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Strength and Flexural Toughness Characteristics of Self-Compacting Fibre-Reinforced Concrete

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ABSTRACT

Results of an investigation conducted to comparatively evaluate the strength and flexural toughness of Self-Compacting Fibre-Reinforced Concrete (SCFRC) containing different volume fractions of steel fibres are presented. An experimental program was planned, in which beam specimens of size 100 x 100 x 500 mm were tested under four-point static flexural loading to obtain the flexural strength and load-deflection curves of SCFRC. In addition, cube specimens of size 150 x 150 x 500 mm were tested to obtain their compressive strength. The specimens incorporated steel fibres in the volume fractions of 0.5%, 1.0% and 1.5%. A suitable SCFRC mix was designed incorporating 33% fly ash. The flexural toughness parameters were obtained following the procedure described in ASTM C-1018 C, JCI Method and ASTM 1609/C 1609M and using Post-Crack Strength (PCS) method. The results indicate that there are significant increases in the compressive strength, flexural strength and flexural toughness characteristics of SCFRC with the increase in volume fraction of steel fibres.

KEYWORDS: Compressive strength, Flexural strength, Flexure toughness, Self-compacting fibre-reinforced concrete.

INTRODUCTION

The addition of fibres in concrete inhibits cracking and considerably enhances its structural properties; *viz.* compressive strength, static flexural strength and flexural toughness. Fibres provide a well defined post-cracking behaviour. However, the improvement mainly depends on the size, shape and type of fibres used, their aspect ratio and the volume fraction of fibres. Therefore, proper knowledge of the influence of these factors on the structural properties of concrete is essential. Different types of fibres have been tried in cement and concrete, but steel fibres are the ones which have been found extensive for *in-situ* and precast engineering applications.

In recent years, Self-Compacting Concrete (SCC) has fascinated researchers all over the world to look into its fresh and hardened mechanical properties. Self-compacting concrete has the ability to fill formworks and compact under its own weight without the use of vibrations. Due to its many benefits over normally vibrated concrete, SCC has become very popular in construction industry dealing with the work of mass concreting in pavements and especially in concrete structures with heavily congested reinforcements, like

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bridge decks and piers, high rise buildings, rapid transportation systems and dams (Domone, 2005; Okamura and Ouchi, 1999). The use of steel fibres in SCC further increases the scope of applications of Self-Compactine-Fibre Reinforced Concrete (SCFRC). But, due to limited information on the structural behaviour of SCFRC, the use of SCFRC is still in its infancy.

Many researchers have investigated various hardened properties of SCFRC in the past. The compressive and tensile behaviours of SCFRC were investigated and modeled. A better performance has been reported as compared to Normally Vibrated Concrete (NVC) (Cunha et al., 2008; Cunha et al., 2011; Torrijos et al., 2008). An investigation was to compare the hardened properties of SCFRC with the Normally Vibrated Fibre-Reinforced Concrete (NVFRC) (Dhonde et al., 2007). The mechanical performance of SCFRC mixtures was found to be better than that of the corresponding NVFRC mixtures and the behaviour of SCC and SCFRC in hardened state was similar or better than that of NVC and NVFRC, respectively. Properties of SCC containing steel fibres were tested and compared with those of NVC (Krishna Rao and Rvindra, 2010). A marginal improvement in the ultimate strength was observed. The addition of fibre significantly enhanced the ductility. The optimum volume fraction (V) and aspect ratio (A) of fibres for better performance in terms of strength were found to be 1.0% and 25, respectively. The effect of steel fibre reinforcement on surface wear resistance of self-compacting mortars has been investigated (Burak et al., 2007). It has also been reported that SCC beams containing 1% steel fibre volume fraction exhibited better structural behavior (Barros et al., 2011; Grunewald, 2004). Greenough and Nehdi (2008) observed that short discrete fibres could significantly improve the shear behaviour of reinforced SCC slender beams and that beams incorporating 1% steel fibres could achieve a 128% increase in shear capacity over that of the reference beams without fibres. Further, SCFRC beams performed better under shear loading than NVFRC beams. In a series of experiments to assess the influence of different fibres on the compressive strength, flexural toughness and failure patterns of beams and slabs of fibre-reinforced self-compacting high-performance-concrete, it has been reported that significant benefits in toughness properties, failure patterns and cost could be achieved (Ambroise et al., 2001; Ding et al., 2009).

Few researchers have recently attempted to explore the effect of different types of fibres and other additions on a variety of concretes in terms of toughness and fracture properties. Wang, Han and Liu (2013) investigated the effect of highly dispersed carbon nanotubes on the flexural toughness of cement-based composites. Rashiddadash, Ramezanianpour and Mahdikhani (2014) conducted an experimental investigation on flexural toughness of Hybrid Fiber-Reinforced Concrete (HFRC) containing metakaolin and pumice. Results showed that HFRC with 0.75% steel fibres and 0.25% polypropylene fibres had higher toughness index, modulus of rupture and impact resistance than other hybrid mixtures. Mo et al. (2014) used steel fibres for the enhancement of flexural toughness, compressive toughness and fracture characteristics of Oil Palm Shell Concrete (OPSC). Addition of 1.0% steel fibres enhanced the flexural toughness of OPSC by up to 16 times. Kim et al. (2015) assessed the flexural toughness and impact resistance of bundle-type polyamide fiber-reinforced concrete. The results obtained demonstrated that bundle-type polyamide fibres undergo fracture without fibre pullout because of the increased inter-fiber gap and specific surface area for bonding, but exhibit poorer flexural fracture behaviour with lower flexural strength and fracture energy when compared to hooked-end steel fibres. Noaman, Abu Bakar and Akil (2016) investigated the compression toughness of rubberized steel fibre-reinforced concrete and observed that there is an improvement in the compression toughness with the increase of crumb rubber content up to 15%. Li et al. (2017) suggested a new approach for flexural toughness evaluation of steel fibre-reinforced Lightweight Aggregate Concrete (LWC). The optimal steel fibre content of 2.0% was proposed based on the degree to which the fibres improved the toughness of LWC. Steel fibre addition could significantly enhance the equivalent initial flexural strength and the equivalent residual flexural strength of LWC.

Research Significance

In the recent past, investigators have attempted to harness the benefits of addition of fibres, especially steel fibres, in SCC. An enhancement in the mechanical properties of SCFRC in hardened state has been reported with the addition of steel fibres, but there exists little understanding of flexural toughness of SCFRC. Though few researchers have investigated the flexural toughness of different types of concretes using various fibres, information is still scanty on the flexural toughness properties of SCFRC. Hence, this investigation was planned to study the flexural toughness of SCFRC containing different volume fractions of steel fibres. Tests, such as compressive strength test and flexural strength test, have been conducted on concrete specimens containing 0.5%, 1.0% and 1.5% of steel fibres. The toughness parameters of SCFRC have been evaluated as per ASTM C 1018 C (1992), JCI Method (1984), 1609 M (2008) and Post-Crack Strength Method (PCS) (Banthia and Sappakittipakorn, 2007; Banthia and Soleimani, 2005).

Experimental Program

The materials used for SCC mix were Ordinary Portland Cement (OPC) of grade 43, Class F flyash sourced from a thermal power plant as supplementary cementing material, crushed stone aggregates (maximum size 12.5mm) and locally available coarse sand, all confirming to the relevant Indian Standard specifications. Corrugated round steel fibres 30mm long and 1mm in diameter (Figure 1) were used in volume fractions of 0.5%, 1.0% and 1.5%. A polycarboxilic ether-based superplasticizer and viscosity modifying agent were also used in the present investigation. The dose of the superplasticizer and viscosity modifying agent were based on the workability requirements of the SCC and SCFRC mixes with fibre volume fractions of 0.5%, 1.0% and 1.5%.

Figure (1): Steel fibres used in the investigation

Proportioning of SCC and SCFRC Mixes

In the present investigation, the control SCC and three SCFRC mixes were prepared according to the EFNARC (2005) and ACI 237R (2007) guidelines (EFNARC, 2005; ACI Committee, 2007). An initial trial mix for SCC was obtained with reference to the procedure suggested in literature (Su et al., 2001). Thereafter, several trials were made keeping in view the basic workability requirements for SCC mix; i.e, passing ability, filling ability, flowability, stability and subsequent adjustments in the mix proportions were made to obtain the suitable SCC and SCFRC mixes with required workability and stability. The slump flow of SCC mix was kept on the higher side (> 700 mm) as the workability of SCFRC mixes was expected to reduce with the addition of fibres. In all the four mixes, the water to powder (cement + fly ash) ratio was kept constant at 0.4, wherein 33% of cement by weight was replaced with fly ash. The dosage of superplasticizer was adjusted to obtain the required workability for all the SCC and SCFRC mixes. The dosage of superplasticizer used in this investigation varied from 1.7% to 2.5% by weight of cement. The SCC mix was quite stable, but bleeding was observed in SCFRC mixes, making these unstable during casting. Thus, viscosity modifying agent was used to stabilize the

SCFRC mixes. The dosage varies from 0.25% to 0.50% by weight of cement in SCFRC mixes with 0.5%, 1.0% and 1.5% volume fractions of steel fibres. The details of the final mix proportions of SCC and SCFRC used in this research work are presented in Table 1.

Table 1. Mix proportions for SCC and SCFRC mixes

Mix	Water/ Binder Ratio	Sand/ Cement Ratio	Aggregates/ Binder Ratio	Fly Ash/ Cement Ratio	Fibre Volume Fraction, V_f	SP* (by Weight of Cement)	VMA** (by Weight of Cement)
SCC	0.40	2.06	2.35	0.50	--	1.7%	--
SCFRC1	0.40	2.06	2.35	0.50	0.5%	1.9%	0.25%
SCFRC2	0.40	2.06	2.35	0.50	1.0%	2.2%	0.35%
SCFRC3	0.40	2.06	2.35	0.50	1.5%	2.5%	0.50%

* SP- Superplastisicer. ** VMA- Viscosity Modifying Agent.

The basic workability requirements of SCC were taken care of using EFNARC guidelines. The slump flow test, J-ring test, V-funnel test and L-box test presented in Figure 2 were performed to evaluate the workability requirements of SCC and SCFRC mixes containing 0.5%, 1.0% and 1.5% fibre volume fractions. The results of the various workability tests conducted are given in Table 2.

Table 2. Workability tests on fresh SCC and SCFRC mixes

Workability Test	Parameter	Result obtained				EFNARC Guidelines
		SCC	SCFRC1	SCFRC2	SCFRC3	
Slump flow test	T_{500} (sec)	3.12	3.29	3.66	4.4	2 - 5 sec
	Slump flow spread (mm)	750	710	705	700	650-800 mm
J-ring test	T_{500J} (sec)	3.26	4.53	3.78	5.35	3 – 6 sec
	Flow spread (mm)	725	710	700	690	600-750 mm
	Blocking step (mm)	6.5	7.5	8.5	9.75	0-10 mm
V-funnel test	V-funnel time (sec)	7.28	7.8	8.94	9.82	6 – 12 sec
L-box test	L- box passing ability	0.91	0.90	0.83	0.81	0.8 -1.0

Figure (2): Workability tests conducted on SCFRC mixes

Casting and Curing of Specimens

After mixing in the rotary mixer for 4-5 minutes, the SCC and SCFRC mixes were placed into the moulds without any mechanical vibration or tamping. The beam specimens 100mm x 100mm x 500mm and cube specimens 150mm x 150mm x 150mm in size were cast in different batches. The specimens were de-moulded after 36 hours of casting. The quality of each batch of concrete was checked by obtaining the 28-day compressive strength for each batch. Curing for cube specimens was carried out for 28 days, whereas the beam specimens were cured for 75 days. Figure 3 shows the variation of compressive strength with curing period for SCC and different SCFRC mixes with fibre volume fractions of 0.5%, 1.0% and 1.5%.

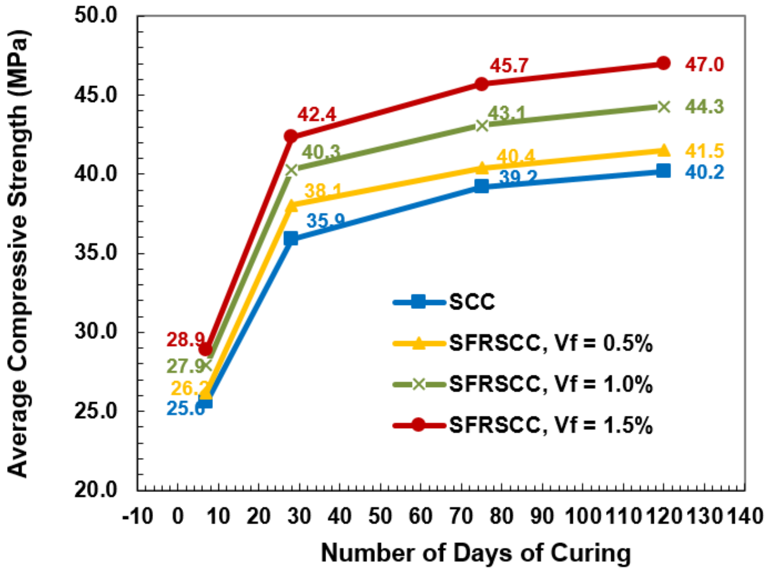

Figure (3): Variation of average compressive strengths of SCC and SCFRC mixes with curing age

It was observed that the increase in compressive strength of concrete from 75 days of curing to 120 days of curing is quite small and that is why a curing period of 75 days was selected for the curing of specimens to be tested in static flexure and subsequently in flexural fatigue. In fact, this paper forms a part of a larger investigation conducted to investigate the flexural fatigue characteristics of SCFRC containing steel fibres. Out of each batch of concrete beam specimens, three were tested in static flexure and the remaining were left for carrying out flexural fatigue tests. This paper reports the results of the static compressive strength and static flexural strength tests only. The compressive strength tests were conducted on concrete cubes using a 2000 kN compression testing machine, whereas the flexural strength tests were conducted using a 100 kN servo-controlled actuator.

RESULTS AND DISCUSSION

Compressive Strength Test Results

The results of the compressive strength test conducted on SCFRC containing 0.5%, 1.0% and 1.5% volume fractions of steel fibres are presented in Table 3. The compressive strength of SCC mix is also presented in Table 3 for reference.

Table 3. Compressive strength test results for SCC and SCFRC

Mix	Fibre volume fraction (%)	28-day compressive strength (MPa)*		
		Batch 1	Batch 2	Batch 3
SCC	0	35.9	36.6	36.3
SCFRC1	0.5	39.9	36.2	39.9
SCFRC2	1.0	41.2	38.8	40.8
SCFRC3	1.5	42.9	41.9	39.9

* *Average of three specimens.*

An increase in the compressive strength of SCFRC has been observed with the addition of steel fibres to the SCC mix and maximum compressive strength was obtained for concrete containing 1.5% of steel fibres of concrete volume. In general, there is an increase in the average 28-day compressive strength over SCC with addition of fibres to SCC in volume fractions of 0.5% to 1.5% with the maximum increase of 15% in the average compressive strength. The average compressive strength of all SCFRC mixes is shown in Figure 4. This percentage increase in compressive strength of SCFRC over plain SCC is also presented in Figure 5.

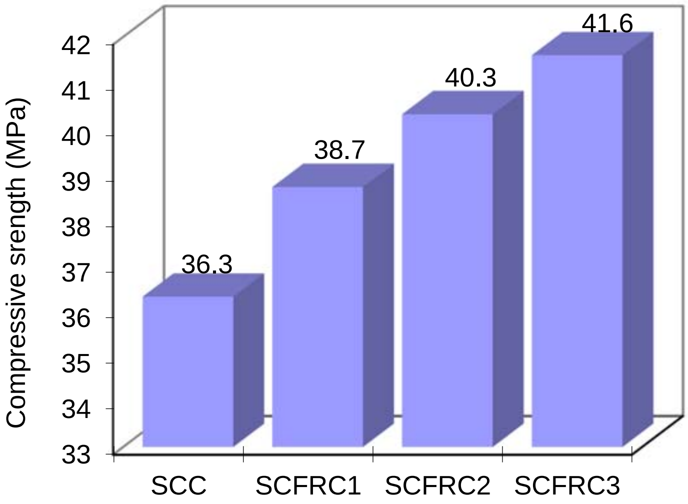

Figure (4): Average 28-days compressive strength results for SCC and SCFRC

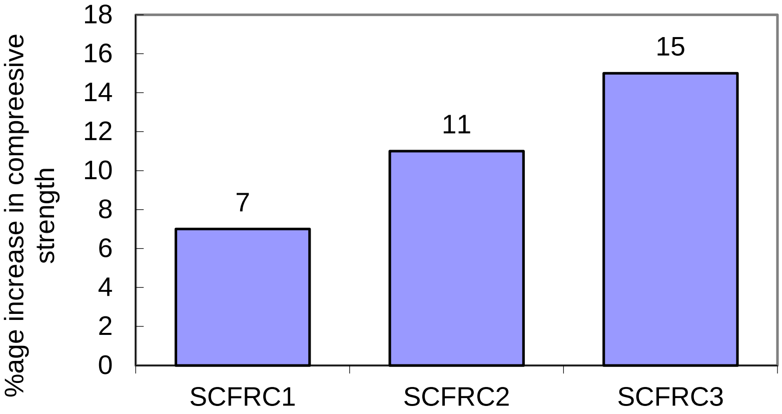

Figure (5): Increase in compressive strength of SCFRC over SCC

Flexural Strength Test Results

The flexural strength tests were performed in displacement control, under a four-point loading arrangement. The flexural strength results for SCFRC containing different volume fractions of steel fibres are presented in Table 4.

Table 4. Static flexural strength test results for SCC and SCFRC

Mix	Fibre volume fraction (%)	28-day flexural strength (MPa)*		
		Batch 1	Batch 2	Batch 3
SCC	0	4.93	4.94[#]	5.25
SCFRC1	0.5	6.35	6.11	6.35
SCFRC2	1.0	7.77	7.90	7.86
SCFRC3	1.5	9.45	8.67	9.04

** Average of three specimens; [#]Average of two specimens.*

The flexural strength of SCC is also listed for reference and comparison. The average flexural strength of the SCFRC mixes is shown in Figure 6. It can be seen that in general, like compressive strength, flexural strength of SCFRC is higher than that of SCC. The percentage increase in flexural strength of SCFRC with respect to SCC is also presented in Figure 7.

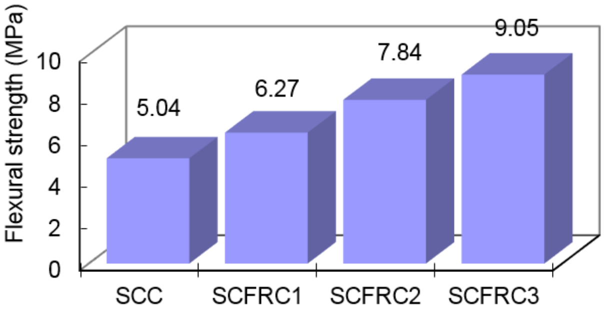

Figure (6): Average static flexural strength of SCC and SCFRC

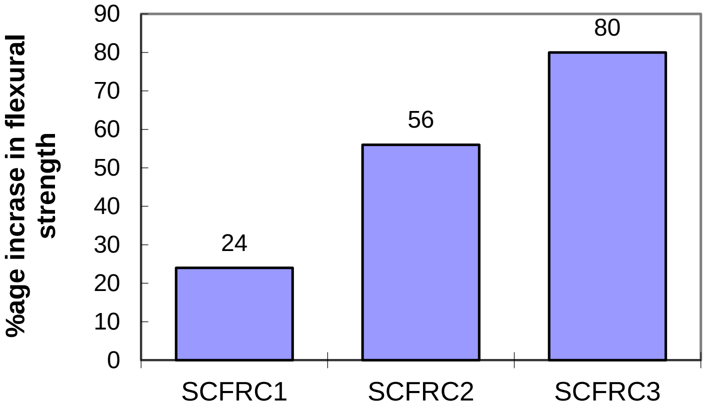

Figure (7): Increase in average flexural strength of SCFRC over SCC

It is evident from Figure 7 that there is a significant increase in the average flexural strength of the SCFRC mixes over SCC. The minimum increase of 24% in flexural strength is observed for SCFRC with 0.5% steel fibres. Mixes containing 1.0% and 1.5% of volume fraction of steel fibres have shown an increase in average flexural strength of the order of 56% and 80%, respectively. This increase in flexural strength of SCFRC may be attributed to the better homogenous mix of SCC compared to normally vibrated concrete and crack arresting properties of steel fibres which may get more or less aligned along the flow of concrete. This enhanced flexural strength of SCC containing steel fibres will further be helpful in achieving better flexural toughness for SCFRC. Typical load-deflection curves obtained in this investigation for SCFRC mixes containing different volume fractions of steel fibres are presented in Figs. 8, 9 and10.

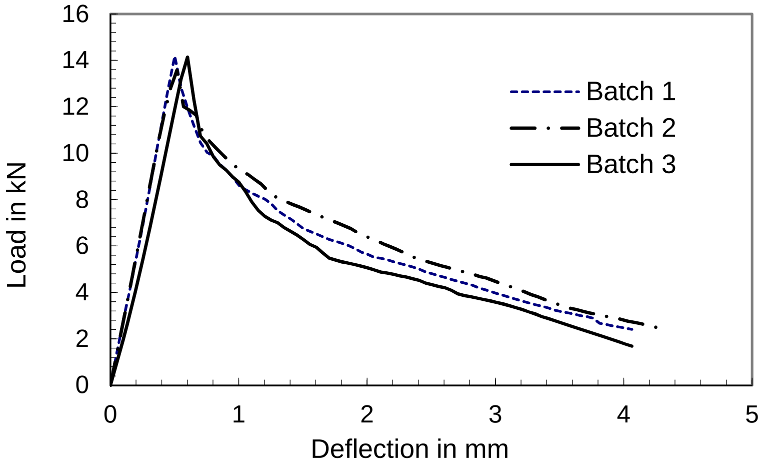

Figure (8): Load - deflection curves for SCFRC with 0.5% of steel fibres

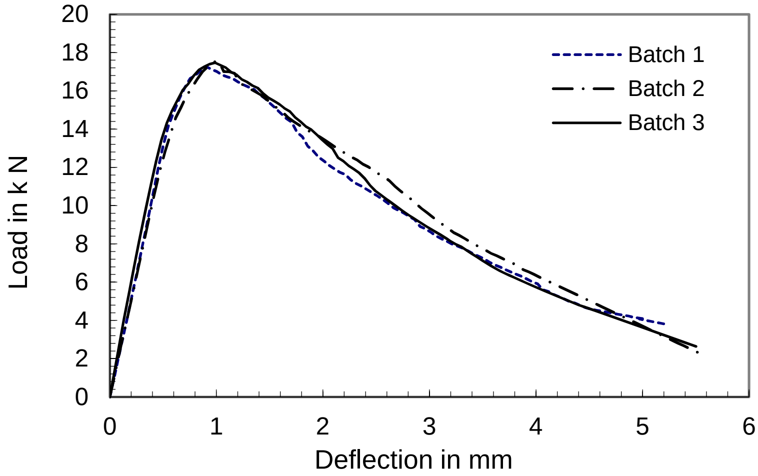

Figure (9): Load - deflection curves for SCFRC with 1.0% of steel fibres

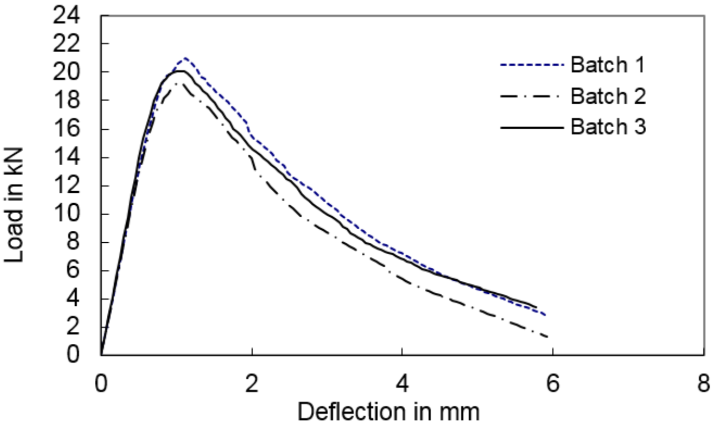

Figure (10): Load - deflection curves forSCFRC with 1.5% of steel fibres

The average peak loads and corresponding deflections for SCFRC containing 0.5%, 1.0% and 1.5% of steel fibres are presented in Table 5.

Table 5. Average peak loads and corresponding deflections

Mix	Fibre volume fraction (%)	Maximum load and corresponding deflection*	
		Deflection (mm)	Load (kN)
SCC	$0^{\#}$	0.415	11.20
SCFRC1	0.5	0.540	13.97
SCFRC2	1.0	0.969	17.44
SCFRC3	1.5	1.070	20.13

- *Test conducted on 3 batches (3 specimens each).*

 # 1 batch contains 2 specimens.

The peak load and corresponding centre point deflection for SCC are also presented for reference. The increase in centre point deflection corresponding to peak load as compared to SCC is 33%, 133% and 158%, respectively for SCFRC with 0.5%, 1.0% and 1.5% steel fibres, respectively. Figure 11 shows the variation of peak load and first crack load with the percentage of steel fibres in the SCFRC mix.

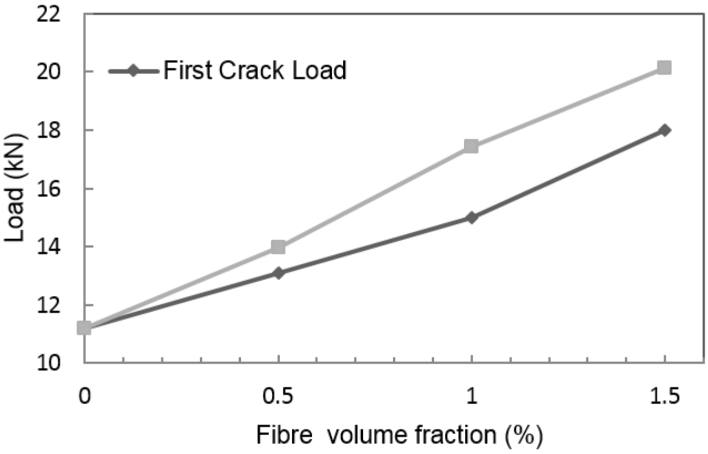

Figure (11): Average first crack load and peak load *versus* steel fibre content in SCFRC

Flexural toughness

Addition of fibres to concrete is known to improve its energy absorption capacity and crack resistance. Thus, flexural toughness is an important parameter in assessing the influence of fibres on the post-peak behaviour of fibre-reinforced concrete. A number of methods have been developed to obtain flexural toughness and performance of fibre-reinforced concrete. In the present investigation, flexural toughness parameter has been obtained using ASTM C-1018 (1992), JCI method (1984) and ASTM C 1609/C 1609M method (2008). In addition, a method based on Post-Crack Strength (PCS) (Banthia and Sappakittipakorn, 2007; Banthia and Soleimani, 2005) has also been used to evaluate the flexural toughness of SCFRC containing different volume fractions of steel fibres. The toughness of fibre-reinforced concrete in terms of indices can be expressed as the ratio between the energy absorbed up to a predetermined deformation level and the energy needed for the onset of cracking.

ASTM C 1018 Method

In the ASTM C 1018 method, toughness is expressed as a ratio of the amount of energy required to deflect the beam to a specified deflection, given as multiples of the first crack deflection (Tejchman and Kozicki, 2010). The evaluation of toughness is made on the basis of dimensionless parameters; namely toughness indices and Residual Strength Factors (RSFs) (Skazlic and Bjegovic, 2009). Toughness indices are strongly dependent on the first crack point; however, the difficulty in objectively identifying the exact location of 'first crack' on the curve affects the ASTM toughness indices' calculation (Banthia and Sappakittipakorn, 2007). RSFs can be obtained directly from toughness indices and represent the level of strength retained after the first crack (ASTMC-1018, 1992). The residual strength may better reflect the flexural toughness of concrete than the toughness index, because the residual strength is not dependent on the first-crack point (Deng and Li, 2006). The toughness indices I_5, I_{10} and I_{20} are calculated by taking the ratios of the energy absorbed to a certain multiple of first-crack deflection and the energy consumed up to the occurrence of the first crack, while RSFs $R_{5,10}$ and $R_{10,20}$ are calculated directly from toughness indices. The residual strength, represented by the average post-cracking load that the specimen may carry over a specific deflection interval, is determined as follows:

$$R_{5,10} = 20[I_{10} - I_5]; \tag{1}$$

$$R_{10,20} = 10[I_{20} - I_{10}]. \tag{2}$$

After obtaining the load–displacement curve for each specimen, the toughness parameters; namely, toughness indices (I_5, I_{10},I_{20}, I_{10}/I_5 and I_{20}/I_{10}) and RSFs ($R_{5,10}$ and $R_{10,20}$) were calculated as mentioned above. Table 6 presents toughness indices and RSF values for all mixes using the ASTM C 1018 method.

Japanese Concrete Institute (JCI) Method

Unlike the ASTM C 1018 method, the JCI method (1984) provides a single value of toughness. In this method, the toughness value T_{JCI} is defined as the area under the load–deflection curve up to the deflection of 1/150 of span (d_{150}). By accounting for the beam size and span, the flexural toughness factor (S_b) (equivalent to the average residual strength) is determined as:

$$S_b = T_{JCI}L / d_{150}bh^2; \tag{3}$$

where T_{JCI} is the energy absorbed (flexural toughness), d_{150} is the deflection of 1/150 of span and L, b and h are the span, width and depth of the specimen section, respectively. The toughness and flexural toughness factor values calculated as per JCI specifications for all SCFRC mixes are given in Table 6. The toughness index for plain concrete ASTM C 1018 method is taken as 1.0, because the plain concrete flexural test specimens fail immediately after the formation of the first crack.

Table 6. Flexural toughness indices using JCI Method and ASTM C-1018

Mix	Fibre Volume Fraction (%)	Toughness Indices*									
		JCI Method			ASTM C – 1018						
		Absolute Toughness	Flexural Toughness Parameter	First Crack Toughness	Toughness Indices			Toughness Index Ratio		Residual Strength Factor	
		$T_{(JCI)}$ (kN-mm)	S_b (MPa)	$T_{F.C.}$ (kN-mm)	I_5	I_{10}	I_{20}	I_{10}/I_5	I_{20}/I_{10}	$R_{5,10}$	$R_{10,20}$
SCC	$0.0^{\#}$	---	---	---	---	---	---	---	---	---	---
SCFRC1	0.5	20.42	3.06	3.27	4.14	6.31	7.59	1.52	1.20	43.40	12.80
SCFRC2	1.0	38.25	5.74	5.70	4.65	7.44	9.11	1.60	1.22	55.80	16.70
SCFRC3	1.5	41.92	6.29	6.36	4.84	7.82	9.59	1.62	1.23	59.60	17.70

** Test conducted on 3 batches (3 specimens each).*

 # 1 batch contains 2 specimens.

In general, it can be observed from Table 6 that the performance of SCFRC improves with the increase in the steel fibre content from 0.5% to 1.5%. The highest values of T_{JCI} and S_{JCI} are 41.92 kN-mm and 6.29 MPa, respectively, for SCFRC with 1.5% of steel fibres. Similarly, the highest values of the parameters obtained using ASTM C 1018 method are for SCFRC containing 1.5% of steel fibres.

ASTM C 1609/C 1609 M Method

It may be worth noting that because of errors arising in the determination of the first crack, toughness indices and RSFs are not always quite appropriate for the evaluation of the behaviour of fibre-reinforced concretes. Because of the disadvantages mentioned above, the ASTMC 1018 standard was replaced with a new standard, ASTM C 1609 (2008). Thus, features contained in ASTM C 1018 with which research studies often found faults were excluded from ASTM C 1609 (Deng and Li, 2006). The ASTM C 1609 test method determines the first-peak and peak loads and the corresponding stresses for toughness evaluation. It also requires the determination of residual loads at specified deflections and the corresponding residual strengths. The following parameters are derived from the load–deflection curve to evaluate the flexural performance of SCFRCs: P_{600} = residual load at net defection of L/600, P_{150} =residual load at net defection of L/150, f_{600} = residual strength at net defection of L/600, f_{150} = residual strength at net defection of L/150, T_{150} = area under the load–deflection curve from 0 to 1/150 of span length, T_{600} = area under the load–deflection curve from 0 to 1/600 of span length, where L = span length or distance between the supports. The flexural performance parameters, such as P_{600}, P_{150}, f_{600}, f_{150}, T_{600} and T_{150}, as obtained using ASTM C 1609/C 1609 M, are presented in Table 7 for SCFRC containing 0.5%, 1.0% and 1.5% of volume fractions of steel fibres. As is evident from Table 7, the residual strengths f_{600} and f_{150} and the toughness parameters T_{600} and T_{150} show more or less similar trends as presented by toughness parameters obtained by the other two methods discussed in the preceding sections. The highest values of toughness T_{600} and T_{150}; i.e., 6.81 Joules and 41.92 Joules, respectively, are shown by SCFRC containing 1.5% of steel fibres, thereby depicting the best toughness performance by SCFRC containing highest volume fraction of steel fibres.

Table 7. Flexural toughness indices using ASTM C-1609

Mix	**Fibre Volume Fraction (%)**	**Toughness Indices***					
		ASTM C – 1609					
		P_{600} kN	**P_{150} kN**	**F_{600} N/mm^2**	**F_{150} N/mm^2**	**T_{600} Joules**	**T_{150} Joules**
SCC	0.0#	---	---	---	---	---	---
SCFRC1	0.5	10.20	4.00	4.59	1.80	5.77	20.42
SCFRC2	1.0	16.15	7.45	7.27	3.35	6.48	38.25
SCFRC3	1.5	18.50	9.94	8.33	4.47	6.81	41.92

** Test conducted on 3 batches (3 specimens each).*

 # 1 batch contains specimens.

The variation in the indices I_5, I_{10} and I_{20} with the increase in volume fraction of steel fibres in SCFRC mix is shown in Figure 12.

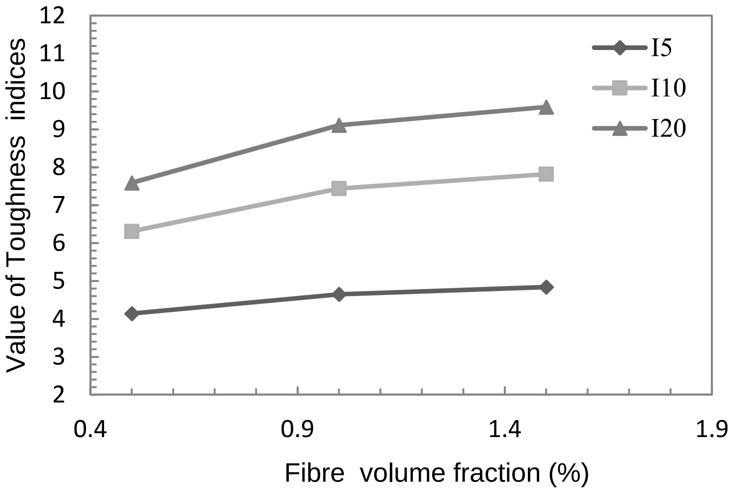

Figure (12): Average values of I_5, I_{10} and I_{20} *versus* steel fibre content in SCFRC

The load-deflection curves as obtained in this investigation for SCFRC containing different volume fractions of steel fibres have also been analyzed by Post-Crack Strength (PCS) method as reported by various researchers for NVC (Banthia and Sappakittipakorn, 2007; Banthia and Soleimani, 2005).

Post-Crack Strength (PCS) Method

As mentioned before, the load *versus* deflection curves were further analyzed by using a recently developed post-crack strength (PCS) method (Banthia and Sappakittipakorn, 2007; Banthia and Soleimani, 2005), which provides a more meaningful characterization scheme for fibre-reinforced concrete. The PCS method is a method of converting a load–displacement curve into an effective (or equivalent) flexural strength curve using simple energy equivalence. The technique thus generates material properties from a structural curve and such properties can then be used in analysis, comparative assessment and design. Briefly, the technique is explained in Figure 13, wherein firstly the peak load (δ_{peak}) is located and the curve is divided into two regions: pre-peak region and post-peak region. The area under the curve is then calculated up to the peak load and termed 'pre-peak energy', E_{pre}. In the post-peak region, points are located corresponding to deflections coinciding with various fractions of the span, L/m (where 'L' is the span of the beam and 'm' has different values ranging from 150 to 360). The area under the curve up to a deflection of L/m is termed "total energy" ($E_{total,m}$). The pre-peak energy is subtracted from this total energy to obtain the post-peak energy, $E_{post,m}$ corresponding to a deflection of L/m. For a beam with a width b and depth h, the post-crack strength PCS_m at a deflection of L/m is given by the following expression (Kim et al., 2015).

$$\mathrm{PCS}_m = \frac{\left(E_{\mathrm{post},m}\right)}{\left(\frac{L}{m} - \delta_{\mathrm{peak}}\right)} \times \left(\frac{L}{b \times h^2}\right). \tag{4}$$

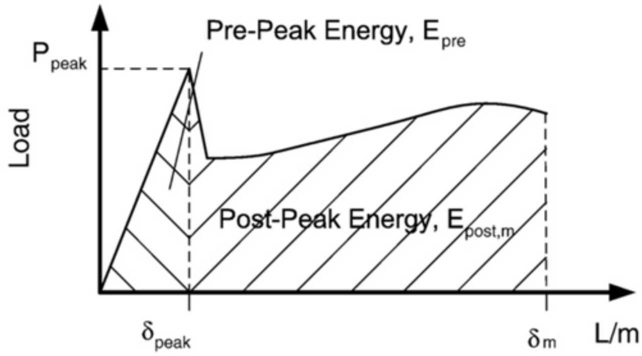

Figure (13): Post-crack strength analysis on fibre-reinforced concrete

In this study, for PCS calculation, eight deflection points (L/m) were selected in the deflection range of 1.25-2 mm. A starting deflection of 1.25 mm was chosen as the deflection at the peak load is always less than 1.25 mm for all three SCFRC mixes. The load-deflection curves for SCFRC obtained in this investigation have been analyzed using the said method and a plot of the CS with respect to L/m ratios for different volume fractions of steel fibres is shown in Figure 14.

It is observed from Figure 14 that the value of PCS increases with the increase in volume fraction of steel fibres from 0.5% to 1.5% in the SCFRC.

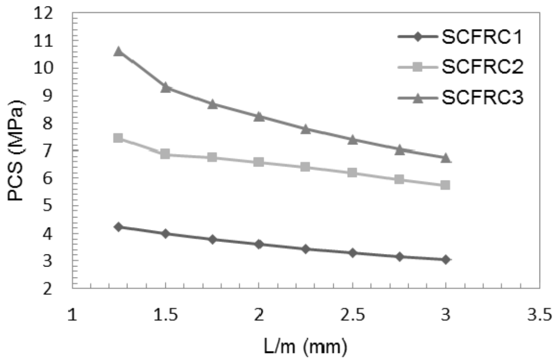

Figure (14): PCS values for SCFRC containing different volume fractions of steel fibres

However, the results of the present study on SCFRC are limited to the type and volume fraction of steel fibres used in this investigation. There is a need of extensive investigation to be carried out to study the effect of different types of steel fibres on flexural toughness and to determine the optimum dose of different types of steel fibres in SCFRC to obtain best performance in terms of flexural toughness indices/parameters.

CONCLUSION

The compressive strength, static flexural strength and flexural toughness of SCFRC containing 0.5%, 1.0% and 1.5% steel fibres have been investigated. The flexural toughness indices/parameters were obtained from load-deflection curves as per procedures laid down in ASTM C 1018, JCI method and ASTM C 1609. The load-deflection curves have also been analyzed using PCS method. A maximum increase in the compressive strength of the order of 15% over plain SCC was observed in case of SCFRC containing 1.5% of steel fibres. In case of static flexural strength tests, a maximum increase in flexural strength of the order of 80% and centre point deflection corresponding to peak load of the order of 158% were observed for SCFRC with 1.5% of steel fibres. The results obtained in this investigation indicate that, in terms of flexural toughness indices/parameters, the SCFRC with fibre volume fraction of 1.5% gives the best performance. In general, it is observed that with the increase in fibre volume fraction up to 1.5%, the strength and flexural toughness of the SCFRC improve.

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