



Technical Note

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

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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

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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] |
| 2 | Modified drop weight impact | Coir | [26, 28] |
| | | PP/ Steel | [16] |
| 3 | Projectile impact(low/ high velocity) | Steel | [28] |
| 4 | Instrumented impact | PP | [8, 17, 22, 23, 37, 38] |
| 5 | Explosive impact | Steel | [15, 17, 37, 38] |
| 6 | Pendulum impact (Charpy/ Izod) | PP | [25] |
| 7 | Modified pendulum impact | Steel | [29] |
| | | | [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

Table 2 Chemical Composition of Cementitious materials (in percentage)

| Chemical composition | CaO | SiO ₂ | AlO ₃ | Fe ₂ O ₃ | MgO | K ₂ O | SO ₃ | P ₂ O 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

Ordinary Portland cement- 53 grade having 28-day compressive strength of 56.5 MPa and fineness by specific surface area of 265 m²/kg complying with IS: 12269-1987, and condensed silica fume having fineness by specific surface area of 23000 m²/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/m³; 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.

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/m³, 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/m³ and for w/cm = 0.3 is 165 kg/m³.

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/mm² = 145 psi; 1 lb/ft³ = 15.723 kg/m³)

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 (%) | Average thickness (mm) | Ultrasonic Pulse velocity (UPV) | | Impact resistance | | PINPB | T (Nm) | Predicted by Eq.(1) N_2 |
|-----------------|-----------|------------------------|---------------------------------|-----------------------|--------------------------|----------------------|-------|--------|---------------------------|
| | | | Transient time (μ s) | Wave velocity (m/sec) | at first crack (N_1) | at failure (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 |

1μ s = 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)

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 \varnothing 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 toughening 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 (Nm) |
|-----------------|-----------|--------------|-----------------------|-------------------|-------|--------|
| | | | Number of blows | | | |
| | | | at first crack, N_1 | at failure, N_2 | | |
| 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 |

$1\mu s = 10^{-6}$ 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.

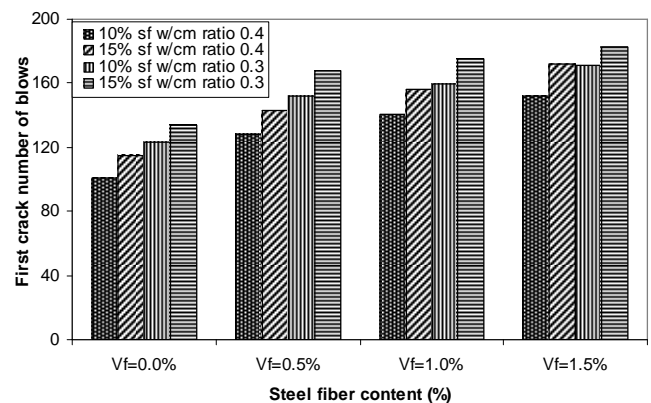


Fig. 3 Impact (first crack) characteristics at 28 days of HPSFRC (w/cm = 0.4 & 0.3)

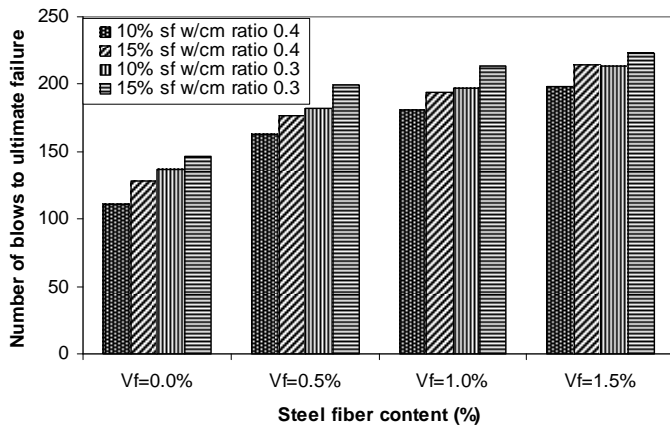


Fig. 4 Impact (ultimate failure) characteristics at 28 days of HPSFRC ($w/cm = 0.4$ & 0.3)

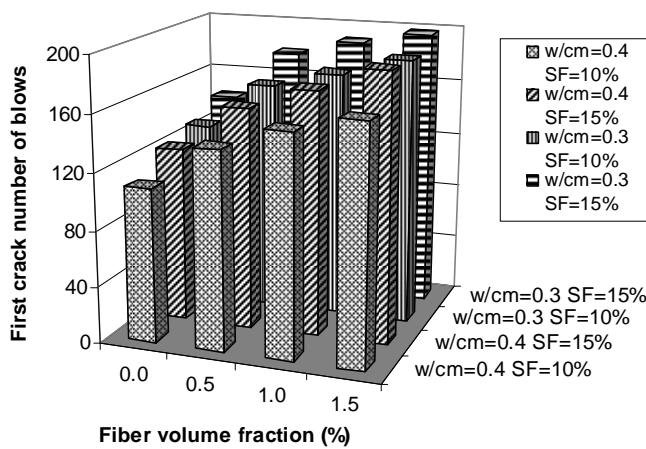


Fig. 5 Impact (first crack) characteristics at 56 days of HPSFRC ($w/cm = 0.4$ & 0.3)

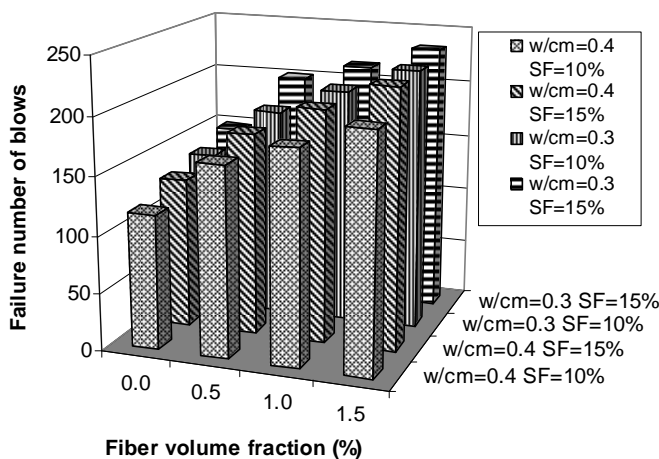


Fig. 6 Impact (ultimate failure) characteristics at 56 days of HPSFRC ($w/cm = 0.4$ & 0.3)

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:

$$N_2 = 1.086N_1 + 24.312 \quad (1)$$

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 for 1 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:

$$IAE = \frac{\sum(Q - P)}{\sum Q} \times 100 \% \quad (2)$$

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 complementary 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.

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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

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