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A new strength model for the high-performance fiber reinforced concrete

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Abstract. Steel fiber reinforced concrete is increasingly used day by day in various structural applications. An extensive experimentation was carried out with w/cm ratio ranging from 0.25 to 0.40, and fiber content ranging from zero to1.5 percent by volume with an aspect ratio of 80 and silica fume replacement at 5%, 10% and 15%. The influence of steel fiber content in terms of fiber reinforcing index on the compressive strength of high-performance fiber reinforced concrete (HPFRC) with strength ranging from 45 85 MPa is presented. Based on the test results, equations are proposed using statistical methods to predict 28-day strength of HPFRC effecting the fiber addition in terms of fiber reinforcing index. A strength model proposed by modifying the mix design procedure, can utilize the optimum water content and efficiency factor of pozzolan. To examine the validity of the proposed strength model, the experimental results were compared with the values predicted by the model and the absolute variation obtained was within 5 percent.

Keywords: silica fume; crimped steel fibers; fiber reinforcing index; high-performance fiber reinforced concrete; compressive strength; modeling, prediction.

1. Introduction

Steel fiber reinforced concrete (SFRC) is increasingly being used in several areas of infrastructures and industrial applications (Balaguru and Shah 1992, ACI 544.1R-96). Balaguru and Shah (1992) have reported that the addition of steel fibers in concrete matrix improves all mechanical properties of concrete, such as tensile strength, compressive strength and toughness. The use of silica fume as cement replacement material (CRM) in concrete increases the C-S-H gel formation that is mainly responsible for the enhancement of strength, durability of concrete and reduction in pore structure in the transition zone and increased impermeability (Aitcin 1998). At low water to binder ratio, to improve the rheological and workability properties, chemical admixtures such as superplasticizer is added to the concrete, which principally depends on the ambient temperature, chemistry of cement and fineness. The combined use of superplasticizer and CRM can lead to economical high performance concrete with enhanced durability.

High-performance concrete (HPC) is defined as concrete, which meets special performance and uniformity requirements that can’t be achieved by using only the conventional materials and normal mixing, placing and curing practice. According to ACI Committee 363 (1992), concrete having a 28-day compressive strength higher than 41 MPa (6000 psi) can be considered as high-strength

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concrete (HSC), and therefore called as high-performance concrete (HPC). Other high-performance requirements are: high tensile strength (above 4 MPa), and enhanced impermeability (permeability less than 10^{-10} m/sec) and other special requirements. High strength and low permeability are logical developments of presence of silica fume and super-plasticizer in concrete (Neviile 2000).

The inverse relation between the strength and ductility is a serious drawback for the use of HPC/ HSC and a compromise to this drawback can be obtained by the addition of short steel fibers in to the concrete matrix (Ezeldin and Balaguru 1992). When concrete cracks, the randomly oriented fibers arrest a micro cracking mechanism and limit the crack propagation, thus improving the strength and ductility thereby enhances the durability of structural elements. To combine the effect of both weight fraction and their aspect ratio, the reinforcing index, (RI = w_f*(l/d)) can be used as the fiber reinforcing parameter for a given type of fiber (Fanella and Naaman 1985).

In concrete mix design and quality control, strength of concrete is regarded as the most desirable property. The 28-day compressive strength is usually determined by a standard uniaxial compression test and is accepted as a common index of concrete strength. There have been several attempts to develop a method for the mixture proportioning with mineral admixture and/ or fibers. Existing methods of mix proportioning (ACI method) could not be applicable for high-performance concrete (HPC) or high-performance fiber reinforced concrete (HPFRC). Therefore, a new mathematical model for mix proportioning has been proposed in this paper.

Forty four series of concrete mixtures were used in this experimental investigation. The results of an extensive experimental investigation on the mechanical characteristics of HPFRC with w/cm ratios of 0.40, 0.35, 0.30 and 0.25, silica fume (SF) 5%, 10% and 15% and four fiber contents (0, 39, 78 and 117.5 kg/m^3) are presented in this paper. Based on the experimental results and the available information, a mathematical model was developed to predict 28-day compressive strength of HPFRC, which may serve as a useful tool to quantify the effects of fiber addition in terms of fiber reinforcing index (RI).

2. Literature review

When the mineral admixture is used as cement replacing material (CRM), its effect on the strength development of concrete varies significantly depending on the characteristics of CRM and with the properties of concrete matrixes. Smith (1967) proposed a factor known as cementing efficiency factor, k such that a mass, s of CRM will be equivalent to a mass k.s of cement in terms of strength development. He found that the strength and workability of fly ash concrete with effective w/b ratio [w/ (c+ks)], is comparable to that of the conventional concrete without fly ash having same water content and w/b ratio. Ganesh and Nageswara Rao (1993) reported that contribution of the fly ash is not a constant determined solely by its chemical and physical properties but also varies depending on the type of cement, w/b ratio etc. and used the relation between w/c ratio and compressive strength, to obtain the efficiency factors. The researchers (Sellevold and Nilsen 1987, Jehran 1983, Sabir 1995) have investigated the behavior of SF in concrete, showing that concrete of very high strength and durability can be developed by using SF. Duval and Kadri (1998) noticed that the optimum replacement of cement by SF is around 10-15%. However, the percentage of the increase in compressive strength for 10% SF remains quite low, about a maximum of 15% after 28 days. They proposed a model to evaluate the compressive strength of SF concrete at any time, which is related to the water-cement and silica-cement ratios. Banja and Sengupta (2002) have developed a non-linear statistical model as a function of SF (%)

for the prediction of 28-day compressive strength of SF concrete with w/cm ratios ranging from 0.3 to 0.42 and SF replacement by mass of cement from 0 to 30%, involving non-dimensional variables, is independent of the specimen parameters. Babu and Praksh (1995) have proposed the parameters were two efficiency factors, first, a general efficiency factor k_e and the second, the percentage efficiency factor k_p (as a multiplication factor to k_e) corresponding to the percentage replacement and then considered overall efficiency factor ($k = k_e\ k_p$) for equivalent cement replacement to give equivalent strength. They showed that w/c ratio of the control concrete and the effective w/b ratio of the silica fume concrete [w/(c+k.s)] will be the same for any particular strength at all percentage of replacement and finally evaluated the overall efficiency factor ($k = k_e\, k_p$) for any particular concrete at any particular replacement using the conceptual diagram of relationship between the compressive strength and w/cm ratio for the control as well as the SF concrete.

Akman and Yucel (1995) have used the Bolomey equation [Eq.(1)] to determine the coefficients.

$$f'_c = K_B\left(\frac{c}{w+v} - k'\right) \tag{1}$$

where f'_c is the compressive strength in MPa, c the cement content in kg/m^3; w the water content in kg/m^3 and v the volume of the voids (dm / m^3).

K_B the Bolomey coefficient, and k' the coefficient were determined using the experimental results. Then by using the above coefficients, efficiency factor (k) is determined by Eq. (2).

$$f'_c = K_B\left(\frac{c+kf}{w+v} - k'\right) \tag{2}$$

where f is the CRM content in kg/m^3.

Ganesh Babu and Prakash (1995) have obtained overall efficiency factor ($k = k_e k_p$) for equivalent cement replacement to give equivalent strength by choosing most acceptable value of 3 for general efficiency factor (k_e) for compressive strength determination at 28 days, between 6.85 and 1.11 for SF at 5 to 40% replacement levels. Dattatreya, *et al.* (2006) have reported that in case of silica fume concretes, k value was always more than 2 and it was in the range of 2.3 to 3.6 and found the SF was to be highly efficient mineral admixture (MA) in contributing to the concrete strength. In this study, efficiency of silica fume on the compressive strength of concrete was investigated. Efficiencies were determined from the compressive strength test results using concepts of cementing efficiency factor, k as suggested by Smith (1967), the equation employed is the modified one of the equation for compressive strength of most of the concrete. If the efficiency factor is known then the strength of HPC mixes can be determined by modifying the Bolomey equation as:

$$f'_c = A_1[c/w] + A_2 \text{ for no SCM mix.} \tag{3}$$

$$f'_c = A_1[(c+ks)/w] + A_2 \text{ for SCM mix.} \tag{4}$$

where f'_c is the compressive strength in MPa, c the cement content in kg/m^3, s the supplementary cementitious material (SCM) or CRM content in kg/m^3, k the efficiency factor and $A_1,$ A_2 are arbitrary constants. These arbitrary constants are reported to be influenced by type, size and grading of aggregate, type of cement, curing period etc., (Cordon 1963). Hence it is necessary to obtain strength to effective w/b ratio relation for a given set of materials and for the same workability.

Wafa and Ashour (1992) have developed a model for predicting the influence of fiber contents on compressive strength of HSFRC with w/c ratio of 0.25, for fiber volume fraction ranging from 0 to

1.5%. Ezeldin, *et al*. (1992) have developed a relationship between steel fiber reinforcing index (RI) and compressive strength of HSFRC with w/cm ratio of 0.35, for fiber content ranging from 0 to 59 kg/m^3. Nataraja, *et al.* (1999) have proposed an equation to quantify the effect of fiber content on compressive strength of concrete in terms of fiber reinforcing parameter.

The statistical models/empirical expressions developed by the different researchers are for HPC and HSFRC/ SFRC with a particular w/cm ratio, without involving efficiency factor of the SF. To the authors' knowledge, no researcher has developed strength-model for HSFRC/ HPFRC, involving efficiency factor of the SF as CRM with wide range of w/cm ratios**.**

3. Experimental investigation

Four basic mixes for SF concrete designated FC1-0.0, FC2-0.0, FC3-0.0 and FC4-0.0 corresponding to the w/cm ratio of 0.4, 0.35, 0.30 and 0.25 were selected.

3.1. Materials and mixture proportions

Ordinary Portland cement-53 grade satisfying the requirements of IS: 12269-1987 and silica fume in powder form, having fineness by specific surface area of 23000 m^2 /kg, a specific gravity of 2.25 were used in the ratio of 9.5:0.5, 9:1 and 8.5:1.5(1:1 by mass) by weight of cementitious materials in all the mixes. Silica fume is a powder by-product resulting from the manufacture of ferrosilicon and silicon metal. It has a high glassy of silicon dioxide (SiO_2) consists of very small spherical particles. Because of this, it has been a popular mineral admixture to use in high strength concrete. The chemical analysis of Silica fume (Grade 920-D) is given in Table 1.

Fine aggregate: Locally available river sand passing through 4.75 mm IS sieve, conforming to grading zone-II of IS: 383-1978 was used. It has fineness modulus of 2.65, a specific gravity of 2.63, and water absorption of 0.98% at 24 hrs.

Coarse aggregate: Crushed blue granite stone with 12.5 mm maximum size, conforming to IS: 383-1978 was used. The characteristics of coarse aggregate are:

Specific gravity = 2.70
Fineness modulus = 6.04
Dry rodded unit weight = 1600 kg/m^3
Water absorption = 0.65% at 24 hrs.

Super-plasticizer: Sulphonated naphthalene formaldehyde (SNF) condensate as high range water reducing (HRWR) admixture conforming to ASTM Type F (ASTM C494) and IS: 9103-1999 was

Table 1 Chemical analysis of silica fume (Grade 920-D) (Analyzed for mandatory parameters of ASTM C1240-1999)

Component	Result	ASTM C1240-99	AASHTO M307-90	Canadian std. Association1986
Silicon dioxide, SiO_2	88.7%	85% (mini.)	85% (mini.)	85% (mini.)
Moisture content	0.7%	3% (max.)	3% (max.)	3% (max.)
Loss of Ignition @ 975^o C	1.8%	6% (max.)	7% (max.)	6% (max.)
Carbon	0.9%	-	-	-
Fineness (by residue on 45 micron)	2%	10% (max.)	10% (max.)	10% (max.)

Table 2 Fiber characteristics (crimped steel fiber)

Geometry and properties	Value
Fiber diameter, d (mm)	0.45
Fiber length, l (mm)	36
Aspect ratio, l/d	80
Ultimate tensile strength, f_u (MPa)	910
Elastic modulus, E_f (GPa)	200
Number of fibers per kg.	22410

used. Specific gravity of SNF = 1.20

Fibers conforming to ASTM A820-01 have been used, are crimped steel fibers of diameter = 0.45 mm and length = 36 mm, giving an aspect ratio of 80. The properties of steel fibers used are given in Table 2.

Mixtures were proportioned using guidelines and specifications given in ACI 211.1-91 and ACI 211.4R-93 and IS: 10262-1982, and recommended guidelines of ACI 544.3R-93. This aspect of work has been reported elsewhere (Ramadoss and Nagamani 2006). Mixture proportions used in the test programme are summarized in Table 3. For each water-cementitious materials ratio, 6 fibrous concrete mixes were prepared with fiber volume fractions, V_f of 0.5, 1.0 and 1.5 percent by volume of concrete (39, 78 and 117.5 kg/m^3). Mixing water was adjusted to correct for aggregate absorption. Super-plasticizer with dosage range of 1.75 to 2.75% by weight of cementitious materials has been used to maintain the adequate workability of plain and fiber reinforced concrete. Slump value obtained was 75 ± 25 mm for plain concrete and VeBe value of 10 ± 2 sec. for fibrous concrete mixes. Degree of compaction obtained for different mixes was in between 0.95 and 0.80.

3.2. Mixing and curing

Due to high cement and micro silica contents, the presence of small size coarse aggregate content and steel fiber content in fresh mix concrete, the efficient mixing of the HPFRC is more difficult than conventional concrete. The main requirement in SFRC mix is to have uniform dispersion of fibers and to prevent the balling of fibers during mixing. Super-plasticizer was used to produce uniform concrete without any segregation. The cementitious materials (cement and silica fume), and aggregate were mixed with 1/4 of water for 1 min. in a laboratory tilting type mixer. The mixing continued for further 1 min. while about 1/2 of water and 1/2 of superplasticizer were added. The mixing was continued for another 1 min. and the fibers were then added continuously for the period of 2-3 minutes. Finally the remaining water along with superplasticizer was added and then mixing was continued for an additional 2 minutes. Concrete was mixed using a tilting type mixer and specimens were cast using steel moulds, compacted by using table vibrator. For each mix at least six 150 mm diameter cylinders and three $100 \times 100 \times 500$ mm prisms were produced. Specimens were demolded 24 hours after casting and water cured at $27 \pm 2^{\circ}$C until the age of testing at 28 days.

3.3. Testing of specimens

3.3.1. Compressive strength

A total of 144 cylindrical specimens (size: 150×300 mm) were prepared. Compressive strength tests were carried out according to ASTM C 39 using 150 mm dia. $\times$ 300 mm height cylinders, loaded uniaxially. At least 3 specimens were tested for computing the average strength value and in

Table 3 Mix proportions for HPFRC (data for 1 m^3)

Mix designation	W/Cm	C kg	FA kg	CA kg	SF kg	W kg	SP (%)	V_f (%)
FC1-0	0.4	416	691	1088	22	175	1.75	0
FC1-0.5	0.4	416	687	1079	22	175	1.75	0.5
FC1-1	0.4	416	682	1071	22	175	1.75	1
FC1-1.5	0.4	416	678	1062	22	175	1.75	1.5
FC1*-0	0.4	394.2	691	1088	43.8	175	1.75	0
FC1*-0.5	0.4	394.2	687	1079	43.8	175	1.75	0.5
FC1*-1	0.4	394.2	682	1071	43.8	175	1.75	1
FC1*-1.5	0.4	394.2	678	1062	43.8	175	1.75	1.5
FC1**-0	0.4	372.2	691	1088	65.8	175	1.75	0
FC1**-1	0.4	372.2	682	1071	65.8	175	1.75	1
FC1**-1.5	0.4	372.2	678	1062	65.8	175	1.75	1.5
FC2-0	0.35	461.7	664	1088	24.3	170	2	0
FC2-0.5	0.35	461.7	660	1079	24.3	170	2	0.5
FC2-1	0.35	461.7	655	1071	24.3	170	2	1
FC2-1.5	0.35	461.7	651	1062	24.3	170	2	1.5
FC2*-0	0.35	437.4	664	1088	48.6	170	2	0
FC2*-0.5	0.35	437.4	660	1079	48.6	170	2	0.5
FC2*-1	0.35	437.4	655	1071	48.6	170	2	1
FC2*-1.5	0.35	437.4	651	1062	48.6	170	2	1.5
FC2**-0	0.35	413.1	664	1088	72.9	170	2	0
FC2**-1	0.35	413.1	655	1071	72.9	170	2	1
FC2**-1.5	0.35	413.1	651	1062	72.9	170	2	1.5
FC3-0	0.3	522.5	624	1088	27.5	165	2.5	0
FC3-0.5	0.3	522.5	620	1079	27.5	165	2.5	0.5
FC3-1	0.3	522.5	615	1071	27.5	165	2.5	1
FC3-1.5	0.3	522.5	611	1062	27.5	165	2.5	1.5
FC3*-0	0.3	495	624	1088	55	165	2.5	0
RC3*-0.5	0.3	495	620	1079	55	165	2.5	0.5
FC3*-1	0.3	495	615	1071	55	165	2.5	1
FC3*-1.5	0.3	495	611	1062	55	165	2.5	1.5
FC3**-0	0.3	467.5	624	1088	82.5	165	2.5	0
FC3**-1	0.3	467.5	615	1071	82.5	165	2.5	1
FC3**-1.5	0.3	467.5	611	1062	82.5	165	2.5	1.5
FC4-0	0.25	608	562	1088	32	160	2.75	0
FC4-0.5	0.25	608	558	1079	32	160	2.75	0.5
FC4-1	0.25	608	553	1071	32	160	2.75	1
FC4-1.5	0.25	608	549	1062	32	160	2.75	1.5
FC4*-0	0.25	576	562	1088	64	160	2.75	0
FC4*-0.5	0.25	576	558	1079	64	160	2.75	0.5
FC4*-1	0.25	576	553	1071	64	160	2.75	1
FC4*-1.5	0.25	576	549	1062	64	160	2.75	1.5

Table 3 Continued

Mix designation	W/Cm	C kg	FA kg	CA kg	SF kg	W kg	SP (%)	V_f (%)
FC4**-0	0.25	544	562	1088	96	160	2.75	0
FC4**-1	0.25	544	553	1071	96	160	2.75	1
FC4**-1.5	0.25	544	549	1062	96	160	2.75	1.5

In mix designation FC1 to FC4, FC1* to FC4*, and FC1** to FC4**, silica fume replacement is 5, 10, and 15 percent respectively by weight of cementitious material, after hyphen denotes fiber volume fraction in percent by volume of concrete.
SP (%) - Super plasticizer in percent by weight of cementitious material
Water present in Super plasticizer is excluded in calculating the water to cementitious material (W/Cm) ratio.
Cm = cementitious materials = (cement + silica fume)
V_f (%) denotes steel fiber volume fraction in percent by volume of concrete

few cases more samples (4 or 5) were considered. The compression tests were conducted in a servo controlled compression-testing machine by applying load at the rate of 14 MPa/min.

3.3.2. Flexural strength

A total of 112 prism specimens (size: 100 × 100 × 500 mm) were prepared. Flexural strength (modulus of rupture) tests were conducted as per the specification of ASTM C 78-94 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 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 average strength value and in few cases more samples (4 or 5) were considered.

3.3.3. Splitting tensile strength

A total of 112 cylindrical specimens (size: 150 × 300 mm) were prepared. Splitting tensile strength tests were conducted according to the specification of ASTM C 496-90 using 150 × 300 mm cylindrical specimens. The tests were conducted in a 1000 kN closed loop hydraulically operated Universal testing machine. Three samples were used for computing the average strength and in few cases more samples (4 or 5) were considered.

4. Analysis of results

The results of the compressive strengths are presented in Table 4. Based on the compressive strength results of plain concretes, the constants in Bolomey equation (Eq. (3)) A_1(=19.47) and A_2 (= –6.30) with correlation coefficient, $r = 0.99$ were determined by the material content and 28 day compressive strength of cylinder specimen using linear regression analysis. It was known that constant A_1, which is the slope of the compressive strength vs. c/w plot where the constant A_2, is the vertical intercept on *y*. After determination of the coefficients, efficiency factor *k* of SF as supplementary cementing materials (SCM) for different replacement levels, using Eq. (4) was determined as given in Table 5.

Relation between equivalent cementitious material (k.s) and SF (SCM) content in concrete is shown in Fig. (3), for Bolomey equation (Eq. 4). A correlation was obtained for an equation which has the form (k.s) = $C' = aX^2 + bX$ with a maximum point in the relation. Where C' is the

Table 4 28-day compressive, flexural, and splitting tensile strengths of high-performance fiber reinforced concrete

Mix Designation	w/cm ratio	Reinforcing Index, RI	f'_{cf} (MPa)	f_{rf} (MPa)	f_{spf} (MPa)	RCSR (f_{rf}/f'_{cf})	TCSR (f_{spf}/f'_{cf})
FC1-0	0.4	0	46.85	5.61	3.88	0.120	0.083
FC1-0.5		1.29	48.94	6.68	4.97	0.136	0.102
FC1-1		2.58	52.00	7.17	5.60	0.138	0.108
FC1-1.5		3.88	52.68	7.46	6.04	0.142	0.115
FC1*-0		0	52.56	6.21	4.38	0.118	0.083
FC1*-0.5		1.29	54.77	7.15	5.48	0.131	0.100
FC1*-1		2.58	56.01	7.73	6.37	0.138	0.114
FC1*-1.5		3.88	57.40	8.19	6.83	0.143	0.119
FC1**-0		0	55.72	-	-	-	
FC1**-1		2.58	60.21	-	-	-	
FC1**-1.5		3.88	61.17	-	-	-	
FC2-0	0.35	0	52.69	6.28	4.41	0.119	0.084
FC2-0.5		1.29	55.64	7.32	5.69	0.132	0.102
FC2-1		2.58	57.85	7.88	6.31	0.136	0.109
FC2-1.5		3.88	58.23	8.44	6.67	0.145	0.114
FC2*-0		0	55.85	6.75	4.75	0.121	0.085
FC2*-0.5		1.29	59.65	8.06	5.94	0.135	0.100
FC2*-1		2.58	61.05	8.54	6.65	0.140	0.109
FC2*-1.5		3.88	61.44	9.15	7.26	0.149	0.118
FC2**-0		0	59.42	-	-	-	-
FC2**-1		2.58	63.41	-	-	-	-
FC2**-1.5		3.88	64.59	-	-	-	-
FC3-0	0.3	0	60.10	7.31	4.86	0.122	0.081
FC3-0.5		1.29	62.81	8.48	6.35	0.135	0.101
FC3-1		2.58	64.01	9.05	6.73	0.141	0.105
FC3-1.5		3.88	64.56	9.58	7.15	0.148	0.111
FC3*-0		0	63.86	7.40	5.12	0.116	0.080
FC3*-0.5		1.29	67.12	8.76	6.35	0.131	0.095
FC3*-1		2.58	68.91	9.32	7.18	0.135	0.104
FC3*-1.5		3.88	69.67	10.13	7.71	0.145	0.111
FC3**-0		0	68.74	-	-	-	-
FC3**-1		2.58	74.58	-	-	-	-
FC3**-1.5		3.88	75.20	-	-	-	-
FC4-0	0.25	0	71.64	7.80	5.15	0.109	0.072
FC4-0.5		1.29	74.45	9.11	6.58	0.125	0.089
FC4-1		2.58	75.65	9.62	7.51	0.127	0.099
FC4-1.5		3.88	76.09	10.16	7.95	0.134	0.104
FC4*-0		0	74.87	8.02	5.62	0.107	0.075
FC4*-0.5		1.29	77.42	9.58	6.95	0.124	0.090
FC4*-1		2.58	79.96	10.36	8.05	0.129	0.101

Table 4 Continued

Mix Designation	w/cm ratio	Reinforcing Index, RI	f'_{cf} (MPa)	f_{rf} (MPa)	f_{spf} (MPa)	RCSR (f_{rf}/f'_{cf})	TCSR (f_{spf}/f'_{cf})
FC4*-1.5		3.88	80.41	11.01	8.48	0.137	0.105
FC4**-0		0	77.95	-	-	-	-
FC4**-1		2.58	85.98	-	-	-	-
FC4**-1.5		3.88	86.99	-	-	-	-

In mix designation FC1 to FC4 and FC1* to FC4*, silica fume replacement is 5 and 10 percent respectively, after hyphen denotes fiber volume fraction, percent
f'_{cf} =150 mm dia. cylinder compressive strength of HPFRC.
f_{rf} represents flexural strength of HPFRC
f_{spf} represents splitting tensile strength of HPFRC
Fiber reinforcing index (RI) = w_f *(l/d), average density of HPFRC = 2415 kg/m^3
Weight fraction (w_f) = (density of fiber/ density of fibrous concrete)*V_f
Aspect ratio (l/d) = length of fiber/diameter of fiber.
RCSR is the ratio of rupture strength (f_{rf}) to cylinder compressive strength (f'_{cf}).
TCSR is the ratio of splitting tensile strength (f_{spf}) to cylinder compressive strength (f'_{cf}).

Table 5 Efficiency factor (k) at 28 days age for SCM (Present investigation)

Efficiency factor, k for supplementary cementitious material (SCM)		
Silica fume (SF)		
5%	10%	15%
1.873	2.103	2.15

equivalent cementitious material and X is pozzolan amount. Equivalent cementitious material (C') for the maximum strength which could be calculated by the curves from Fig. (3) for modified Bolomey equation. The line $X = C'$ illustrates the efficiency factor (k) for pozzolan is equal to 1.

5. Strength modeling

The compressive strengths obtained for various mixes are given in Table 4. Fig. 1(a), (b) and (c) show the variation of compressive strength of HPFRC as a function of fiber reinforcing index, RI for 5%, 10% and 15% silica fume replacement respectively. Based on the test results, using linear regresion analysis, the compressive strength of HPFRC may be estimated in terms of compressive strength of SF concrete, f'_c and reinforcing index, RI as follows:

$$f_{cf} = f'_c + 1.323 \text{ (RI) (for 5\% SF replacement)} \tag{5}$$

$$f_{cf} = f'_c + 1.397 \text{ (RI) (for 10\% SF replacement)} \tag{6}$$

$$f_{cf} = f'_c + 1.776 \text{ (RI) (for 15 \% SF replacement)} \tag{7}$$

Combining the Eqs. (5), (6) and (7), a common equation derived regardless of SF replacement level is given by:

$$f_{cf} = f'_c + 1.498 \text{ (RI)} \tag{8}$$

Table 6 Comparison of predicted values of compressive strength by the model with the actual experimental values

Mix Designation	w/cm ratio	Reinforcing Index, RI	f'_{cf} (experimental) (MPa)	f'_{cf} (predicted) (MPa)	Absolute variation (%)
FC1-0	0.4	0	46.85	44.57	4.87
FC1-0.5		1.29	48.94	46.50	4.98
FC1-1		2.58	52.00	48.44	6.85
FC1-1.5		3.88	52.68	50.37	4.16
FC1*-0		0	52.56	47.81	9.05
FC1*-0.5		1.29	54.77	49.74	9.18
FC1*-1		2.58	56.01	51.68	7.74
FC1*-1.5		3.88	57.40	53.61	6.60
FC1**-0		0	55.13	50.85	7.76
FC1**-1		2.58	60.21	54.72	9.12
FC1**-1.5		3.88	61.17	56.66	7.38
FC2-0	0.35	0	52.69	51.79	1.71
FC2-0.5		1.29	55.64	53.73	3.44
FC2-1		2.58	57.85	55.66	3.78
FC2-1.5		3.88	58.23	57.60	1.09
FC2*-0		0	55.85	55.50	0.63
FC2*-0.5		1.29	59.65	57.44	3.71
FC2*-1		2.58	61.05	59.37	2.75
FC2*-1.5		3.88	61.44	61.31	0.22
FC2**-0		0	59.42	58.96	0.77
FC2**-1		2.58	63.41	62.83	0.91
FC2**-1.5		3.88	64.59	64.77	0.28
FC3-0	0.3	0	60.10	61.44	2.23
FC3-0.5		1.29	62.81	63.38	0.90
FC3-1		2.58	64.01	65.31	2.03
FC3-1.5		3.88	64.56	67.25	4.16
FC3*-0		0	63.86	65.76	2.97
FC3*-0.5		1.29	67.12	67.69	0.86
FC3*-1		2.58	68.91	69.63	1.04
FC3*-1.5		3.88	69.67	71.57	2.72
FC3**-0		0	68.74	69.80	1.54
FC3**-1		2.58	74.58	73.67	1.22
FC3**-1.5		3.88	75.20	75.60	0.53
FC4-0	0.25	0	72.64	74.98	3.22
FC4-0.5		1.29	74.45	76.92	3.31
FC4-1		2.58	75.65	78.85	4.23
FC4-1.5		3.88	76.09	80.79	6.17
FC4*-0		0	74.87	80.17	7.08
FC4*-0.5		1.29	77.42	82.11	6.05

Table 6 Continued

Mix Designation	w/cm ratio	Reinforcing Index, RI	f'_{cf} (experimental)	f'_{cf} (predicted)	Absolute variation
			(MPa)	(MPa)	(%)
FC4*-1		2.58	79.96	84.04	5.10
FC4*-1.5		3.88	80.41	85.98	6.92
FC4**-0		0	77.95	85.01	9.06
FC4**-1		2.58	85.97	88.89	3.39
FC4**-1.5		3.88	86.99	90.82	4.40

where f_{cf} = compressive strength of high-performance fiber reinforced concrete (HPFRC), MPa; f'_c = compressive strength of SF concrete, MPa; RI= steel fiber reinforcing index.

The above strength Eq. (8) combines the strength of SF concrete (HPC) and improvement in strength due to the inclusion of steel fibers in term of steel fiber reinforcing index (RI). Using the Eq. (8), one can model the strength or predict the strength of HPC as well as HPFRC. In modeling the strength of HPC, the parameter RI in Eq. (8) becomes zero.

Inserting Eq. (4) in Eq. (8), a new equation [Eq. (9)] to predict the compressive strength of HPFRC mixes at 28-days, is obtained as:

$$f_{cf} = A_1[(c+ks)/w] + A_2 + 1.498(RI) \tag{9}$$

where f_{cf} = compressive strength of HPFRC in MPa; c = cement content in kg/m^3; w = water content in kg/m^3; s = supplementary cementitious material (SCM) content in kg/m^3; k = efficiency factor and A_1, A_2 are arbitrary constants; RI= steel fiber reinforcing index.

The predicted values as obtained by Eq. (9) for w/cm ratios of 0.4, 0.35, 0.30 and 0.25 were compared with the experimental values and are presented in Table 6. The validation of the proposed procedure (strength Eq. (9)) was checked with the data of Ezeldin and Balaguru (1992), Wafa and Ashour (1992), Banja and Sengupta (2002), and Nataraja, *et al.* (2001). The predicted strengths given in Table 7, were within ±13 percent (average absolute variation = 6.3%) of the actual strengths. It may be seen from the Fig. 4 that the predicted compressive strengths by the Eq. (9) are having a good correlation with experimental values of different researchers.

6. Mechanical properties

6.1. Compressive strength

The compressive strengths for various mixes obtained vary from 46 to 86 MPa, are presented in Table 4. Figs. 1(a), (b) and (c) show the variation of strength on the effect of fiber content in terms of fiber reinforcing index. Fig. 2 shows the variation of strength of SF Concrete at different SF replacement levels. Addition of fiber volume fractions from 0.5 to 1.5% (RI = 1.29-3.88) increases the compressive strength by about 12.5 percent compared to zero-20 percent given in the literature (ACI 544.4R-89, Saluja, *et al.* 1992) for normal strength concrete. It is observed from the test results that for 1.0 percent fiber content (RI = 2.58), the increase in strength is about 11 percent but beyond 1.0% fiber content, there is marginal increase in strength.

Table 7 Comparison of predicted values of strength by the model with the actual experimental values of different researchers

Previous Researcher	C	SF	W	RI	Compressive strength, f'_{cf} (MPa)		Absolute error
					Actual	Predicted	percent
Wafa and							
Ashour (1992)	577	115.4	144.3	0	93.49	105.03	12.34
150×300 mm	577	115.4	144.3	0.6	95.1	105.93	11.39
cylinder	577	115.4	144.3	1.21	97.32	106.84	9.78
	577	115.4	144.3	1.81	96.47	107.74	11.68
	577	115.4	144.3	2.42	97.14	108.65	11.85
	577	115.4	144.3	3.65	97.83	110.50	12.95
Ezheldin, *et al.*							
(1992)	413	41.3	144.6	1.25	70.1385	62.88	10.35
Converted to	413	41.3	144.6	2.5	67.5165	64.75	4.10
150dia.cylinder							
Nadaraja, *et al.*	517	0	195	0	43.01	45.32	5.37
(2001)	517	0	195	0.9	45.84	46.67	1.81
150×300 mm	517	0	195	1.79	46.97	48.00	2.20
cylinder	517	0	195	1.34	45.65	47.33	3.68
	517	0	195	1.98	46.12	48.29	4.70
	517	0	195	2.67	49.23	49.32	0.18
Banja and							
Sengupta (2002)	520	0	135.2	0	68.06	68.58	0.77
150×300 mm	496	26	135.2	0	77.19	72.14	6.54
cylinder	468	52	135.2	0	77.61	76.84	0.99
	442	78	135.2	0	80.51	81.50	1.23
	510	0	153	0	58.7	58.60	0.17
	484.5	25.5	153	0	68.5	61.43	10.32
	459	51	153	0	69.8	65.76	5.79
	433.5	76.5	153	0	70.6	69.80	1.14
	500	0	170	0	48.9	50.96	4.22
	475	25	170	0	60.6	54.12	10.69
	450	50	170	0	63.6	57.28	9.94
	425	75	170	0	67	60.44	9.79
	490	0	186.2	0	43	44.94	4.50
	465.5	24.5	186.2	0	46.8	47.17	0.80
	441	49	186.2	0	54.9	50.59	7.85
	416.5	73.5	186.2	0	60.7	53.78	11.41

6.2. Tensile strength

Table 4 presents the variation of the flexural strength (modulus of rupture), f_{rf} on the effect of fiber content in terms of fiber reinforcing index. It is observed from the test results that there is a significant improvement in flexural strength in increasing the steel fiber content from 0 to 1.5 percent for all the mixes, varying from 16 to 38 percent of plain concrete. The increase in strength of 38 percent for 1.5% fiber content and 29 percent for 1.0% fiber content reveal that toughness is considerably improved compared to that of plain concrete.

The variation of the splitting tensile strength, f_{spf} in the range of 4.0 to 8.5 MPa on the effect of fiber content in terms of fiber reinforcing index (RI) is shown in Table 4. Addition of steel fibers by 1.50 percent volume fraction (RI=3.88) results in an increase of 56 percent in the splitting tensile strength compared with the no fiber matrix. The significant improvement in strength reveals that toughness will be much more than that of plain concrete.

According to Chinese standard GB 81-1985, the ratio of rupture strength to compressive strength (RCSR) is varying between 0.107 and 0.149, and the ratio of splitting tensile strength to compressive strength (TCSR) is varying between 0.072 and 0.119, which indicate that HPFRC has higher energy absorption capacity and ductility.

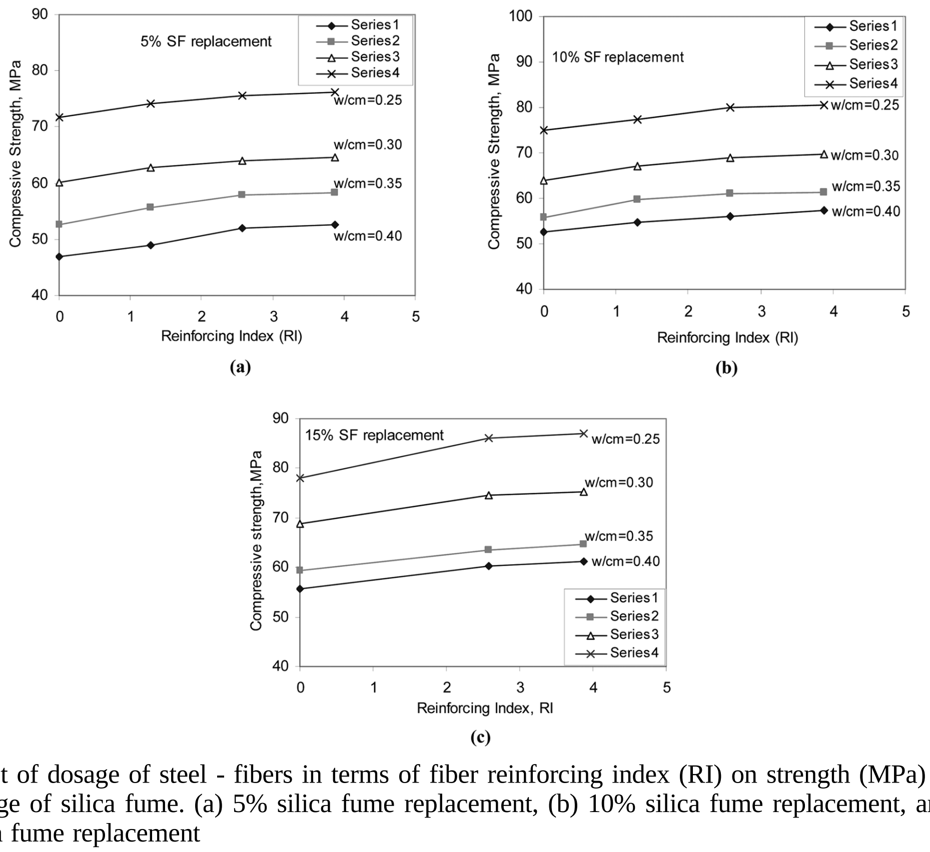

Fig. 1 Effect of dosage of steel - fibers in terms of fiber reinforcing index (RI) on strength (MPa) at constant dosage of silica fume. (a) 5% silica fume replacement, (b) 10% silica fume replacement, and (c) 15% silica fume replacement

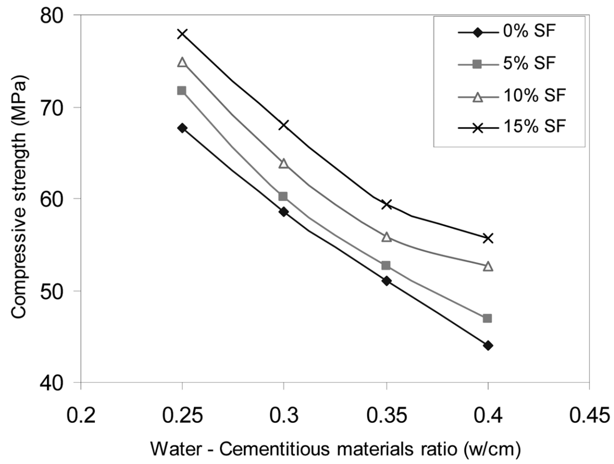

Fig. 2 Relation between compressive strength of silica fume concrete and w/cm ratio at different silica fume replacement

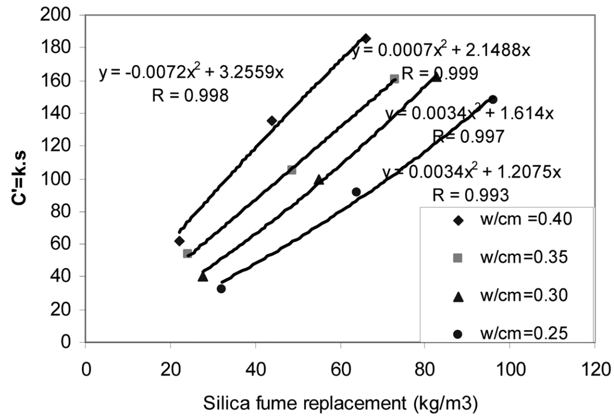

Fig. 3 Equivalent cementitious materials (C') Vs. silica fume replacement (kg/m^3)

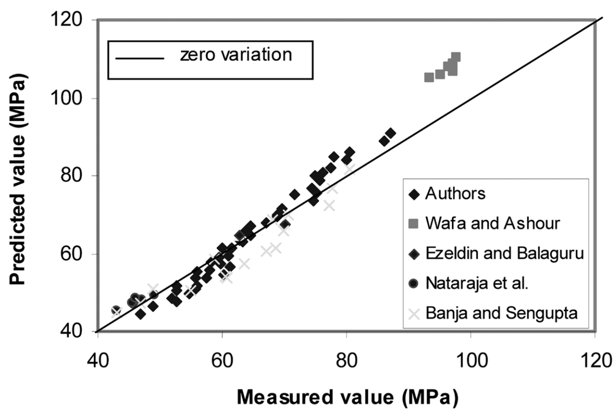

Fig. 4 Relationship between Predicted strength (MPa) and Experimental strength (MPa)

7. Conclusions

Based on the test results of the experimental investigation, the following conclusions can be drawn.

1. Proposed method of mix proportioning can be used to obtain HPFRC mixes, which combines the use of SCM, SP and steel fibers.
2. The average efficiency factor for SF mixes increases with the increase of the pozzolan/cement ratio.
3. There is an increase in total binder content as the effective w/b or w/cm ratio decreases. However as the SCM content increases, the cement required per unit strength reduces. Thus, it is possible to effectively utilize the cement by adopting lower effective w/b ratio with higher SCM.
4. Predicted values of the compressive strength compare well with the experimental results (within ±10%) obtained in the present investigation and data from some of the published literature.
5. Addition of steel fibers by 1.50 percent volume fraction (RI = 3.88) results in 12.4% increase in the compressive strength, an increase of 38 percent in the flexural strength, and results in an increase of 56 percent in the splitting tensile strength compared with the no fiber matrix.
6. Comparing the experimental values obtained by the investigation with the predicted values by the proposed Eq. (9), the absolute variation obtained is 5 percent.

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Notations

HPC	= high-performance concrete.
HPFRC	= high-performance fiber reinforced concrete.
f'_c	= cylinder compressive strength of plain concrete/silica fume concrete, MPa.
f_{cf}, f'_{cf}	= compressive strength of HPFRC, MPa.
V_f (%)	= volume fraction of steel fiber, percent.
w_f	= weight fraction.
l/d	= aspect ratio.
RI	= fiber reinforcing index.
s	= supplementary cementitious material (SCM), kg/m^3
k	= efficiency factor.

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