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Original Article

Performance Enhancement of Hybrid SIFCON Through Steel-Glass-Polypropylene Fibre Synergy for Improved Workability and Mechanical Efficiency

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Abstract *- Slurry Infiltrated Fibrous Concrete (SIFCON) is an advanced cementitious composite characterized by a high level of fibre content, high ductility, and high-quality crack resistance. Its broader use is limited, however, by issues of slurry intrusion and fibre congestion when single-type fibres are employed in more intense dosages. In order to address these shortcomings, this research paper investigates the synergistic outcome of steel, glass, and polypropylene fibres on fresh and mechanical characteristics of hybrid SIFCON. The main goal was to find a good hybrid fibre mixture that can strengthen and improve flexural performance without distorting the workability. M40 grade concrete was used in the form of the base matrix in thirteen hybrid SIFCON mixes with the addition of OPC 53 grade cement, fly ash as an additional binder, and a water-cement ratio of 0.45 held constant. Steel fibres were sustained at 4% volume in selected mixes; glass fibres were varied from 1% to 4%, and polypropylene fibres were included at 0.5% where applicable. To determine flowability and passing ability, the slurry was infiltrated into pre-laid fibres, and fresh state properties were evaluated by using V-funnel and J-ring tests. Compressive, split tensile, and flexural strength tests were performed at 7 and 28 days in order to evaluate mechanical behavior. The incorporation of hybrid fibres produced a great improvement in the mechanical performance as compared to the control mix. The mix HS4G2P05 that had 4% steel, 2% glass, and 0.5% polypropylene fibres delivered the best results with a split tensile strength of 28 days of 6 Mpa, compressive strength of 50 Mpa, and flexural strength of 9.5 MPA, representing increases of 14.2%, 81.8%, and 111% respectively over the control concrete. The Performance Index (PI) improved from 0.105 to 0.190, indicating superior flexural efficiency. Statistical significance was confirmed by one-way ANOVA of all the parameters of strength as the decisive effect of fibre hybridization. Overall, the study confirms that well-proportioned hybrid fibres enhance multi-scale crack bridging, improve slurry infiltration, and yield superior structural performance.*

Keywords *- Hybrid SIFCON, Slurry Infiltration, Steel Fibres, Glass Fibres, Polypropylene Fibres, Fresh Properties, Split Tensile Strength, Compressive Strength, Flexural Behavior.*

1. Introduction

Slurry Infiltrated Fibrous Concrete (SIFCON) is a type of ultra-high-performance fibre-reinforced cementitious composite that is significantly high in fibre content and has higher mechanical performance [1]. Unlike traditional fibre-reinforced concrete, which requires mixing fibres directly into the fresh matrix, SIFCON was produced through a two-step process: the fibres must first be placed inside the mold, and then a highly flowable cementitious slurry infiltrates the fibres [2]. The special production method results in constant distribution of fibres, high-density packing, and close interaction between fibre and matrix, leading to excellent enhancement of ductility, toughness, impact resistance, and energy absorption capacity. Due to its superior performance, SIFCON was employed in constructing blast-resistant facilities, airport pavements, factory floors, and for seismic reinforcement and structural retrofitting [3].

The fibre type, geometry, and volume fraction are the primary factors that influence the mechanical response of the SIFCON [4]. The hooked-end steel fibres are common in high tensile resistance, with the ability to maintain large crack openings. However, there are also certain drawbacks associated with having a larger number of steel fibres exceeding 6%, which are the loss of slurry mobility, high potential of fibres entanglement, high cost of material, and the issue of casting [5]. Such limitations have led to studies that focused on hybrid fibre systems, which are composed of fibres of different sizes and characteristics to enhance mechanical performance without affecting the workable mix properties.

The hybrid systems usually comprise macro and micro fibres. Steel is a macro fibre that provides resistance to extensive cracking and helps to redistribute the loads during the post-cracking phase [6]. Microscopic fibres like polypropylene and glass inhibit the initial crack and smooth out the network of cracks [7]. Glass fibres are very effective in tensile strength and do not impact the retention of microcracks during the first loading. The polypropylene fibres are known to exert an influence on the control of the plastic shrinkage effect, thermal distortion, and the deformation capacity once the cracking has started [8]. Multi-scales of reinforcement during mechanical loading are achieved by conglomerating the use of steel, glass, and polypropylene fibres that aid in enhancing better control of crack propagation, initiation, and overall stability in the case of mechanical loading.

Past studies on hybrid fibre reinforced composites have also indicated enhanced tensile response, better flexural strength, and increased toughness values than single fibre systems. Hybridization in mixtures of higher fibre density, such as in SIFCON, enables more control over the stress distribution throughout the matrix and gives greater resistance to brittle failure modes [9]. The lack of data on the optimal proportions of the different macro and micro fibres in the SIFCON matrix and the effect that the different combinations could have on fresh state behavior is critical in ensuring successful infiltration of slurries [10].

The fresh properties are essential in SIFCON production since the slurry flowability and passing ability are the factors of how deeply the cementitious matrix penetrates the fibrous skeleton already in place [11]. Disparities in the stiffness of fibres, volume, and surface appearance influence the slurry viscosity and mobility, thereby affecting the uniformity of infiltration [12]. The lack of infiltration results in the presence of voids as well as uneven distributions of fibre volumes and declines in the efficiency of the mechanism. Although a lot of research has been done on SIFCON and fibre-reinforced composites, a number of gaps are still significant. The majority of the literature has concentrated on individual fibre systems or smaller hybrid combinations, and has not looked at the synergistic interaction between macro and micro fibres on a multi-scale basis. Also, little effort has been put into streamlining hybrid fibre ratios, in particular with regard to SIFCON, where the slurry infiltration and fibre congestion play a critical role. Moreover, the joint assessment of fresh properties, the mechanical behavior, and structural efficiency with the help of performance indices has not been fully investigated.

In this context, the present study introduces a novel multiscale hybrid fibre system incorporating steel, glass, and polypropylene fibres in optimized proportions. In contrast to the earlier studies, the study is a systematic examination of the combined impact of hybridization on the workability, mechanical strength, and flexural efficiency with statistical validation. The paper also suggests a combined performance measurement based on a Performance Index (PI), which provides a more detailed analysis of structural performance in hybrid SIFCON systems. The following research will focus on setting up the impact of a hybrid steel-glass-polypropylene fibre mixture on fresh characteristics, split tensile power, compressive power, and flexural action of SIFCON. The main aims of the research are:

- To study the influence of hybrid fibre composition: steel, glass, and polypropylene on the fresh and hardened properties of SIFCON.
- To determine an optimal hybrid fibre proportion that enhances compressive, split tensile, and flexural strengths without adversely affecting slurry workability.
- To measure the effects of fibre hybridization on slurry infiltration, flowability, and passing ability on V-funnel and J-ring tests.
- To determine the mechanical performance of hybrid SIFCON mixes during 7 and 28 days and compare it to conventional concrete.
- To determine the structural efficiency of hybrid SIFCON with the PI, the flexural performance should be related to compressive capacity.
- To test the statistical significance of the improvements in the parameters of strength observed after one-way ANOVA.

The remaining portion of this study is structured as follows: Section 2 offers a review of the literature on SIFCON and hybrid fibre reinforcement systems. Section 3 details the materials, mix proportions, casting procedure, and testing methodology adopted for the hybrid SIFCON mixes. Section 4 discusses the experimental results, including fresh property evaluation, mechanical performance, PI analysis, and statistical validation. Section 5 concludes the study by summarizing the key findings and identifying the optimal hybrid fibre combination, along with its practical relevance for structural applications.

2. Literature Review

Hashim et al. [13] experimented with the SIFCON using treated and untreated waste rubber as a partial fine aggregate substitute at 5, 10, and 15 percent. It was preplaced with steel fibres and infiltrated with slurry, and flexural, compressive, and splitting tensile strength testing were done after 28 days. The addition of rubber led to a progressive decrease in mechanical performance, with compressive strength losses of more than 40 percent at the maximum replacement level. Flexural and splitting tensile strengths also reduced over 35% and 45%, respectively, compared to the control mix. NaOH pretreatment improved interfacial adhesion and resulted in moderate strength recovery of approximately 10% compared to untreated rubber mixes; however, performance remained inferior to the reference. The research was constrained by the high strength loss at higher contents of rubber caused by the formation of voids, low bonding, and the reduction of stiffness of rubber particles.

Penda & Reddy [14] compared SIFCON made using steel fibres obtained through scrap tires and SIFCON reinforced with commercially obtained fibres. Preplacement and infiltration of cement slurry into the matrix were done with fibres of between 4% and 7%. The measurement of compressive and split tensile strengths was performed using cube and cylinder specimens after 3, 7, and 28-days. The 28-day compressive strength improved from 56.65 Mpa for plain SIFCON to 63.36 Mpa at 6% scrap tire fibres, while commercial fibres yielded 92.48 MPa at the same dosage.

Split tensile strength increased from 4.69 MPa to 7.88 MPa with scrap fibres and 16.06 Mpa with commercial fibres respectively. The deterioration of performance was observed at 7% fibre volume because fibre clustering and workability decreased, which means that there is an upper limit of inclusion.

Ali et al. [15] examined the use of SIFCON, which entails the use of Waste Polyethylene Terephthalate (WPET) fibres acquired through discarded beverage containers. Mortar-based mixes were produced with three fibre contents like 3%, 5%, and 7%, and tested for flexural strength and toughness using 100×100×400 mm prisms at 28 and 56 days. As a reference, a conventional concrete mix was used. The blend with 7 percent WPET fibres (S7) attained the best flexural strength of 4.92 Mpa at 28 days and 5.356 Mpa at 56 days. The 56-day toughness was also 726% higher, which demonstrated an improvement in post-crack behavior. Nonetheless, the compressive strength of S7 dropped to 39.84 MPa, which showed a weakness towards the plastic fibres' high content and the incompatibility of the matrices and fibres.

Alsheameri et al. [10] studied the impact of a modified casting sequence on SIFCON with straight steel fibres on the mechanical performance. The conventional multi-layer placement and a gradual mixing method of casting were compared based on specimens that were experimented on with regard to hardened properties. The gradual approach was more efficient with a compressive strength increase of 15.21%, a splitting tensile strength increase of 8.06%, a modulus elasticity increase of 9.07%, and a modulus rupture increase of 5.26%, as associated with the traditional way. The improvements were attributed to more uniform fibre dispersion achieved through controlled incorporation. Nevertheless, the study only analysed a single type of steel fibres and not on hybrid combinations, and the durability of these fibres, which hinders the generalizability of the results.

Hassan & Fawzi [16] investigated modified-weight SIFCON by adding the use of single and combined fibres so as to improve performance whilst decreasing density. The use of cement and fine aggregates was substituted to a large extent with glass waste to ensure that there was minimal environmental impact. Six mixes containing 4% fibre volume in different configurations were examined through ultrasonic pulse velocity, compressive strength, and density tests.

Hybrid reinforced with basalt, micro steel, and polypropylene provided the most desirable response with significant increases in compressive strength and pulse velocity compared to that of the reference mix. Single polypropylene fibres decreased density, and hybrid composites decreased the effect of density on slurry infiltration and void distribution. Though the hybrid system improved mechanical and physical performance, the research was limited to a constant fibre volume and did not investigate optimization of the fibre dosage and the improved mechanical performance parameters, like flexural strength.

AbdulRehman [17] investigated SIFCON produced using slag as the main binder, replacing cement to reduce environmental impact. After 28 days, straight and hooked steel fibres were introduced at 5, 10, and 15 percent ratios, and the mixes were analyzed in terms of water absorption, compressive strength, and abrasion resistance. The addition of steel fibres enhanced compressive strength, with the 10% micro steel fibre mix achieving a 14.96% increase compared to the reference specimen. Fibre addition, however, increased water absorption by 3.4, which is an indication that there was formation of vacant spaces in the structure. The best abrasion resistance occurred with 10% hooked steel fibres, reducing abrasion depth by 72.5%. Although beneficial mechanically, the study lacked tensile and flexural evaluations, limiting a full understanding of the fibre-matrix interaction.

Yas et al. [18] compared the results of SIFCON slabs reinforced with different geometry steel fibres, micro steel, hook end fibres and hybrid fibres in terms of their performance during an impact load and under a constant load. The authors have pointed out that curing of 7-56 days showed a significant increase in compressive strength of micro steel, hybrid, and hook end fibres by 42, 44, and 52 percent, respectively.

Improvements were also reported in elastic modulus, which increased by 26%, 28%, and 27.5%, while splitting tensile strength rose by 15.3%, 15%, and 13.7% for the same fibre categories. Under impact loading, the hybrid-fibre SIFCON slab endured 1324 blows compared with only 580 blows for normal concrete, confirming superior energy absorption and crack control. Although effective in enhancing strength and impact resistance, the research remained confined to steel-based fibre configurations and did not investigate multiscale hybridization involving non-metallic fibres.

Mohammed and Al-Azzawi [19] examined the use of SIFCON jackets in the reinforcement of beams of reinforced concrete under pure torsion. Seven beams were experimented with, one having no torsional reinforcement, one having torsional reinforcement, and five beams reinforced with 5%-fibre SIFCON jackets (full and three sides) using steel, glass, and hybrid fibres.

Fresh tests indicated that SIFCON acted as self-compacting concrete, and hardened tests indicated more compressive, flexural strength, splitting tensile, and modulus of elasticity than normal concrete. SIFCON strengthening under torsion enhanced cracking torque by up to several hundred percent and ultimate torque more than twofold in comparison to reference beams, with the greatest benefits provided by full side steel-fibre jackets. Limitations included focus on torsion only, fixed fibre volume, and absence of long-term durability or flexural-shear interaction evaluation.

Ali et al. [20] observed the mechanical behavior of SIFCON produced using cement-based and geopolymer-based slurries with 7.5% hooked steel fibres. Fibres were preplaced in molds, followed by slurry infiltration, and specimens were tested under compression, splitting tension, and flexure. The inclusion of fibres improved compressive, tensile, and flexural responses for both SIFCON and G-SIFCON relative to control mixes. Geopolymer matrices exhibited higher gains than cement-based slurries, reflecting enhanced particle packing and fibre-matrix interaction. Ultrasonic pulse velocity showed reductions attributed to entrapped voids within dense fibre networks. The experimental setup was restricted to one fibre volume fraction and did not evaluate durability, long-term performance, or behavior under different loading regimes.

Hassan and Aljalawi [21] examined the effect of adding waste glass and hybrid fibres to Slurry Infiltrated Fibre Concrete. The slurry was prepared by a cement/fine aggregate ratio of 1:1, and cement and fine aggregates were partly replaced by glass powder and crushed glass. Hybrid fibre reinforcement was made of micro steel, basalt, and polypropylene fibres in various volume ratios.

The combination of 1% basalt, 2% micro steel, and 1 percent polypropylene gave the best results and gave the highest modulus of elasticity, splitting tensile strength, and lowest void ratio. Effective fibre bridging and improved matrix packing were associated with improvements. Investigation was limited to hybrid combinations of a constant amount of fibre and not on fatigue, long-term steadiness, or the structural reaction to the varied loading conditions.

Several studies have highlighted limitations that remain unresolved in existing SIFCON research. Previous studies have documented considerable strength deterioration in the case of adding waste rubber because of the existence of holes and poor bonding, without providing a solution to address the shortcomings [13]. Research comparing different fibre sources focused on strength enhancement but did not address workability reduction and fibre clustering at higher dosages [14]. Studies using PET and slag-based SIFCON improved certain parameters but failed to optimize flexural response and hybrid fibre synergy [15,18]. Investigations on steel or single-fibre systems did not explore multiscale hybridization or its effect on slurry flowability and infiltration [18-21].

3. Materials and Methods

3.1. Materials Used

3.1.1. Cement

Ordinary Portland Cement (OPC) of 53 Grade conforming to IS 12269:1987 was utilised as the primary binder. Laboratory characterization was performed in accordance with IS 4031 to determine specific gravity, standard consistency, and setting times. The cement exhibited a specific gravity of 3.15, indicating adequate density for structural concrete. Standard consistency was determined using the Vicat apparatus (IS 4031 Part IV:1988). The water content required to produce standard plasticity was calculated using Equation 1.

$$\text{Water Content}(\%) = \frac{W_2}{W_1} \times 100 \qquad (1)$$

Where W_1 represents the Weight of Cement (g) and W_2 provides the weight of Water Added (g). The standard consistency was found to be 32%. The setting time was calculated using the Vicat needle apparatus. Initial setting time and final setting time were within IS code limits, confirming adequate handling and hydration characteristics. Table 1 illustrates the cement properties.

Table 1. Cement properties

Property	**Value**
Cement Type	OPC 53 Grade
Specific Gravity	3.15
Standard Consistency	32%
Initial Setting Time	35 min
Final Setting Time	580 n

3.1.2. Coarse Aggregate

Crushed coarse aggregate having an extreme particle size of 12.5 mm was obtained locally. It is a deliberate choice of the reduced size of the aggregate to achieve the slurry infiltration process and to prevent the hindrance as the fibres are deposited in SIFCON. The aggregate contained 0.6% of water absorption and 2.80 of specific gravity, which was measured in compliance with the IS 383:2016. These characteristics suggest that the aggregates are strong enough and have low porosity and dimensional stability. The chosen gradation provides an increase in the packing density and a reduction in the voids, which advances the interlocking of the fibres and the allocation of the stress to the reinforcement fibres applied to the load of the matrix.

3.1.3. Fine Aggregate

Natural river sand was utilised as fine aggregate. It had a 2.70 specific gravity and was visually tested to be free of organic impurities. Clean and well-graded sand is used to increase the slurry cohesion, lessen segregation, and efficiently fill voids in the thick network of fibres in SIFCON. This helps in enhancing the densification of the matrix and enhancing mechanical performance.

3.1.4. Fly Ash

The mix was a supplementary cementitious material with the addition of class C fly ash. The fly ash had 2.31 specific gravity. It increases both the workability of the slurry and the microstructure of the hardened matrix. Secondary reactions through hydration also help to alleviate brittleness and enhance long-term strength growth with the help of fly ash.

3.1.5. Superplasticizer

A sulphonated naphthalene-based superplasticizer (Conplast SP430) was used with a dosage of 2% by cement weight. The main reason behind this admixture was the enhancement of the fluidity of cement slurry and not augmenting the water content. This becomes essential in SIFCON, whereby the slurry should penetrate through closely spaced fibres without causing segregation and cavity development.

3.1.6. Water

Potable water was utilized for both mixing and curing throughout the study. Proper water quality enables the cementitious materials to be properly hydrated to guarantee sufficient strength gain and durability. Clean water is also used to avert any adverse chemical reactions that could have otherwise impacted the performance of concrete.

3.1.7. Fibres

This study included three varieties of fibres, namely hooked-end steel fibres, glass fibres and polypropylene fibres that were added to improve the mechanical performance of hybrid SIFCON, as in Table 2. Each type of fibres played a different role in the reinforcement of the cementitious matrix by giving strength to the cementitious matrix at various levels of crack propagation.

Hooked-end steel fibres, as shown in Figure 1, are primarily responsible for improving post-cracking behavior. The hooked ends increase mechanical anchorage, enhancing pull-out resistance and qualifying the composite to endure further load once cracking occurs. These fibres enhance toughness to a significant degree, arrest crack propagation, and enhance ductility, thus allowing hybrid SIFCON to possess high post-crack load-carrying capacity.

Fig. 1 Hooked-end steel fibres

The glass fibres illustrated in Figure 2 enhance the tensile resistance of the matrix due to the smooth, corrosion-resistant surface and tensile strength of the material. Their small size assists in the even distribution of tensile forces to decrease the surface cracking and the minimization of brittleness. Glass fibres enhance the rigidity of the composite and structural integrity by regulating the crack openings and containing the stress concentration along the localized joints.

Fig. 2 Glass fibres

Polypropylene fibres, as depicted in Figure 3, function at the microstructural level, where they effectively control early age microcrack formation. Their fine diameter and flexible nature help reduce plastic shrinkage and thermal cracking during the initial hydration period. These fibres enhance the cohesion of the matrix and crack resistance, leading to high durability and dimensional stability of hybrid SIFCON.

Fig. 3 Polypropylene fibres

The effectiveness of hybrid SIFCON relied significantly on the geometric and physical characteristics of the fibres, particularly their diameter, length, and aspect ratio. The parameters identify the fibre matrix interaction, stress transfer efficiency, and resistance to fibre pull out in loading conditions. An increase in aspect ratio improved the capability of the fibres to bridge cracks and resist pull-out, which is directly related to curbing the crack propagation of fibres and post-cracking performance. Additionally, the appearance and surface texture of the fibres determine the level of mechanical interlock and bonding of the cementitious slurry.

Table 2. Fibre properties

Fibre Type	Diameter	Length	Aspect Ratio (L/D)	Appearance
Hooked-end steel fibres	0.5 mm	30 mm	60	Clear, bright, hooked
Glass fibres	0.02 mm	12 mm	600	Shiny white, smooth
Polypropylene fibres	0.03 mm	12 mm	400	White, soft

3.2. Mix Proportion of Test Specimens

In this research, the concrete mixes were designed based on the M40 grade concrete as the benchmark, which was prepared with OPC of 53 Grade. The blend consisted of a proportional mix of cement, fine aggregate and coarse aggregate in the ratio 1: 1.5: 2.67 with a fixed Water to Cement (w/c) ratio of 0.45. This proportion was selected to achieve adequate strength while ensuring compatibility with the slurry infiltration process required for SIFCON production. Hybrid SIFCON mixtures have been developed as an outcome of adding various blends of hooked-end steel fibres, glass fibres and polypropylene fibres to the cementitious slurry. Contrary to traditional concrete, SIFCON manufacture is a process that entails placing fibres on molds and then inundating the fibres with a highly pourable slurry. Hence, the consistency of the slurry and the dosage of the fibres are important in order to get the intended composite performance.

A sulphonated naphthalene-based superplasticizer was incorporated with all the mixes at a proportion of 2% of the cement weight in order to achieve the proper mix flowability and penetration of slurry in the dense fibre network. The proportion of fly ash was added at 0.10 in comparison to cement to enhance the slurry viscosity, increase the packing density, and minimize the interfibrous spaces. Thirteen mixtures of hybrid SIFCON were made with the only differences in fibre type and volume fraction. The steel fibre volume was maintained at 4% in selected mixes, while the glass fibre content was varied from 1% to 4%, and polypropylene fibres were added at a fixed dosage of 0.5% in designated combinations. Others were steel and glass fibre-based mixes without polypropylene, and others were mixes of all three fibres thus making it possible to compare mechanical synergy. Table 3 shows the precise proportions of mixtures and fibre combinations applied in this study.

Table 3. Mix proportions of hybrid SIFCON

Mix No.	Cement	FA	Fly ash	W/c	SP %	Steel fibre volume (%)	Glass fibre volume (%)	Polypropylene fibre volume (%)
HS4G1P0	1	1.5	0.10	0.45	2	4	1	-
HS4G2P0	1	1.5	0.10	0.45	2	4	2	-
HS4G3P0	1	1.5	0.10	0.45	2	4	3	-
HS4G4P0	1	1.5	0.10	0.45	2	4	4	-
HS4G0P05	1	1.5	0.10	0.45	2	4	-	0.5
HS0G1P05	1	1.5	0.10	0.45	2	-	1	0.5
HS0G2P05	1	1.5	0.10	0.45	2	-	2	0.5
HS0G3P05	1	1.5	0.10	0.45	2	-	3	0.5
HS0G4P05	1	1.5	0.10	0.45	2	-	4	0.5
HS4G1P05	1	1.5	0.10	0.45	2	4	1	0.5
HS4G2P05	1	1.5	0.10	0.45	2	4	2	0.5
HS4G3P05	1	1.5	0.10	0.45	2	4	3	0.5
HS4G4P05	1	1.5	0.10	0.45	2	4	4	0.5

3.3. Experimental Programme

The experimental program was designed to assess the fresh and hardened properties of hybrid SIFCON incorporating different combinations of steel, glass, and polypropylene fibres.

The primary objective was to analyze the impacts of hybrid fibre reinforcement on workability performance and mechanical characteristics, including split tensile strength, compressive strength, and flexural strength.

3.3.1. Specimen Preparation

A systematic process of casting was used in preparing all hybrid SIFCON specimens to ensure that there was uniformity between the mixes. Firstly, the predetermined amounts of cement, fine aggregate, fly ash, and superplasticizer were weighed and mixed to produce a highly flowable slurry suitable for infiltration.

After the slurry had attained an even consistency, the predetermined combinations of fibres of the mix design were then placed in the moulds manually based on the specified volume fractions of each mix.

Fibres were distributed evenly within the mold to avoid clumping and confirm uniform reinforcement across the specimen. The slurry was then added to the fibre filled moulds wherein it was allowed to enter the fibre matrix due to gravity and constant vibration. Proper infiltration was critical to eliminate voids and ensure complete saturation of the fibre network, which is a defining characteristic of SIFCON. Figure 4 shows the process of casting used in hybrid SIFCON specimens. Specimens were prepared in three shapes to accommodate mechanical tests, as shown in Table 4. These dimensions complied with the requirements specified in the relevant Indian Standards.

Fig. 4 Casting hybrid SIFCON specimens

Table 4. Specimen types and dimensions adopted for mechanical strength evaluation

Test Type	Specimen Shape	Dimensions
Split Tensile Strength	Cylinder	150 mm diameter × 300 mm height
Compressive Strength	Cube	150 mm × 150 mm × 150 mm
Flexural Strength	Beam	100 mm × 100 mm × 500 mm

3.3.2. Curing

The specimens were then allowed to dry without any interventions after the casting process, and then kept for 24 hours at the ambient laboratory temperature. After demoulding, they were placed into a curing tank with potable water.

All test specimens were allowed to cure to their respective testing age so that they could be properly hydrated and develop strength. The curing process ensured that there were sufficient moisture conditions that avoided early age shrinkage, and so the fibres and matrix bonded to their optimum strength.

3.3.3. Testing Procedures

The concrete specimens that were hardened underwent mechanical testing following the end of the curing period. Fresh properties were assessed using the V-funnel and J-ring tests, whereas mechanical performance tests were carried out on cube, cylindrical, and beam specimens. All the tests were conducted to the best standards to prove reliability and reproducibility.

V-Funnel and J-Ring Tests

Hybrid SIFCON workability factors were identified based on the recommendations of EFNARC and IS 10262:2019. Figure 5 shows that the V-funnel test was utilised to measure the flow time of slurry, which measures the viscosity of the slurry and the filling capacity. The J-ring test in Figure 6 was used to estimate the passing capacity of the mix in the face of obstructions, hence the probability of blockage caused by the fibre content. Table 5 shows the fresh property test results. High values of fibre content led to increased V-funnel discharge times and low values of J-ring flow diameters, which means that the addition of fibres decreases workability because of high internal resistance and low mobility of the flow.

Fig. 5 V-Funnel test

Fig. 6 J-Ring test

An increase in fibre content resulted in higher V-funnel discharge times and reduced J-ring flow diameters, indicating that the incorporation of fibres decreases workability due to increased internal resistance and reduced flow mobility.

Table 5. Fresh property results of hybrid SIFCON mixes

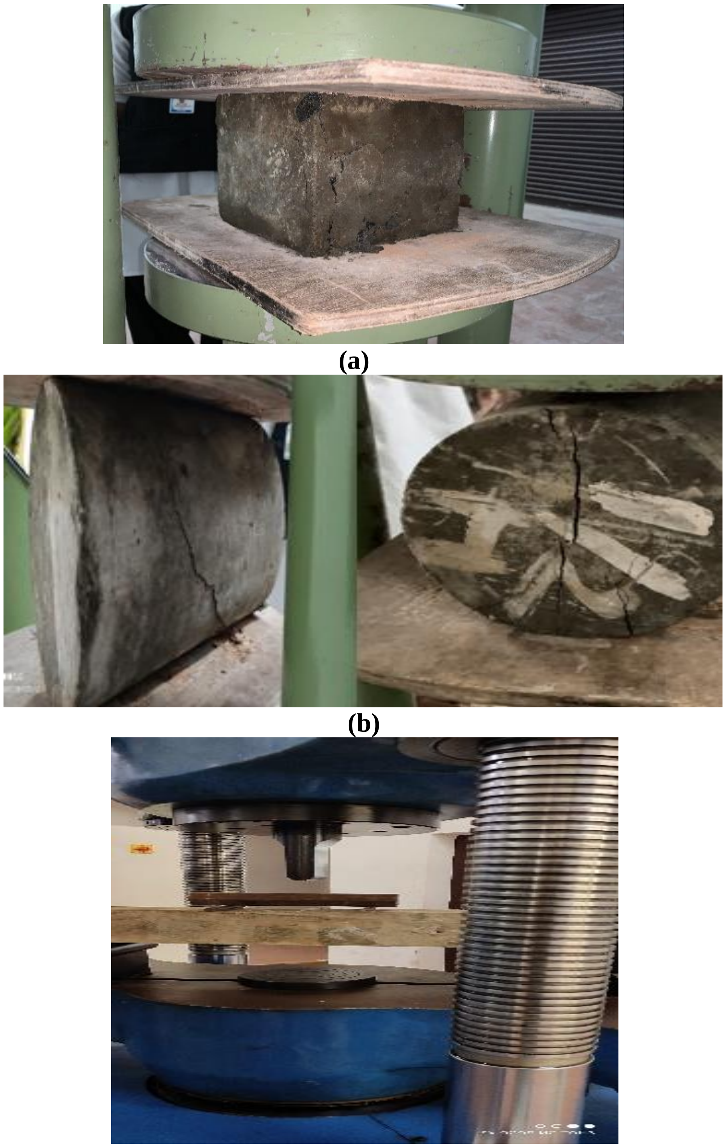
Mix	V-Funnel (s)	J-Ring (cm)	Purpose / Remarks
HS4G1P0	10	62	Baseline with hybrid fibres, acceptable flowability
HS4G2P0	11	61	Slight reduction in passing ability due to increased glass fibre
HS4G3P0	12.5	59	Increased flow time is an indication of higher viscosity
HS4G4P0	13	56	Maximum fibre congestion, reduced passing ability
HS4G0P05	11	60	The addition of polypropylene increased cohesion
HS0G1P05	9	64	Best workability, lower viscosity
HS0G2P05	10	62	Slight decrease in passing ability due to fibre interaction
HS0G3P05	11	60	Balanced flow and passing characteristics
HS0G4P05	12.5	58	Higher resistance to flow due to fibre volume
HS4G1P05	10.5	62	Hybridization improved flow uniformity
HS4G2P05	11	60	Optimal hybrid mix performance
HS4G3P05	11.5	58	Increased viscosity with more fibres
HS4G4P05	13	56	Lowest passing ability due to the highest fibre content

Strength Testing

Mechanical strength tests were shown on cylinders for split tensile strength, cubes for compressive strength, and beams for flexural strength. Proper loading procedures were followed on each of the tests until they failed. The tests were made to guarantee the assessment of the fibre effects on resistance against cracking, the carrying capacity, and the post-cracking behavior of the loads. All specimens were tested under controlled conditions, and the results derived from these tests form the basis for performance comparison between mixes. Table 6 shows the different mechanical tests performed on the hybrid SIFCON specimens, as well as the dimensions of the specimens, testing method, and Indian Standard code used, which had to be followed in the process of testing. All the tests were done on calibrated equipment to provide accuracy and reproducibility of the results. Figure 7 depicts mechanical testing methods that were used on the hybrid SIFCON, with cube specimens being tested on compressive strength, cylindrical specimens being tested on split tensile strength, and beam specimens being tested under flexural loading to establish their bending performance.

Table 6. Mechanical testing procedures

Test Type	Specimen Dimensions	Testing Method	Standard Followed	Remarks
Compressive Strength	150 × 150 × 150 mm (Cube)	The load is applied using a compression testing machine until failure	IS 516	Average of 3 specimens per mix
Split Tensile Strength	150 mm diameter × 300 mm height (Cylinder)	Diametral load applied, causing the specimen to split	IS 5816	Determines indirect tensile resistance
Flexural Strength	100 × 100 × 500 mm (Beam)	Third point loading on the universal testing machine	IS 516	Evaluates flexural capacity and crack resistance


(a)

(b)

(c)

Fig. 7 Mechanical testing procedures (a) compressive strength, (b) split tensile strength, and (c) flexural behavior of hybrid SIFCON.

4. Results and Discussion

The mechanical behavior of hybrid SIFCON reinforced with hooked-end steel fibres, glass fibres and polypropylene fibres was evaluated by conducting split tensile, compressive, and flexural strength tests at 7 and 28 days. The performance of these hybrid mixes was compared with Control Concrete (CC) to understand the synergistic effects induced by fibre hybridization on mechanical response.

4.1. Compressive Strength

The values of compressive strength obtained at 7 and 28 days revealed a significant enhancement in strength for all Hybrid SIFCON mixes related to the control concrete. At 7 days, the CC recorded 27.5 MPa, whereas the hybrid mixes exhibited strengths ranging from 26.5 MPa to 36 MPa. Among the mixes that incorporated all three fibres, HS4G2P05 achieved the highest strength of 36 MPa, surpassing the control by approximately 30.9%, indicating that the interaction of fibres at the initial hydration stages was beneficial. The other mixes like HS4G3P0 and HS4G4P0 offered 34 Mpa and 35 Mpa respectively, and this proved that only adding steel fibres to the mix improves compressive behaviour considerably, and the addition of polypropyrene fibres enhances micro crack resistance and load transfer capacity.

The 28-day compressive results followed a similar pattern but with more pronounced variations. Although 42.9 MPa was apparent in the control mix, there were values of hybrid mixes ranging between 40 MPa and 50 MPa. The optimum mix HS4G2P05 reached 50 MPa, marking an increase of 14.2% related to the control concrete. This result confirms the synergistic interaction among 4% steel fibres, 2% glass fibres and 0.5% polypropylene fibres, which collectively enhance crack arresting, reduce stress concentrations, and improve matrix densification. Mixes with higher fibre volume, such as HS4G4P05, displayed a lower strength of 45.5 MPa, indicating that excessive fibre content impedes slurry infiltration, leading to localized clustering and reduced compressive efficiency. The progressive rise in strength up to the optimal combination and subsequent decline beyond it confirms that Hybrid SIFCON exhibits a threshold behavior governed by fibre dispersion, interfacial bonding, and structural continuity. Table 7 and Figure 8 present the compressive strength values for all mixes tested at 7 and 28 days.

Table 7. Compressive strength of hybrid SIFCON mixes at 7 and 28 days

Mix	7 Days (MPa)	28 Days (MPa)
CC	27.5	42.9
HS4G1P0	30	40
HS4G2P0	32.5	42.5
HS4G3P0	34	48
HS4G4P0	35	45
HS4G0P05	28	46
HS0G1P05	26.5	40
HS0G2P05	28	41.5
HS0G3P05	32	44
HS0G4P05	30	43
HS4G1P05	30	40.2
HS4G2P05	36	50
HS4G3P05	35	48
HS4G4P05	32	45.5

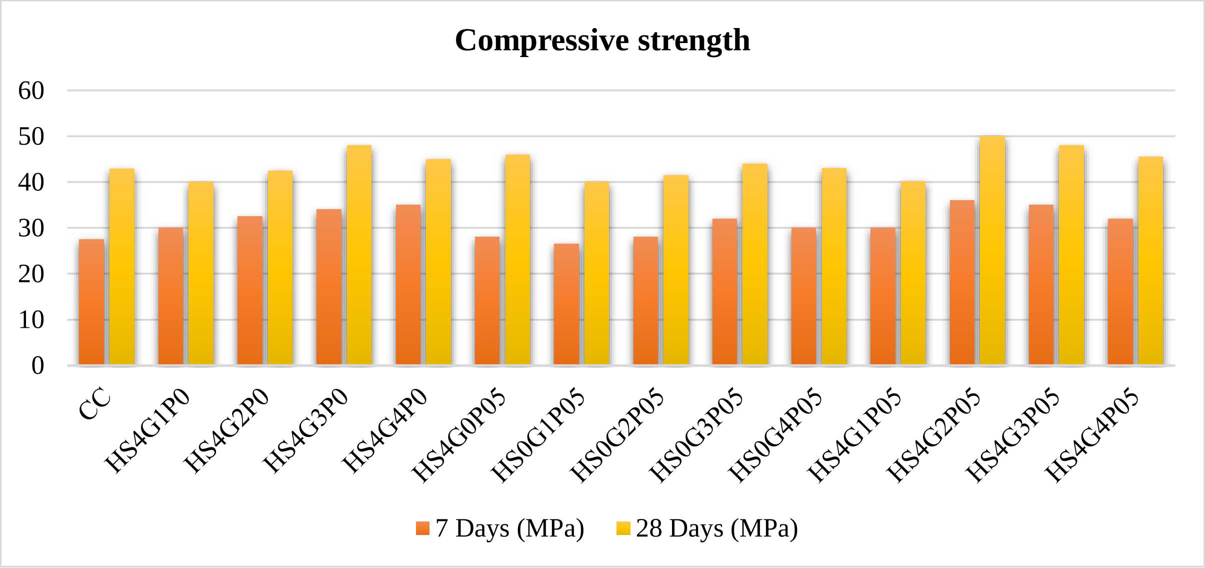


Fig. 8 Visualization of compressive strength of hybrid SIFCON mixes at 7 and 28 days

4.2. Split Tensile Strength

Figure 9 and Table 8 give the split tensile strength, which shows that tensile resistance is significantly improved in the case of fibre hybridization. The split tensile strength test results further validate the load-sharing capacity imparted by hybrid fibres. Control concrete recorded tensile strengths of 2.2 MPa and 3.3 MPa at 7 and 28 days, respectively. Hybrid mixes demonstrated considerably superior performance. Tensile strengths at 7 days were found to be 2.3 Mpa in HS0G2P05, and 4 Mpa in HS4G2P05, and the tensile strengths in the control mix were 0.6Mpa. Similarly, at 28 days, the control concrete attained 3.3 MPa, whereas the hybrid fibre mix HS4G2P05 reached the highest tensile resistance with a value of 6 MPa, which was almost twice that of the ordinary concrete.

The improvement in tensile strength is explained by the hierarchical control of cracks provided by hybrid fibres. Steel fibres delayed the development of macro cracks by bridging the crack faces, while the smooth, high tensile glass fibres restricted crack widening. Polypropylene fibres inhibited the cracking of shrinkage at early ages, and therefore, the microstructural weakness was not expressed in tensile fractures. It is clear that mixes without polypropylene fibres like the HS4G2P0, with a 5.5 MPa tested well but with a lower strength compared to the hybrid combination of all three fibres. This data indicates that while steel fibres contribute to primary tensile strength, polypropylene fibres play a critical role in stabilizing the matrix and preventing premature crack formation, thereby enabling the composite to sustain higher tensile loads over time.

Table 8. Split tensile strength of hybrid SIFCON mixes at 7 and 28 days

Mix	7 Days (MPa)	28 Days (MPa)
CC	2.2	3.3
HS4G1P0	2.5	4
HS4G2P0	3.8	5.5
HS4G3P0	3.5	4.5
HS4G4P0	3.2	5
HS4G0P05	3.5	5.2
HS0G1P05	2.5	3.2
HS0G2P05	2.3	3
HS0G3P05	3.4	4.6
HS0G4P05	3.3	4.2
HS4G1P05	3.1	4.5
HS4G2P05	4	6
HS4G3P05	3.8	5.5
HS4G4P05	3.5	5.2

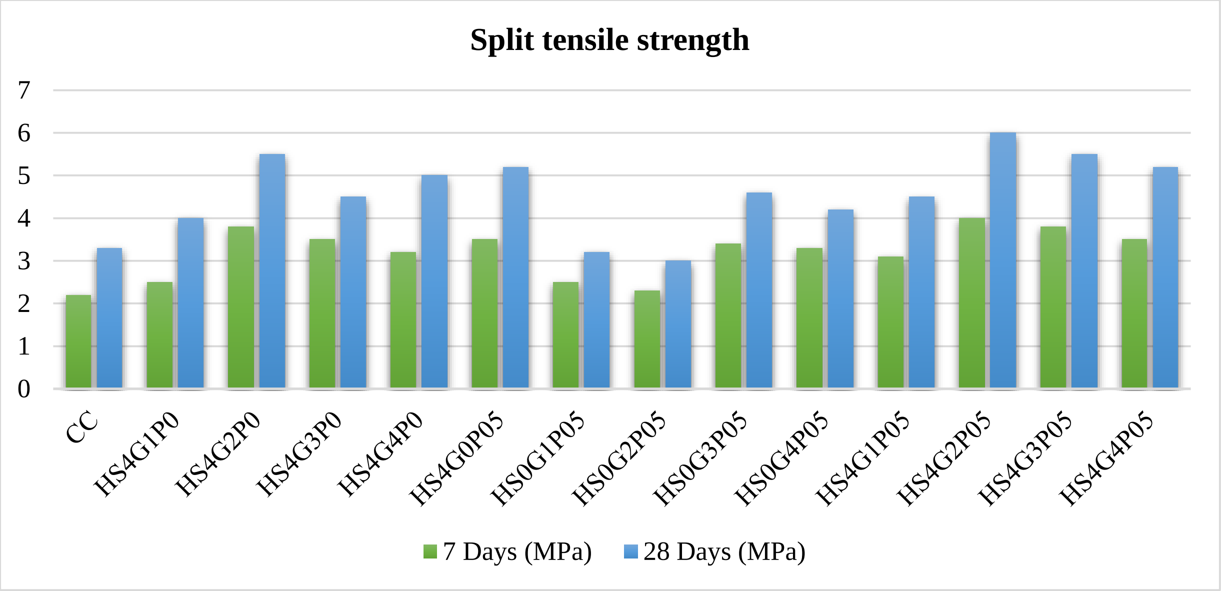


Fig. 9 Visualization of split tensile strength of hybrid SIFCON mixes at 7 and 28 days

4.3. Flexural Strength

Table 9 and Figure 10 present the results of flexural strength. The greatest improvements were observed in the flexural strength results of all mechanical properties to demonstrate the outstanding bending resistance imparted by hybrid fibres. The control concrete demonstrated flexural strengths of 1.8 MPa and 4.5 MPa at 7 and 28 days, respectively. Conversely, hybrid mixes exhibited values between 3 MPa and 6 MPa at 7 days, with HS4G3P0 reaching the highest flexural strength of 6 MPa, more than triple the control. The flexural behavior improved at 28 days, with the hybrid mixes taking a range of 4.2 Mpa in HS0G1P05 to a range of 9.5 Mpa in the optimum mix of HS4G2P05.

The flexural strength of HS4G2P05 measured at 9.5 Mpa represents an enhancement of more than 111% compared to conventional concrete. This improvement is attributed to effective load redistribution through steel fibres under flexural tension, glass fibres resisting brittle fracture initiation, and polypropylene fibres contributing to post-cracking ductility. Mixes with excessive glass fibre content, such as HS4G4P05 with 8 MPa showed slight reductions in strength due to improper slurry penetration and fibre agglomeration, confirming that hybridization benefits plateau beyond an optimum dosage.

Table 9. Flexural strength of hybrid SIFCON mixes at 7 and 28 days

Mix	7 Days (MPa)	28 Days (MPa)
CC	1.8	4.5
HS4G1P0	3	5
HS4G2P0	4.5	6
HS4G3P0	6	8.5
HS4G4P0	5.2	8
HS4G0P05	5	8
HS0G1P05	1.9	4.2
HS0G2P05	3	4.5
HS0G3P05	5	7.25
HS0G4P05	4	6.15
HS4G1P05	2.5	4.8
HS4G2P05	6	9.5
HS4G3P05	5	8.5
HS4G4P05	4.5	8

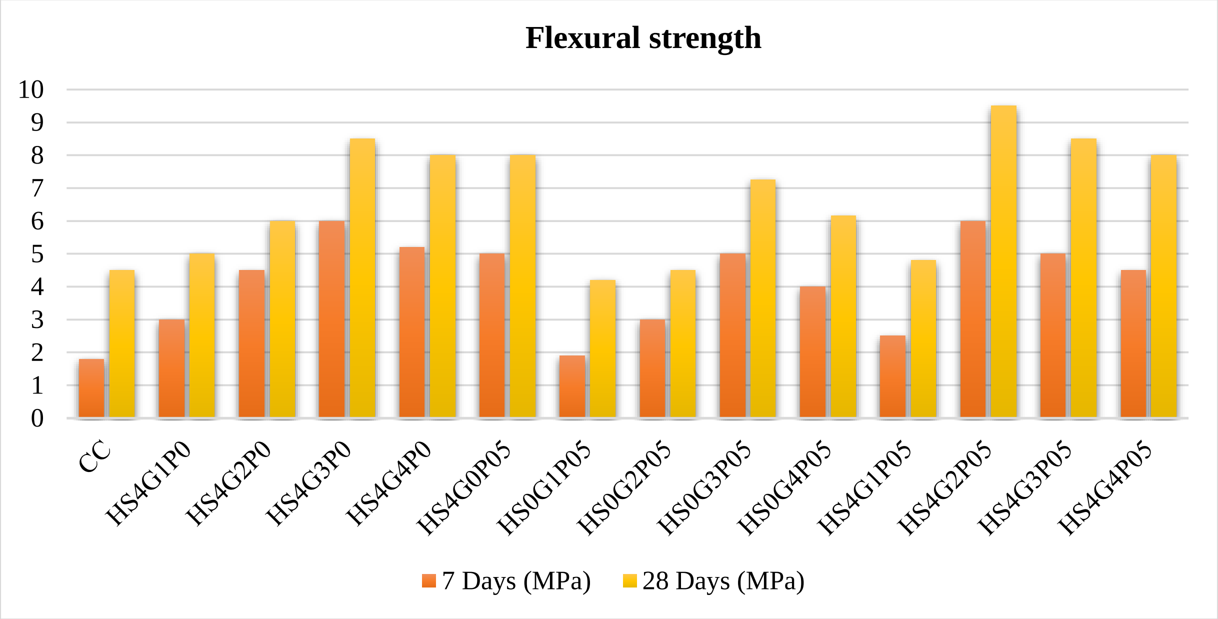


Fig. 10 Visualization of flexural strength of hybrid SIFCON mixes at 7 and 28 days

4.4. Optimum Hybrid Mix Performance

The comparison of the mechanical properties of hybrid SIFCON blends reinforced with various concentrations of steel, glass, and polypropylene fibres proved that the hybridization is crucial in terms of the improvement of the structural performance. Among all the mixes tested, HS4G2P05 containing 4% steel fibres, 2% glass fibres and 0.5% polypropylene fibres consistently demonstrated superior performance across all strength parameters. The results were related to the conventional control concrete mix without any fibres and the improvements observed at 28 days are summarized in Table 10.

Table 10. Mechanical performance of optimum hybrid SIFCON mix at 28 days

Mix ID	Steel Fibre (%)	Glass Fibre (%)	Polypropylene Fibre (%)	Compressive Strength	Split Tensile Strength	Flexural Strength
CC	0	0	0	42.90	3.30	4.50
HS4G2P05	4	2	0.5	50.00	6.00	9.50

The comparison of mechanical properties substantiates the fact that HS4G2P05 is the best hybrid SIFCON mix and shows significant improvement in comparison with the control concrete. Compressive strength changed to 50.00 MPa against 42.90 MPa, and split tensile strength also changed to 6.00 MPa against 3.30 MPa. The most notable enhancement was in flexural strength, which more than doubled from 4.50 MPa to 9.50 MPa, indicating superior crack resistance and post-cracking performance. These improvements result from the complementary actions of the three fibres: steel fibres provide macro crack bridging and enhance ductility, glass fibres arrest microcracks and improve stiffness, and polypropylene fibres reduce early-age cracking and enhance matrix cohesion. This is an overall balance that generates good transfer of stress, balanced distribution of the cracks, and enhanced toughness. In contrast to mixes with high levels of fibre that had poor slurry penetration and fibre congestion, HS4G2P05 attained an optimum packing condition, which allowed uniform dispersion and complete infiltration, which are some of the main factors that contributed to its high structural performance.

The failure patterns observed in hybrid SIFCON were characterized by controlled cracking and gradual load reduction, unlike the brittle failure seen in control concrete. This behavior is attributed to effective crack bridging by steel fibres and microcrack control by glass and polypropylene fibres, indicating improved fibre–matrix interaction and enhanced microstructural integrity.

From a resource efficiency perspective, the optimized hybrid mix achieves higher strength with controlled fibre dosage, reducing excessive material usage. Although multiple fibres are used, the improved structural efficiency and durability can offset initial material costs by reducing long-term maintenance and repair requirements.

The SEM image in Figure 11 reveals a dense cementitious matrix with well-dispersed and embedded fibres, indicating strong fibre–matrix interaction. The presence of fibre pull-out and partially fractured fibres suggests effective stress transfer and crack bridging mechanisms within the composite. These features demonstrate that the hybrid combination of steel, glass, and polypropylene fibres contributes to multiscale crack control, limiting crack propagation and enhancing structural integrity. The reduced presence of large voids further indicates improved packing density and slurry infiltration.

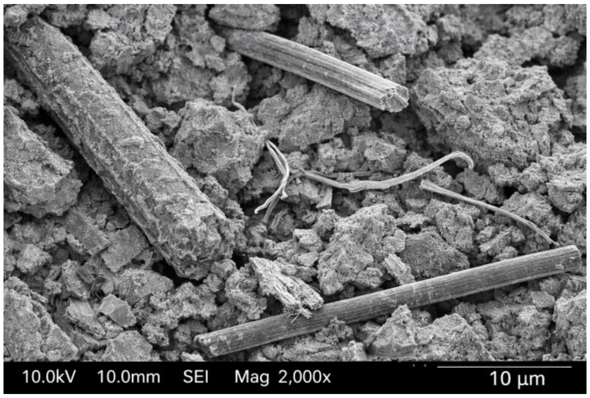


Fig. 11 SEM image of hybrid SIFCON showing fibre–matrix interaction and crack bridging

4.5. Performance Index (PI) Evaluation

To further quantify the structural efficiency of hybrid SIFCON mixes, a PI was calculated as expressed in Equation 2. The PI establishes the relationship between compressive strength and flexural strength, thereby indicating how effectively a mix converts its compressive load-bearing capacity into flexural resistance. This parameter is particularly relevant for SIFCON, where the primary enhancement expected from fibre hybridization lies in flexural behavior and post-cracking performance.

$$PI = \frac{\text{Flexural Strength (MPa)}}{\text{Compressive Strength (MPa)}} \tag{2}$$

A higher PI value reflects a more efficient composite, capable of mobilizing a greater proportion of its compressive strength into resisting bending stresses. Table 11 presents the PI values derived for the CC and the optimum hybrid mix HS4G2P05 at 28 days.

Table 11. Performance index of control mix and optimum hybrid SIFCON mix at 28 days

Mix ID	Compressive Strength	Flexural Strength	Performance Index (PI)
CC	42.90	4.50	0.105
HS4G2P05	50.00	9.50	0.190

The control mix exhibited a PI of 0.105, indicating limited flexural efficiency typical of conventional concrete. In contrast, the optimum mix HS4G2P05 achieved a PI value of 0.190, representing an 81% improvement over the control. This substantial enhancement confirms that the hybrid combination of 4% steel fibres, 2% glass fibres and 0.5%

polypropylene fibres significantly elevates the ability of SIFCON to translate compressive capacity into bending resistance. The elevated PI value of HS4G2P05 evidences the efficiency of multi-scale fiber reinforcement, in which steel fibres give macro crack bridging, glass fibre holds micro cracks, and polypropylene fibres give early age stability. All these mechanisms combine to achieve better crack control and redistribution of stress that can allow hybrid SIFCON to maintain higher flexural loads when compared to compressive strength. Therefore, HS4G2P05 is the most efficient structural formulation that the PI confirms to be the best.

The selection of fibres was based on achieving multiscale reinforcement. Steel fibres (4%) improve load capacity and post-cracking behavior, glass fibres (1–4%) enhance tensile resistance, and polypropylene fibres (0.5%) control microcracking. The proportions were optimized to balance strength and workability while avoiding fibre congestionFor reproducibility, dry materials were mixed uniformly, followed by the addition of superplasticizer to obtain a flowable slurry. Fibres were preplaced in molds, and slurry was infiltrated under vibration to ensure full penetration. Specimens were water-cured after 24 hours. Workability was assessed using the V-funnel (flow time) and J-ring (passing ability) tests, which are critical for evaluating slurry infiltration in SIFCON.

4.6. Statistical Analysis

In order to ascertain the statistical significance of the observed differences in the mechanical strength of the hybrid SIFCON mixes, a one-way ANOVA was performed on the 28-day split tensile strength, compressive strength, and flexural strength values. Each mix was tested on three specimens, and the mean values of the strength were compared. A control mix without fibres (CC) was used as a baseline for comparison. Standard deviation was also evaluated to assess variability, which indicated low dispersion and good experimental consistency.

Table 12 shows the results of ANOVA. The p-values calculated for all three mechanical properties were below the significance level (α = 0.05, 95% confidence level), indicating that the performance differences among the SIFCON mixes are statistically significant. This confirms that the changes in fibre proportions, not random variation, were responsible for the observed strength enhancements.

Table 12. One-way ANOVA results for hybrid SIFCON mixes at 28 days

Test Type	F-Statistic	p-Value	Significance (α = 0.05)
Compressive Strength	47.83	0.00013	Significant
Split Tensile Strength	39.72	0.00020	Significant
Flexural Strength	91.45	0.00001	Significant

The F-statistic reached the peak with flexural strength (91.45), which meant that hybrid fibre modification had the greatest impact on the performance of bending. This is in line with the experimental observation that hybrid SIFCON allows significant gains in flexural behavior owing to multiple-scale crack bridging. Compressive and split tensile strengths also showed statistically significant differences among mixes with F values of 47.83 and 39.72, respectively.

This is a further justification of the mechanical improvements made due to the hybridization of the steel, glass, and polypropylene fibres. Hence, there was a statistically significant impact on the tensile, compressive, and flexural strength of SIFCON by the combination of the hybrids.

Furthermore, the enhanced performance is associated with improved crack control and better stress distribution in hybrid mixes, indicating improved microstructural integrity.

To assess experimental consistency, each test result represents the average of three specimens. The variability in results was low, indicating good reproducibility of the experimental procedure. Table 13 presents the standard deviation values for key strength parameters.

Table 13. Statistical variability of optimum mix

Property	Mean Value	Standard Deviation
Compressive Strength	50 MPa	±1.5
Split Tensile Strength	6.0 MPa	±0.3
Flexural Strength	9.5 MPa	±0.5

4.7. Sensitivity Analysis of Fibre Proportions

A sensitivity analysis was performed to evaluate the influence of fibre proportions on the mechanical performance of hybrid SIFCON. The variation in compressive, split tensile, and flexural strengths with increasing glass fibre content (1% to 4%) at constant steel (4%) and polypropylene fibre (0.5%) dosage is presented in Table 14. The results indicate that mechanical properties improve with increasing fibre content up to an optimum combination and subsequently decline beyond that level. The optimum mix, HS4G2P05 (4% steel, 2% glass, and 0.5% polypropylene fibres), exhibited the highest performance with a compressive strength of 50 MPa, split tensile strength of 6 MPa, and flexural strength of 9.5 MPa. When the glass fibre content was increased from 1% to 2%, a significant improvement in all strength parameters was observed, indicating enhanced crack bridging and improved stress transfer across multiple scales. However, further increases in glass fibre content beyond 2% resulted in a gradual reduction in strength. The results clearly demonstrate that the mechanical behavior of hybrid SIFCON is highly sensitive to fibre dosage, and that an optimal balance between macro fibres (steel) and micro fibres (glass and polypropylene) is essential to achieve maximum structural efficiency. The sensitivity trend further confirms that beyond the optimum fibre content, the negative effects of fibre clustering and reduced workability outweigh the benefits of additional reinforcement.

Table 14. Sensitivity of mechanical properties to fibre proportions

Mix ID	Steel (%)	Glass (%)	Polypropylene (%)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
HS4G1P05	4	1	0.5	40.2	4.5	4.8
HS4G2P05	4	2	0.5	50.0	6.0	9.5
HS4G3P05	4	3	0.5	48.0	5.5	8.5
HS4G4P05	4	4	0.5	45.5	5.2	8.0

4.8. Durability and Serviceability Performance

The durability and serviceability performance of hybrid SIFCON are critically influenced by its enhanced crack resistance and dense matrix structure. The incorporation of steel, glass, and polypropylene fibres provides multiscale crack control, effectively limiting crack initiation and propagation under both static and cyclic loading conditions. Steel fibres contribute to fatigue resistance by bridging macro-cracks and sustaining load transfer after cracking, while glass and polypropylene fibres control micro-crack formation, reducing permeability and delaying deterioration. The improved crack control significantly enhances resistance to aggressive environmental conditions such as moisture ingress, chloride penetration, and freeze–thaw effects, thereby increasing long-term durability.

The dense fibre network and improved matrix packing reduce voids and permeability, which are key factors governing durability in cementitious composites. These characteristics align with durability provisions outlined in standards such as IS 456:2000 and relevant guidelines for high-performance concrete. From a serviceability perspective, the reduced crack widths and enhanced post-cracking behavior improve structural integrity, stiffness retention, and deformation control over time. Although long-term experimental evaluations such as fatigue life, shrinkage, and durability under harsh exposure conditions were not conducted in this study, the observed mechanical performance and crack resistance indicate strong potential for durable structural applications. Future work may include detailed durability testing in accordance with standardized protocols.

4.9. Practical Applications and Cost–Benefit Analysis

The enhanced mechanical performance and crack resistance of hybrid SIFCON make it suitable for a wide range of structural applications requiring high strength and durability. Potential applications include industrial floors, bridge decks, seismic-resistant structures, impact-resistant elements, and retrofitting or strengthening of existing structures. The superior flexural strength and post-cracking behavior observed in the optimum mix (HS4G2P05) indicate its effectiveness in load redistribution and resistance to dynamic and cyclic loading conditions. From an implementation perspective, the preplacement of fibres and the slurry infiltration process requires controlled casting procedures; however, it can be adopted in precast construction and specialized in-situ applications. The improved workability achieved through optimized hybrid fibre content also reduces issues related to fibre congestion commonly observed in conventional SIFCON.

In terms of cost–benefit analysis, although the inclusion of multiple fibre types may increase initial material costs, the significant improvement in strength and durability can reduce overall lifecycle costs by minimizing maintenance, repair, and structural rehabilitation needs. Additionally, the enhanced performance allows for reduced member dimensions, leading to material savings at the structural level. Therefore, the proposed hybrid SIFCON system offers a cost-effective solution when evaluated from a long-term performance and durability perspective.

4.10. Sustainability and Environmental Impact Assessment

The sustainability of the proposed hybrid SIFCON system was assessed considering material efficiency, durability, and environmental impact. Although SIFCON generally contains a high cement and fibre content, the enhanced mechanical performance achieved through hybridization allows for reduced structural dimensions and improved load-bearing efficiency, thereby lowering overall material consumption in practical applications. The incorporation of fly ash as a supplementary cementitious material partially replaces cement, contributing to reduced CO_2 emissions and improved environmental performance.

From a material perspective, steel fibres are recyclable and can be recovered through magnetic separation, supporting circular construction practices. Glass fibres, despite their energy-intensive production, enhance durability and crack resistance, thereby extending service life. Polypropylene fibres are used in minimal quantities (0.5%) and play a key role in controlling early-age cracking, reducing the risk of premature deterioration. A qualitative life cycle perspective suggests that improved durability and reduced maintenance requirements lead to lower long-term environmental impact compared to conventional concrete and mono-fibre systems. However, a detailed quantitative life cycle assessment (LCA) is beyond the scope of this study and may be considered for future research to validate sustainability performance further.

4.11. Comparative Analysis

A comparative evaluation of the present results with recent studies on SIFCON and advanced fibre-reinforced systems highlights the effectiveness of the proposed hybrid approach. The optimum mix (HS4G2P05) achieved a compressive strength of 50 MPa, which is comparable to steel fibre-based SIFCON systems typically reported in the range of 45–55 MPa, while avoiding the workability limitations associated with higher steel fibre dosages. In contrast, studies incorporating waste or synthetic fibres such as PET reported lower compressive strengths around 39–42 MPa, indicating reduced structural efficiency.

The split tensile strength of 6 MPa obtained in this study falls within or above the upper range of conventional SIFCON systems (approximately 4–6 MPa), demonstrating improved crack resistance due to multiscale fibre interaction. Notably, the flexural strength of 9.5 MPa exceeds values commonly reported in hybrid and single-fibre systems, which typically range between 5–8 MPa. This significant enhancement reflects the effective synergy between steel, glass, and polypropylene fibres in controlling crack initiation and propagation across multiple scales. Unlike previous studies that primarily emphasize individual strength parameters, the present investigation achieves a balanced improvement in compressive, tensile, and flexural properties simultaneously. This confirms that optimized hybridization not only enhances mechanical performance but also provides a more efficient and practical solution compared to conventional and non-optimized fibre-reinforced systems.

5. Conclusion

This study examined the impacts of hybrid combinations of steel, glass, and polypropylene fibres on the fresh and mechanical properties of SIFCON. The experimental findings showed that fibre hybridization is important to increase material performance by increasing workability balance, matrix reinforcement, and crack control at different levels. Although the addition of fibre was inclined to slow down the flowability of the slurry, the addition of polypropylene and controlled dosages of the glass fibre contributed to the preservation of expected infiltration properties, thus allowing the slurry to easily penetrate densely packed fibres. Among the thirteen mixes evaluated, the Hybrid SIFCON mix containing 4% steel fibres, 2% glass fibres and 0.5% polypropylene fibres (HS4G2P05) revealed the best performance. This optimum was reported to have a 28-day compressive strength of 50 MPa, a split tensile strength of 6 Mpa and flexural strength of 9.5 Mpa, which are very high compared to conventional concrete. The analysis of the performance index also supported that HS4G2P05 showed a better flexural efficiency, which justifies its better load redistribution capacity and after-cracking characteristics. One-way ANOVA results indicated that the observed differences among mixes were statistically significant, reinforcing the influence of fibre synergy on strength development. The overall findings confirm that hybridization of steel, glass, and polypropylene fibres effectively mitigates the limitations associated with single fibre SIFCON systems and leads to superior mechanical performance without compromising fresh state behavior. Further studies may explore the long-term durability performance of hybrid SIFCON under environmental exposure and evaluate its behavior in full-scale structural elements to facilitate wider engineering adoption.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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