Compression and Shear Resistance of Self-compacting Concrete with Arch-Type Steel and Polypropylene Fibres

Kasilingam Senthil, Davinder Singh and Ivjot Singh

Abstract The experimental investigations were carried out on fibrous self-compacting concrete (SCC) elements subjected to monotonic loading to study the influence of arch-type steel fibre (AF) in terms of shear and compressive properties. The influence of polypropylene fibres (PF) at varying proportions was also studied along with arch-type steel fibrous self-compacting concrete. The tests were carried out on both fresh concrete as well as hardened concrete. In fresh concrete, slump and L-box tests were carried out and the results thus measured against varying combinations of both the fibres have been compared. In hardened concrete, compressive strength and shear strength test was conducted and their behaviour was compared. It was observed from slump test as well as L-box tests, the workability of hybrid fibre-reinforced self-compacting concrete was found to be reduced with increase in the volume of fibres. It is also observed that arch-type steel fibres showed exceptional post-cracking behaviour along with the polypropylene fibres for each mix.

Keywords Compression · Shear resistance · Self compacting concrete · Arch-type steel · Polypropylene fibers

1 Introduction

Concrete is widely used orthotropic systems, however, the system have its own limitations. Concrete has low ductility, low brittle in nature and also it has low tensile strength. To overcome this, the most common way is to add reinforcement. Reinforcement, usually in the form of steel reinforcing bar, is provided where tensile stresses are expected in the structure. Another way to overcome this limitation is by using a technique called prestressing. In addition to that, concrete may exhibit low structural integrity against impact and repeated loads.

These deficiencies of concrete may be removed by reinforcing it with small, discrete fibres, randomly oriented, uniformly distributed throughout the concrete. In

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the case of fibrous-reinforced concrete, it is observed that one of the major problems that are to be faced related to concrete is at the time of placing is congestion. Proper compaction of concrete is very much required to achieve its desirable hardened properties for which it is known to be an excellent construction material. These limitations can be taken care of by a special type of concrete, known as fibrous self-compacting concrete. There has been a lot of experimental work which is related to the fibrous-reinforced concrete. Hsie et al. (2008) explored the mechanical properties of hybrid fibre-reinforced concrete containing two types of polypropylene fibres-staple and monofilament fibres. Results depicted that the hybrid fibre-reinforced concrete containing polypropylene fibres had 14.60–17.31% more compressive strength, 8.88–13.35% splitting tensile strength and 8.99–24.60% flexural strength than the ones with single fibre-reinforced concrete. Aslani and Nejadi (2013) developed a prediction model to determine the mechanical properties of four types of SCC mixes—plain SCC, polypropylene, steel and HFRSCC. Hybrid fibre-reinforced SCC mix proved to be the best among the other mixes for the elasticity modulus and quite similar results were given in agreement with the model prediction. Ponikiewski and Katzer (2014) was concentrated on self-compacting concrete (SCC) modification by the addition of polymer and steel fibres to depict the maximum amount of fibre composition allowed to achieve flowing properties of self-compacting concrete. It is observed that the varying length of the fibres used, we can extend this limit dosage while maintaining the self-compacting effect. Rambo et al. (2014) investigated hooked-end and straight steel fibres with unlike diameter and lengths at volume fractions of 1 and 1.5% to examine the consequences of hybridization of steel fibres on the mechanical and rheological properties of concrete which requires no vibration for compaction. The observations indicated that crack width control increased the limit of serviceability by introducing the concept of fibre hybridization. In addition, researchers have been working on the structural performance in RC members with self-compacting concrete under monotonic loads in the past few years (Afroughsabet and Ozbakkaloglu 2015; Won et al. 2015; Tabatabaeian et al. 2017; Lee et al. 2016; Senthil et al. 2016a, b; Senthil et al. 2017; Yoo et al. 2017). Based on the literature survey, it is observed that the fibres can enhance various properties of self-compacting concrete. Different shapes of steel fibres are coming up to improve the anchorage properties of the fibres but still, their pull out at a lower force had been observed in most of the fibre shapes. A lot of research has been done on the concept of hybridization of fibres but still there are chances of exploring some new things. We also know that the SCC is comparatively weak in shear but limited research has been carried out on shear resistance of fibrous-reinforced self-compacting concrete. Thus, in the present study, the authors tried to consider all these aspects as authors are chosen arch shape fibres along with the polypropylene fibres by making a hybrid mix of self-compacting concrete to study its fresh properties and hardened concrete properties. The fresh properties of hybrid fibre-reinforced self-compacting concrete containing arch-type steel fibres and polypropylene fibres have been studied at different proportions, using slump test and L-box test. The compressive strength and shear strength of hybrid fibre-reinforced self-compacting concrete containing different proportions of arch and polypropylene fibres have also been studied.

2 Methodology

In this section, there is an elaborate depiction of the materials which has been used in the experimental work. The method that has been adopted to carry out the work has also been described. The experimental program included the testing of slump flow test, L-box test, compressive strength test and shear strength test and discussed here.

2.1 Materials

Arch-type steel fibre (AF)-reinforced cementitious composites exhibited higher flexural performance to composites formed using hooked-end-type steel fibres. Curvature radius can augment the performance of an arch-type steel fibre. Interfacial toughness increases with the decrease in the curvature radius. There was a pronounced effect of bend length for a given curvature radius for the arch-type steel fibres. Figure 1 shows the schematic diagram of arch-type steel fibre to have a proper look at those two parameters. Additionally, the bond strength and interfacial toughness increased with increasing bend length regardless of the curvature radius. Optimal dimensions of the arch-type steel fibre, chosen on the behalf of previous studies were: radius $R = 35$ mm, aspect ratio (l/d) = 72, diameter of the fibre 0.7 mm, circular in shape, l_e is 1.5 mm. The total length of the fibre = 50.4 mm and tensile strength of the fibre = 1300 MPa.

Polypropylene is made through polymerization of the monomer propylene. It has high strength and high resistance to fatigue. The melting point and elastic modulus are low compared to many other fibres. Due to this, these fibres may not be fit for certain situations, however, in most of the situations, these fibres have been used. Polypropylene fibres had been proved the best among the synthetic fibres available in the market in terms of strength characteristics properties of the polypropylene fibres used: length of the fibre is 19 mm, diameter 0.5 mm, shape of fibre is straight and circular in crosssection and tensile strength of fibre is 570–660 MPa.

Ordinary Portland Cement (OPC) grade 43 (UltraTech) was used in the present study. The fine aggregates were available locally and used to carry out the experimental investigations. The sand was dry and free from any unwanted materials. Sieve analysis tests were performed to find the fineness modulus, for fine and coarse

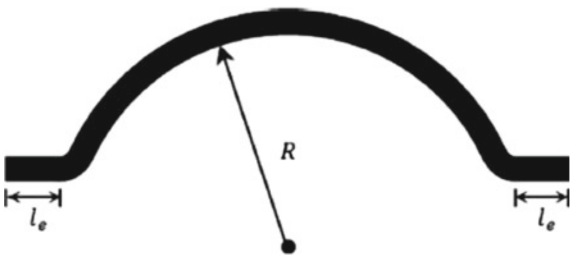


Fig. 1 Schematic diagram of arch-type steel fibre

aggregate, i.e. 2.89 and 7.07, respectively. The specific gravity test has been conducted for coarse and fine aggregates are 2.67 and 2.62, respectively. Super plasticizers, also known as high range water reducers, are chemical admixtures used where well-dispersed particle suspension is required. The aim of adding silica fume to the mix was to influence its viscosity in the fresh state. The used silica fume was characterized SiO_2 content equal to 92.8%. When silica fume is added to concrete, initially it remains inert.

2.2 Experimental Program

The influence of arch-type steel fibre (AF) and polypropylene fibres (PF) at varying proportions were studied along with arch-type steel fibrous self-compacting concrete shown in Table 1. The arch-type steel fibres with aspect ratio 72 and polypropylene fibres of 19 mm length were considered in the present study. The length and diameter of polypropylene fibres is 19 and 0.5 mm, respectively was considered. The combination of fibres were named as: SCC0 (0% fibre), SCC1 (0.8% of 0.5% AF and 0.3% PF), SCC2 (1.6% of 1.0% AF and 0.6% PF) and SCC3 (2.4% of 1.5% AF and 0.9% PF).

2.3 SCC Mix Proportion

The SCC mixes were prepared according to the ratios proposed by Ponikiewski and Katzer (2014), is shown in Table 2.

2.4 Tests on Fresh Concrete

The slump flow and L-box test have been conducted to study the fresh properties of self-compacting concrete. For each proportioning of the fibres, we conducted three trials for the slump flow test. The slump flow test was used to assess the horizontal free flow of self-compacting concrete in the absence of obstructions. About 6 L

Table 1 Fibre volume proportions

S. no.	Description	Arch-type steel fibres (%)	Polypropylene fibres (%)
1	Plain SCC	0	0
2	SCC1	0.5	0.3
3	SCC2	1	0.6
4	SCC3	1.5	0.9

Table 2 SCC mix composition, Ponikiewski and Katzer (2014)

S. no.	Ingredient	Quantity (kg/m^3)
1	Cement (OPC 43 Grade)	485
2	Fine aggregates (0–2 mm)	810
3	Coarse aggregates (2–8 mm)	457.7
4	Coarse aggregates (8–16 mm)	457.7
5	Water (tap water)	202
6	Super plasticizer	18.6
7	Silica fumes	48.5

of concrete was needed to perform the test, sampled normally. Moistened the base plate and inside of slump cone, place base plate on level stable ground at least 700 mm square, marked with a circle marking the central location for the slump cone and a further concentric circle of 500 mm diameter or marking on the four sides symmetrically on the square plate denoting the same circle could be made and the slump cone held down firmly centrally on the base plate. Fill the cone with the help of scoop and without tamp, simply struck off the concrete level with the top of the cone by using trowel. Then removed surplus concrete from around the base of the cone. After that, the cone was raised vertically and allowed the concrete to flow out freely. Then, the reading was noted along the longest line of the flow in any direction.

The L-box test is also one of the tests for workability ,which assessed the flow of the self-compacting concrete and also the extent to which it is subjected to blocking by reinforcement. The apparatus consisted of rectangular section box in the shape of an 'L', with a vertical and horizontal section, separated by a movable gate, in front of which vertical length of reinforcement bar was fitted. The vertical section was filled with concrete, and then the gate lifted to let the concrete flow into the horizontal section. When the flow stopped, the height of the concrete at the end of the horizontal section was expressed as a proportion of that remaining in the vertical section. It indicates the slope of the concrete when at rest. This is an indication passing ability, or the degree to which the passage of concrete through the bars was restricted.

2.5 Casting

Originally, the moulds available were of size 100 × 100 × 500 mm, however, with the help of wooden piece and thermocol pieces, the length of mould reduced to 300 mm and made the grooves, respectively. The mould 100 × 100 × 300 mm for shear test were prepared and tested for shear in a compression testing machine by making two symmetrical grooves of 25 × 50 mm and applying the load in the direction as shown in Fig. 2a. The mould used for casting is arranged on a clean flat and non-absorbent

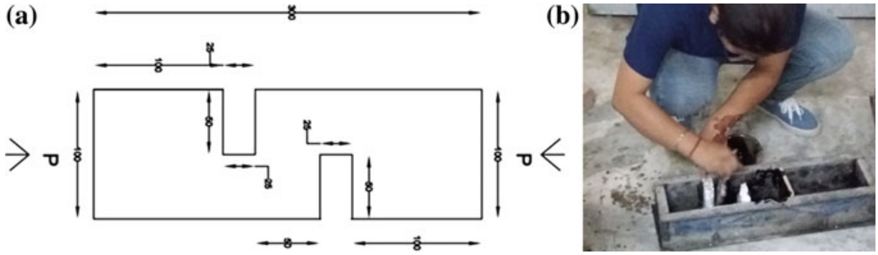


Fig. 2 **a** Schematic shear test specimen and **b** oiling on mould

surface. The exact quantities of materials are kept ready on another platform for preparing specimen and after mixing, the concrete is filled in three layers in the mould. Compressive strength moulds were of standard size cubes, i.e. 150 × 150 × 150 mm. After getting the moulds of the required size and their oiling was done as shown in Fig. 2b, all the materials were mixed in the drum mixer properly, poured into the wide square plate and then the specimens were casted.

2.6 Testing of Specimens

The specimens of 150 × 150 × 150 mm cube were casted and for compression test after 28 days of curing. The cubes with various volumes of fibre additions were casted and tested to check whether it had some appreciable effect on its compressive strength or not. The specimen was wiped off its surface moisture and grit on the previous day of its testing date and it is white washed. After the white wash, the surface was dried, the surface of the frame was marked with lines to study the crack pattern. The compression tests were carried out on hydraulic compression machine having the capacity of 1000 kN at a loading rate of 0.1 mm/min. Shear strength test was also carried out under compression testing machine as explained earlier by keeping all the other parameters same as shown in Fig. 2a. All the shear specimens were tested at 7 and 28 days of curing. During the testing of the specimens, deflection at various intervals was noted. During testing, the onset of shear cracking was also observed until the ultimate failure of the specimen.

3 Results and Discussion

In fresh concrete, slump and L-box tests were carried out and the results thus measured against varying combinations of both the fibres have compared. In hardened concrete, compressive strength and shear strength test were conducted and their behaviour was compared. Slump flow and L-box test along with compressive and shear test results for various proportions of arch-type steel and polypropylene fibres have been discussed in this Section.

3.1 Comparison of Slump Results of PF and AF Concrete

It is observed from Fig. 3 that slump flow of the concrete composite kept on decreasing as we increased the percentage of fibres to be incorporated in the mix. Conventional SCC0 mix showed the maximum slump flow with a value of 800 mm which can provide an excellent self-compacting effect. Generally for a good flowing ability, minimum value for the slump flow is to be taken as 650 mm, Ponikiewski and Katzer (2014). Thus from our experimental results, it is observed that the SCC3 mix containing a total of 2.4% fibre addition (1.5% arch fibres and 0.9% polypropylene fibres), could not offer the self-compacting effect as the value is much lower, i.e. 508 mm. Even the SCC2 proportion has the slump flow of 610 mm, however, it is acceptable to some extent because in that case, compensation can be made by increasing the amount of plasticizer or by decreasing the volume of polypropylene fibres because the main reason behind the decline in the slump flow values was the incorporation of polypropylene fibres as their capacity of water absorption is quite significant. This decline was also supported by the arch shape fibres as they anchor themselves very well in the mix because of their geometry. Therefore, it is concluded that the fibres more than 1.6% by volume in total may not be used in the self-compacting concrete composite as they may hamper the basic property of the SCC.

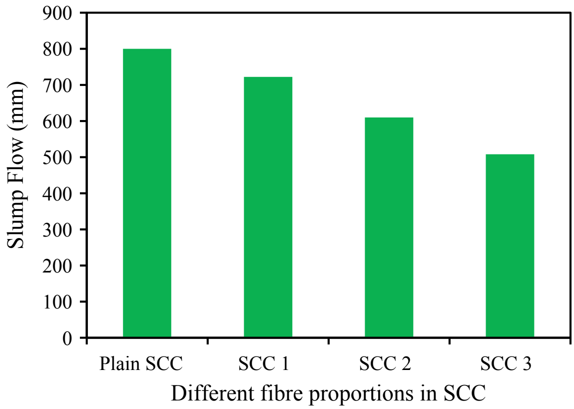
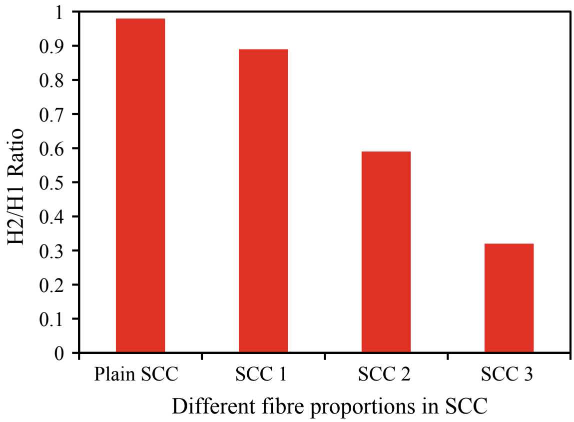


Fig. 3 Slump values against varying fibre volume proportions

Fig. 4 H_2/H_1 ratio values at various fibre volume proportions



3.2 Comparison of L-Box Results of PF and AF Concrete

The L-box test results found similar to that of slump tests and it was also noticed that the workability of SCC mix decreases with increasing fibre content, see Fig. 4. For a good workable mix, a range of 0.8–1.0 of H_2/H_1 ratio is acceptable, Ponikiewski and Katzer (2014). The mixes SCC0 (0% fibre addition) and SCC1 (0.8% fibre) have shown very good results to ensure a good workable mix at the time of pouring. SCC2 mix of 1.6% fibre addition showed a bit different behaviour in the L-box test having 0.59, much lesser than the acceptable limit for the mix to be in a good workable condition. The maximum percentage addition of fibres mix, i.e. SCC3 has a very low 0.32 which signifies a very poor mix.

3.3 Comparison of Compressive Strength of PF and AF Concrete

The compressive strength of hybrid fibre-reinforced self-compacting concrete containing different proportions of arch and polypropylene fibres have been studied. It is observed from Table 3 that the compressive strength has found to be increased considerably up to SCC2. The compressive strength of SCC2 was found to be maximum among the chosen mix proportion. However, the compressive strength of SCC3 mix was found dropped significantly. The reason may be due to the presence of polypropylene fibres in large amount which absorbs water significantly and also because of the fact that concrete alone also shows an excellent behaviour under compression which could have been affected by the more fibre addition that covers the space earlier filled by the basic ingredients of concrete. Therefore, it is concluded that the compressive strength of concrete was found to be increased up to 1.6% fibre content including AF and PF fibres, whereas in case of fibre content increase beyond 1.6%, the compressive strength is found to be decreased significantly.

Table 3 Compressive strength of hybrid fibre-reinforced self-compacting concrete

Description	Compressive strength (MPa)
SCC0	86.5
SCC1	95.8
SCC2	98.5
SCC3	90.7

3.4 Comparison of Shear Strength of PF and AF Concrete

The shear strength of hybrid fibre-reinforced self-compacting concrete containing different proportions of arch and polypropylene fibres have also been studied for both 7 and 28 days. It is observed from Fig. 5 that the shear strength of SCC0 was found lowest among the other mixes as the cracks easily grew widened in the mix containing no fibres. SCC1 showed a drastic improvement in the shear strength of the SCC mix as the value increased from 2.3 to 3.6 N/mm^2 at 7 days curing and 4 to 6.1 N/mm^2 at 28 days curing. This was due to the incorporation of fibres which provided the bridging effect between the crack openings and delayed the failure of the concrete. SCC2 mix had also given superior strength than the previously tested SCC1 mix as the fibre percentage was further increased, however, the increase in the shear stress resistance from SCC1 to SCC2 was found less as compared to the increase from SCC0 to SCC1. Also, it was observed that maximum shear stress 8.2 MPa at 28 days in case of SCC3 mix which has maximum shear strength among the selected cases.

More than one and a half times (52.5%) strength improvement was observed from SCC0 to SCC 1 mix because of the fibre hybridization as the addition of two different fibres enhanced the shear strength much more by complementing each other as a matter of the fact that the steel fibres prevent the growth of macro-cracks whereas polypropylene fibres reduces micro crack width. There was a decrease in the rate of

Fig. 5 Shear strength of 7 and 28 days cured shear specimens

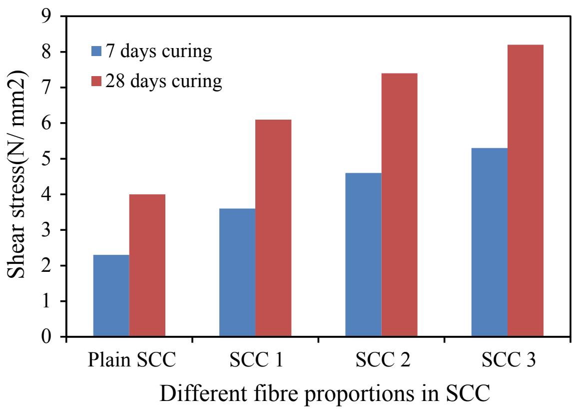


Table 5 Average shear load at first crack and ultimate failure

Description	Shear load at first crack (kN)	Ultimate shear load at failure (kN)
SCC0	–	19.8
SCC1	10.8	30.4
SCC2	14.1	36.8
SCC3	19.9	40.8

increase in ultimate shear stress on increasing the amount of fibres as only 21.3% enhancement was monitored in case of SCC2 mix. The reason may be due to high volume of fibre replacement from the normal SCC concrete causes utmost importance in the chemical reactions to be occurred during the reaction period. 10.8% hike in the shear strength was examined from SCC2 to SCC3 mix subjected to a maximum value of 8.2 N/mm^2 ultimate shear stress after 28 days curing sample. The reason behind the further decrease of rate of increase has already been explained in the above-mentioned point.

The shear load of hybrid fibre-reinforced self-compacting concrete containing different proportions of arch and polypropylene fibres have been studied in terms of first crack as well as ultimate failure load as shown in Table 5. It is observed from Table 5 that all the fibre volume proportions showed an excellent post-cracking behaviour. SCC1 had 10.8 kN shear load at first crack whereas it actually failed at a very high ultimate load value of 30.4 kN. The difference between first crack and ultimate failure shear loads of SCC1 mix was 19.6 kN. The same was observed in the case of SCC2 and SCC3 mix configurations, showing a difference of 22.7 kN and 20.9 kN between the first crack and ultimate failure shear loads. It is observed that the post-yield behaviour of chosen mix, i.e. SCC1, SCC2 and SCC3 was found to be almost similar.

Improvement in post-cracking behaviour in shear was observed with the addition of arch and polypropylene fibres. The shear strength of SCC0 was found lowest and failed by brittle in nature and maximum displacement of 0.35 mm as shown in Fig. 6a. A trend of load versus deflection of specimens was found almost similar to all fibre volume fractions as shown in Fig. 6b–d. The load deflection curve follows an approximately straight, steep ascending portion followed by a sudden change in slope at point of appearance of first crack as shown in Fig. 6b–d. This was followed by an increase in load-carrying capacity for some extend, at this point load reaches its peak. This point is called as maximum post-cracking load or ultimate load. The trend was further followed by a descending portion and from this point load-carrying capacity of member decreases with increasing deflection. The maximum deflection of specimen SCC1, SCC2 and SCC3 was found to be 17.4, 22 and 25 mm, respectively.

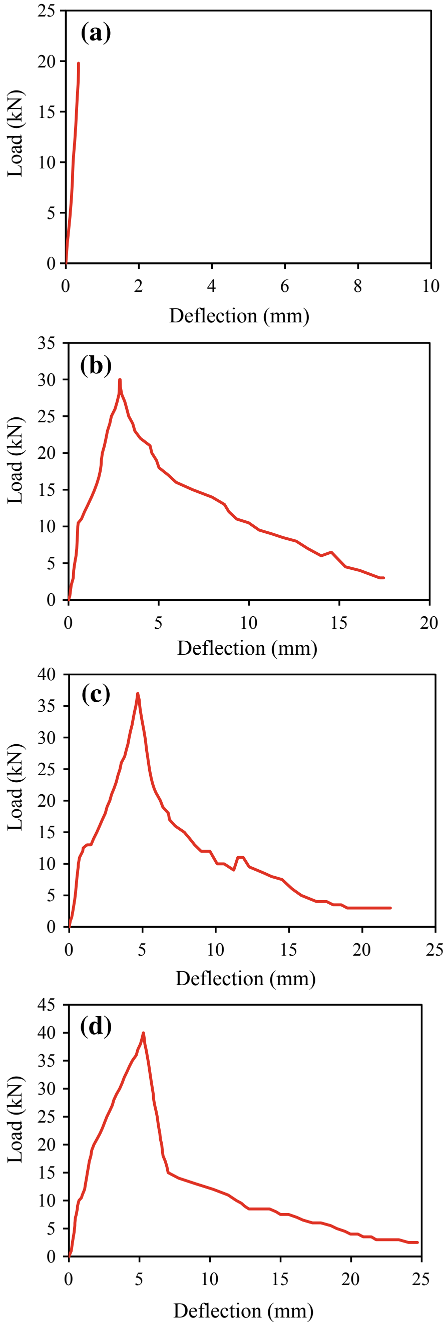


Fig. 6 Load versus deflection of **a** SCC0 **b** SCC1 **b** SCC2 and **c** SCC3

4 Conclusions

The experimental investigations were carried out on fibrous self-compacting concrete (SCC) elements subjected to monotonic loading to study the influence of arch-type steel fibre (AF) in terms of shear and compressive properties. The influence of polypropylene fibres (PF) at varying proportions was also studied along with arch-type steel fibrous self-compacting concrete. The tests were carried out on both fresh concrete as well as hardened concrete and the following conclusions were drawn:

- Workability of hybrid fibre-reinforced self-compacting concrete found to be reduced both in slump flow and L-box tests with increase in the volume of fibres. It is concluded that the fibres more than 1.6% by volume in total may not be used in the self-compacting concrete composite as they may hamper the basic property of the SCC.
- It is concluded that the compressive strength of concrete was found to be increased up to 1.6% fibre content including AF and PF fibres whereas in case of fibre content increase beyond 1.6%, the compressive strength found decreased significantly.
- It is also concluded that the shear strength characteristics showed an excellent improvement with the introduction of fibre hybridization at each fibre volume proportion. The addition of 0.8, 1.6 and 2.4% of combination of steel and polypropylene fibres in the mix was found to increase the shear strength by 52.5, 21.3 and 10.8%, respectively as compared to the conventional SCC mix.
- Arch-type steel fibres showed exceptional post cracking behaviour along with the polypropylene fibres for each mix. The SCC1, SCC2 and SCC3 mix carried 1.8, 1.6 and 1.05 times more load, respectively, after the onset of shear cracking than the load carried by them till the appearance of first crack.

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