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RESEARCH

Optimisation of polypropylene and steel fibres for the enhancement of mechanical properties of fibre-reinforced concrete

Bhawani Antarvedi[1] · **Nawal Kishor Banjara**[2] · **Suvir Singh**[2]

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Abstract
The study is aimed to determine the effect of varying percentage of dosage of steel and polypropylene fibres in fresh concrete properties and find that optimum percentage of steel–polypropylene fibre which can enhance the compressive strength and flexural strength and also delays the process of crack initiation and reduction of shrinkage cracks. The results present that flexural and compressive strength characteristics influenced by steel and polypropylene fibres. Uses of steel fibres are found to be more effective for the enhancement of flexural strength characteristics and reducing the cracks propagation. Two types of steel fibres, namely, crimped steel fibre and hooked end steel fibre, are used separately with polypropylene fibres. The crimped steel fibre is found to be more effective than the hooked end steel fibre and it is found that the workability is also affected by the addition of steel fibres. Workability is more affected by the crimped steel fibres than hooked steel fibres. The amounts of fibres in the SPFRC mixes are varied from 0.5 to 1% of the total volume of concrete. The variation is also carried out in the combination of steel and polypropylene fibres to enhance the properties of SPFRC Mixes. Steel fibre varies from 0.25 to 0.85%, whereas polypropylene fibre varies from 0.15% and 0.25%. After all the tests carried out on the SPFRC samples, it showed that the type of steel fibre to be preferred with optimum content of fibre mix is proposed.

Keywords Steel fibres · Polypropylene fibres · Flexural strength · Compressive strength · Workability

Introduction

The application of plain concrete is limited by a number of factors, including its low ductility, low resistance to cracking, high brittleness, poor toughness, etc. Slab cracking may be caused by structural and environmental reasons, although the majority of cracks are caused by internal micro-cracks and the material's inability to withstand tensile stresses. Surface cracks in the slab were also formed by shrinkage. These shortcomings are addressed using Steel–Polypropylene Fibre-Reinforced Concrete (SPFRC). Steel–Polypropylene Fibre-Reinforced Concrete (SPFRC) is formed when concrete is reinforced with steel and polypropylene fibres. With the inclusion of fibres as reinforcement works as a crack arrestor and improves its static and dynamic properties by preventing the propagation of cracks. Also, enhancement in flexural strength characteristics and compressive strength characteristics as well as increases its tensile strength. Combination of both steel and polymeric fibres increases the overall performances of concrete (Kumar et al., 2014).

Steel–polypropylene fibre-reinforced concrete (SPFRC) is composite of conventional Concrete and uniformly dispersed steel and polypropylene fibre. Steel fibre provides the structural improvement, whereas polypropylene fibre enhances the resistance to plastic shrinkage cracking.

Chang et al. (1995) studied the behaviour of fibre-reinforced concrete. They suggested that with the use of steel fibres, increases the flexural strength and ductility of concrete due to the ability of the fibres to restrain cracks. All concrete contains flaws since its early stage which could increase in size under loads even it is less than 50% of the ultimate load. The fatigue failure mechanism for concrete or mortar develops in three stages:

✉ Bhawani Antarvedi
bhawani2609@gmail.com

Nawal Kishor Banjara
nawal1234@gmail.com

Suvir Singh
suvir_singh@yahoo.com

[1] AcSIR, CSIR-Central Building Research Institute, Roorkee 247667, India

[2] CSIR-Central Building Research Institute, Roorkee 247667, India

(i) The first stage, flaw initiation, is an inherent quality of concrete such as the presence of air voids and weak or debonded regions between aggregate and paste.
(ii) The second stage, the slow growth of flaws to a critical size, is a complex mechanism in a heterogeneous material, such as concrete. The growth of the inherent flaws under static loading of concrete is called micro-cracking. From the previous studies, it was stated that there would be some flaws of a shape, size, and orientation in the stress field that may grow slowly in a stable manner to a critical size and then increase rapidly.
(iii) In this third stage, when a sufficient number of unstable cracks join to form a continuous crack, failure of the member follows quickly.

The first and third stages of the failure mechanism cannot be prevented, but there is the possibility of delaying the growth of the flaws in the second stage using closely spaced and randomly dispersed steel and polypropylene fibres as reinforcement in the concrete or mortar.

It is evident that the fibre composition, aspect ratios, orientations, and geometrical shapes all affect the behaviour of SPFRC (Chang et al., 1995; IS 2013; Kang et al., 2011; Kumar et al., 2014; Qureshi et al., 2013). Figure 1 shows the concept of SPFRC mixes. The mechanical properties of concrete are also significantly improved by the uniformly dispersed fibre in the concrete matrix, particularly in terms of dynamic and fatigue resistance, shear, and post-cracking strength (Kang et al., 2011; Kumar et al., 2014; Rokade et al., 2014; Banjara et al., 2018). Fibre parameters (diameter, length, and volume proportion), matrix fluidity, technique of placement, and form shape all have a significant impact on fibre distribution. The strengthening effect of fibre is lessened by uneven fibre dispersion (Kang et al., 2011). If the fibres are unevenly distributed and perpendicular to the load direction, the tensile strength enhancement of composites will be lost. There is a significant loss in the fresh qualities of concrete following the inclusion of fibres (IS 2013; Yap et al., 2013). By uniformly dispersing the fibres in the mix and lowering the viscosity of cement paste, the use of superplasticizer, plasticizer, or mineral admixtures can increase workability (Kaikea et al., 2014, Rokade et al., 2014). Since with the addition of fibres, it considerably improves the flexural strength characteristics, hence, SPFRC is more efficient than the normal concrete mixes.

Behaviour of steel and polypropylene fibres in concrete

The experimental work is oriented towards concrete reinforced with steel and polypropylene fibres, so it is most important to understand how these fibres behave in the concrete mix. The plain concrete structure cracks into two pieces when the structure is subjected to the peak tensile load and cannot withstand further load or deformation. The fibre-reinforced concrete structure cracks at the same peak tensile load, but does not separate and can maintain a load to very large deformations due to the ridging effect. The area under the curve presents the energy absorbed by the SPFRCs after cracking when subjected to tensile load. This can be termed as flexural toughness or the post-cracking behaviour of the SPFRCs (Rokade et al., 2014).

In hardened FRC, fibres of much elastic modulus are effective in crack prevention. For both of plastic shrinkage and structural strength, a proper combination of micro-polymeric fibres (i.e., polyester, polypropylene, polyethylene, nylon, etc.) and macro-fibres (which may be polymeric or steel fibre) may give the economical span. Hence, it can be concluded that to control cracks in all stages of concrete, hybrid fibres can be more effective.

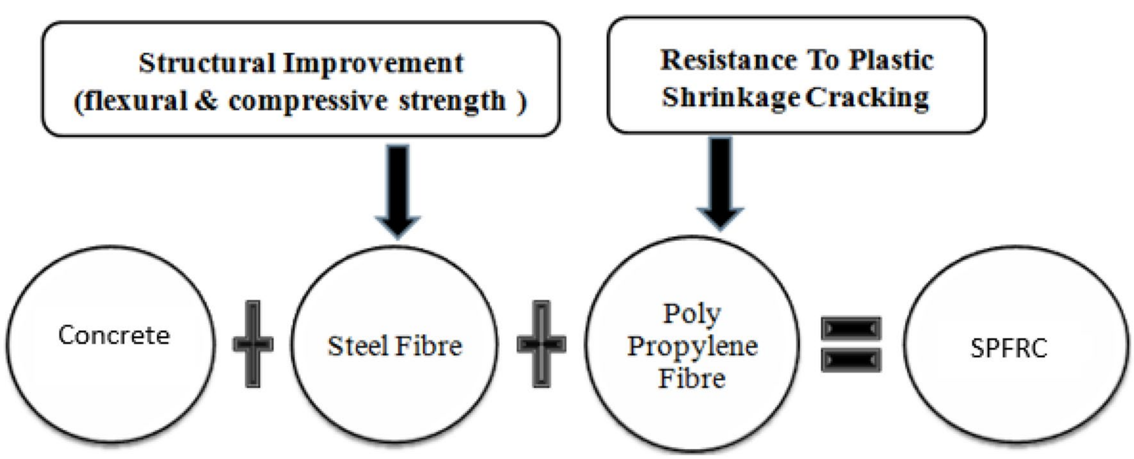

Fig. 1 Concept of SPFRC mixes (Kumar et al., 2014)

Objective of the study

The main objective of the present study is to assess the effect of steel and polypropylene fibres on concrete mixes. Further, to achieve this, the broad objectives of the study are listed as follows:

(1) To determine the influence of steel and polypropylene fibres on workability of mixes.
(2) To determine the effect of steel and polypropylene fibres on the compressive strength characteristics of mixes.
(3) To determine the effect of steel and polypropylene fibres on the flexural strength characteristics of mixes.

Significance of the study

Steel–polypropylene fibre-reinforced concrete is useful in concrete structures to control cracking (plastic shrinkage, reflection etc.), to enhance flexural strength (Qureshi et al., 2013), to impart high toughness, to provide post crack ductility, and to improve impact resistance and fatigue resistance (Rokade et al., 2014).

SPFRC has been used to provide durable concrete layer with improved cracking resistance and reduction in the required slab thickness (Banjara et al., 2019).

The study is required to determine the effect of varying percentage of dosage of steel and polypropylene fibres in fresh concrete properties and find that optimum percentage of steel–polypropylene fibre which can enhance the more compressive strength, flexural strength, and fatigue life.

Scope of the study

The scope of work is limited to concrete mixes modified using steel and polypropylene fibres. Mainly, two types of steel fibres, i.e., crimped and hooked end steel fibres, are used. The study is limited to a total percentage of fibre content 0.5% and 1%. In the present study, steel fibre varies from 0.25 to 0.85%, whereas polypropylene fibre varies from 0.15 to 0.25%. To enhance the workability of SPFRC mixes superplasticizer is used. Further, the study emphasises on compression and flexural strength characteristics of SPFRC mixes. The paper focuses on the tests results and analysis of SPFRC Mixes. Further, the paper deals with the results of workability characteristic, compressive strength characteristic, and flexural strength characteristic of various SPFRC mixes.

Methodology for usage of steel and polypropylene fibres in concrete mixes

The evaluation of SPFRC properties includes various stages such as determination of properties of constituents of SPFRC like aggregate, sand, and cement, and also to study the effect of variation of dosage of fibre and their geometry on the SPFRC mixes. Figure presents methodology for usage of steel and polypropylene fibres in Concrete mixes. When adopting the SPFRC Mix, there may be the variations in the target strength at a certain age due to variations in quality of cement, grading of aggregates, degree of compaction, etc. Hence, to check the suitability of materials, tests are conducted as per the relevant standards. To check the suitability of cement, fineness test, standard consistency test, initial and final setting time test, and strength test is carried out.

Similarly, the properties of the aggregate are required to be evaluated so as to determine that whether they can be effectively used for the purpose they are intended to be. Important tests are required like sieve analysis, specific gravity & water absorption test, aggregate impact test, and aggregate abrasion test.

Before each batching, the mixer was washed and cleaned properly, so that the mixer is free from any other chemicals or impurities in it. Whilst mixing, first, a part of coarse aggregate and fine aggregate were added and allowed to mix for a minute. A little amount of water is added to the mix, so that when cement and fibres are added, they stick to the aggregate. Since PP fibres absorbs water, it is added in the dry mix itself. Half the amount of PP fibre is added, then it is rotated for half a minute. Remaining PP fires are added in the cement bag itself and mixed thoroughly. Now, complete aggregates and cement were added to the mix. It is again rotated for half a minute. Now, 60% of water is added to the mix. Then, superplasticizer is well mixed with the remaining water and stirred. It is then poured to the mix. As superplasticizers acts as lubricants, it was required to run the mix for 4–5 min, so that we can achieve a well-homogenous mix at the end. Concrete is placed uniformly over the length of the standard steel mould in three layers and compacted satisfactorily. Demoulding is done after 24 h and the specimens are cured under water. After 7 days and 28 days, the specimens are removed from curing tank and taken for testing. Then, properties of fresh concrete are obtained by slump test, compression test, and flexure test. The amounts of fibres in the SPFRC mixes are varied from 0.5 to 1% of the total volume of concrete. The variation is also carried out in the combination of steel and polypropylene fibres to enhance the properties of SPFRC Mixes. Steel fibre varies from 0.25 to 0.85%, whereas polypropylene fibre varies.

This paper also presents the strategy of research work, where systematic approach is applied to get outstanding results. For this purpose, two types of steel fibres, namely, crimped steel fibre and hooked end steel fibre, are used separately with polypropylene fibres. After that, compression and flexural test is carried out on the SPFRC samples. Now, after comparing the test results, the type of steel fibre to be preferred with Optimum Content of Fibre Mix is proposed (Fig. 2).

Material characteristics

Cement

Cement used in this present study was ultra tech ordinary Portland cement 43 grade confirming to IS 8112-2013. Cement was stored in dry place to avoid the adverse effect of humidity on cement properties. To find the suitability of OPC cement, various tests were conducted like fineness test, consistency test, initial setting and final setting time test, and compressive strength test are carried as per Indian specifications. Table 1 presents the results of test on Ordinary Portland Cement and their acceptable limits as per the IS:1489-Part 1 (Indian Standard 1991b) specifications.

The results show that the consistency, initial and final setting time, and compressive strength were observed within the specified limits of Indian standard specifications.

Coarse aggregates

When concrete is formed, aggregates comprise as much as 60–80% of a typical concrete mix, so they must be

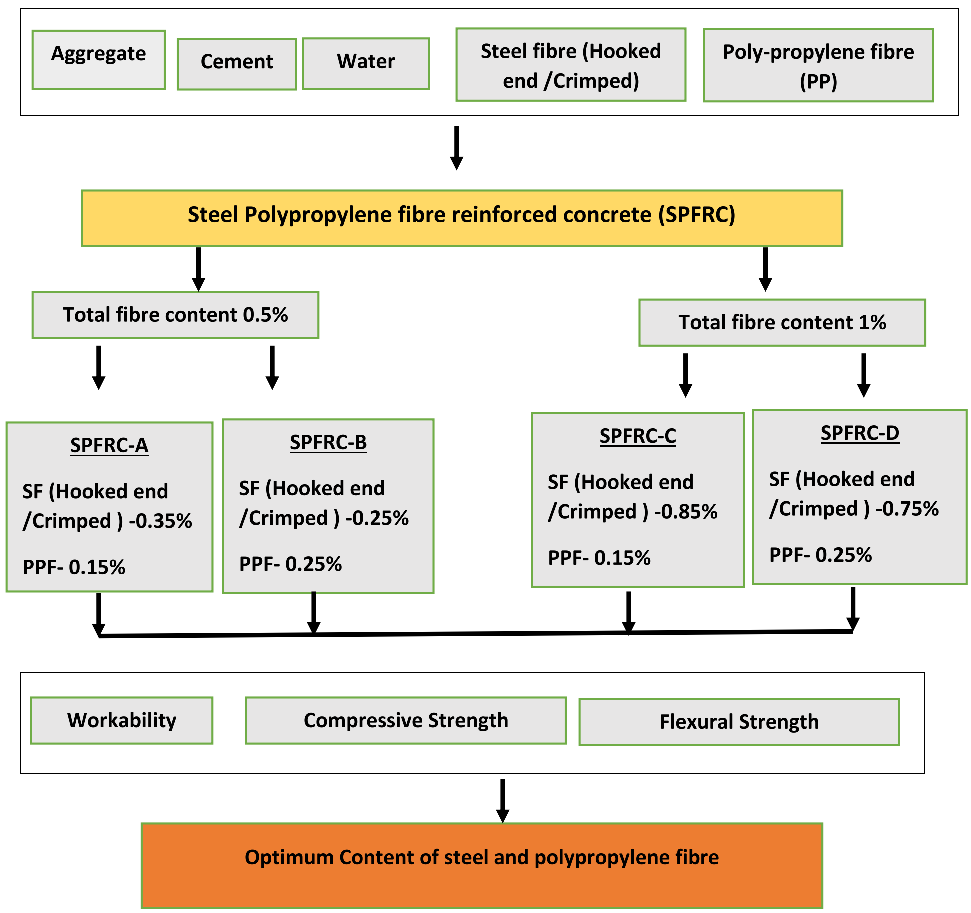

Fig. 2 Methodology for usage of steel and polypropylene fibres in concrete mixes

Table 1 Results of test on cement

S. No.	Test		Results	IS Specifications
1	Normal consistency		33.5%	Min 33%
2	Initial setting time		2 h 35 Min	Minimum 30 Minutes
3	Final setting time		4 h 20 Min	Max 10 Hours
4	Compressive strength	At 3 days	22 MPa	23 MPa
		At 7 days	32 MPa	34 MPa
		At 28 days	42 MPa	43 MPa

properly selected to be durable, blended for optimum efficiency, and properly controlled to produce consistent concrete strength, workability, finishability, and durability also aggregates play major role and influence in the properties of both fresh and hardened concrete. To find the suitability of aggregates for the SPFRC mix design, the sieve analysis, specific gravity test, water absorption test, aggregate impact test, and loss angles abrasion test are carried out as per IS:2386 (Bureau of Indian Standards 1997).

Tables 2 and 3 present the results of test on aggregates and their grading requirement as per IS: 44-2008 specifications.

The above results of test on aggregates present that all the properties are observed within the specified permissible limits as per IS: 44-2008. Hence, this is suitably used for SPFRC mix design.

Fine aggregates

Fine aggregates used in this study were natural clean sand from river sized 4.75 mm maximum and 150 micron minimum with specific gravity 2.67 conforming to zone II. As per IS:SP46-2013, if the fibre dosage is more than 1% by volume of concrete, the total finer material including cement, mineral admixture, and finer portion of fine aggregates together passing through 300 micron sieve should not be less than 400 kg/m^3. Table 4 presents the grading requirement of zone-III sand as per IS: 44-2008 guidelines.

Steel fibres

The steel fibres (hooked and crimped) used are as shown in Fig. 3. The properties of steel fibres are as given in Table 5.

Table 2 Results of test on aggregates

S. No.	Test	Results	IS specifications
1	Specific gravity of coarse aggregates	2.75	–
2	Specific gravity of sand	2.68	–
3	Water absorption	1.01%	2%
4	Aggregate impact value	16.4%	30%
5	Los Angles abrasion value	20.6%	35%

Table 3 Grading of coarse aggregates

S. No.	Sieve size (mm)	% Passing for the single-sized aggregate	IS specifications
1	40	100	100
2	20	100	85–100
3	10	16.8	0–20
4	4.75	4.3	0–5
5	2.36	1.1	–

Polypropylene fibres

The polypropylene fibres are shown in Fig. 4. The properties of polypropylene fibres are shown in Table 6.

Mix proportion

Design of SPFRC mixes

For getting probable strength of concrete, various proportion of mix design are checked, and from that, final proportion is selected as given in Table 7.

With the combinations of varying percentage of steel and polypropylene fibres various SPFRC mixes, i.e., SPFRC-A (SF—0.35% + PPF—0.15%), SPFRC-B (SF—0.25% + PPF—0.25%), SPFRC-C (SF—0.85% + PPF—0.15%), and SPFRC-D (SF—0.75% + PPF—0.25%) with hooked end fibre and crimped steel fibres were prepared. The design of mix was done as per guidelines of IS: 44-2008 (Indian Road Congress 2008) and is tabulated in Table 7. Ordinary Portland Cement (OPC-53) was used during the entire experimental work. Natural coarse aggregates of 20 mm nominal size and natural sand. Further to ease the placing of SPFRC mixes during casting, superplasticiser was added to enhance the workability requirement of SPFRC mixes. The dosage of super-plasticiser was used 0.5% by weight of cement. Table 8 presents the proportions of SPFRC mixes.

Table 4 Requirements of fine aggregates

S. No.	Sieve size	% passing
1	10 mm	100
2	4.75 mm	90–100
3	2.36 mm	85–100
4	1.18 mm	75–100
5	600 micron	60–79
6	300 micron	12–40
7	150 micron	0–10

Source IS: 44-2008

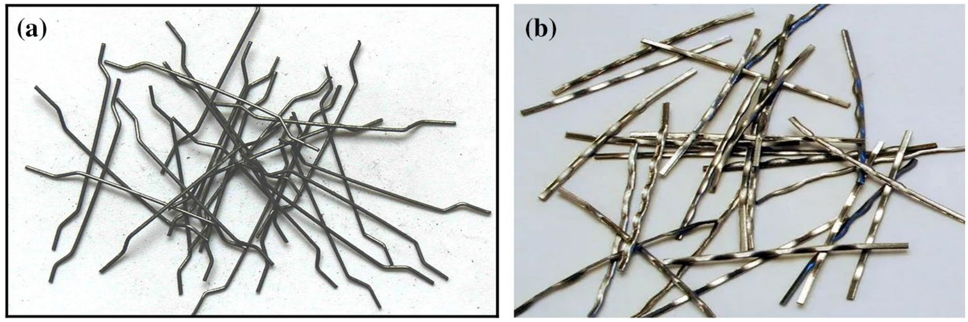

Fig. 3 **a** Hooked steel bars and **b** crimped steel bars

Table 5 Properties of steel fibres

Specification	Crimped	Hooked
Length (mm)	37	35
Diameter (mm)	0.5	0.55
Aspect ratio	100	55
Tensile strength (in MPa)	700	1100
Specific gravity	7.0	7.0

Fig. 4 Polypropylene fibres

Table 6 Properties of polypropylene fibres

Properties	Values
Form	Monofilament
Length (mm)	25–50
Diameter (mm)	0.34
Aspect ratio (L/D)	158.8
Specific gravity	0.91
Tensile strength (MPa)	680
Elastic modulus (GPa)	0.68
Elongation at break (%)	19.1
Melting point (°C)	168

Table 7 Mix proportion

Material	Proportion by weight of cement	Weight in Kg/m3
Cement	1	544.11
Water	0.34	185
Fine aggregate	1.124	677
Coarse aggregate	1.85	1006

The total fibre content for the mix SPFRC-A and SPFRC-B is 0.5% by volume of concrete, whereas for the mix SPFRC-C and SPFRC-D, the total fibre content is 1% by volume of concrete.

Experimental investigation of SPFRC mixes

The concrete mix design was proposed using IS: 10262:2009 (Indian Standard 2009) with the water-to-cement ratio of 0.43 for the design compressive strength of 48.25 N/mm^2 and design flexural strength 4.86 N/mm^2, a total of 36 cubes size 150 mm, and 36 beams size (100 × 100 × 500) mm were casted. The experimental results consist of the flexural strength characteristics and compressive strength characteristic of SPFRC Mixes. Total 48 cubes of 150 mm size and 48 beams of 100 × 100 × 500 mm size with varying percentage of steel and polypropylene fibres were casted. The results of various SPFRC Mixes are explained in the further sections.

Workability of SPFRC mixes

Slump test is adopted as the primary measure of concrete workability confirming to IS: 1199-1959, and was performed to evaluate the influence of PP fibres and steel fibres on workability. The apparatus for conducting the slump test consist of metallic mould in the form of frustum of cone having internal dimensions, bottom diameter

Table 8 Proportions of SPFRC mixes

W/C = 0.38
Super plasticizer (SP) = 0.5% by weight of cement

Total fibre content	Mix	Quantity (kg/m^3)						
		Cement	CA	Sand	SF	PPF	SP	Water
0.5%	SPFRC-A	465	1223	589.64	27.48	1.36	2.32	176.7
	SPFRC-B	465	1224.68	590.42	19.63	2.27	2.32	176.7
1%	SPFRC-C	465	1213.93	585.24	66.73	58.88	2.32	176.7
	SPFRC-D	465	1215.22	586.22	1.36	2.27	2.32	176.7
Nil	NCC	465	1229.75	592.86	Nil		2.32	176.7

Fig. 5 Slump test apparatus

20 cm, top diameter 10 cm, and height 30 cm. Figure 5 shows the slump test apparatus test used in the laboratory and the process of tests being conducted.

In the present experimental work, polypropylene fibre and two types of steel fibre, namely, crimped steel fibre and hooked end steel fibre, were used and their influence on workability behaviour is accessed.

Compressive strength of SPFRC specimens

Various SPFRC Mixes were prepared with varying percentage of steel and polypropylene fibres to access the compressive strength characteristics. The compression strength of concrete is tested for normal concrete specimen with different percentage of steel fibre from 1 to 10% by weight of cement. All the tests are conducted after 28 days from casting date. The tests are conducted on UTM.

The strength is calculated by the following formula:

Compression strength $(\sigma) = \frac{P}{A}$,

where

σ = compression strength.

P = load at which cube fails in N.

A = cross sectional are of cube in mm^2.

Split tensile strength

The test is conducted on U.T.M., and the concrete is casted of with cement with various percentage of steel fibre (1–10%) and normal concrete specimen, the result of which are calculated by the following equation:

$$\text{Tensile strength}(\sigma) = \frac{2P}{\pi DL},$$

where

σ = Tensile strength in N/mm^2.

P = Compressive Line Load at failure in N.

L = Length of cylinder in mm.

D = Diameter of cylinder in mm.

The test was conducted as per IS 5816-1999. For tensile strength test, cylinder specimens of dimension 150 mm diameter and 300 mm length were cast. The specimens were demoulded after 24 h of casting and were transferred to curing tank wherein they were allowed to cure for 7 and 28 days. These specimens were tested under compression testing machine. In each category, three cylinders were tested and their average value is reported (Fig. 6).

Flexure strength test on beam

Flexural tensile strength or modulus of rupture of concrete has been determined by applying the failure load on prismatic specimen after 28 days of curing with a size of 100 × 100 × 500 mm, using the universal testing machine of 100 ton capacity as shown in Fig. 7 under four-point loading under rate of 0.5 mm/min. Flexural strength test was carried out in the same Universal testing Machine (UTM) as described earlier. The testing machine is capable of evaluating flexural strength based on IS 516 (Indian Standard 1959). The specimens were kept on the roller support, so that loading arrangements of the prism be a four-point loading. All rollers were mounted in such a way that load applied axially and without any torsional stress on the prism (Indian Standard 1991a). The loading

Fig. 6 Split tensile test

Fig. 7 Flexure test on beam

arrangements on the prism are shown in Fig. 8. The load was increased until the specimens fails. Here, the maximum load is noted which is used to calculate flexural strength of the concrete specimens. Also, the crack pattern that appeared were highlighted, so that the first crack appeared under a particular load can be evaluated. The location of the crack was also checked, in case if the cracks had appeared away from mid-span, then the distance of the crack from the end were noted. The flexural strength of the specimen is expressed as the modulus of rupture f_{cr}, which is stated as follows:

$$f_{cr} = \frac{pl}{bd^2},$$

f_{cr} = flexural strength (MPa),
b = measured width of the specimen (mm).

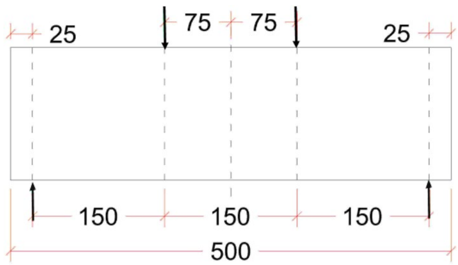

Fig. 8 Schematic diagram for loading arrangements

d = measured depth of the specimen at the point of failure (mm).

l = length of the span on which the specimen was support (mm).

P = maximum applied load (N).

Experimental results

Workability of SPFRC mix

Steel fibres considerably affect the workability behaviour. As the steel fibre content increases the workability decreases. Also when crimped steel fibre was used in place of hooked end steel fibre, a little reduction in workability was observed. The maximum slump loss about 52% was obtained in SPFRC-C mix made by crimped steel fibre having higher dose of steel fibre, i.e., 0.85%. Whereas in the same mix, when hooked end steel fibres were used, the reduction was about 44%, as shown in Fig. 9. The workability of SPFRC-C is followed by workability of SPFRC-D. In the SPFRC-D, the reduction was 40% observed when crimped steel fibres were used and 30% reduction was observed when hooked end steel fibres were used. For SPFRC-B made by hooked end steel fibre slump loss

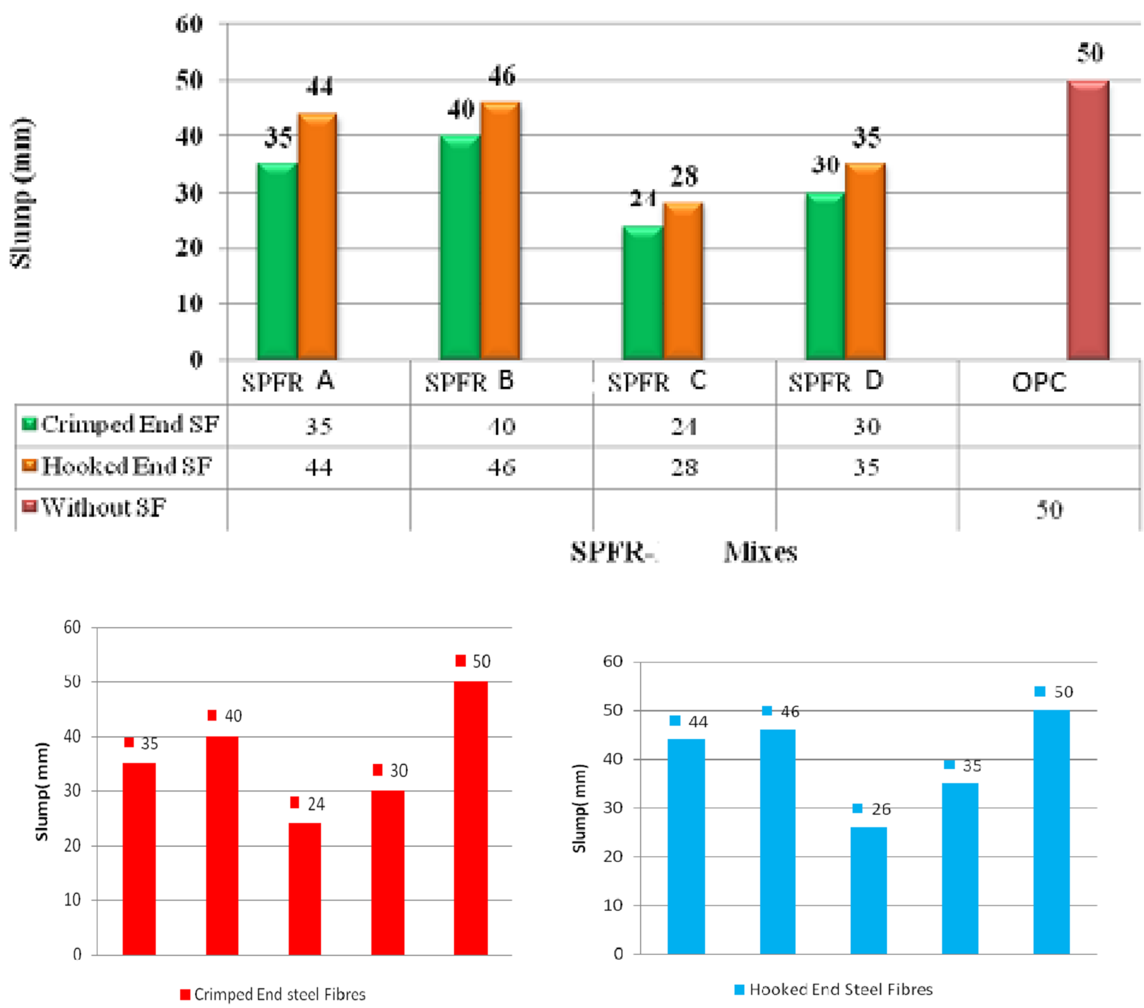

Fig. 9 Slump of SPFRC mixes

was less and it was about 8%. The reason of this reduction in workability characteristics is, crimped steel fibres form more strong fibre matrix bond than hooked end steel fibre. Due to this, viscosity of concrete increases and the distribution of cement matrix is restricted; hence, the reduction in the workability was observed in the SPFRC Mixes. Polypropylene fibres does not much affect the workability characteristics. Since the dosage of polypropylene fibres was low (0.15–0.25%), the workability did not had much effect. The addition of superplasticizer too had a positive impact on the workability by dispersing the fibres in mix uniformly and reducing the viscosity of cement paste. Figure 9 presents the slump of SPFRC mixes.

Compressive strength for mix with steel fibre

This section deals with the results of compression test on SPFRC Mixes. It is observed that compressive strength of all SPFRC mixes is more than compressive strength of plain concrete. Compressive Strength is considerably influenced by steel fibre and increases by increasing the quantity of steel fibre. In the present experimental work, the SPFRC Mixes were classified into two groups. One group includes the SPFRC made by crimped steel fibre and other group includes SPFRC made by hooked end steel fibre. The total fibre contents were 0.5% and 1%. Figure 10 presents the variation of compressive strength with percentage of steel fibre at 28 days. Also, Figs. 11 and 12 present the variation of compressive strength with percentage of steel fibre at 7 days. The results indicate when SPFRC-C includes crimped steel fibres, the compressive strength at 7 days increases by 32.2% than the normal concrete. Similarly, for 28 days, this value increases by 37% than normal concrete. On the other hand, when SPFRC-C comprises the hooked end steel fibres, the compressive strength at 7 days is increased by 21.42% than the normal concrete. Whereas for 28 days, this value is increased by 26% than normal concrete. The compressive strength of SPFRC-B consisting of either crimped steel fibre or hooked end steel fibres was less as compared to other SPFRC mixes, because less steel fibre content was used. For SPFRC-B which consists of crimped steel fibre the compressive strength at 28 days increased by 13% than

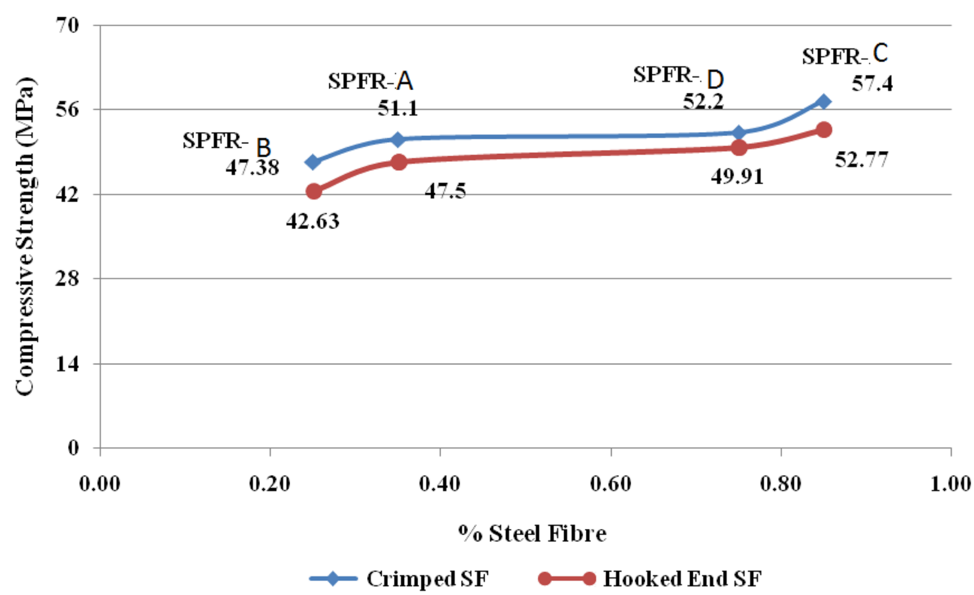

Fig. 10 Variation of compressive strength with % steel fibres at 28 days

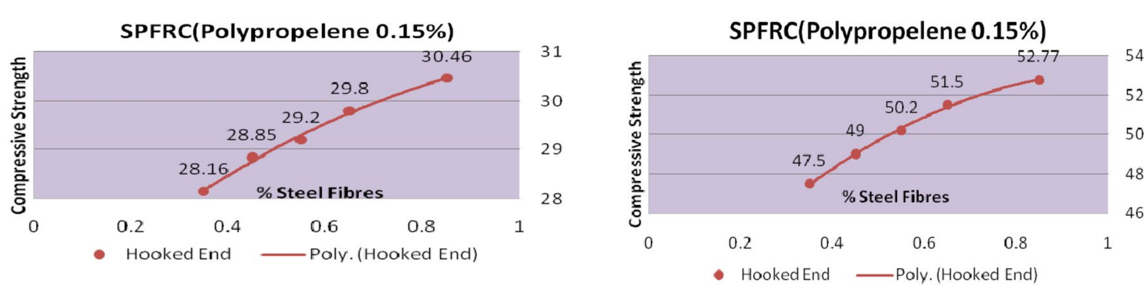

Fig. 11 Variation of compressive strength with % steel fibres at 7 days

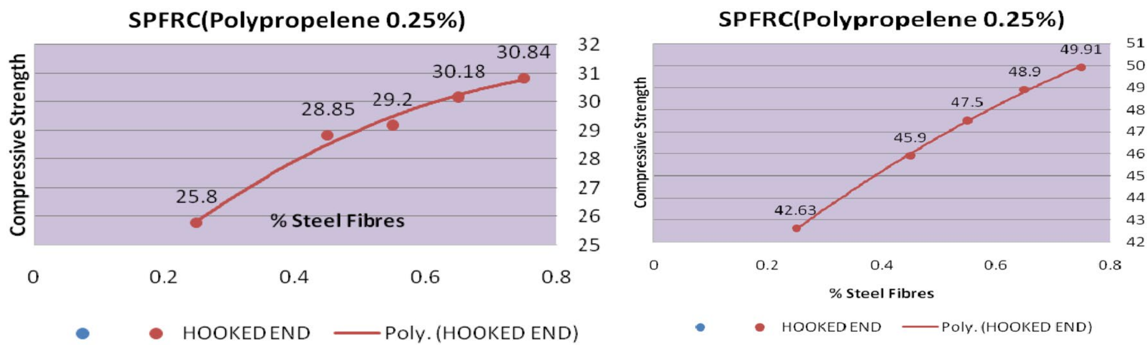

Fig. 12 Variation of compressive strength with % steel fibres at 7 days

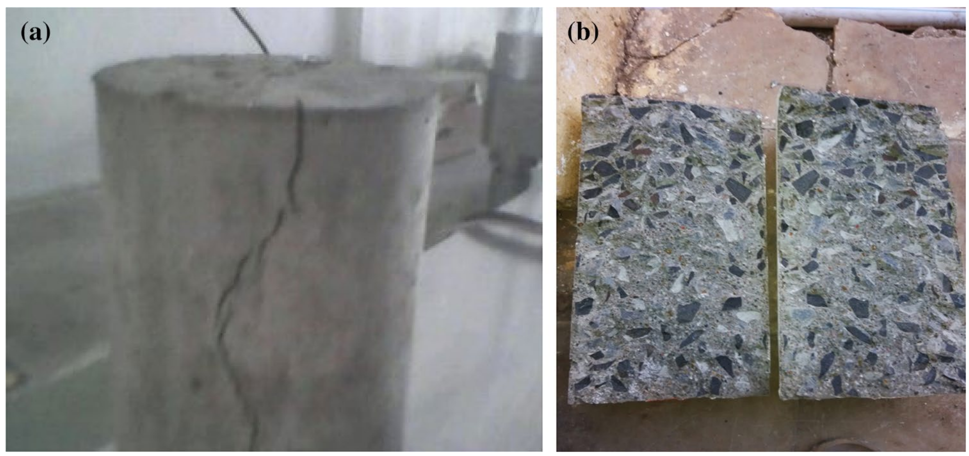

Fig. 13 Crack pattern in cylinder without use of hybrid frcc

normal concrete and when consist of hooked end steel fibre, compressive strength at 28 days increased by 1.74%.

Split tensile strength

It is well known that concrete is strong in compression but weak in tension. Even a very small eccentricity of load will induce bending and axial force condition and the concrete fails at apparent tensile stress other than the compression strength. Under an increasing compression loading, cracks will initiate and advance. Figure 13(a) shows the crack pattern in cylinder without hybrid fibres in it. When the advancing crack approaches a fibre, the debonding at the fibre–matrix interface begins due to the tensile stresses perpendicular to the expected path of the advancing crack. As the advancing crack reaches the interface, the crack tip stress concentration is reduced, and, thus, the propagation of cracks is blunted and blocked. This process is the bridging effect or crack arresting ability of fibres in concrete. The uniformly dispersed fibres create the bridging effect of fibre; hence, tensile strength increases.

From graphs and Table 9, it is observed that tensile strength of normal concrete is less. With addition of steel fibre from 1 to 10%, there is increase in tensile strength.

Table 9 Tensile strength with % of steel fibres

Sr no.	Mix proportion	Load (KN)	Tensile strength (N/mm^2)
1	NC	23.67	3.283
2	NC + 1% steel fibre	29.67	4.115
3	NC + 2% steel fibre	30.67	4.254
4	NC + 3% steel fibre	31.33	4.345
5	NC + 4% steel fibre	32.33	4.484
6	NC + 5% steel fibre	33.67	4.6233
7	NC + 6% steel fibre	34	4.7158
8	NC + 7% steel fibre	34.33	4.808
9	NC + 8% steel fibre	35.33	4.9
10	NC + 9% steel fibre	35.67	4.947
11	NC + 10% steel fibre	36.33	5.0389

Flexural strength of SPFRC specimens

This section deals the results of flexure test on SPFRC Mixes. Various SPFRC Mixes were prepared with varying percentage of steel and polypropylene fibres to access the compressive strength and flexure strength characteristic. Figure 14 presents the variation of flexure strength with

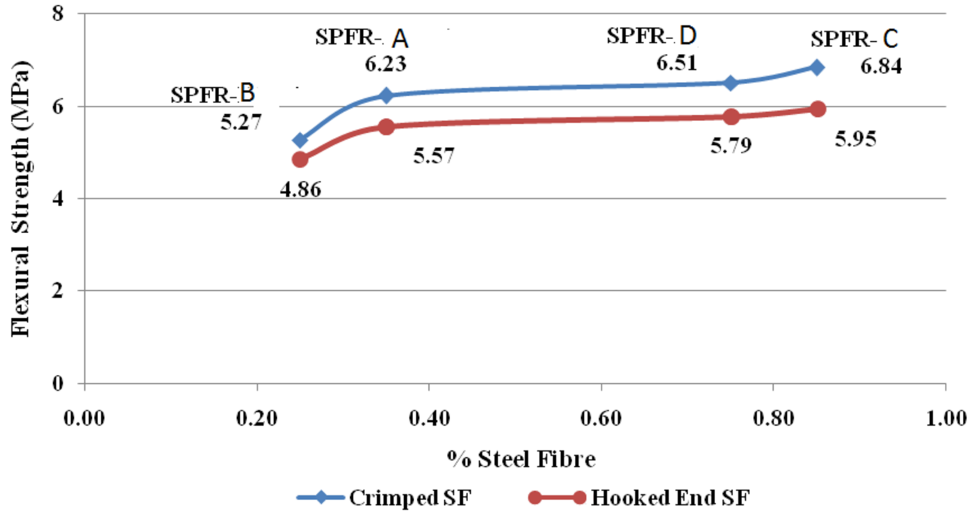

Fig. 14 Variation of flexure strength with the dosing of steel fibres at 7 days

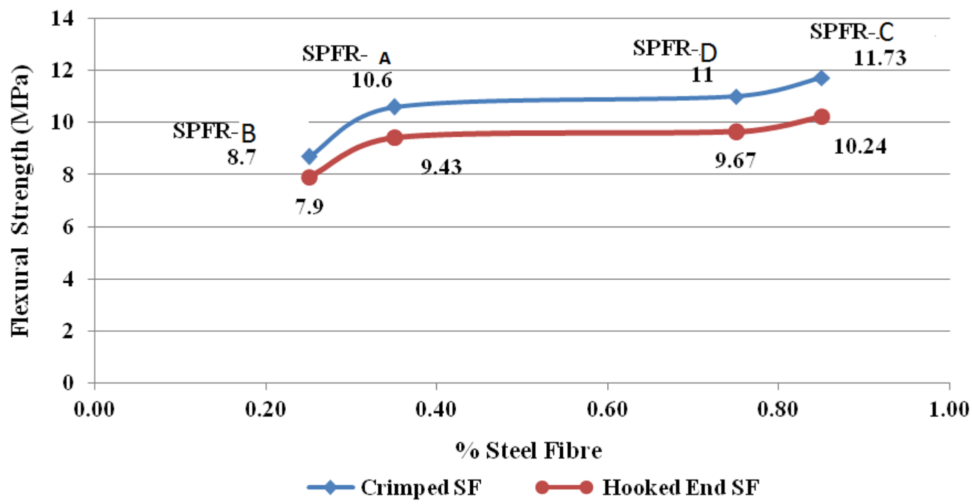

Fig. 15 Variation of flexure strength with the dosing of steel fibres at 28 days

percentage of steel fibre at 7 days. Also, Fig. 15 presents the variation of flexure strength with percentage of steel fibre at 28 days. The results indicate when concrete SPFRC-C includes crimped steel fibres, the flexure strength at 7 days increases by 45.9% than the normal. Similarly, for 28 days, this value increases by 120% than normal concrete. On the other hand, when SPFRC-C comprises the hooked end steel fibres, the flexure strength at 7 days is increased by 21.42% than the normal concrete. Whereas for 28 days, this value is increased by 92% than normal concrete. The flexural strength of SPFRC-B consisting of either crimped steel fibre or hooked end steel fibres was less as compared to other SPFRC mixes, because less steel fibre content was used. For SPFRC-B, which consists of crimped steel fibre, the flexural strength at 28 days is increased by 63.22% than normal concrete and when consist of hooked end steel fibre, flexural strength at 28 days is increased by 48.21%. Flexure strength is also considerably influenced by steel fibre and increases by increasing the quantity of steel fibre.

Uniaxial stress–strain behaviour

We can see from the stress–strain curves that the curves for each batch of concrete mix are comparable, but the control sample's curve is the only one that differs from the others. According to the pattern of the control sample stress–strain curve, plain concrete is a brittle material that cannot strain-harden. Because the break point occurs simultaneously at lower strain at the ultimate strength point, the normal stress–strain curve for brittle materials will be linear after it reaches that point. Additionally, the control sample curve has a steep slope in comparison to FRC. A steeper slope will result in a high modulus of elasticity value, indicating that the material is stiff or brittle, whilst a gentle slope will result in a lower value, indicating that the material has become more ductile and can flex more following the addition of more load. Based on the observation from the plotted graph, it is also evident

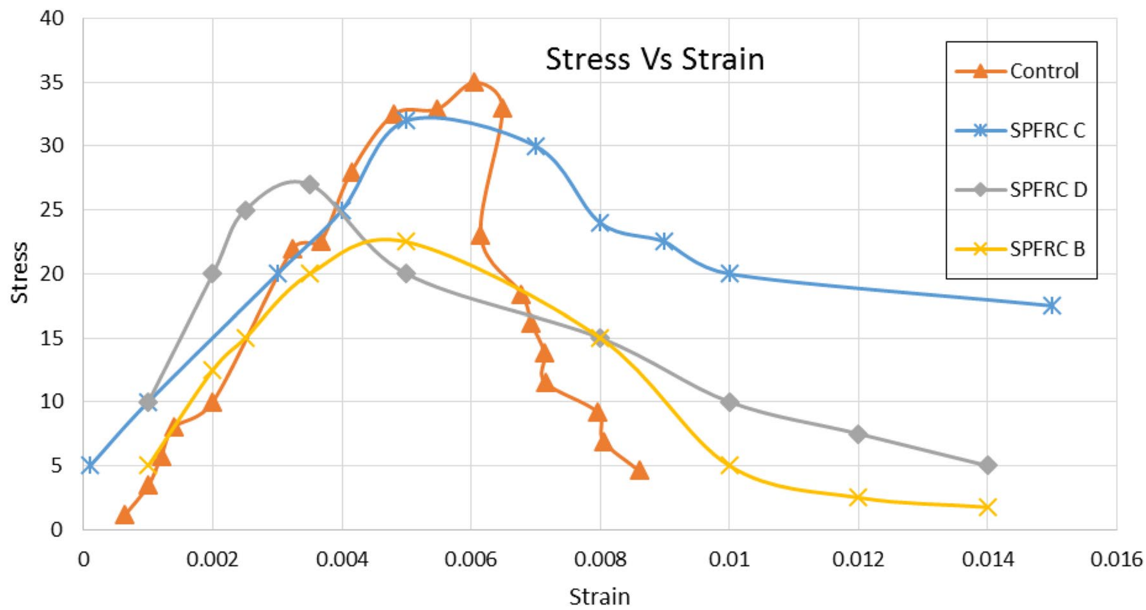

Fig. 16 Stress–strain behaviour of SPFRC concrete

that as the fibre content increased, the peak stress for all batches of concrete mix showed a substantial reduction, whilst the peak strain increased gradually. The control sample contributes to smaller areas under the curves that signify low energy absorption capacity in comparison to the sample containing fibres, since it has a steeper peak stress slope but less strain. Concrete with low energy absorption reaches its limit and fails at lower strains, because it is unable to absorb any more stress (Fig. 16).

Regression model for prediction of mechanical properties of high-strength concrete

This model produces a reliable relationship between mechanical properties (compressive strength and flexural strength) of concrete and the characteristics of the fibre. Also, the workability (slump) of the concrete was used as variable in this model for its important role in the explanation of strength development process of concrete. The multi-variable power equation was used to relate all these variables with the strength of concrete at the specified ages until getting the final and best form of the mathematical model.

Given below is the relationship between the predicted and observed or experimental 28 day compressive strength for high-strength concrete. This model predicts the compressive strength of high-strength concrete at different ages give coefficient of correlation of 99.99% for each strength (Figs. 17, 18, 19, 20, 21, 22, 23, 24).

Fibre content
Type of steel fibre: hooked steel fibre.
Polypropylene fibre: 0.15%

Compressive strength

Curing age: 28 days.

Compressive strength $= -3.38x^2 + 8.6212x + 25.578$; x = % of steel fibre.

$R^2 = 0.9942$.

%Sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.35	25.8	28.16	27.3	28.173
0.45	28.85	28.85	28.508	28.765
0.55	29.2	29.2	29.484	29.281
0.65	30.18	29.8	30.228	29.745
0.85	30.84	30.46	31.022	30.455

Curing age: 7 days

Compressive strength $= -11.885x^2 + 24.91x + 40.209$; x = % of steel fibre.

$R^2 = 0.9983$.

Polypropylene fibre: 0.25%

Type of steel fire: hooked steel fibre

Curing age: 7 days

Compressive strength $= -11.589x^2 + 21.349x + 21.257$.

$R^2 = 0.9859$.

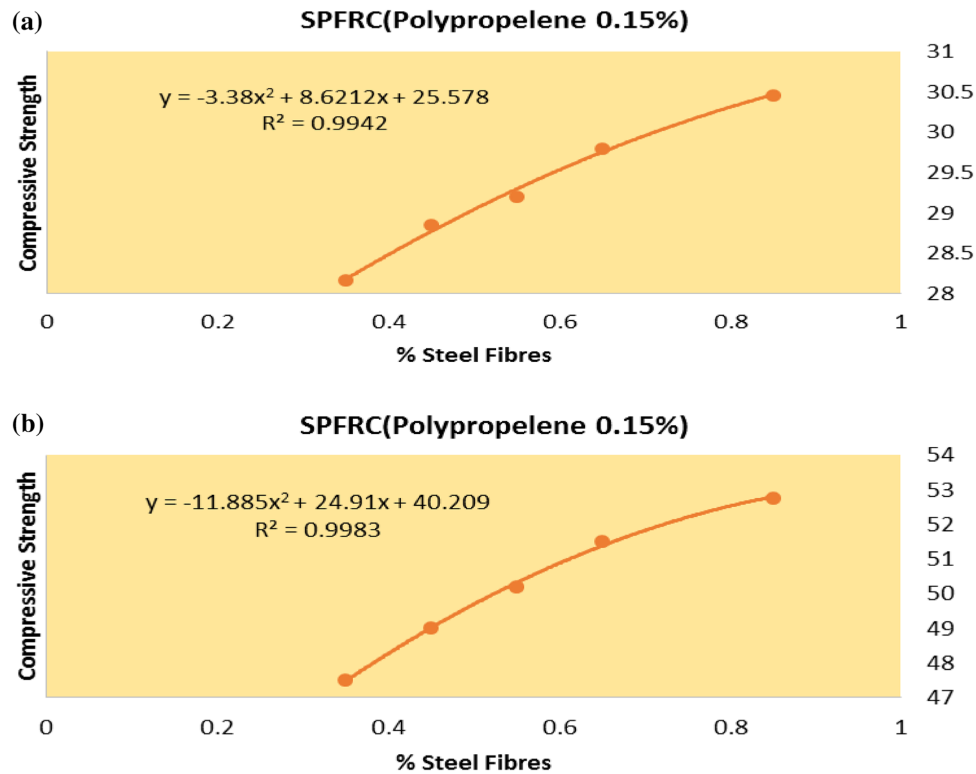

Fig. 17 **a** Compressive strength of concrete containing PP fibres (0.15%) and different dosages of steel fibres. **b** Compressive strength of concrete containing PP fibres (0.15%) and different dosages of steel fibres

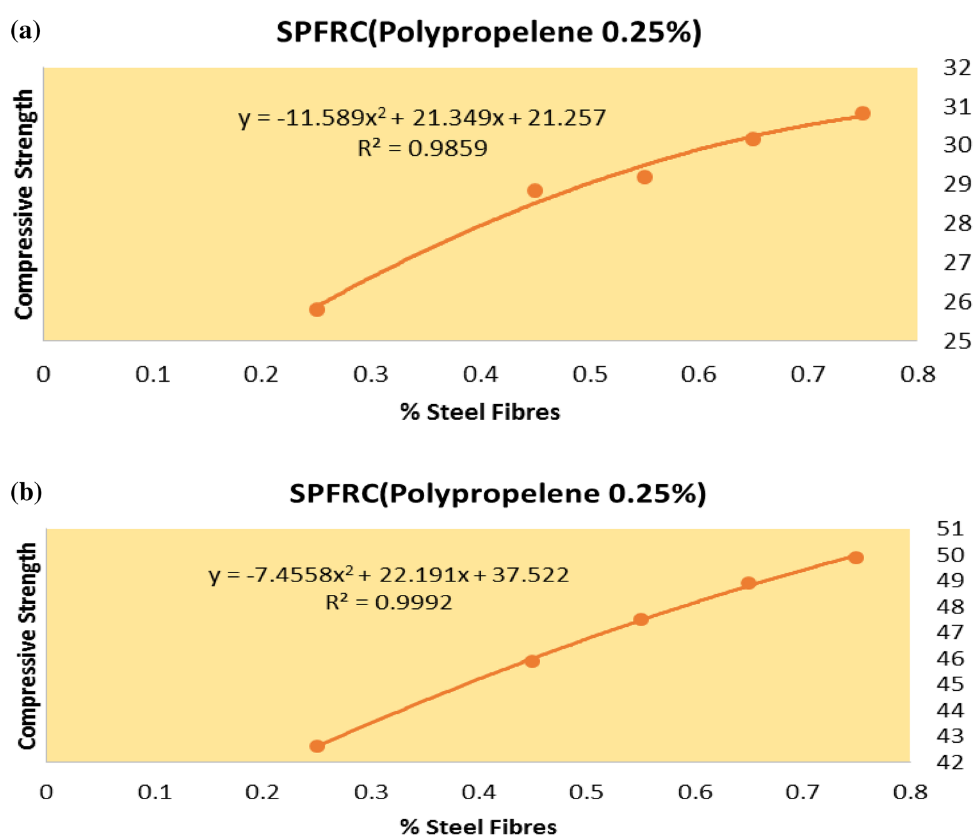

Fig. 18 **a** Compressive strength of concrete containing PP fibres(0.25%) and different dosages of hooked steel fibres. **b** Compressive strength of concrete containing PP fibres (0.25%) and different dosages of hooked steel fibres

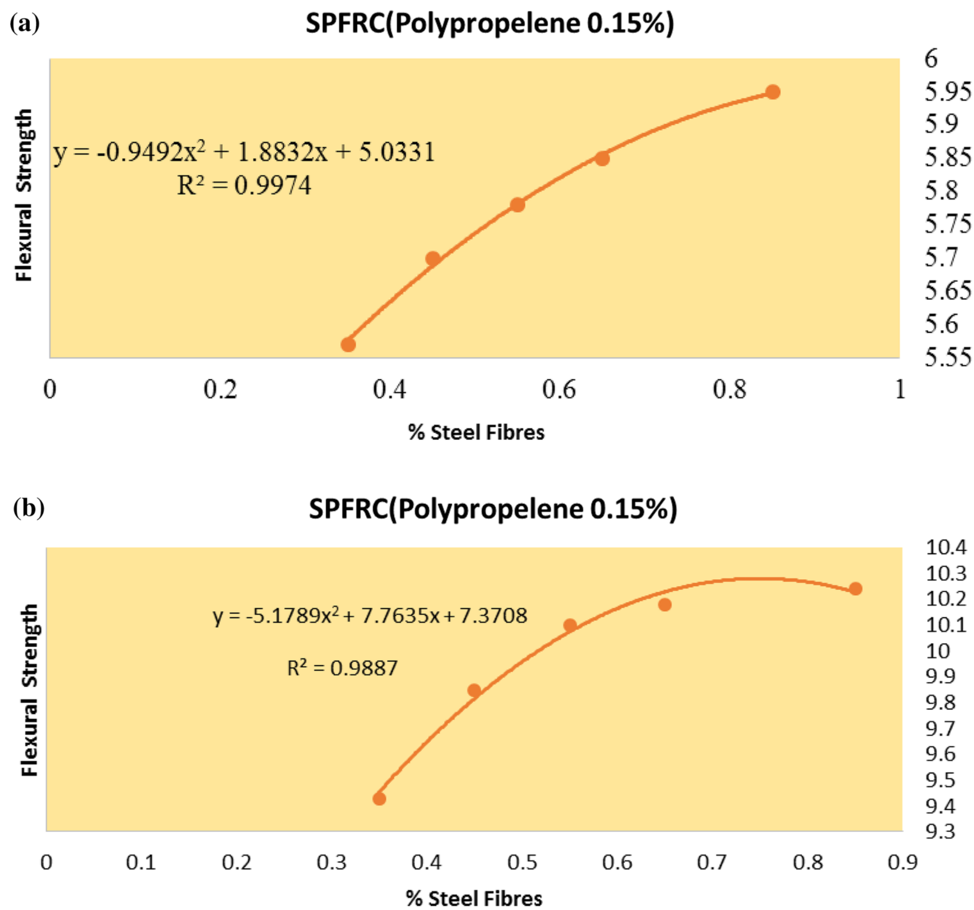

Fig. 19 **a** Flexural strength of concrete containing PP fibres (0.15%) and different dosages of hooked steel fibres. **b** Flexural strength of concrete containing PP fibres (0.15%) and different dosages of hooked steel fibres

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.35	47.5	42.63	47.463	42.601
0.45	49	45.9	49.003	45.995
0.55	50.2	47.5	50.306	47.469
0.65	51.5	48.9	51.372	48.793
0.85	52.77	49.91	52.79	50.995

Curing age: 28 days
Compressive strength $= -7.4558x^2 + 22.191x + 37.522$.
$R^2 = 0.9992$.
Flexural strength
PP fibre content 0.15%
Curing age: 7 days
Flexural strength $= -0.9492x^2 + 1.8832x + 5.0331$.
$R^2 = 0.9974$.

%Sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.35	5.57	9.43	5.558	9.452
0.45	5.7	9.85	5.665	9.814
0.55	5.78	10.1	5.754	10.073
0.65	5.85	10.18	5.823	10.228
0.85	5.95		10.24	10.227

Curing age: 28 days
Flexural strength $= -5.1789x^2 + 7.7635x + 7.3708$.
$R^2 = 0.9887$.
PP fibre content 0.25%
Curing age: 7 days
Flexural strength $= -1.8476x^2 + 3.715x + 4.0407$.
$R^2 = 0.9905$.

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.25	4.86	7.9	4.853	7.921
0.45	5.3	8.9	5.337	8.96
0.55	5.58	9.3	5.524	9.313
0.65	5.65	9.54	5.674	9.555
0.75	5.79	9.67	5.787	9.706

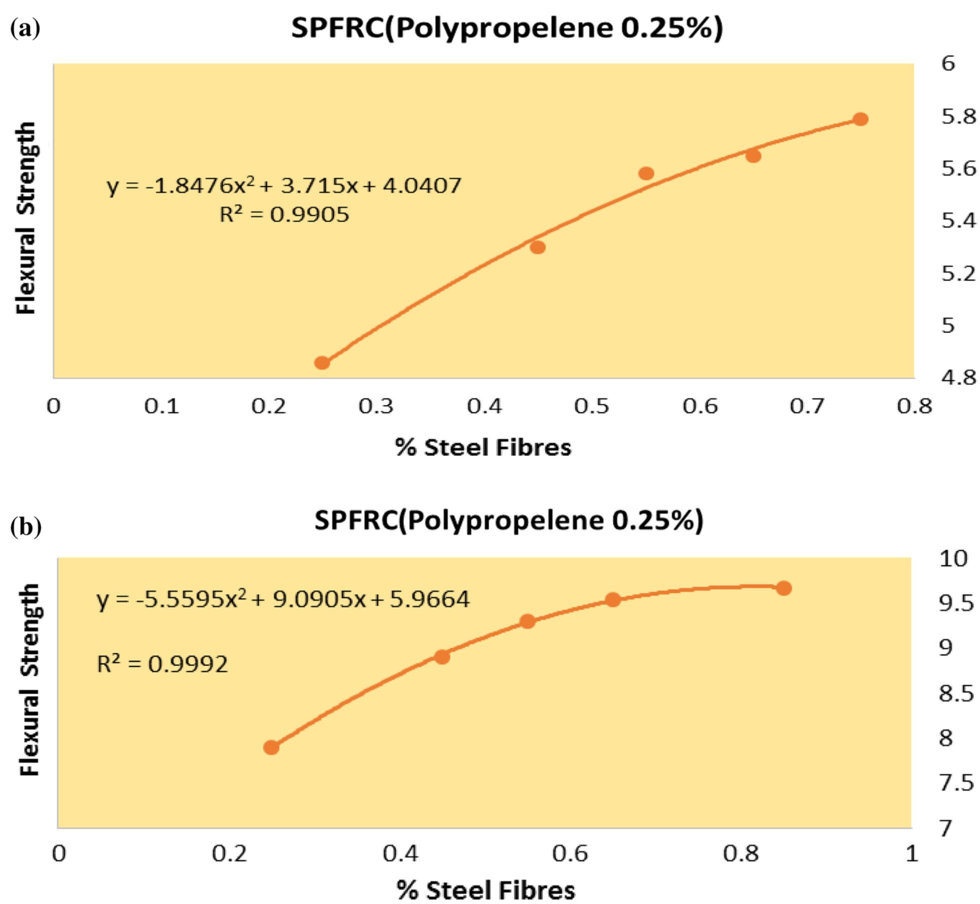

Fig. 20 **a** Flexural strength of concrete containing PP fibres (0.25%) and different dosages of hooked steel fibres. **b** Flexural strength of concrete containing PP fibres (0.25%) and different dosages of hooked steel fibres

Curing age: 28 days

Flexural strength = $-5.5595x^2 + 9.0905x + 5.9664$.

$R^2 = 0.9992$.

Crimped steel fibres

Compressive strength

PP fibre content 0.15%

Curing age: 28 days

Compressive strength = $-20.434x^2 + 37.187x + 40.547$.

$R^2 = 0.935$.

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.35	29.2	51.1	29.1	51.050
0.45	30.3	53	30.3	53.133
0.55	31.2	55	31.4	54.808
0.65	32.5	56	32.2	56.075
0.85	33.1	57.4	33.6	57.382

Curing age: 7 days

Compressive strength = $-11.443x^2 + 21.825x + 22.877$.

$R^2 = 0.9862$.

PP fibre content 0.25%

Curing age: 7 days

Compressive strength = $-7.4227x^2 + 11.186x + 26.322$.

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.25	28.5	47.38	29.323	50.144
0.35	29.6	52.3	29.848	52.57
0.45	29.9	54.9	30.223	54.594
0.55	30	56.2	30.451	56.216
0.75	30.6	57.4	30.46	58.255

Curing age: 28 days

Compressive strength = $-20.096x^2 + 40.335x + 38.498$.

$R^2 = 0.9973$.

Flexural strength

PP fibre content 0.15%

Curing age: 7 days

Flexural strength = $-2.916x^2 + 4.811x + 4.865$.

$R^2 = 0.9577$.

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.35	6.23	10.6	6.191	10.663
0.45	6.35	11.2	6.439	11.081
0.55	6.68	11.4	6.628	11.394

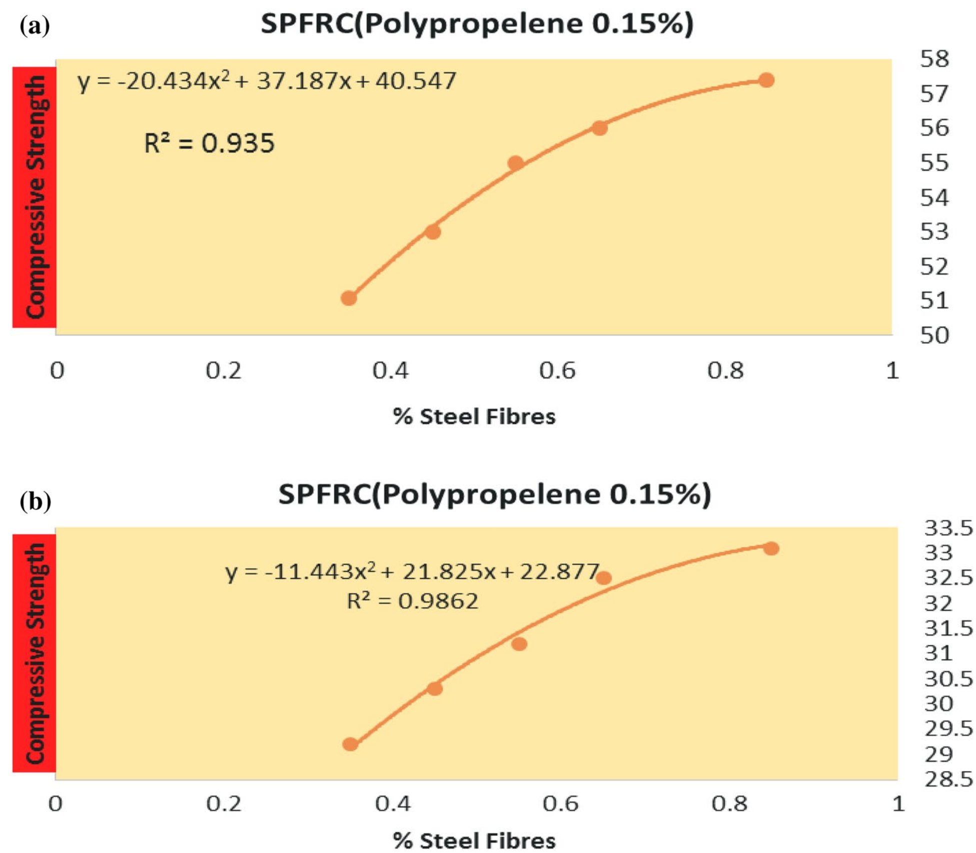

Fig. 21 **a** Compressive strength of concrete containing PP fibres (0.15%) and different dosages of crimped steel fibres, **b** Compressive strength of concrete containing PP fibres (0.15%) and different dosages of crimped steel fibres

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.65	6.77	11.52	6.76	11.602
0.85	6.84	11.73	6.847	11.704

Curing age: 28 days
Flexural strength = $-5.2445x^2 + 8.3764x + 8.3746$.
$R^2 = 0.829$.
PP fibre content 0.25%
Curing age: 7 days
Flexural strength = $-9.1141x^2 + 11.297x + 3.1213$.
$R^2 = 0.9306$.

%sf	Experimental		Theoretical	
	7 days	28 days	7 days	28 days
0.25	5.27	8.7	5.373	9.377
0.35	6.15	9.8	5.956	9.976
0.45	6.38	10.6	6.355	10.455
0.55	6.43	10.87	6.573	10.814
0.75	6.51	11	6.461	11.054

Curing age: 28 days
Flexural strength = $-5.9809x^2 + 10.773x + 6.3414$.
$R^2 = 0.9837$.

Conclusions

In the present study, steel fibres and polypropylene fibres are added in the mixes, and the workability, flexural strength, and compressive strength characteristics are assessed. The study revealed that steel fibres and polypropylene fibres can be effectively used in the Concrete Mixes. The concrete showed an improvement in the flexural strength and compressive strength characteristics. Further following conclusions are drawn from the present study:

(1) The workability of SPFRC Mixes is affected with the type of steel fibre and their dosage. It is observed that as the dosage of steel fibre increases, workability reduces. Also, workability reduces more when crimped steel fibres are used in place of hooked end steel fibre. The crimped steel fibres form more strong fibre matrix bond than hooked end steel fibres. Due to this, the viscosity of concrete increases and the distribution of cement matrix is restricted; hence, the reduction in the workability is observed in the SPFRC Mixes. Polypropylene fibres have not found to affect the workability characteristics, which is in contrast with many authors reporting the fact that PP fires reduce the workability. This could be due to the fact that the dosage of PP fibres reported by them is comparatively higher (1.25–1.75%),

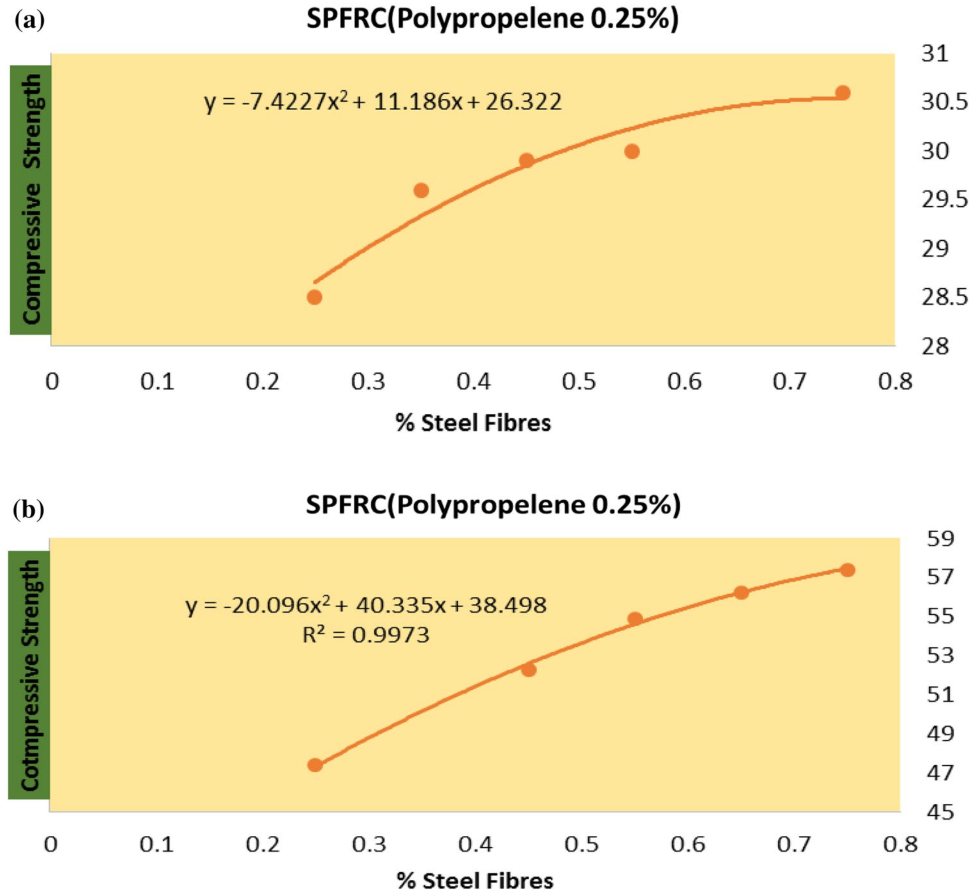

Fig. 22 **a** Compressive strength of concrete containing PP fibres (0.15%) and different dosages of crimped steel fibres. **b** Compressive strength of concrete containing PP fibres (0.25%) and different dosages of crimped steel fibres

which in turn makes the mix dry due to high water absorption of PP fibres. PP fibres used in this study are very low as compared to them (0.15–0.25%). Also, the addition of super-plasticizer improved the workability by dispersing the fibres in mix uniformly and reducing the viscosity of cement paste. Maximum slump loss was observed for the SPFRC-C Mix consisting 0.85% crimped end steel fibre and 0.15% polypropylene fibres.
(2) Strength characteristics are also influenced by the type of fibres and their dosage. The experimental investigation revealed that crimped steel fibres are more effective than the hooked end steel fibres. Further with the increase in dosage of crimped steel fibres, compressive strength characteristics also increase. The maximum compressive strength is observed for the SPFRC-C mix consisting of 0.85% crimped end steel fibres and 0.15% polypropylene fibres. Compressive strength increased by 37% when SPFRC-C mix is prepared. This is due to the geometrical form of the fibres which provides more anchorage, rough surface, and the large aspect ratio of the steel fibres added into the mixes that enable them to develop high bond between the matrix and the fibre. As a result, they effectively delay and arrest the unstable growth of micro-cracks, as soon as they are opened. Steel fibres provides structural improvement, i.e., enhancement in flexural strength characteristics, whereas PP fibres reduce the possibility of micro-surface cracking due to shrinkage.
(3) The maximum increase in flexural strength is observed for the mix SPFRC-C consisting crimped steel fibres. The flexural strength is increased by 120% when SPFRC-C mix is prepared. This increase in flexural strength characteristic may be largely attributed to bridging effect of fibres which offers considerable resistance to crack opening. The utilisation of crimped steel fibres and polypropylene fibres enhanced the flexural strength of mixes.
(4) It is possible to produce fibre concrete composites using polypropylene fibres in combination with steel fibres. The performance of such concrete will be better than plain concrete. The addition of steel fibres aids in converting the properties of brittle concrete to a ductile material, but addition of steel fibres with polypropylene fibres makes the results better than that, and generally, it improves the compressive strength and flexural strength of plain cement concrete, but the improvement

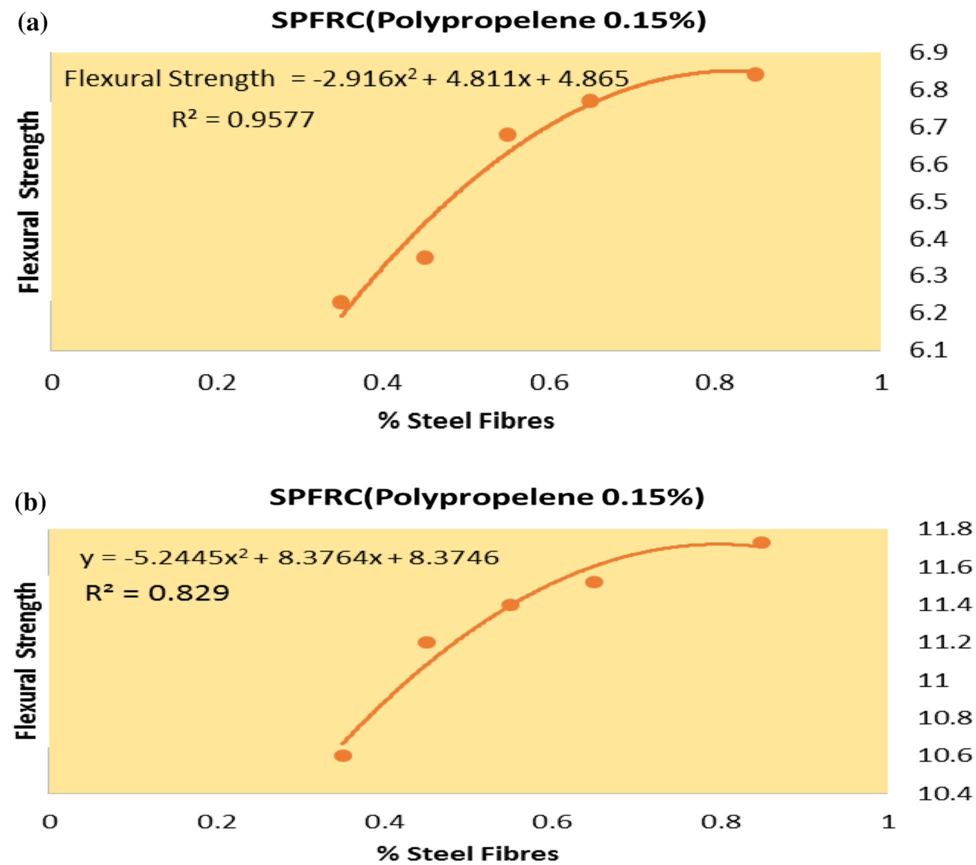

Fig. 23 **a** Flexural strength of concrete containing PP fibres (0.15%) and different dosages of crimped steel fibres. **b** Flexural strength of concrete containing PP fibres (0.15%) and different dosages of crimped steel fibres

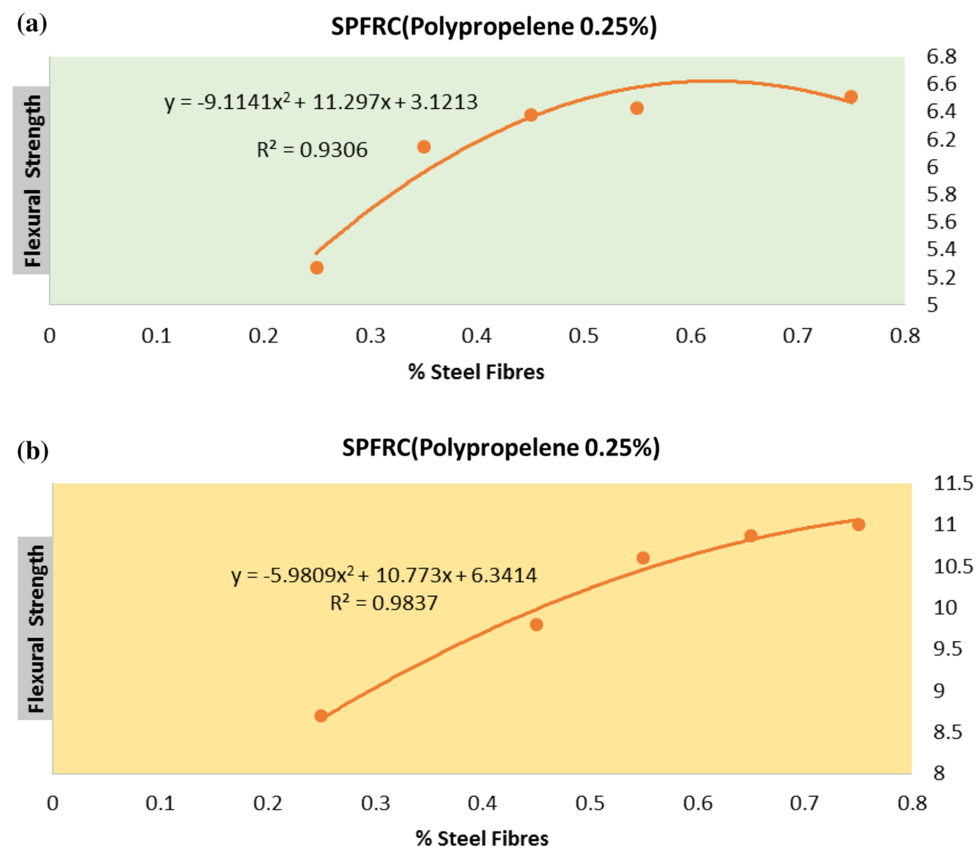

Fig. 24 **a** Flexural strength of concrete containing PP fibres (0.25%) and different dosages of crimped steel fibres. **b** Flexural strength of concrete containing PP fibres (0.25%) and different dosages of crimped steel fibres

in strength does not always increase with a larger dosage of fibres.

(5) Hybrid of steel fibre and polypropylene fibres reduced the number of cracks and width of cracks at comparable load levels. It does not allow concrete to break and fall down at failure as it holds at the bottom, so it can be used in strengthening the beams of seismic zones.

(6) The slope of stress–strain curve illustrates the modulus of elasticity. Steeper slope will give high value of modulus of elasticity, meaning that the material is stiff or brittle, whilst gentle slope gives smaller value as the material becomes more ductile. Thus, the most desirable is sample with lowest modulus of elasticity. From the result, it can be seen that sample with SF—0.85% + PPF—0.15%) fibre content has the lowest modulus of elasticity of 24.31 GPa. Toughness value represents the ability of concrete to absorb energy to resist fractural damage. Therefore, the higher the toughness value, the better the concrete. Overall, we may conclude that the optimum dosage of fibre content is SF—0.85% + PPF—0.15%) to produce concrete with better stress–strain behaviour, flexural strength, and tensile strength.

Recommendations for further study

The following is recommended for the further study:

(1) In the present study, steel and polypropylene fibres of single aspect ratio are used. Studies may be carried out using steel fibres of different aspect ratio and also on different types of synthetic fibres like nylon, polyethylene, polyamide, acrylic etc. Also the various other combinations of fibres can be used for the assessment of workability, flexural strength, and compressive strength characteristics of Concrete Mixes.

(2) The present study is based on the assessment of flexural strength and compressive strength characteristics of mixes. Studies may also be carried out on fatigue analysis of SPFRC.

(3) The present study is based on the assessment of strength characteristic of mixes which is equivalent to M 40 grade concrete. Studies may be carried out on other grades of concrete like M 25, M 30, and high-strength concrete mixes like M 60, etc.

(4) Study the effects of addition of steel and polypropylene fibre at higher dosage.

(5) Effects of fibres as temperature and shrinkage reinforcement.

(6) Further work can be extended using combination of glass fibres and steel fibres together at different proportions (hybrid fibre-reinforcement concrete).

(7) Other than compressive and split tensile strength tests, toughness test, abrasion test, pull out test, acid resistance test, and flexure test can also be performed.

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Author contributions BA (main author) wrote the whole manuscript along with tables and figures.

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Data availability The data that support the findings of this study are available from [CSIR-CBRI] but restrictions apply to the availability of these data, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of [CSIR-CBRI].

Declarations

Conflict of interest The author states that there is no conflict of interest.

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