and Fly ash, ACI 211.4R-93, *ACI Manual of concrete practice*.

ACI Committee 544.2R- 89 (2006), Measurement of properties of fiber reinforced concrete, ACI 544.2R-89, *American Concrete Institute,* Detroit.

ACI Committee 544.4R-89 (2006), Design considerations for steel fiber reinforced concrete, ACI 544.4R-1989, *American Concrete Institute*, Detroit.

ACI Committee 544.3R-93 (2006), Guide for specifying, mixing, placing and finishing steel fiber reinforced concrete, ACI 544.3R-93, *American Concrete Institute*, Detroit.

ACI Committee 544-96 (2006), State-of-the-art report on fiber reinforced concrete, ACI 544.1R-96, *American Concrete Institute*, Detroit.

Alhozaimy, A.M., Soroushian, A. and Mirza F. (1996), "Mechanical properties of polypropylene fiber reinforced concrete and the effect of pozzolanic materials", *Cement Concrete Compos.,* **18**, 85-92.

ASTM C39-1992 (1999), Standard test method for compressive strength of fiber reinforced concrete, *Annual book of ASTM standards*, American Society for Testing and Materials.

ASTM C78-1992 (1992), Standard test method for flexural strength of fiber reinforced concrete, *Annual book of ASTM standards*, American society for testing and materials.

Badr, A. and Ashour, A.P. (2005), "Modified ACI drop weight impact test for concrete", *ACI Mater. J.*, **102**(4), 249-255.

Balaguru, N. and Ramakrishnan, V. (1986), "Mechanical properties of super plasticized fiber reinforced concrete developed for bridge decks and highway pavements", Concrete in transportation, SP-93, *American Concrete Institute*, p. 563-584.

Balaguru, N. and Shah, S.P. (1992), *Fiber reinforced concrete composites,* McGraw Hill International edition, New York.

Balasubramanian, K., Barathkumar, B.H., Gopalakrishnan, S. and Parameswaran, V.S. (1996), "Impact resistance of steel fiber reinforced concrete", *Indian Concrete J.,* **9**, 256-262.

Banthia, N.P. and Mindess, S. (1987), "Impact behavior of concrete beams", *Mater. Struct.,* **20**, 293- 302.

Bindiganavile, V. and Banthia, N. (2001), "Polymer and steel fiber reinforced cementitious composites under impact loading -part 2: Flexural toughness", *ACI Mater. J.,* **98**(1), 17-24.

Deng, Z. and Li. J. (2007), "Mechanical properties of concrete combined with steel and synthetic macro-fibers", *Comput. Concrete,* **4**(3), 207-220.

Ezeldin, A.S. and Balaguru, N. (1989) "Bond behavior of normal and high strength fiber reinforced concrete", *ACI Mater. J.,* **86**(5), 515-523.

Farhad, A. and Natoori, M. (2013), "Stress-strain relationships for steel fiber reinforced self compacting concrete", *Struct. Eng. Mech., **46***(2).

Gopalaratnan, V.S. and Shah, S.P. (1986), "Properties of fiber reinforced concrete subjected to impact

loading", *ACI Mater. J.*, **83**(1), 117-126.
Gopalaratnan, V.S., Shah, S.P. and John, R.A. (1984), "Modified instrumental charpy test for cement based composites", *Exper. Mech.*, **24**(2), 102-111.
Hippert, A.P. and Hannant, D.J. (1981), "Impact resistance of fiber concrete", *Trans. of road research laboratory (UK)*, DEDT Suppl. Rep., p. 625-54.
Huges, B.P. and Nourbakhsh, F. (1986), "Impact resistance of reinforced concrete beams with fiber reinforced in FRC-86", Developments of fiber reinforced cement and concrete, Swamy R.N. *et al*., editors, Proceedings RILEM Symp., 2, paper no.8.12.
IS: 12269-1987 (1999), *Specification for 53 graded OPC*, Bureau of Indian Standards, New Delhi, India.
IS: 383-1970 (1999), *Specification for coarse and fine aggregate from natural sources for concrete*, Bureau of Indian Standards, New Delhi, India.
IS: 516-1979 (Reaffirmed in 1999), *Standard methods of tests for strength of concrete*, Bureau of Indian Standards, New Delhi, India.
IS 1311(Part 1)-92 (1992), Methods of non-destructive testing of concrete: Part-1 Ultrasonic pulse velocity, *Bureau of Indian Standards*, New Delhi.
Kankam, C.M. (1999), "Impact resistance of palm kernel fiber reinforced concrete pavement slab", *J. Ferrocement*, **29**(4), 279-286.
Luo, X. (2000), "Characteristics of high performance fiber reinforced concrete subject to high velocity impact", *Cement Concrete Res.*, **30**, 907-914.
Mohammadi, Y., Carkon-Azad, R., Sing, S.P. and Kaushik, S.K. (2009), "Impact performance of steel fibrous concrete containing fibers of mixed aspect ratio", *Const. Build. Mater.*, **23**(1), 183-189.
Mahmoud, N. and Afroughsabet, V. (2010), "Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete", *Int. J. Impact Eng.*, **37**(8), 879-886.
Mindess, S. and Vondran, S. (1988), "Properties of concrete reinforced with polypropylene fibers under impact loading", *Cement Concrete Res.*, **8**, 109-1215.
Mindess, S. and Yan, C. (1993), "Perforation of plain and fiber reinforced concrete subjected to low velocity impact loading", *Cement Concrete Res.*, **23**, 83-92.
Nataraja, M.C., Dhang, N. and Gupta, A.P. (1999), "Statistical variations in impact resistance of steel fiber reinforced concrete subjected to drop weight test", *Cement Concrete Res.*, **29**(7), 989-995.
Nataraja, M.C., Nagaraj, T.S. and Basvaraja, S.P. (2005), "Reproportioning of steel fiber reinforced concrete mixes and their impact resistance", *Cement Concrete Res.*, **35**, 2350-2359.
Ramadoss, P. (2008), *Studies on high-performance steel fiber reinforced concrete under static and impact loads*, Doctoral thesis, Structural Eng. Division, Anna University-Chennai.
Ramadoss, P. and Nagamani, K. (2013), "Stress-strain behavior and toughness of high-performance steel fiber reinforced concrete in compression", *Comput. Concrete*, **11**(2), 153-169.
Ramakrishnan, V., Coyal, W.V. and Kulandaisamy, V. (1981), "Performance characteristics of fiber reinforced concrete with low fiber contents", *ACI Mater. J.*, **78**(5), 388-394.
Ramasamy, H.S., Ahuja, B.M. and Krishnamoorthy, S. (1983), "Behavior of concrete reinforced with jute, coir, and bamboo fibers", *Int J Cement Compos. Light Weight Concrete*, **5**(1), 3-13.
Robins, P.J. and Calderwood, R.W. (1978), "Explosive testing of fiber reinforced concrete", *Concrete*, **12**(1), 26-38.
Savastano Jr, H. (1990), "The use of coir fibers as reinforcement to Portland cement mortars", Edit. Sobral H., Proceding of the Second International Symposium on Vegetable plants and their fibers as Building materials, Salvodor Brazil, Sep. 17-21, *Chapman and Hall, London*, 150-158.
Shah, S.P. and Gopalarathnan, V.S. (1987), "Impact measurement for fiber cement composites in FRC-87", Developments in fiber reinforced cement and concrete, Swamy R.N., *et al*., editors, *RILEM Symp.*, 1, paper no. 3.9.
Song, P.S., Hwang, S. and Sheu, B.C. (2004), "Statistical evaluation for impact resistance of steel fiber reinforced concrete", *Magazine Concrete Res.*, **56**(8), 437-442.
Song, P.S., Hwang, S. and Sheu, B.C. (2005), "Strength properties of nylon and polypropylene fiber reinforced concrete", *Cement Concrete Res.*, **35**, 1546-1550.

Song, P.S., Wu, J.C. and Sheu, B.C. (2005), "Assessment of statistical variations in impact resistance of high-strength concrete and high-strength steel fiber reinforced concrete", *Cement Concrete Res.,* **35**(2), 393-399.
Song, P.S., Wu, J.C., Wang, S. and Sheu, B.C. (2005), "Statistical analysis of impact strength and strength reliability of steel-polypropylene hybrid fiber reinforced concrete", *Const. Build. Mater.,* **19**, 1-9.
Soroushian, P., Khan, A. and Hsu, J. (1992), "Mechanical properties of concrete materials reinforced with polypropylene or polyethylene fibers", *ACI Mater. J.,* **89**(6), 535- 540.
Sridhara, S., Kumar, S. and Sinare, M.A. (1971), "Fiber reinforced concrete", *Indian Concrete J.,* **10**, 428-430.
Suaris, W. and Shah, S.P. (1983), "Properties of concrete subjected to impact", *ASCE, J. Struct. Eng.,* **109**(7), 1727-1741.
Tara, R., Behnam, K. and Mohammad, S. (2011), "Statistical and experimental analysis on the behavior of fiber reinforced concrete subjected to drop weight test", *Const. Build. Mater.,* **31**, 360-369.
Wang, N., Mindess, S. and Ko, K. (1996), "Fiber reinforced concrete beams under impact loading, *Cement Concrete Res.*, **26**(3), 363-376.
Wang, Z.L., Shi, Z. and Wang, J.G. (2011), "On the strength and toughness properties of steel fiber reinforced concrete under static and dynamic compression", *Compos.Part B: Eng.,* **42**(53), 1285-1290.
Yan, H., Sun, W. and Chen, H. (1999), "The effects of silica fume and steel fibers on the dynamic mechanical performance of high-strength concrete", *Cement Concrete Res.,* **29**, 423-426.

Notations and conversion factors

HPSFRC = high-performance steel fiber reinforced concrete
f'_{cf}, f_{cf} = cylinder, cube compressive strength of HPSFRC, MPa or N/mm^2
f_{rf} = flexural strength (modulus of rupture) of HPSFRC, MPa or N/mm^2
T = impact toughness of HPSFRC, N.m. or Joules [1ft.lb = 1.356 N.m]
IAE = integral absolute error
I_{rs} = residual impact strength ratio
C_r = crack resistance factor
IT = impact toughness (failure resistance) in Joules; Kinetic energy for 1 blow = 20.347 Nm
FIS = failure impact strength in Joules or Nm; [1 Joule = 0.738 ft.lb].
l/d = aspect ratio of fiber.

CC