PERFORMANCE OF HIGH STRENGTH STEEL FIBRE REINFORCED CONCRETE SUBJECTED TO FLEXURE AND IMPACT LOADINGS

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In this research, the flexural and impact resistance of steel fibre reinforced concrete (SFRC) under static and impact loadings was experimentally investigated. High-strength reinforced concrete steel fibre containing 1% by volume fibre content with a constant w/c 0.39. Hooked steel end fibers were used with a circular cross section of 1 mm in diameter and an aspect ratio of 30. Flexural behaviour of SFRC was carried out on a beam specimen of size 1200 x 100 x 200 mm subjected to two-point bending test as per ASTM C78 standard specification. Impact resistance was performed on a thin SFRC slab specimen of size 600 x 600 x 50 mm subjected to low velocity drop weight impact test as per the prescribed ACI 944-89. For comparison purpose, the conventional RCC specimens were also cast and tested. The test results found that the flexural strength and toughness of SFRC specimen remarkably increased by 35% and 50% respectively compared to RCC specimen. The addition of steel fibers to concrete increases the stiffness and ductility characteristics. The first crack and ultimate energy absorption potential of SFRC slab specimens were increased by 173.5 and 3.72 times, respectively, compared with RCC slab specimens. From the test results concluded that the flexural and impact resistance was significantly improved with addition of steel fibres in concrete.

Keywords: *HSFRC, Toughness, Ductility, Energy absorption, Impact residual strength ratio.*

1. Introduction

High strength concrete (HSC) or high-performance concrete (HPC) is basically a brittle material with high compressive strength. The mechanical properties such as energy absorption capacity, ductility, toughness and ultimate load carrying capacity were improved by the addition of short discrete fibers in concrete. The inclusion of fibers into the high strength concrete enhances the structural performance and the mode of failure was changed from brittle into ductile.

Soutsoset al.[1] investigated experimentally the flexural performance of fibre reinforced concrete with incorporation of steel and synthetic fibres. The test results found that the flexural toughness of concrete considerably increased with the addition of both steel and synthetic fibres and also improved the ductility factor. **Bhikshma et al. [2]** examined the mechanical properties of fibre reinforced concrete subjected to static loading. It was concluded that the mechanical properties were increased marginally with the addition of fiber content from 0.5 to 1.5 % and aspect ratio of 40 and 60. **Khali et al. [3]** reported that the load-deflection response and ultimate load carrying capacity were significantly improved with the addition of both types of steel fibers in UHPC. It was concluded that the flexural performances were improved with addition of hooked end fibers than crimped fibers. **Doo-YeolYooet al. [4]** examined the mechanical behaviour of UHPFRC containing four different fibre volume (1%, 2%, 3% and 4%). The test results reveal that the addition of 3% fibre content significantly improves the ultimate load carrying capacity and young's modulus subjected to compression. **Elavarasi et al**. [5] analyzed the output of reinforced Slurry-Infiltrated Fibrous Concrete (SIFCON exposed to impact loading) The test results showed that, compared to RCC and PCC slabs, SIFCON's energy absorption potential with and without conventional reinforcement slabs exhibits superior energy absorption. The structural behaviour of ultra high-performance steel fiber reinforced concrete with varying fiber content was investigated by **Doo-YeolYoo et al. [**6]. From the test results concluded that the ultimate load carrying capacity increases with the addition of 2% of steel fibre in UHPC compared to without steel fibres. It also observed that the post-peak response and ductility behaviour were improved with increased length of smooth and twisted fibres. The low-velocity impact response of drop hammer impact loading of SIFCON slabs was investigated by **Sudarsana Rao et al.**[7]. The findings concluded that SIFCON's impact resistance containing 12% of fiber content exhibits superior performance relative to all other slab specimens.To estimate the energy absorption at the initiation of the first crack and ultimate failure of SIFCON slabs, the Linear Regression analysis was developed from the experimental results. **JavadYahaghi et al. [8]** studied the performance of oil palm shells concrete containing polypropylene fibers under impact loading. Test results reveal that the service and ultimate energy absorption capacity increased by 7.8 and 5.6 times with addition of 0.3 % of polypropylene fibers than without PP fibers. **Soon Poh Yap et al. [9]** studied the flexural toughness characteristics of oil palm shell concrete with hybrid fibers and observed that the inclusion of steel fibers significantly improved the first crack flexural

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deflection and ductility in oil palm shell concrete. **Annadurai et al. [10]** investigated the flexural performance of hybrid fiber reinforced high strength concrete (FRHSC) subjected to flexure. The experimental outcomes made it evident that the HSC reinforced with 2 % of hybrid fibers (Steel 80 % + polypropylene 20 %) by volume fraction significantly improves the flexural strength compared to HSC with and without steel fibers. **Ramakrishnan et al. [11]** reported that the first crack strength was increased from 15 % to 90 % and flexural strength increased from 5 % to 129 % with the addition of fiber compared to plain concrete. FRC containing 1 % of hooked end fiber volume shows significant improvement in the above properties when compared with 1 % of straight fibers. **Kim Hung Mo et al. [12]** studied the impact strength of oil palm shell concrete reinforced with hybrid fibres subjected to impact loading. It was concluded that the hybrid fiber reinforced oil palm shell concrete (0.9 % of steel+ 0.1 % polypropylene fibers) panel exhibit superior energy absorption capacity increased by 60 times than oil palm shell concrete without fibers. **Trevor et al. [13]** reported that the reinforced FRC slabs showed excellent energy absorption capacity than reinforced concrete slabs without steel fibers. The incorporation of hooked end fibers in concrete enhances the energy absorption, the stiffness and displacement capacity of the slab and reduced crack widths and also observed the mode of failures as shear. **Murnal et al. [14]**examined the impact strength of FRC containing hooked end fibre with varying fibre volume (0.5, 1.0, 1.5, 2.0 and 2.5 %) under a drop hammer impact test as per the standard ACI-544 committee recommendation. From the test results, it was found that the impact resistance of FRC specimens remarkably increased with the increased volume of fiber content. **Rafat Siddique [15]** investigated the fracture toughness and impact strength of high volume flyash concrete reinforced with natural san fibres and concluded that the impact strength does not significantly get affected due to the addition of FA compared to control concrete. It was also concluded that the incorporation of an increased volume of fiber content enhances impact resistance and fracture toughness of FRC. **Mahmoud Nili et al. [16]**The outcome of the test results showed that the addition of SF in FRC improved the strength characteristics due to high pozzolanic reaction and its filler effects also noticed that the inclusion of hooked end fibers increases the ductility and energy absorption of FRC significantly due to the fiber bridging mechanism between the fibers and matrix thus improves bond strength. **Trilok Gupta et al. [17]** stated that, due to the inclusion of rubber fibers and SF in concrete, the energy absorption at first crack formation and ultimate failure was significantly improved. The ductility performance of rubber fiber reinforced concrete increases with increased volume of rubber fiber. **Vijayakumar et al. [18]** the test results observed that the workability of concrete decreases with increased fiber volume and the hardened properties of concrete were significantly improved because of the inclusion of lathe fibers, which in further enhances the strength characteristics subjected to static and impact loadings compared to conventional concrete. **Ramakrishna et al. [19]** it was found that the impact resistance of mortar slab reinforced with natural fibers increased by 3 to 18 times when compared to plain mortar slab and concluded that the impact strength of coir fibers reinforced mortar slab showed better performance than all other types of fibers.

There is still a lack of research on the durability of high-strength steel fibre reinforced concrete subjected to static and impact loadings. Consequently, a better understanding of this subject is very important. The flexural and impact resistance of reinforced SFRC specimens have been cast and tested in this study and the findings are compared to traditional RCC specimens.

2. Experimental Program

2.1 Materials used

The following materials were used throughout the entire experimental work and the physical properties of materials such as cement, fine and coarse aggregates were tested as per the standard specifications. Properties like physical, chemical and mechanical properties of materials for cement, fine aggregate, coarse aggregate and steel fibres etc. are presented in the following sections.

2.1.1 Cement

Ordinary Grade 53 Portland Cement (OPC) obtained from the local supplier and compliant with **IS 12269-1987[20]**was used.

2.1.2 Fine aggregate

River sand, conforming to grade III as per IS 383-1970 that is available from a local source has been used. The sand passing through 4.75 mm and retained on 150 µm IS sieve was used. The physical properties of aggregates were studied as per **IS 2386-1986[21].**

2.1.3 Coarse aggregate

Crushed granite aggregate available from local sources has been used. The aggregate passing through 12.5 mm and retained on 10mm IS sieve was used.

2.1.4 Steel fibers

Hooked end steel fibers were used with a circular cross-section of 1 mm in diameter and 30 aspect ratio.

Table 1

Mix proportions of the concrete mixtures for 1m^3

Type of mix	Cement (kg)	FA (kg)	CA (kg)	Water (lit.)	Fiber (%)	Mode of compaction
RCC	470	470	1316	183	-	Hand
SFRC	470	470	1316	183	1	Hand

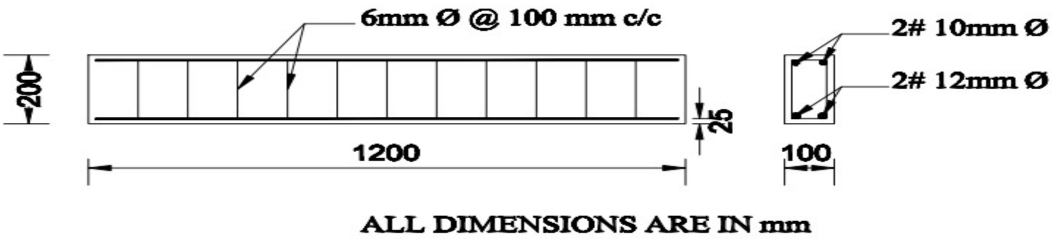


Fig.1 - Reinforcement Details of Beam.

2.1.5 Water

Fresh and portable water which is available from local sources having a pH value of 7 confirming to **IS 456-2000[22]**is used for casting and curing of specimens.

2.2 Mix proportions

High strength concrete with M50 grade of concrete mix 1:1:2.8 and water cement ratio of 0.39 were used for casting of reinforced beam and slab specimens. The mix proportions of concrete mixtures are presented in the Table 1.

2.3 Mixing, Casting and Curing

2.3.1 Preparation and Casting of Beams

The flexural strength test was conducted on 100 x 200 x 1200 mm beam specimens. The beam is reinforced with 2 nos. at the bottom of 12 mm diameter Fe 415 steel bars and 2 nos. at the top of 10 mm diameter Fe415 steel bars as hanger bars and 6 mm diameter stirrups at 100 mm c/c spacing, and the reinforcement details are shown in Figure 1. First, the mould was kept on a smooth levelled surface, and for easy removal of the specimen from the mould, oil coating was done on the sides of the mould. After 24 hours, the sample was removed and kept in water for 28 days and allowed to dry at room temperature for one day. On all four sides of the beam, white washing was performed for good visibility of the first crack formation and pattern of failure.

2.3.2 Preparation and Casting of slab

The impact resistance was carried out on 600 x 600 x 50 mm slab samples which were cast and tested for 28 days. As shown in Figure 2, slab specimens were reinforced with HYSD bar of Fe 415 having a diameter of 8 mm at a spacing of 150 mm c/c in both directions. After 24 hours, the specimens were demoulded and kept in water for 28 days and then removed from the water and put at room temperature for one day. For easy visibility of cracks, which are created on the surfaces by visual observation, white washing was performed on the top and bottom surfaces of the slab.

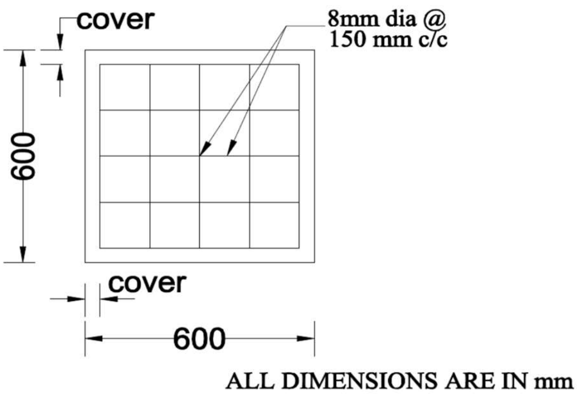


Fig. 2 - Reinforcement Details of Slab

2.4 Testing of specimens

he specimens were removed and cleaned off the surfaces with clean cloth after 28 days of water curing and allowed to dry at room temperature for 1 day.

2.4.1 Testing Procedure of SFRC Beams under Static Loading

To investigate the flexural behavior of SFRC beam (100 x 200 x 1200 mm) containing a constant fiber content (1 %) by volume fraction subjected to two-point bending test using a self-balancing loading frame with a capacity of 1000 kN. The test setup and loading arrangements areshown in Figure 3. The machine was controlled by the deflection measured using linear velocity displacement transducers (LVDTs) placed on the specimen. The load deflection responses at various stages such as first crack, yield point, ultimate point and breaking point and their corresponding mid span deflections were measured by using LVDT.

Fig. 3 - Flexural Test Setup (Two-Point Loading)

2.4.2.Testing Procedure of SFRC under impact Loading

The setup for drop weight impact testing was manufactured in compliance with **ACI Committee 544.2R-89[23]**for slab testing subject to impact loading, as shown in Figure 4. The impact measuring system consists of a 4.5 kg steel ball that is attached to a steel wire that passes via a frictionless pulley.

The steel ball is lowered from a height of 457 mm to meet the middle of the slab. It reported the number of blows needed to initiate the initiation of the first crack and ultimate failure. The specimen's energy absorption capacity is determined using the expression below.

Energy absorption (E) = mgh x N

Where,
m is the mass of steel ball
g is the acceleration due to gravity in kgm/s^2
h is the drop height
N refers to the number of blows

Fig. 4 - Drop weight impact loading test setup.

3. Results and discussions

3.1 Load deflection Response

The load-deflection responses of SFRC and RCC specimens at various stages are presented in the Table 2. The ultimate load carrying capacity of SFRC beam is reached to 110.7 kN and first crack load was yielded 50.8 kN. Whereas, the first crack and ultimate load carrying capacity of RCC beam were found to be 73.8 kN and 29.8 kN respectively. Figure 5, clearly shows that the load carrying capacity of SFRC is higher than conventional RCC beam. This may be attributed due to the addition of fibers significantly improved the load carrying capacity of specimen.

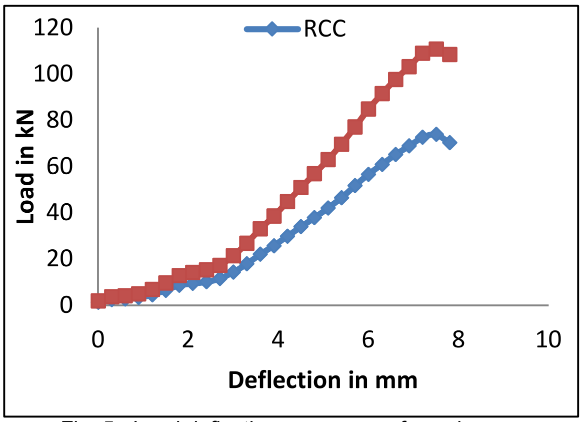


Fig. 5 - Load deflection responses of specimens.

The ultimate moment of resistance is calculated as per the **IS 456:2000[22]**specifications. The bending moment at ultimate stage from experimental results are well satisfied with the analytical design consideration. The moment of resistance and capacity ratio of RCC and FRC beam specimens

Table 2

Load deflection responses of RCC and SFRC beams at various stages

Sl. No.	Type of Mix	First Crack stage		Ultimate stage		Failure stage	
		Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
1.	RCC	29.8	4.2	73.8	7.5	67.2	8.1
2.	SFRC	50.8	4.5	110.7	7.5	108.4	7.8

Table 3

Comparison of Experimental results with theoretical design

S.No.	Type of mix	Theoretical moment, $M_{theo.}$ (kNm)	Experimental moment, $M_{exp.}$ (kNm)	Capacity Ratio $M_{exp.}/M_{theo.}$
1.	RCC	12.845	13.53	1.053
2.	SFRC	12.955	20.167	1.557

are calculated and presented in the Table 3. From the test results found that the ultimate moment of resistance of FRC specimen is increased by 47.8 % when compared to the RCC specimen.

3.2 Flexural strength

The flexural strength of steel fiber reinforced concrete is higher than RCC as shown in Figure 6. The test results reveal that the flexural strength of SFRC is increased by 35 % when compared to RCC. It can be attributed due to the incorporation of fibers in concrete enhances the flexural performance of SFRC.

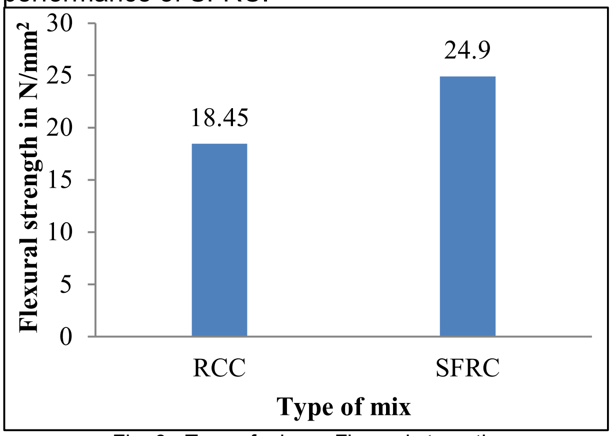


Fig. 6 - Type of mix vs. Flexural strength.

3.3 Toughness

Toughness is calculated from area under the load deflection curve. The toughness of SFRC specimen is increased by 50% compared to RCC specimen. Figures 7 (a) and (b) illustrated the area under the load defection curves at ultimate load (toughness) for RCC and SFRC specimens. The addition of fibers in concrete improves the ductility performance enhances the load defection responses at ultimate stage.

3.4 Ductility factor

Ductility factor is the ratio of deflection at ultimate stage to the deflection at yield point. Figure 8 illustrated the ductility factor of SFRC and RCC specimens. From the test results found that the ductility factor of SFRC is higher than RCC specimen. The incorporation of steel fibers in concrete increased the ductility factor by 27.5% when compared to RCC.

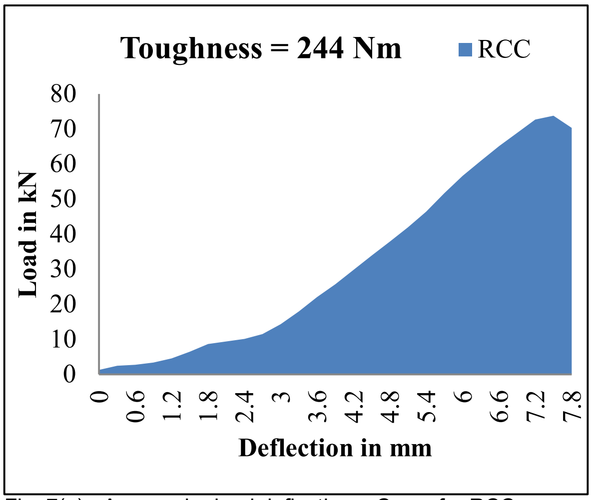


Fig. 7(a) - Area under load deflection – Curve for RCC.

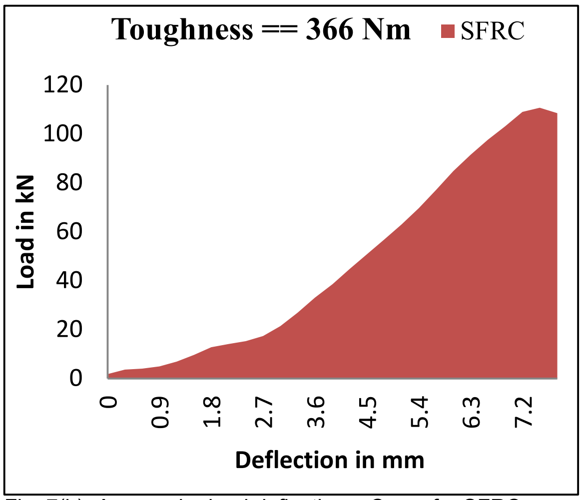


Fig. 7(b)- Area under load deflection – Curve for SFRC.

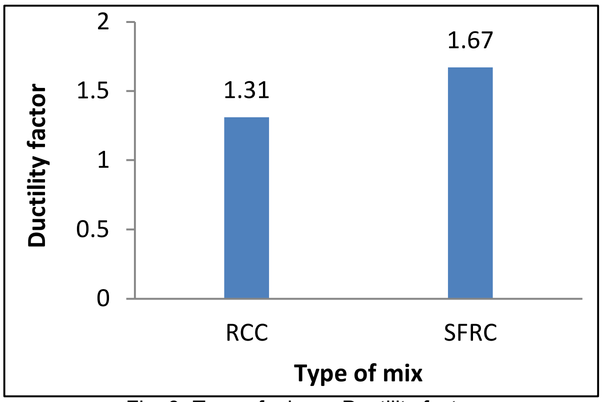


Fig. 8 -Type of mix vs. Ductility factor

3.5 Ultimate stiffness

Stiffness is the rigidity of the element. It is the extent at which it resists the deformation to the applied load. Figure 9a illustrates the ultimate stiffness of SFRC and compared the results with RCC specimens. The addition of fibers in concrete enhancing the load carrying capacity without increasing the deformation resulted significantly improves the stiffness performance. Stiffness was increased by 50% when compared to RCC specimen.

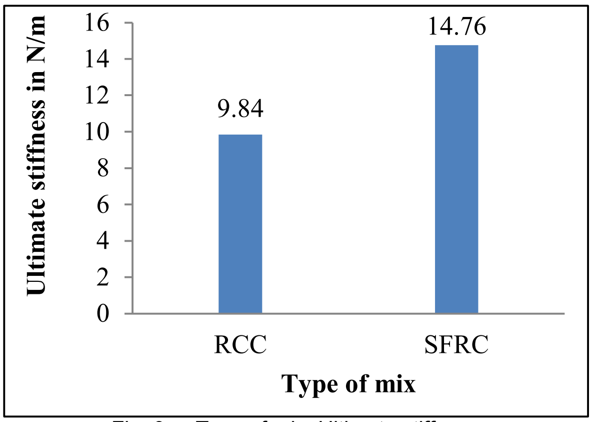


Fig. 9a - Type of mix. Ultimate stiffness

3.6 Fracture energy

Fracture energy is calculated based on **RILEM TC 50- FMCTechnical committee[24]**. Fracture energy is the amount of toughness or energy dissipated per unit area of the specimen and mainly and mainly depends on the area under the load deflection curve known as toughness. The fracture energy of SFRC and RCC were found to be 20303 N/m and 12396 N/m. The fracture energy of SFRC is higher than RCC specimen. This may be attributed due to the incorporation of fibers enhancing the fiber bridging mechanism thus improves the bond strength between the matrix.

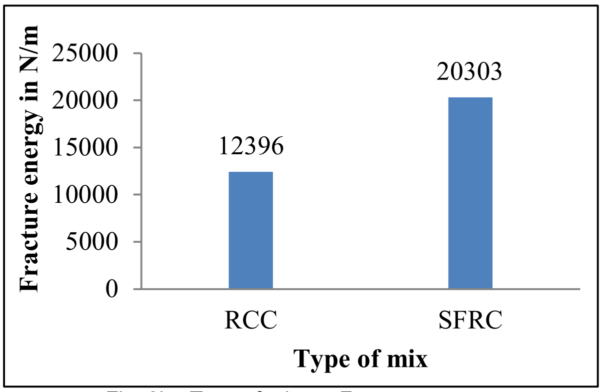


Fig. 9b - Type of mix vs. Fracture energy.

3.7 Energy absorption capacity

Figure 10(a) illustrated the number of blows needed for the initiation of the first crack and the eventual failure of reinforced concrete slab samples with and without steel fibers. The number of blows required was greater than that of the RCC slab specimen to allow the first crack to develop. Due to the method of fiber bridging between the matrix, the inclusion of concrete fibers prevented the growth of the first crack. The first crack and ultimate energy absorption capacity of SFRC and RCC specimens are illustrated in Figure 10(b). The energy absorption potential of the SFRC slab is clearly shown to be superior to the traditional RCC slab. The test results show that the energy absorption potential was increased by 173.5 and 3.72 times respectively at the initiation of the first crack and ultimate failure of the reinforced SFRC slab when compared to RCC slab specimen. It may be attributed due to the process of fiber bridging, thereby improving the bond strength between the matrix.

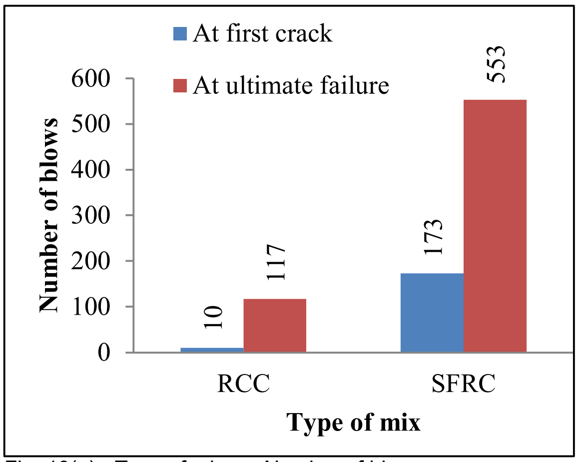


Fig. 10(a) - Type of mix vs. Number of blows.

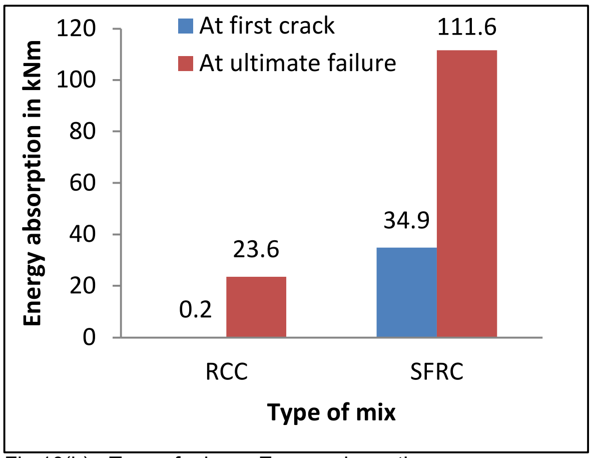


Fig.10(b) - Type of mix vs. Energy absorption

3.8 Impact residual strength ratio

The impact residual strength ratio or ductility index of SFRC and RCC specimens are illustrated in the Figure 11. It is the ratio between energy absorption at ultimate failure to the energy absorption a first crack. The number of blows needed to cause first crack is more due to the incorporation of fibers in concrete arrested the formation of cracks. The impact residual ratio of SFRC is less than RCC specimen.

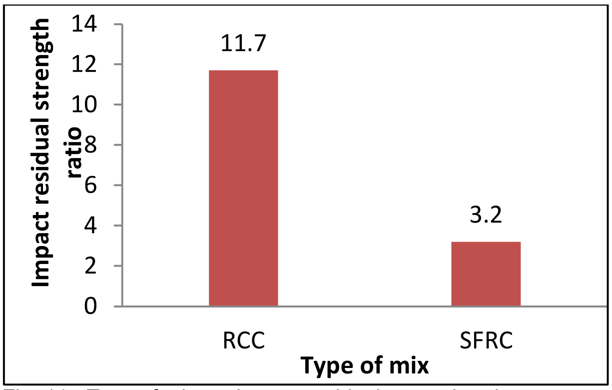


Fig. 11 - Type of mix vs. Impact residual strength ratio.

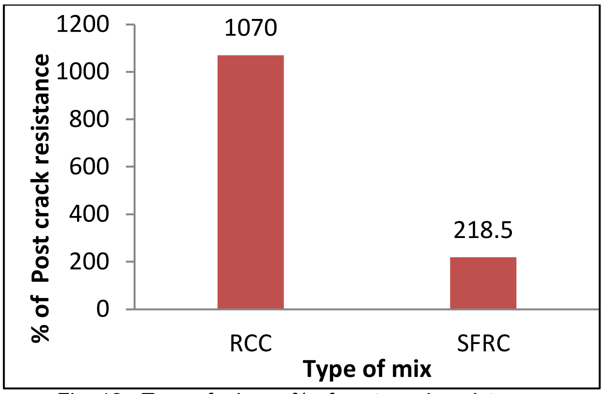
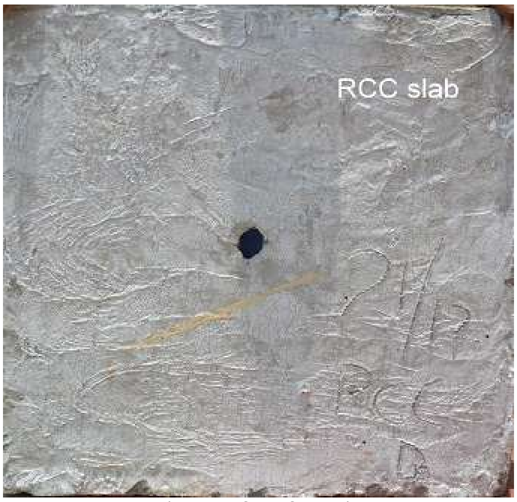


Fig. 12 - Type of mix vs. % of post crack resistance.



(Top surface failure)

(Bottom surface failure)

Fig. 13 - Failure of RCC specimen after 117 blows.

(Top surface failure)

(Bottom surface failure)

Fig. 14 - Failure of SFRC specimen after 553 blows.

3.9 Post crack resistance ratio

Figure 12 shows the percentage of post crack resistance ratio of SFRC and RCC specimens. The percentage of SFRC post crack resistance is lower than that of the RCC slab. Due to the first crack energy potential of SFRC, the decreased post crack resistance is more than energy absorption at ultimate failure.

3.10 Failure pattern

Figures 13 and 14 demonstrate the failure pattern of slab specimens. For ultimate failure, the SFRC specimen needed more blows than the RCC slab specimen. The loss of the SFRC slab specimen is slightly lower than that of the RCC. Punching shear failure was observed in both reinforced SFRC and RCC slab specimens.

The failure of RCC slab is more with lesser amount of energy due to the matrix is converted into powder form. In SFRC slab, the cracks were propagated in a radial manner and extended away from its centre due to fibre bridging mechanism of the matrix.

4. Conclusions

Based on the results obtained from the tests on the performance of high strength fibre reinforced concrete under flexure and impact loading conditions, the following conclusions can be drawn,

- The load carrying capacity of SFRC is higher than conventional RCC specimen.
- The flexural strength of steel fiber reinforced concrete increased by 31% when compared to RCC.
- The ductility factor of SFRC was significantly increased by 27.5% than RCC.
- The toughness of concrete with addition of fibers increased by 50% compared to concrete without fibers.
- The fracture energy of SFRC is higher than RCC.
- The energy absorption yielded 34.6 kNm and 0.202 kNm at the initiation of the first crack of the SFRC and RCC slabs.
- The ultimate energy absorption of SFRC with conventional reinforcement is increased by 3.72 times compared to RCC slab.
- RCC is superior to the first crack energy absorption potential of SFRC. It can be related to the growth of cracks due to the addition of fibers arrested, thereby improving the energy absorption at the initiation of the first crack.
- The impact residual strength ratio and percentage of post crack resistance of SFRC were lesser than RCC slab specimen.

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