Influence of hybrid fibers on the fresh and hardened properties of silica fume blended concrete

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Abstract. This research explores impact of hybrid steel (ST) and polypropylene (PP) fibers on both fresh and hardened behavior of 10% silica fume (SF) blended M30 concrete. Hybrid fibers are introduced at dosages of 0%, 0.5%, 1.0%, 1.5%, and 2.0% total volume (equal proportions of ST and PP). As the fiber dosage increased, the slump declined from 132 mm (control) to 34 mm (2.0% hybrid fiber), reflecting decreased workability. The initial and final setting times increased from 3 h 15 min and 5 h 20 min (control) to 5 h 30 min and 7 h 50 min (2.0% hybrid fiber). The 28-day compressive strength augmented to a maximum of 49.5 MPa at 1.0% hybrid fiber compared to 39 MPa for the control sample. However, the flexural strength increased from 4.3 MPa to a highest of 6.5 MPa at 1.0% hybrid fiber. Increasing the fiber dosage increased fiber balling, contributing to less strength due to poor packing. Therefore, the optimal hybrid fiber dosage is determined to be 1.0% by volume (0.5% ST + 0.5% PP) because this dosage provides the best mechanical performance, crack resistance, and acceptable fresh properties. This configuration provides good post-crack performance as well as acceptable workability and setting times for structural applications.

1 Introduction

Concrete is the utmost extensively utilized building material because of its versatility, casting simplicity, and availability. However, traditional concrete is brittle, has poor tensile strength, and cracks easily when subjected to tensile stresses, which involves the long-term durability and serviceability of concrete properties exclusively in structural applications [1]. For this reason, considerable research on the usage of Supplementary Cementitious Materials (SCMs) in conjunction with fibers to potentially alter both fresh and hardened concrete properties has been conducted. Silica fume (SF) is considered to be the most popular SCM and is a derivative of the silicon and ferrosilicon alloy industry that has become synonymous with

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ultra-high-performance concrete; as a result, SF is viewed as having a high-performance pozzolanic material designation. SF exerts its influence and high performance due to a very fine particle size, high silica content, refining pore structure, and encapsulating permeability, while producing a denser microstructure [2]. By utilizing SF blended concrete, concrete can achieve higher compressive strength (CS), lower chloride permeability, and improved chemical attack resistance. However, when used in concrete mixtures, SF may reduce workability, extend setting times, and produce competitive shrinkage, thus warranting additional counter strategies to offset these characteristics. The use of discrete fibers is another avenue which may mitigate these shortcomings [3]. Steel (ST) fibers enhance ductility and load transfer across cracks, resulting in a better flexural strength (FS), toughness and impact resistance. Polypropylene (PP) fibers on the other hand, are effective at reducing plastic shrinkage and at controlling the onset of micro-cracking during the early hydration stage. The idea of hybrid fiber reinforcement that utilizes two or more fiber types became of great interest recently because of its apparent ability to yield a complementary effect. By merging the crack bridging potential of steel fibers with the shrinkage control of PP, hybrid fiber reinforced concrete will augment both the fresh and hardened concrete performance [4]. Former research has generally engaged on the independent effects of SF or discrete fibers on concrete performance; while studies have shown improvements due to hybrid fibers, there have not been systematic studies to assess their effects on fresh properties such as workable nature or setting time when blended with SF (SFBC). Moreover, there is a lack of understanding regarding optimal hybrid fiber dosage that should be to produce workability, mechanical strength, and post-cracking performance. This has limited the effective use of hybrid fiber reinforced SF concretes in structural applications [5]. The current research purposes to fill this void by exploring the outcome of hybrid ST and PP fiber on the fresh and hardened characteristics of M30 grade SFBC. The investigation used SF at a replacement level of 10%, by weight, and hybrid fiber dosages of 0%, 0.5%, 1.0%, 1.5%, and 2.0% by volume in equal proportions. Fresh properties are tested using slump and setting time, while hardened properties are tested in terms of CS and FS. In particular, the research aims to identify the optimum dosage of hybrid fibers, therefore, finding the ability to attain the best mechanical performance with reasonable fresh concrete qualities. In this sense, the work investigates and expands upon the understanding of hybrid fibers-SF interactions while offering experimental proof for developing durable and high-performance concretes.

2 Materials and procedures

2.1 Binders

The primary binder utilized in this inquiry is 53 grade Ordinary Portland Cement (OPC), compliant with IS 12269–2013, and supplied by KPC. The use of OPC 53 grade is essential to achieve sufficient early-age strength development and element degree of compatibility with SCMs. SF is used as a supplementary binder (10% cement replacement by weight) that is purchased from a local supplier, Hyderabad. It is an ultrafine highly pozzolanic product that densifies the concrete matrix and reduces its permeability, thus boosting strength and durable characteristics by modifying the concrete microstructure. The list of the oxide composition of the OPC and SF employed in this work is given in Table 1, while Figure 1 represents the physical appearance of the binders. Portable water is used for mixing and curing.

Table 1. Oxide analysis of OPC and SF.

Oxide	OPC	SF
SiO_2	21.5	94.0
Al_2O_3	5.2	1.5
Fe_2O_3	3.5	0.5
CaO	63.5	0.6
MgO	2.1	0.4
SO_3	2.4	0.2
$Na_2O + K_2O$	0.6	1.8
Loss on Ignition (LOI)	1.2	1.0

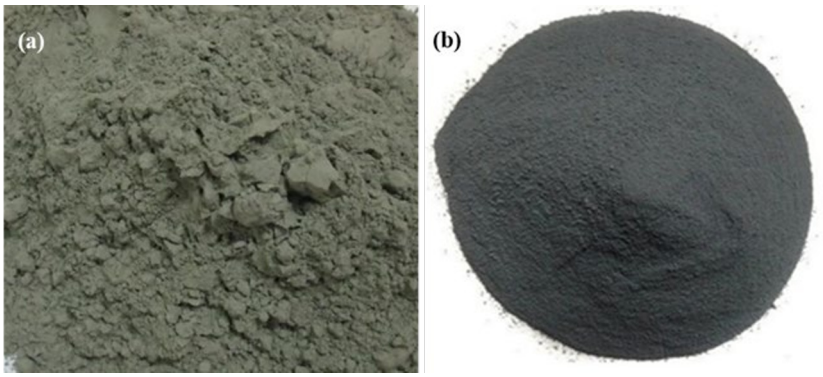

Fig. 1. Binders (a) Cement, and (b) Silica fume.

2.2 Aggregates

Aggregates form the largest percentage in the concrete and serve an important purpose in providing volume stability, and wear resistance. In this study, natural river sand satisfying Zone III grade (as per IS 383–2016) is utilised as a fine aggregate. River sand is a naturally occurring material, created through long-term weathering and erosion of the rocks, which is typically fine granular, and comes in rounded particles due to constantly being abraded and moved within water currents. Table 2 presents the specific gravities of all raw materials used in this work. The coarse aggregate utilized in this investigation consisted of crushed stone at 20 mm nominal maximum size specified in IS 383–2016. The coarse aggregate is well graded, with water absorption of 0.83%, ensuring good performance in the concrete mixing process and durability aspects.

Table 2. Specific gravities of materials.

Oxide	OPC
Cement	3.01
SF	2.2
SP	1.2
Coarse aggregate	2.7
Fine aggregate	2.6

2.3 Fibers

The current investigation utilized a hybrid fiber arrangement including crimped ST and PP fibers anticipated to progress the mechanical and durable performance of concrete blended with SF. The ST used are crimped type, 30 mm long and of 0.75 mm diameter (aspect ratio 40). These ST fibers work primarily on improving crack-bridging capacity, FS, and post-cracking toughness, which are important properties in regards to damaging microcracks or cracks under service loading conditions. Also added are PP which are 19 mm long and of 30 μm diameter (aspect ratio = 633). PP fibers are effective in controlling plastic shrinkage cracking and in limiting micro-crack initiation and growth during early hydration. The combination of both fiber types is expected to produce synergy; whereby ST fibers impart strength and toughness while PP fibers provide improvement in the ability to withstand crack growth due to shrinkage. All combinations of hybrid fibers are designed in equal volumetric proportions of ST and PP fibers (i.e., 0-1.0% ST + 0-1.0% PP).

2.4 Super plasticizer

To enhance the workable nature of SFBC without raising the water content a superplasticizer (SP) Conplast SP430, a product of Fosroc and of the sulphonated melamine formaldehyde (SMF), is used in this study. Mix design of M30 grade SFBC for a constant w/c ratio of 0.4 designed as per IS 10262:2019 is displayed in Table 3. Conplast SP430 provides superior ability to upsurge the flow qualities of concrete mixes allowing for use in applications requiring high early strength, a dense microstructure, and a superior surface finish. Including this admixture in the present study is intended to counteract the loss of workability associated with SF and fiber, thus ensuring uniform dispersion of all materials and a consistent quality in the concrete mixes prepared.

Table 3. Mix Design of M30 grade SFBC as per IS 10262 :2019 (kg/m^3).

Mix Designation	ST Volume fraction (%)	PP Volume fraction (%)	Cement	SF	Fine Aggregate	Coarse Aggregate	Water	SP
S0	0	0	418	0	630	1150	152	4.18
S1	0	0	380	38	630	1150	152	4.18
S2	0.25	0.25	380	38	630	1150	152	4.18
S3	0.5	0.5	380	38	630	1150	152	4.18
S4	0.75	0.75	380	38	630	1150	152	4.18
S5	1	1	380	38	630	1150	152	4.18

2.5 Fresh concrete tests

Fresh concrete properties show a vital part in the ease of placement, compaction, and ultimately the performance of concrete. The workability and setting characteristics of SFBC are evaluated in this study by the following tests. The slump cone test followed IS 1199: Part 2: 2018 to govern the workable nature of fresh concrete. The test uses a standard frustrum (300 mm height, 200 mm base diameter, 100 mm top diameter) cone filled with fresh concrete in three layers compacted with 25 tamping. The cone is lifted straight up and the drop in the height of the concrete sample (slump) is determined. The result of the slump cone test is a direct measurement of the uniformity of fresh concrete and determine ease of workability. The evaluation of setting time of concrete is undertaken using IS 1199: Part 2: 2018 which states that the initial setting time of a mix is the period concerning when the mix initiates to harden and by the final setting time when there is enough stiffness to resist penetration. The setting time measurement of concrete is relevant in understanding how the addition of SF and fibers are affecting the hydration reaction and the workability window of fresh concrete.

2.6 Hardened concrete tests

The hardened characteristics of concrete provide a direct measure of the load-bearing capabilities and structural performance. Compressive strength (CS) and Flexural strength (FS) tests are accomplished on SFBC specimens after 28days of curing. The tests are executed in accordance with IS 516: Part 1: Sec 1: 2021 for CS and FS. CS is determined on 150 mm cube specimens using a compression testing machine (CTM). A vertical axial load is applied at a persistent rate to failure, noting the maximum load. CS is determined as failure load divided by the cross-sectional area of the specimen. This is the most basic measure of the concrete's defiance to compressive stresses. FS is assessed from 100 × 100 × 500 mm beam specimens using a two-point loading setup. The load is put until the specimen failed, then the modulus of rupture is calculated. The FS test evaluates the tensile capacity of concrete in flexure, and while it provides insight into the cracking resistance and softening behavior of the material, the impact of fibres in the post-cracking behavior is better measured separately.

3 Results and discussions

3.1 Workable nature

The outcomes of the Abram's slump cone test indicated a decisive decrease in workability with the addition of SF and increased hybrid fiber content. The control mix (S0) with only OPC, and no SF or fibers, produced a 132 mm slump, indicating the concrete has high workability. This is expected since S0 has no pozzolanic replacement and no fibers, allowing for a slightly fluid mix in terms of the water– cement ratio. The slump in S1 (114 mm) decreased again for the 10% SF replacement. This slump predominantly resulted from the ultrafine particle size of SF and its high surface area. Both of these factors led to increased water demand, while decreasing the free water available for lubricating the aggregates. Although a SP is used, the inherent reduction in workability due to inclusion of SF is still present. In S2 with 0.25% ST and 0.25% PP, the slump reached 97 mm. The continued reduction in workability is a combination of the interlocking and balling effect from the fibers that restrict the constituents of the concrete from free movement and the reduced free water due to the fibers [6]. PP are stiffening towards the fresh mix due chiefly to the fiber's large aspect ratio. S3 (0.5% each fiber content) slump reduced to 78 mm, representing another loss of slump. The mixing at this dosage greatly intensified the fiber interaction and there is further clustering of fibers and greater internal friction in the pack. A clear decrease has shown the combination of the fineness of the SF is restricting flow as similarly experienced with the hybrid fibres. S4 (0.75% each fibre content) slump decreased again drastically to 56 mm slump, denoting very poor workability. At this dosage, the fibre entanglement effects obviously prevail over the other factors, and, as well as SF, the load is limiting further flow. Even with the moderation of SP, the high fibre volume having has substituted a portion of water, requires water to disperse well and it isn't being provided so that water-cement ratios are retained. Finally, S5 (1% ST and 1% PP) has the lowest slump of 34 mm [7]. This considerable loss of workability highlights that high volumes of hybrid fiber absorb excessive paste, create artificial internal friction, and reduce the effects of water and SP as a lubricant. The concrete in this state has become stiff and unmanageable, which illustrates the practical limits of fiber dosage where excessive consumption would be expected by to surpass the optimum. Ultimately, it seems that SF along with fibers advance the mechanical properties of concrete but reduce workability, with the reduction worsening as the hybrid fiber dosage increases. Figure 2 shows the image of slump of SFBC. The slump reduced by about 26%, 42%, 58%, and 74% compared to control (S0) for overall hybrid fiber dosages of 0.5%, 1.0%, 1.5%, and 2.0%, correspondingly, showing a nearly linear decrease in workability with increasing fiber content.

Fig. 2. Slump of SFBC.

3.2 Setting times

The setting time results showed an incremental postponement in both initial and final setting times with the upsurge of SF and hybrid fiber inclusion. For the control mix (S0) the reported initial and final setting times of 3 h 15 min and 5 h 20 min, correspondingly, are anticipated as the typical hydration behaviour of OPC based concrete without any SCMs or fibers where C_3S would contribute to an initial stiffening and C_3A would provide the initial set (Figure 3). In S1 with 10% SF, the initial and final setting times augmented, to 4 h 05 min and 6 h 10 min, correspondingly. This interruption results from the delayed pozzolanic response of SF, which takes longer to consume the calcium hydroxide than the immediate contribution to the early hydration process, in so doing prolonging the stiffening stage. In S2 mix, the initial and final setting times are further delayed to 4 h 20 min (initial) and 6 h 25 min (final). The introduction of the hybrid fibers facilitated a more condensed matrix, which created internal restraints and additionally restricted the ease of particle mobility and delayed the dissipation of heat produced by the hydration, thereby delaying the set [8]. For S3 mix, the initial setting time reached 4 h 40 min, while final setting time increased to 6 h 55 min. The rate of hydration reactions is impeded because of the higher fiber loading, which not only took up some of the cement paste around the fiber surfaces, but also restricted the release of free water. The trend continued with S4, with an initial setting time of 5 h 05 min and final setting time of 7 h 20 min. At this loading, coalescence of fibers led to the paste being restricted even more, which created difficulties in attaining rigidity. The most significant delay is noted in S5 (1.0% each of ST and PP), with initial and final setting times extending to 5 h 30 min and 7 h 50 min, respectively [9]. The high fiber volume fraction essentially slowed the hydration kinetics by trapping water in the interfacial transition zones and restricting the continuous formation of a rigid skeleton, therefore retarding both the initial and final stiffening phases. In summary, the results indicate that the addition of SF alone will produce moderate delays in setting times, and the cumulative effects of adding hybrid fibers will further delay the setting times due to the increased paste demand and restricted particle functionality and water entrapping around the fibers. A graphical representation of the initial and final setting times can be seen in Figure 3 for the different mixes.

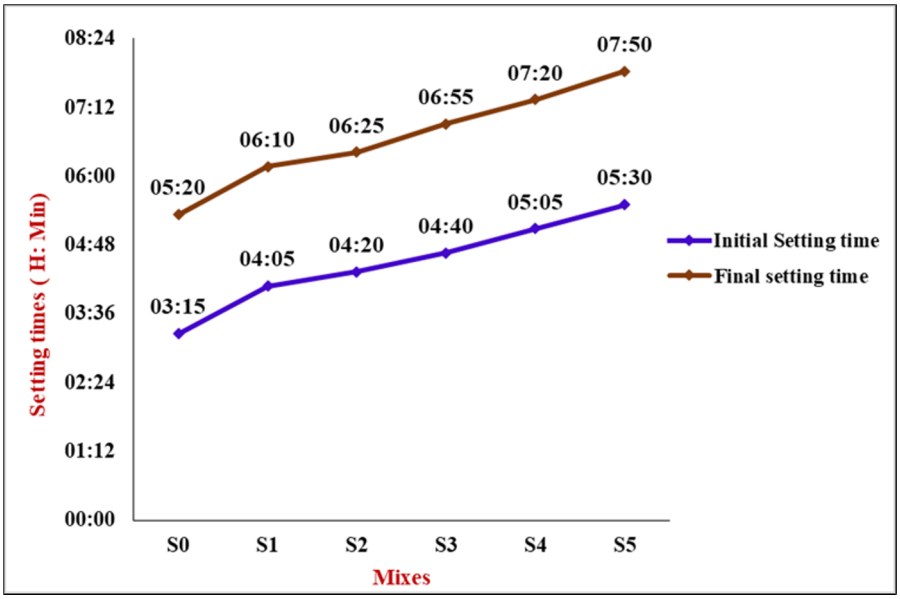

Fig. 3. Initial and Final setting times for various SFBC mixes.

3.3 Compressive strength

The CS results specify that the SF inclusion and hybrid fiber dosage has a profound effect on strength development of concrete specimens at 28 days. In the control mix (S0), the CS is 39 MPa, consistent with the expected performance of M30 grade, OPC-based concrete as discovered in Figure 4. The strength is primarily the result of hydration of the clinker phases that generated calcium silicate hydrate (C-S-H) gel which developed the binding matrix. In replacing 10% of the cement with SF in S1, brought CS to 44.5 MPa, this enhancement in robustness is ascribed to the pozzolanic response of the SF, which yields a finer pore structure, a more densely packed matrix and improved bonding at the interfacial transition zone (ITZ), giving it better load bearing capacity than S0 [10]. In S2, CS further increases to 47 MPa. The hybrid fibre system delivered the capacity to redistribute stresses and delay crack propagation allowing for better utilisation of the matrix strength. The confinement of the concrete core also increased compressive load resistance of concrete as there are fibres entrained in the matrix. The maximum CS is noted in S3 (0.5% of each ST and PP) with 49.5 MPa. The combination of SF densification and fiber reinforcement synergy to reduce cracking indicates that 1% hybrid fiber content to be the required optimal fiber content. ST facilitated macro-crack bridging while polypropylene fibers controlled the initiation of micro-cracks, further facilitating the passive performance of the concrete under compression. The subsequent mixes showed an overall lack of performance regarding compressive CS as these mixes included relevant hybrid fiber content that caused slightly to significantly decreased performance [11]. In S4 (48.8 MPa) and S5 (46.7 MPa), the combination of excessive fiber overall with workability caused excessive difficulty in compaction, possible clustering of fibers in areas of the mix that contributed to voids that could have caused weak zones enclosed by the matrix. In S4 and S5, the negatives of fibers outweighed the positives, regarding compressive performance, versus S2, S3, and S4's maximum potential CS, which could have also assisted in fiber performance. Overall, it can be noted that increasing the SF concentration will improve CS via matrix densification and the use of hybrid fibers improves crack resistance and load transfer. Similarly increasing the hybrid fiber concentration beyond

a total of 1.0% has an overall negative effect to CS, due to the lack of workability-related deficiencies, and therefore validates the hybrid contribution but also advice per maximum usage, of a maximum fiber dosage [12].

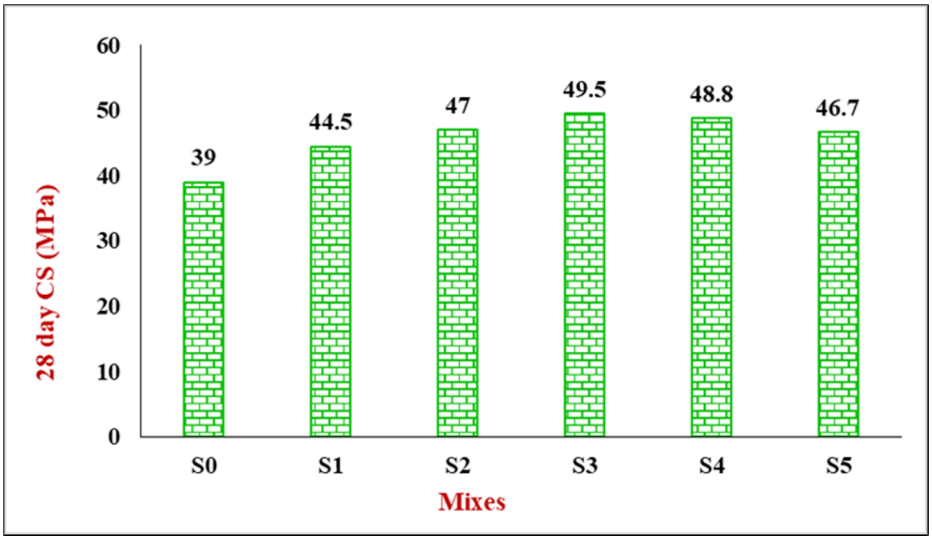

Fig. 4. 28-day CS for various SFBC mixes.

3.4 Flexural strength

Reduced FS results presented a steady upsurge with the addition of SF and hybrid fibers to the maximum dosage level followed by a decrease after maximum level of fiber is added. A 10% addition of SF in S1 increased the FS of concrete to 5.0 MPa as shown in Figure 5. This apparent increase in FS is a function of improved microstructure and improved strength of the ITZ which improved bond of the cement paste to aggregates and delayed crack initiation when the concrete is flexed. With the addition of hybrid ST at 0.25% and PP at 0.25% in S2, FS increased to 5.7 MPa [13]. At this dosage, the fibers actively formed a bridge across freshly forming cracks and re-distributed tensile stresses over the section, increasing the energy absorbency of the concrete in bending. The highest FS observed is 6.5 MPa in S3 (0.5% ST and 0.5% PP). This represents the optimum hybrid dosage for the two types of fibers because the PP aided in micro-crack control while the ST aided in macro-crack bridging. This synergistic effect produced a delay in crack propagation and provided any post-cracking resistance which afforded this specimen better flexural performance. There is a slight decrease in the FS in the higher fiber volume specimens. S4 (6.1 MPa) and S5 (5.6 MPa) both exhibited lower values then S3 [14]. This diminution in strength can be ascribed to loss of workability and clumping of the fibers, which led to fibre dispersion being incomplete. In these cases, there are parts of the beam where fibres are lacking, which enabled cracks to propagate simply and stabilize leading to a reduced overall FS. Overall, while SF may enhance the matrix–aggregate bond strength, hybrid fibers increase ductility and crack confrontation in bending. The optimum dosage of hybrid fibre is one percent total volume (0.5% ST and 0.5% PP) as at this point the negatives of workability and distribution of fibres cancelled out the benefits of fibre reinforcement [15].

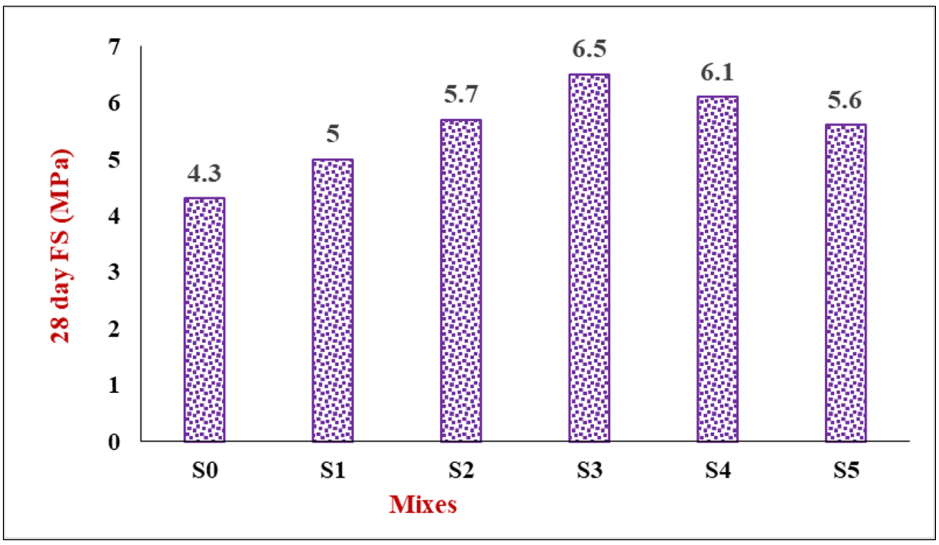

Fig. 5. 28-day FS for various SFBC mixes.

4 Conclusions

This experimental work explored the hybrid ST and PP fibers influence on the fresh and hardened properties of SF blended M30 grade concrete. The laboratory programme leads to the following conclusions:

- The slump reduced from 132 mm (S0) to 34 mm (S5), higher fiber dosage hugely reduced concrete's flowability due to higher internal friction and less free paste.
- The initial and final setting times are augmented with the fiber dosage. The control mix has 3h 15min initial and 5h 20min final set times. When 2.0% fibers are used, the initial and final set times increased to 5h 30 min and 7h 50 min respectively.
- SF (10%) + hybrid fibers have improved CS, up to the optimum dosage.
- The results of CS demonstrated a maximum strength of 49.5 MPa with 1.0% hybrid fibre volume (S3) which is a significant improvement when associated to the control mix (39 MPa).
- FS increased from 4.3 MPa (S0) to 6.5 MPa (S3), however with higher fiber content the FS declined.
- The results show the optimum dosage of hybrid fibre is 1.0% (0.5% ST + 0.5% PP) while achieving a balance between strength and while maintaining an acceptable workability and setting times.

For structural engineers, the combination 0.5% ST + 0.5% PP, preserves the strength while not sacrificing workability considerably. This dosage can be efficiently used in slabs, pavements and precast components where cracking mitigation and ductility is paramount. It is important to mention that fiber doses greater than 1.0 percent of the total volume significantly compromise workability (slump < 60mm), and this level of workability will make it difficult to place and compact the fiber-reinforced concrete without advanced vibration or self-compacting admixtures. Thus, it is recommended that 1.0 percent is the practical upper limit for conventional casting techniques. Additional research could examine sustainability durability aspects (i.e. drying shrinkage, fatigue, and impact resistance) related to the SF–hybrid fiber composites. Research could also provide a means to test extended

curing regimes and other sustainability exposure testing to achieve long-term field performance with these composites.

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