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Reproportioning of steel fibre reinforced concrete mixes and their impact resistance

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Abstract

In this experimental investigation, a practical rapid method of proportioning steel fibre reinforced concrete (SFRC) mixes is developed and validated. The basis for developing this is to use the reproportioning method, which has already been developed for proportioning normal density cement concrete mixes, for SFRC mixes. Based on the results of the trial mix, two SFRC mixes having 28 day target strength of 30 and 50 MPa are designed using this technique and examined regarding its validation. In addition, the impact resistance of these reproportioned Plain Concrete (PC) and SFRC is studied at 7 and 28 days. It is observed that the SFRC has developed significant impact resistance even for a small addition of steel fibres. Pulse velocity test is conducted at different ages to assess the quality of concrete. It is found that all concrete specimens could be classified under good quality.

Keywords: Mixture proportioning; Fibre reinforcement; Mechanical properties; Compressive strength and workability

1. Introduction

Concrete is the most widely used construction material in the world. Its consumption is around 10 billion tons per year, which is equivalent to 1 ton per every living person [1]. Hence, judicious use of cement has distinct economic and environmental impacts. The art of arriving at a proper mix through a suitable combination of cement, aggregates, water, and (if necessary) admixtures to suit workability, strength and durability requirements lies in the proportioning of concrete mixes. Mix proportioning should lead to an economical mix while satisfying workability, strength, and, indirectly, durability requirements.

Plain concrete is a brittle material. Under impact loading plain concrete exhibits extensive cracking and undergoes brittle failure. The inclusion of fibres in concrete, mortar and cement paste can enhance many of the engineering properties of these materials, such as fracture toughness, flexural strength, resistance to fatigue, impact, thermal shock and spalling [2,3].

Many researchers have studied the behaviour of SFRC under impact and observed a significant increase in the impact resistance when compared with unreinforced concrete [4–7]. Tensile and flexural strengths of concrete are also enhanced significantly due to the addition of steel fibre. There is always a reduction in workability with the addition of fibres, which can be compensated for by use of higher water contents and/or admixtures [4].

It is well known that inclusion of discrete short fibres is akin to admixing non-interacting particulate material of very low volume fraction to cement based composites in a similar way to that of fine and coarse aggregate in normal density concrete [8]. It is premised that the role of fibres is to impart ductility and energy absorption characteristics without any marked influence on compressive strength of concrete. Arriving at the desired fibre reinforced mix to obtain required strength involves two stages. The trial mix is to

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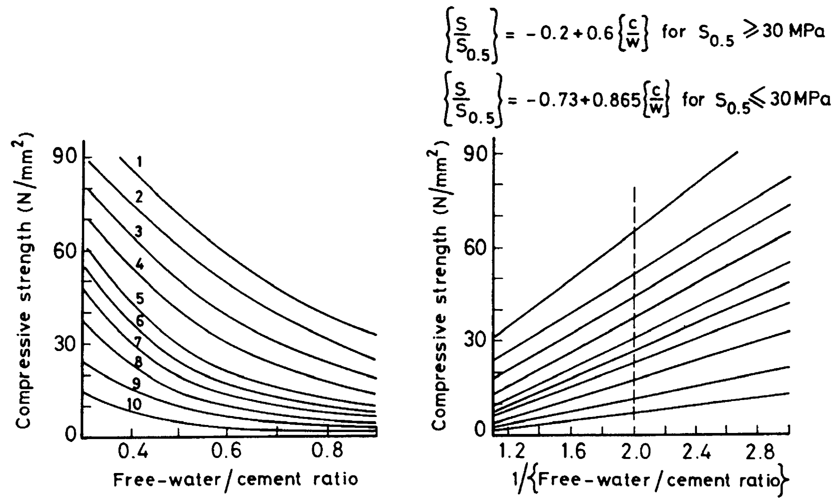

Fig. 1. Compressive strength versus water–cement ratio and their generalization [8].

find the synergy between different constituents. Using the strength and workability of this trial mix, the desired mix is reproportioned. In this present experimental investigation, the applicability of the reproportioning technique, already developed for normal density conventional concrete mixes, has been examined for the proportioning of SFRC. The following is a very brief detail of the reproportioning method of concrete mixes.

2. Reproportioning method of concrete mixes

Concrete mix proportioning involves trial mixes and then balancing such factors as placement, strength, and durability requirements, which finally leads to a satisfactory mix. It is necessary to determine the water–cement and aggregate–cement ratios to satisfy workability requirements and obtain the target compressive strength at 28 days. This involves several trials. To minimise the number of trials and to develop the model to compute water–cement ratios required for various levels of strength development from the data of a single trial mix, Abrams' law has been generalized [9]. In the generalization of this law, considering cement based composites as chemically bonded ceramics (CBC), the consequent strength development with age is essentially a constant volume solidification process. As a result, the hydrated gel particles fill the space, resulting in the compatible gel space ratios. By considering the strength at water–cement ratio of 0.5, ($S_{0.5}$), as the reference mark to reflect the synergy between different constituents of concrete, the following generalized relationships have been obtained [9] (vide Fig. 1)

$$\left\{\frac{S}{S_{0.5}}\right\} = -0.2 - 0.6\left\{\frac{c}{w}\right\} \quad \text{for } S_{0.5} > 30\,\text{MPa} \qquad (1)$$

$$\left\{\frac{S}{S_{0.5}}\right\} = -0.73 - 0.865\left\{\frac{c}{w}\right\} \quad \text{for } S_{0.5} \leq 30\,\text{MPa} \qquad (2)$$

Where S = compressive strength of the target mix $S_{0.5}$ = compressive strength of trial mix at 0.5 water–cement ratio c/w = cement–water ratio.

In these relationships, the strength ratio reflects the same order of gel space ratios (residual porosity) at a particular age compatible with the physico-chemical characteristics of cement and its synergy with coarse aggregate. With these equations, a comprehensive method to proportion concrete mixes has been advanced [10]. The trial mix proportions for a water–cement ratio of 0.5 and for a particular water content to meet the workability requirement are arrived at for which the strength development is determined. With $S_{0.5}$ value known for a given set of ingredients it would be possible to compute the water–cement ratio required for a specified strength development be calculated. It is also possible to calculate the magnitude of the strength development for the normal range of variation of water–cement ratios (0.3–0.7). With this underlying approach a comprehensive method of proportioning concrete mixes has been advanced and validated [10]. It is very well known that the volume fraction of steel fibres used in conventionally placed concretes is in the range of less than 2%. Since the fibres are

Table 1
Volume of dry rodded coarse aggregate per unit volume of concrete

Maximum size of aggregate (mm)	Fineness modulus of sand			
	2.40	2.60	2.80	3.00
10	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
20	0.66	0.64	0.62	0.60
25	0.71	0.67	0.67	0.65
40	0.76	0.74	0.72	0.70
50	0.78	0.76	0.74	0.72
70	0.81	0.79	0.77	0.75
150	0.87	0.85	0.83	0.81

Note: Table 1 is from the recommended practice for selecting proportions for normal weight concrete reported by ACI committee 211 (ACI manual of concrete practice, Part-1, 1979) ACI, USA.

Table 2
Test results of ordinary Portland cement (Birla Super 53 Grade)

Sl. no	Properties	Test results	IS: 12269—1987 requirements
1	Standard consistency	30%	–
2	Initial setting time	90 min	Minimum of 30 min
3	Final setting time	220 min	Maximum of 600 min
4	Specific gravity	3.15	
5	Compressive strength, MPa		
	3 days	29.54	Minimum of 27
	7 days	39.85	Minimum of 37
	28 days	60.85	Minimum of 53

particulate materials similar to other non-interacting constituents, such as fine and coarse aggregate, the applicability of reproportioning method merits examination. Hence this, investigation is undertaken.

3. Proportioning of SFRC mixes

Steel fibres in a concrete mix act essentially as 'rigid inclusions' with a large surface area and a geometry different from that of coarse aggregate. Fibre reinforced concrete, therefore, requires considerably greater amount of fine material than plain concrete so that it may be conveniently handled and placed [10–12].

The slender shape of the fibres promotes interlocking, and the large surface area results in the drying of the mix by causing adsorption of the free water that would otherwise be available to enhance workability. Fibre reinforced concrete, therefore, generally requires a greater proportion of paste than conventional concrete. Normal concrete contains 25–30% of paste of the total volume of concrete, SFRC requires a paste content of the order of 35–45% of the total volume of concrete depending up on the fibre geometry and volume [2].

There are no accepted methods of mix design for SFRC. Mix proportioning generally depends on the intended application of the material. The prime considerations are uniform dispersion of fibres and, adequate workability for placing and compacting with the method dependent on the equipment available. The reproportioning method suggested by Nagaraj and Banu [10] is used for SFRC mixes in this investigation. A typical example to explain the method is presented in the following paragraphs.

The following are the steps in the procedure adopted in the reproportioning method.

Table 4
Characteristics of aggregates used and the trial mix details

Coarse aggregate	Type	Crushed granite
	Size	12mm and smaller and 4.75 mm retained
	Bulk density (SSD condition)	1581 kg/m^3
	Specific gravity (SSD condition)	2.7
Fine aggregate	Type	Natural river sand conforms to zone I
	Fineness modulus	3.0
	Specific gravity (SSD condition)	2.54
Trial mix	Water–cement ratio : 0.5	
	Maximum size of coarse aggregate : 10 mm	
	Water content : 190 kg/m^3	
	Air content : 2%	

1. Fix the water–cement ratio at 0.5 to obtain the compressive strength of the trial mix for use as reference state. It is to be remembered that the coarse aggregate should possess crushing strength higher than the concrete strength desired. The workability and strength data forms a basis with which only reproportioning can be done subsequently. This is a deviation from the usual procedure of arriving at a mix for a targeted strength for a specific practical requirement. While reproportioning the mixes as per the requirement of the target strengths to be met with water–cement ratios can be arrived for the entire strength range by computation and examined by corresponding trials if found necessary.
2. Based on the maximum size of the aggregate and its bulk density and the fineness modulus of sand, determine the coarse aggregate content per unit volume of concrete from Table 1, (ACI committee 211—1979), providing information about volume of dry rodded coarse aggregate per volume of concrete. Volume of dry rodded coarse aggregate per unit volume of concrete given in Table 1.
3. Fix the water content at 190 kg/m^3. This value is the reference state in the generalisation of flow behaviour of fresh mixes and used to calculate slumps as per practical needs while reproportioning the mixes.
4. Based on the water–cement or fluid–binder ratio determine the cement content or cementitious materials content, and finally using the absolute volume method and specific gravity of fine aggregate determine the fine aggregate content. An air content of 2% is assumed in finding the volume for calculating sand content.
5. For the trial mix/mixes developed determine the workability and compressive strength of samples at 7, 14 and

Table 3
Properties of fibres used

Shape	Cross section	Tensile strength, MPa	Young's Modulus GPa	Aspect ratio	Weight g	No. of fibres per kg
Crimped	Circular	1010	205	40	0.245	4080

Table 5
Trial mix details

Water/Cement ratio	0.5
Water content	190 kg/m^3
Cement	380 kg/m^3
Fine aggregate	1049 kg/m^3
Coarse aggregate	695 kg/m^3
Aggregate–cement ratio	4.59
Compaction factor	0.81
Slump	25 mm

28 days. As per different target strengths requirement, determine the water–cement ratios or fluid–binder ratios as the case might be using the appropriate Eqs. (1) and (2).

6. Using the appropriate relations for compressive strength data at water–cement ratio or fluid–binder ratio 0.5, i.e., $S_{0.5}$, obtained from the trial mix, it is possible to compute water–cement ratios or fluid–binder ratios for the entire range of strengths for normal concrete mixes within the usual limits of less than 0.3 to 0.7 and beyond, if necessary.
7. Irrespective of the water–cement ratio used, without altering the coarse aggregate mortar ratio, change the water content to be adopted to obtain the desired slump with Sl_{190} determined experimentally. The Eq. (3) is derived by normalization of slump values by the slump value at water content of 190 l of water as reference value for the series of flow lines obtained with the coarse aggregate size and water–cement ratio as variables [13].

$$Sl/Sl_{190} = -16.36 + 0.091w \quad (3)$$

Where, Sl = Desired slump of the mix Sl_{190} = Slump of trial mix concrete for 190 l of water w = water content to get the desired slump.

8. Recompute the weight of cement and sand for the same coarse aggregate content following the procedure as stated above.

4. Materials used

In the present investigation, the following materials are used.

Cement: Birla super 53 grade ordinary Portland cement conforming to the requirements of Indian Standard IS: 12269—1987 [14] is used. The results obtained from tests conducted as per Indian Standard IS: 4031—1991 [15] are provided in Table 2.

Fine aggregate: locally available river sand is used. Its fineness modulus and specific gravity corresponding to saturated surface dry condition (ssd) are 3.00 and 2.54. It conforms to Zone 1 of Indian Standard IS: 383—1970 [16]. Zone I sand means course sand and its fineness modulus is about 2.6 to 3.2. In the present work it is 3.00.

Coarse aggregate: 12 mm and smaller size granite aggregate satisfying the requirements of Indian Standard IS: 383—1970 [16] is used. The specific gravity corresponding to saturated and surface dry (SSD) condition is 2.7.

Water: potable water free from salts, acids, oils, alkaline and organic materials satisfying the requirements of Indian Standard IS: 456—2000 [17] is used for mixing and curing of concrete cubes and discs.

Fibres: round crimped steel fibre having a of diameter 1mm and 40 mm length with an ultimate tensile strength of 1010 MPa is used. The fibres are supplied by VCT India Ltd., Chennai. Some important properties of fibre are listed in Table 3. This is the most commonly used commercial fibre in India [18].

Table 7
Mix designs

	30 MPa mix	50 MPa mix
Water–cement ratio	0.61	0.4
Water	223 kg/m^3	223
Cement	365/3.15=115 kg/m^3	557/3.15=176 kg/m^3
CA	695/2.7=257 kg/m^3	695/2.7=257 kg/m^3
Air	2%=20 kg/m^3	2%=20 kg/m^3
Total	615 kg/m^3	676 kg/m^3
Volume of fine aggregate	1000 − 615=385	1000 − 676=324
Weight of fine aggregate	385 × 2.54=977 kg/m^3	324 × 2.54=822 kg/m^3
W/C	0.61	0.4
A/C	4.51	2.71

5. Characteristics of aggregates and mix design

Characteristics of aggregates used and the trial mix details are presented in the Table 4.

Table 6
Test results of fresh concrete

Volume fraction v_f, %	Aspect ratio	Trial mix			30 MPa concrete			50 MPa concrete		
		Slump mm	CF	VB s	Slump mm	CF	VB s	Slump mm	CF	VB s
0.0	40	25	0.81	NC	26	0.85	NC	20	0.8	NC
0.5	40	15	NC	25	12	NC	18	10	NC	18
1.0*	40	10	NC	60	10	NC	20	8	NC	21
1.5	40	6	NC	80	3	NC	25	3	NC	25

* 1.0% means 78 kg/m^3, NC means test not conducted.

Table 8
Mix proportions per cubic meter of concrete for 30 and 50 MPa mixes

Target strength MPa	Cement kg	Fine aggregate kg	Coarse aggregate kg	Water l
30	365	977	695	223
50	557	822	695	223

From Table 1, volume of coarse aggregate (CA) = 0.44 m^3.

Therefore weight of coarse aggregate = 0.44 × bulk density.
= 0.44 × 1581 = 695 kg/m^3
Weight of cement = 380 kg/m^3
Volume of solids:
Cement = 380/3.15 = 120 kg/m^3
CA = 695/2.7 = 257.0 kg/m^3
Water = 190/1 = 190 kg/m^3
Air content = 2% = 20.0 kg/m^3
Total = 587.0 kg/m^3
Volume of fine aggregate = 1000 − 587.00 = 413 kg/m^3
Weight of fine aggregate (FA) = 413 × 2.54 = 1049 kg/m^3
Water–cement ratio = 0.5, aggregate–cement ratio (A/C) = 4.59
C = 380 kg/m^3, FA = 1049 kg/m^3, CA = 695 kg/m^3
Mix proportion is C:FA:CA = 1:2.76:1.83

Details of trial mix for different parameters are presented in Table 5.

6. Mixing, casting and curing

All ingredients are weighed separately as per the mix details. Mixing is done by hand to cast 6 cubes and 6 discs for each mix. The uniformity of concrete and proper distribution of fibres mainly depends on the mixing procedure. Cement and aggregates are mixed thoroughly and then fibres are added manually. While the mixing operation is in progress, 80% of water is added first and mixed for about 5 min then the remaining water is added and mixed thoroughly. For each mix, a total of 24 cubes of 150 × 150 × 150 mm and 24 discs of 150 mm diameter × 64 mm are cast. After 24 h the specimens are de-moulded, immersed in portable water and cured until testing. The water is at a temperature of around 28 °C.

Table 9
Details of mixes considered in the present study

Target strength MPa	Volume fraction v_f, %	W/C ratio	Fibre content kg/m^3	Aspect ratio
30	0.0	0.61	–	–
30	0.5	0.61	39	40
30	1.0	0.61	78	40
30	1.5	0.61	117	40
50	0.0	0.4	–	–
50	0.5	0.4	39	40
50	1.0	0.4	78	40
50	1.5	0.4	117	40

Table 10
Test results of trial mix designed as per reproportioning method (mix 1:2.76:1.83)

Volume fraction v_f, %	Average compressive strength in MPa	
	7 days	28 days
0.0	26.92 (1.04)*	38.25 (1.35)
0.5	31.93 (1.08)	38.66 (1.44)
1.0	21.00 (0.98)	33.92 (1.27)
1.5	27.47 (1.12)	38.65 (2.04)

* Value within the brackets represents standard deviation.

7. Testing

All mixes are tested for workability in terms of slump, compacting factor (CF) and Vee-Bee (VB) time as per Indian Standard IS: 1199—1959 [19].The main purpose of these tests is to check the consistency and the uniformity of concrete from batch to batch. Slump values are not so consistent indicating the fact, that this is not a good measure of workability for SFRC (Table 6). It is in general noticed that conventionally popular tests like slump and compacting factor tests are not as appropriate and accurate in determination of workability of fibre reinforced concrete as they are for plain concrete [20]. This is essentially because of interlocking of fibres thereby affecting normal workability due to concrete ingredients. Still upon vibration the fibre reinforced concretes exhibited needed workability for placement. However, the concrete is compacted easily by means of a needle vibrator.

8. Reproportioning mixes for 30 and 50 MPa

Here, from the results of the trial mix, two mixes to have 28-day strengths of 30 and 50 MPa are designed as follows; to find the water–cement ratio

$S/S_{0.5} = -0.2 + 0.6\,(C/W)$,
S = the required compressive strength of the mix
$S_{0.5}$ = compressive strength of trial mix at water–cement ratio 0.5

Table 11
Test results of reproportioned mix — 30 MPa (mix 1:2.67:1.9)

Volume fraction v_f, %	Average compressive strength in MPa	
	7 days	28 days
0.0	18.02 (1.34)*	33.15 (0.38)
0.5	24.44 (0.56)	30.65 (1.23)
1.0	17.59 (1.12)	27.98 (1.59)
1.5	23.36 (1.36)	28.04 (134)

* Value within the brackets represents standard deviation.

Table 12
Test results of reproportioned mix — 50 MPa (mix 1 : 1.47 : 1.24)

Volume fraction v_f, %	Average compressive strength in MPa	
	7 days	28 days
0.0	37.41 (0.84) *	50.62 (0.68)
0.5	39.34 (0.56)	50.36 (1.01)
1.0	32.99 (0.98)	47.25 (1.33)
1.5	43.76 (1.02)	50.66 (1.56)

* Value within the brackets represents standard deviation.

$30/38.25 = -0.2 + 0.6\ (C/W)$,
$W/C = 0.61$

To find the modified water content, use the slump value of the trial mix and target the slump of the required mix.

$Sl/Sl_{190} = -16.36 + 0.091W$
Sl = target slump
Sl_{190} = slump of trial mix at water content 190 l/m^3
W = quantity of water required to target required slump
$100/25 = -16.36 + 0.091W$
$W = 223$ kg/m^3
$\therefore$ Cement $= 223/0.61 = 365$ kg/m^3

Similarly for 50 MPa target strength the water/cement ratio has been calculated as follows

$S/S_{0.5} = -0.2 + 0.6\ (C/W)$,
$50/38.25 = -0.2 + 0.6\ (C/W)$,
$W/C = 0.4$

Using the slump equation, the modified water content is 223 kg/m^3

$W/C = 0.4$
$C = 223/0.4 = 557$ kg/m^3

Mix design details are shown in Table 7.

Mix proportions for these mixes and other details of mixes considered are presented in Tables 8 and 9. The trial mix results for SFRC are presented in Table 10.

Two mixes having 28 day target strength of 30 MPa and 50 MPa, for different volume fractions (0%. 0.5%, 1.0%, 1.5%) of fibre, are designed using this technique which is based on the results of trial mixes. In addition, the impact resistance of this reproportioned Plain Concrete (PC) and SFRC is studied at 7 and 28 days. Test results of 30 and 50 MPa concrete based on the average of three samples are presented in Tables 11 and 12.

For each mixes, a total of 24 cubes and discs are cast separately and tested for their compressive and impact strengths. Pulse velocity tests are conducted on all samples at 7 and 28 days. Workability tests are conducted for plain and steel fibre reinforced concrete to study the behaviour in the fresh state.

9. Impact resistance of SFRC

Since it has been possible to proportion mixtures with and without fibres to the same order of compressive

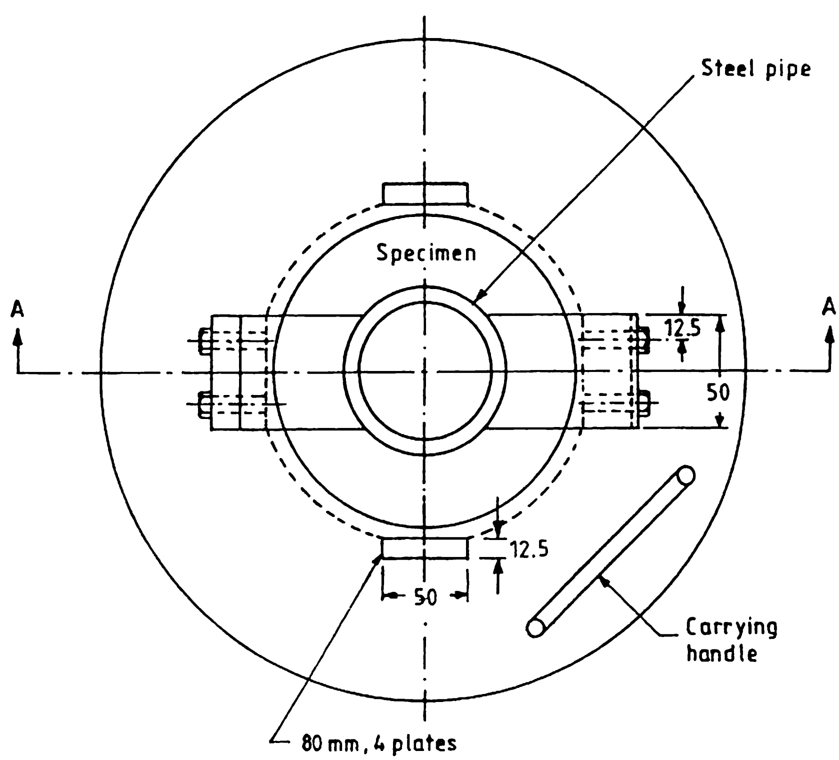

Fig. 2. Plan view of test equipment for measuring impact strength.

strength by reproportioning method, impact resistance of OPC and SFRC at the comparable compressive strength has been determined for relative comparison of response of these mixtures. Drop weight impact test, also known as repeated impact test, is conducted for evaluating the impact resistance. In this method the specimens are broken by known weight (4.5 kg) dropped from known distance (45 cm). The load is transferred from the hammer to the specimen through a 64 mm steel ball placed at the centre of the disc. This is the simplest test for evaluating impact resistance. The test method cannot be used to determine basic properties of composites. Rather, the method is designed to obtain the relative performance of plain and SFRCs containing different volume fractions of fibres. The test specimen consists of concrete discs 150 mm diameter by 64 mm thick. The impact test equipment and procedure have been published [5]. The test equipment was fabricated according to standards for testing as per in ACI Committee 544 [3] and can be seen in Figs. 2 and 3.

Discs are removed from the water tank and air-dried for 2–3 h before testing. For each set of parameters, 6 samples are tested for impact resistance. In order to restrict variability in results, the test is performed on a concrete platform specially cast for this testing whose size is sufficient to accommodate the set-up and is $400 \times 400 \times 400$ mm SFRC bed (see Fig. 4). Thickness of the specimens is recorded to the nearest millimetre at the centre and at the edges prior to the test. The specimens placed on the base plate with the finished face up and positioned within four lugs of the impact testing equipment. The bracket with the cylindrical sleeve is fixed in place and the hardened steel ball is placed on the top of the specimen within the bracket. The drop hammer is then placed with its base upon the steel ball and held vertically. The hammer is dropped repeatedly, and the number of blows required for the first visible crack to form at the top surface of the specimen is noted. Similarly the number of blows at which the specimen fails thereby touches any three of the

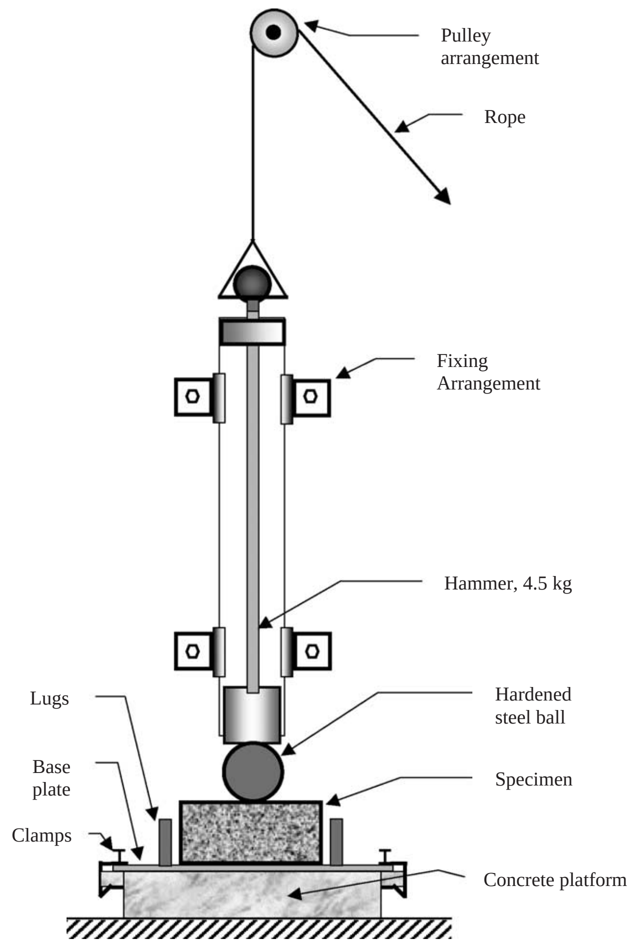

Fig. 4. Schematic diagram of impact test set-up.

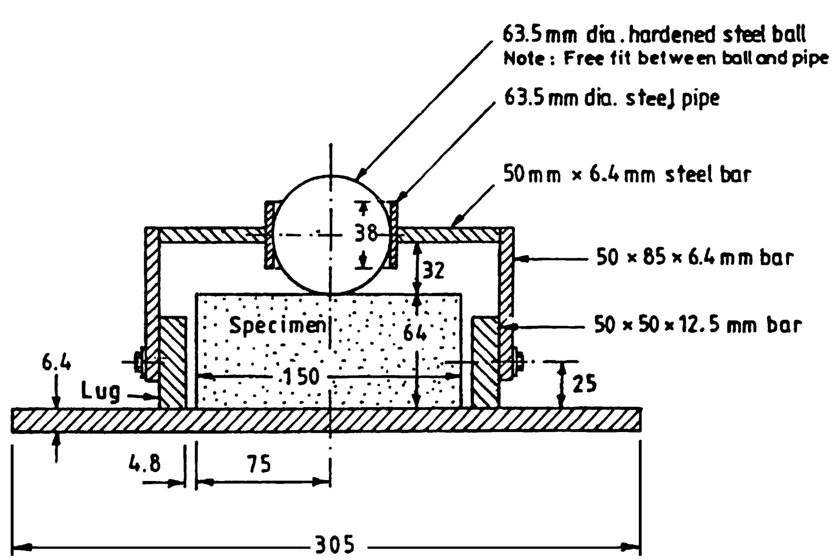

Fig. 3. Section through test equipment for measuring impact strength shown above (A–A). Dimensions are in millimeter.

Table 13
Results of pulse velocity for different volume fraction of fibres with respect to age (trial mix)

Volume fraction v_f, %	Average pulse velocity m/sec	
	7 days	28 days
0.0	4950 (25.4)*	5275 (16.6)
0.5	4962 (26.9)	5291 (19.5)
1.0	5090 (42.4)	5302 (53.4)
1.5	5099 (32.6)	5362 (49.1)

* Value within the brackets represents standard deviation.

four lugs represents the ultimate failure is also noted. The results of these tests found to exhibit high variability and may vary considerably with different types of mixes and fibre contents and the earlier investigators also observed the same [7].

10. Results and discussions

10.1. Workability test

In the present investigation, slump and compacting factor tests measure workability of the plain concrete mixes. VB test is done for SFRC in addition to slump test. Test results of fresh concrete for workability in terms of slump, compacting factor and VB for trial mix and for reproportioned mixes are presented in Table 6.

From Table 6, it can be observed that the workability of steel fibre reinforced concrete decreases considerably with the addition of fibres. For 1.0% of fibres, the slump is very low. However, the concrete is compacted with the help of needle vibrator without much difficulty. For higher volume fraction, the slump is negligible and its variation is marginal. Workability has decreased significantly with the addition of fibres. The decrease in workability is slightly more for mixes with higher volume fraction of fibres. The magnitude of workability obtained did not conform to the predictions by the equations. This is attributed to the bunching of fibres and hence it can be inferred that the generalized equation is not applicable for fibre reinforced mixes. The applicability is limited to the extent in only attaining water content so as to impart required workability by normal placement methods.

Table 14
Results of pulse velocity for different volume fraction of fibres with respect to age (reproportioned mix 30 MPa)

Volume fraction v_f, %	Average pulse velocity m/s	
	7 days	28 days
0.0	4674 (22.2)*	5124 (34.3)
0.5	4725 (29.3)	5135 (28.7)
1.0	4742 (35.8)	5182 (39.2)
1.5	4782 (39.6)	5218 (66.4)

* Value within the brackets represents standard deviation.

Table 15
Results of pulse velocity for different volume fraction of fibres with respect to age (reproportioned mix 50 MPa)

Volume fraction v_f, %	Average pulse velocity m/s	
	7 days	28 days
0.0	5001 (22.2)*	5125 (28.3)
0.5	5056 (16.4)	5148 (18.5)
1.0	5051 (19.4)	5198 (37.8)
1.5	5108 (23.8)	5218 (32.2)

* Value within the brackets represents standard deviation.

10.2. Ultrasonic pulse velocity test

Pulse velocity is measured using Ultrasonic Concrete Tester (PUNDIT). Test is conducted as per IS: 13311(PT1)—1992 [21]. The variation in pulse velocity is marginal indicating the uniformity of the concrete [22]. All samples are tested for pulse velocity on the pre marked positions at the centre of specimen. Testing is done 2 h after the specimens are taken from the curing tank at all ages. Average pulse velocity is reported in Tables 13–15.

The influence of fibre content and the strength of concrete on the variation of pulse velocity can be seen in Tables 13–15. It is observed that the pulse velocity of SFRC increases marginally with the increase in fibre content. In few cases, the pulse velocity decreased which may be due to an increase in air content. The increase in pulse velocity between 7 and 28 days is significant for 30 MPa concrete and not so significant for 50 MPa concrete. The pulse velocity depends on the nature of concrete along the pulse path.

The pulse velocity increases marginally as strength of concrete increases. This is true both for plain and fibre concrete. The pulse velocity for 50 MPa strength concrete, for the given reinforcing parameters and age, is higher compared to that of 30 MPa strength concrete.

10.3. Impact test

The impact test results are presented in Tables 16 and 17. The average results of six samples for each mix are shown in Tables. The number of blows for first crack as well as the number of blows to ultimate failure increased

Table 16
Results of impact test for 30 MPa concrete (average values of 5 samples)

Volume fraction v_f, %	First crack resistance, FCR, blows	Ultimate resistance, UR blows	Percent increase in resistance from FCR to UR	$FCR]_{SFRC}$/ $FCR]_{PC}$	$UR]_{SFRC}$/ $UR]_{PC}$
0.0	76 (13.3)*	79 (9.9)	3.90	–	–
0.5	214 (18.6)	291 (12.4)	35.98	2.8	3.68
1.0	300 (12.6)	555 (24.5)	85.00	3.95	7.03
1.5	1083 (45.6)	1600 (58.4)	47.73	14.25	20.25

* Value within the brackets represents standard deviation.

Table 17
Results of impact test for 50 MPa concrete (average values of 5 samples)

Volume fraction v_f, %	First crack resistance, FCR, blows	Ultimate resistance, UR. blows	Percent increase in resistance from FCR to UR	$FCR]_{SFRC}$/ $FCR]_{PC}$	$UR]_{SFRC}$/ $UR]_{PC}$
0.0	137 (9.7)*	140 (18.6)	2.20	–	–
0.5	908 (23.4)	1459 (34.3)	60.70	6.60	10.42
1.0	1140 (55.6)	1542 (34.1)	35.26	8.32	11.01
1.5	2522 (88.5)	3582 (102.3)	42.03	18.40	25.59

* Value within the brackets represents standard deviation.

with the increase in volume fraction of fibre for all mixes. Because of the nature of the impact test and non-homogeneous condition of concrete, the data from the impact test can be noticeably scattered. It is true for both plain concrete as well as steel fibre reinforced concrete.

Plain concrete specimens failed in brittle manner. Plain concrete specimen does not have considerable post crack resistance, as it resisted only few additional blows after the crack. In the case of 30 MPa plain concrete mix, specimens failed immediately after the formation of first crack and the broken pieces touched the positioning lugs of the apparatus with the addition of few blows. In the case of 50 MPa mix, specimens resisted few more additional blows before touching the lugs. It is observed from the tables that the increase in post crack resistance is negligible in case of plain concrete. However, in case of SFRC, this increase in post crack resistance is of the order of 40% to 60% depending on fibre content.

The increase in number of blows for the first crack is significantly higher in case of SFRC. Even for a small addition of fibres the enhancement in impact resistance of SFRC is quite considerable compared to that of plain concrete. Increase in compressive strength and fibre content increases the impact resistance significantly. The impact resistance of 50 MPa concrete with 1.5% fibre is about 25 times compared to its plain concrete counterpart.

11. Conclusions

The following conclusions emerge from this experimental study conducted on reproportioned plain and fibre reinforced concrete mixtures. It is observed that the reproportioning technique developed for plain concrete can be used for SFRC as well. This is in accordance with inclusion of low volume fraction of fibres, which are particulate in nature. All mixes resulted in the design target strength at 28 days substantiating the applicability of comprehensive method of the proportioning mixes. Trial mix results of 30 MPa concrete considered for both plain and fibre concrete have almost the same compressive strength irrespective of fibre content. As is well known, inclusion of fibre has not contributed much towards increase in compressive strength. The reproportioned concrete mixes have developed the target strength of about 30 MPa, demonstrating the applicability of the method to SFRC. Results are quite similar in case of 50 MPa concrete mixes as well. Following are other observations made in the study.

1. The pulse velocity for SFRC varies depending on the volume fraction of the fibre. The quality of concrete is excellent, since pulse velocity is greater than about 4575 m/s at 28 days in all the cases.
2. Post crack resistance in impact is negligible in case of plain concrete. However, the percentage increase in post crack resistance is about 50% in SFRC.
3. Due to variability in the test results, it is necessary to consider more samples for impact resistance test. Extremely high and low values may have to be discarded to minimise the variation in the results.
4. From the above study it is clear that the addition of steel fibres significantly improves the impact resistance of concrete and thus it is a suitable material for structures subjected to impact loads.

References

[1] T.S. Nagaraj, S.G. Shashiprakash, B.K. Raghuprasad, Reproportioning concrete mixes, ACI Mater. J. 90 (1) (1993) 50–58.
[2] N. Balaguru, S.P. Shah, Fibre Reinforced Cement Composites, McGraw-Hill International Edition, 1982, pp. 179–214.
[3] ACI Committee 544, Measurement of properties of fibre reinforced concrete, ACI Mater. J. 85 (6) (1988) 583–589.
[4] V. Ramakrishna, W.V. Coyle, V. Kulandisamy, E.K. Schrdar, Performance characteristics of fibre reinforced concrete with low fibre contents, ACI Mater. J. 78 (5) (1981) 388–394.
[5] E.K. Schrader, Impact resistance and test procedure for concrete, ACI Mater. J. 78 (2) (1981) 141–146.
[6] W. Suaris, S.P. Shah, Properties of concrete subjected to impact, J. Struct. Eng., vol. 109 (7), ASCE, 1983, pp. 1727–1741.
[7] V.S. Gopalaratnam, S.P. Shah, Properties of steel fibre reinforced concrete subjected to impact loading, ACI Mater. J. 83 (14) (1986) 117–126.
[8] T.S. Nagaraj, H.V. Dwarakanath, Structural response of partially fibrous concrete beams, Journal of Structural Engineering, 110 (11), 2798–2812.
[9] T.S. Nagaraj, Zahida Banu, Generalisation of Abrams' law, Cem. Concr. Res. 26 (6) (1996) 933–942.
[10] T.S. Nagaraj, Zahida Banu, Relative efficacies of different concrete mix proportioning methods, J. Struct. Eng., India 26 (2) (1999) 107–112.
[11] ACI Committee 544, State of the art report on fibre Reinforced Concrete, ACI 544 IR-82, Concr. Int. 4 (5) (1982) 9–30.
[12] ACI Committee 544, Guide for specifying, proportioning, mixing, placing and finishing steel fibre reinforced concrete, ACI Mater. J. 90 (1) (1993) 94–101.
[13] T.S. Nagaraj, Workability of concrete mixes — analysis and assessment, ICI workshop on Recent Trends in Testing of Concrete and Concrete Structures, Bangalore, India, March 1997, 1997, pp. 31–39.
[14] 1S: 12269—1987, Specifications for 53 grade ordinary Portland cement, Bureau of Indian Standards, New Delhi, India.
[15] IS: 4031—1991, Methods of physical test for hydraulic cement, Bureau of Indian Standards, New Delhi, India.

[16] IS: 383—1970, Specification for coarse and fine aggregates from natural sources for concrete, Bureau of Indian Standards, New Delhi, India.

[17] IS: 456—2000, Code of practice for plain and reinforced concrete, Bureau of Indian Standards, New Delhi, India.

[18] Information brochure, Ribtec Fibers India Limited, Chennai, India.

[19] IS: 1199—1959, Method of sampling and analysis of concrete, Bureau of Indian Standards, New Delhi, India.

[20] A.K. Sachan, C.V.S. Kameswara Rao, A cone test for workability of fibre reinforced concrete, Mat. Struct. 21 (1988) 448–452.

[21] IS: 13311(PT1)—1992, Methods of non-destructive testing of concrete: Part 1 ultrasonic pulse velocity, Bureau of Indian Standards, New Delhi, India.

[22] PUNDIT Manual, CNS Instruments limited, 61–62, Holmes Road, London.