Performance Evaluation of SIFCON Incorporating Waste Materials and Hybrid Fibers: A Study on Durability and Mechanical Properties

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ABSTRACT

Slurry Infiltrated Fiber Concrete (SIFCON) is a specialized type of High-Performance Fiber-Reinforced Concrete (HPFRC). Durability is an essential factor regarding concrete performance, particularly in severe conditions or structures designed for extended service, and thus in SIFCON design. This study examines the impact of incorporating glass waste into SIFCON, as well as the influence of hybrid fiber reinforcement using Micro Steel Fibers (MSF), Basalt Fibers (BF), and Polypropylene Fibers (PF) on the sustainability and performance of the resulting material. The SIFCON slurry was designed with a cement-to-Fine Aggregate (FA) ratio of 1:1 and a water-to-cement ratio of 0.33. The compressive strength of the slurry was evaluated by replacing cement with Glass Powder (GP) at proportions of 10%, 15%, 20%, and 25%, and FA with Crushed Glass (CG) at proportions of 10%, 20%, 30%, and 40%. The optimal results were achieved with 15% GP and 10% CG. SIFCON durability was assessed through tests measuring void ratio, and permeability, alongside an examination of its mechanical properties via splitting tensile strength and modulus of elasticity tests. A BF ratio of 1% to 4% of the fraction volume was used in all hybrid fiber mixes utilizing MSF and PF in three different ratios (1.5%:1.5%,1%:2% and 2%:1%). The SS4 mix (1% BF, 2% MSF, and 1% PF) showed an optimal increase in SIFCON void ratio, splitting tensile strength, and modulus of elasticity compared to the mixes SS2 (1% BF, 1.5% MSF, and 1.5% PF) and SS3 (1% BF, 1% MSF, and 2% PF).

Keywords-sustainable SIFCON; glass waste; crushed glass; hybrid fiber durability

I. INTRODUCTION

SIFCON is a superior concrete type in both strength and ductility. However, due to its high fiber content, its unit weight is greater than that of conventional fiber-reinforced concrete [1]. SIFCON consists of a flowing slurry matrix designed to effectively infiltrate a densely packed fiber network placed in molds [2]. The matrix excludes coarse aggregates but includes highly cementitious components, such as fly ash, microsilica, latex emulsions, and fine sand. Typical mix proportions involve a 1:1 ratio of cement to sand, although variations, such as 1:1.5 or 1:2 are also commonly used. The water-to-cement ratio in SIFCON typically ranges from 0.30 to 0.40 [3]. The SIFCON system differs from other types of concrete. While MORE advanced composites, like SIFCON, have fiber volume fractions ranging from 4% to 20%, conventional and HPFRC typically contain only 1% to 2% fiber volume [4, 5]. SIFCON is a versatile material with high energy absorption, abrasion and impact resistance, durability, and modulus of elasticity, making it suitable for various applications, such as impact and blast-resistant constructions, protective revetments, refractories, pavement repairs, seal plates, pressure cast tubes, furnace lintels, and saddle piers. [6-9]. Despite its benefits, sustainable concrete production and SIFCON pose environmental and global warming concerns. Portland cement production releases significant amounts of gases, contributing to air pollution. Green materials, like waste glass, can address these issues [10]. Ultra-High Performance Glass Concrete (UHPGC) enhances the workability and rheological properties of fresh concrete by mixing recycled glass with GP. This material reduces water absorption, provides a polished surface, and improves mechanical properties, like tensile, compressive, and flexural strength [11]. Authors in [12] examined fiber distribution, comparing random and ordered arrangements of crimped steel fibers with an aspect ratio of 60 at volume fractions of 7% and 9%. The results indicated that random distribution yielded superior compressive and flexural strength increases of 1.5%, 6.9%, 23%, and 6.5%, respectively. Authors in [13] investigated hybrid fibers, combining MSF, macro-hooked end steel, and PF in volumetric ratios of 7%, 4%, and 3%, respectively, to analyze flexural behavior. Authors in [14] studied the effects of replacing cement with silica fume in SIFCON, using hooked-ended steel fibers at 6%, 8%, and 11% volume, finding that silica fume substitution improved mechanical properties. Authors in [15] focused on the split tensile behavior of fiber concrete with steel and polyolefin fibers, achieving a 494% increase in splitting tensile strength while reducing density by 140 kg/m^3 with a mix of two-thirds polyolefin and one-third hook-end steel fibers. Authors in [16] used scrap tire steel fibers to create alkali-activated slag-based SIFCON. The concrete, activated with sodium hydroxide and sodium silicate solutions, increased flexural strength and toughness, promoting environmental sustainability and high-performance concrete primarily from waste or by-products [16]. Authors in [17] investigated the use of ground waste glass as an alternative silicate source in alkali-activated mortars. The mixtures were activated with sodium hydroxide solution and liquid sodium silicate, and their mechanical and durability properties were examined under various curing conditions. The results showed that waste glass can be a viable alternative silicate source in alkali-activated mortars.

This study aims to develop sustainable SIFCON reinforced with hybrid fibers in two stages: first, by producing an eco-friendly slurry through the replacement of cement with GP and FA with CG; and second, by evaluating the effects MSF, BF, and PF on the properties of SIFCON. The difference between previous research and this study lies in the materials used to achieve sustainability. While earlier studies used materials, such as silica fume and fly ash, this research utilizes glass waste as a pozzolanic material—replacing cement with GP and FA with CG—to produce sustainable concrete. Three types of fibers were used to reinforce SIFCON: MSF, PF, and BF, which have not been previously used in a hybrid form.

II. THE EXPERIMENTAL PROGRAM

A. Materials

Table I presents the physical properties of cement, while Table II provides the results of its chemical analysis. This study utilized Ordinary Portland Cement (OPC) CEM I 42.5 R, in accordance with Iraqi standard specification (IQS No. 5:2019) [18].

The FA used in this research is classified as Zone 4 according to Iraqi specification (IQS No.45, 1984) [19]. Tables III and IV present the analytical parameters, as well as the FA physical and chemical properties and characteristics, based on the sieve analysis. Tapped water was used in this project, complying with all relevant standards and mix requirements as per IQS No. 1703 (2018) [20]. Hyperplast PC175 was utilized as the Superplasticizer (SP), with a proposed dosage of 0.4 to 2.5 L per 100 kg of cement, as specified by the manufacturer, complying with ASTM C494 (2019) [21], Types F and G. Its characteristics are listed in Table V.

TABLE I. OPC PHYSICAL TEST

Physical properties		Test results	IQS no. 5 2019 requirements
Setting time	Initial (mins)	1;35	Min. 45 (mins)
	Final (hrs.)	4;25	Max 10 (hrs.)
Compressive strength (MPa)	2 days	23.8	Min. 20
	28 days	45.5	Min. 42.5

TABLE II. OPC CHEMICAL TEST

Oxide composition		Content %	IQS no. 5 2019 requirements
CaO %		61.78	-
SiO_2 %		20.79	-
Al_2O_3 %		4.80	-
Fe_2O_3 %		4.40	-
MgO %		3.67	Max 5
SO_3 %max	C_3A < 3.5%	Not applicable	2.5
	C_3A > 3.5%	2.13	2.8
LOI %		2.34	Max 4
I R %		0.98	Max 1.5
C_3S %		48.87	-
C_2S %		22.38	-
C_3A %		5.28	-
C_4AF %		13.38	-

TABLE III. FA SIEVE ANALYSIS

Sieve size (mm)	Passing (%)	Requirements for zone 4 according to IQS no. 45/1984 (%)
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	100	80-100
0.3	22	15-50
0.15	7	0-15

TABLE IV. FA CHEMICAL AND PHYSICAL PROPERTIES

Properties	Tests results	Requirements according to IQS no. 45/1984
Fineness modulus	1.71	-
SO_3 %	0.34	≤ 0.5(%)
Absorption %	1.21	-
Specific gravity	2.61	-
Bulk density (kg/m^3)	1620	-

TABLE V. SP PROPERTIES

Properties	Description
Color	Yellowish liquid
PH	6
Specific gravity	1.08
Chloride content	Nill

Glass waste bottles were gathered, cleaned, and subsequently pulverized utilizing a Los Angeles machine. Following the grinding operation, the particles that traversed the 600-micron screen were utilized as CG rather than FA. The residual particles on the 600-micron sieve were pulverized into GP and utilized as a substitute for cement. The test results for CG and GP are given in Tables VI-VIII, and comply with IQS No. 45 (1984) [19] and ASTM C618 (2015) [22], respectively. The process of GP and CG preparation is shown in Figure 1.

(a) (b) (c) (d)

Fig. 1. Process of GP preparation: (a) glass waste, (b) CG, (c) retained on 600 μm sieve, (d) GP.

TABLE VI. CG SIEVE ANALYSIS

Sieve size (mm)	Passing (%)	Requirements for zone 4 according to IQS no. 45/1984 (%)
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	100	80-100
0.3	34	15-50
0.15	5	0-15

TABLE VII. CG CHEMICAL AND PHYSICAL PROPERTIES

Properties	Tests results	Requirements according to IQS no. 45/1984
Fineness modulus	1.61	-
SO_3 %	0.12	≤ 0.5(%)
Absorption %	0.81	-
Specific gravity	2.33	-
Bulk density (kg/m³)	1325	-

TABLE VIII. GP CHEMICAL AND PHYSICAL PROPERTIES

Composition	Test results	(ASTM C618, 2015) Class N Specification
SiO_2 %	69.3	Min 70
Al_2O_3 %	10.4	
Fe2O3 %	7.8	
SO_3 %	2.7	Max 4
CaO %	5.3	-
MgO %	1.9	-
Loss on ignition %	4.1	Max 10
Retained on 45 μm	25	Max 34 (%)
Strength activity index at 7 days (MPa)	89.1	Min 75
Strength activity index at 28 days (MPa)	93.3	Min 75

This research used three types of fibers: MSF, PF, and BF. Table IX displays the fiber properties, according to the manufacturer's data sheet. Figure 2 portrays the fibers used in this work.

(a) (b) (c)

Fig. 2. Fibers: (a) MSF, (b) PF, (c) BF.

TABLE IX. PROPERTIES OF FIBERS ACCORDING TO MANUFACTURER DATA SHEET

Description	MSF	PF	BF
Length (mm)	25	12	12
Diameter (μm)	0.3	18	13
Density (kg/m³)	7860	910	2650
Tensile strength (MPa)	2800	300-400	2600-2480
Modulus of elasticity (GPa)	200	4	80-115

B. Slurry and Slurry Infiltrated Fiber Concrete Design

The first stage involved designing sustainable slurry using glass waste according to the trail mix of slurry. Table X shows the mix design of sustainable slurry. Stage two includes the design of SIFCON by hybrid fibers, as depicted in Table XI. Slurry workability was evaluated using mini-slump flow and V-funnel tests, according to [23], which helped determine the appropriate SP dosage. Consequently, an SP amount of 1.4% by weight of cement was used. In previous studies, after the mix design was finalized, an electric mixer was utilized to blend the materials for the SIFCON slurry. After mixing dry cement, aggregate, GP, and CG, the mixture was mixed with water and rehydrated. The SP was dissolved in the remaining water and mixed for two min. If cement clumps are detected, the mixing time should be extended until a uniform slurry is obtained.

TABLE X. SUSTAINABLE SLURRY MIX PROPORTION DETAILS (kg/m³)

Mix symbol	Cement	FA	GP	CG	Water	SP (L/m³)
GP0	800	800	0	0	264	11.2
GP10	720	800	80	0	264	11.2
GP15	680	800	120	0	264	11.2
GP20	640	800	180	0	264	11.2
GP25	600	800	200	0	264	11.2
CG10	680	720	120	65.5	264	11.2
CG20	680	640	120	131	264	11.2
CG30	680	560	120	196	264	11.2
CG40	680	480	120	262	264	11.2

TABLE XI. SIFCON MIX PROPORTION DETAILS (kg/m³)

Mix symbol	Cement	FA	GP	CG	Water	SP (L/m³)	MSF* %	PF* %	BF* %
SS1	680	720	120	65.5	264	11.2	0	0	0
SS2	680	720	120	65.5	264	11.2	1.5	1.5	1
SS3	680	720	120	65.5	264	11.2	1	2	1
SS4	680	720	120	65.5	264	11.2	2	1	1

*Replacement by volume of slurry.

III. RESULTS AND DISCUSSION

A. Compressive Strength Test

This test was conducted according to ASTM C109-20 [24], by using a cube size of 50 × 50 × 50 mm, with a total of 54 samples being tested. After replacing four different percentages of GP by weight of cement (10%, 15%, 20%, and 25%), the mix (GP15) gave the highest percentage increase in compressive strength. This increase was observed when using

GP without CG, with compressive strength increases of 14.2% and 9.2% at 7 and 28 days, respectively, compared to the mix without GP. Regarding FA replacement with CG by volume at four percentages (10%, 20%, 30%, and 40%), the mix CG10 showed the highest compressive strength increase of 16.9% and 14.7% at 7 and 28 days, respectively, compared to the mix without GP and CG. Table XII and Figure 3 present the compressive strength results of the slurry at 7 and 28 days.

Waste glass, particularly finely ground, contains amorphous silica that reacts with calcium hydroxide in cement hydration, forming additional calcium silicate hydrate gel, enhancing cement strength. These results confirm the findings of [25-27].

TABLE XII. RESULTS OF COMPRESSIVE STRENGTH TEST OF SLURRY

Mix symbol	Compressive strength (MPa)	
	7 days	28 days
GP 0	41.8	56.5
GP10	44.5	57.9
GP15	48.7	62.2
GP20	39.2	55.3
GP25	35.3	49.1
CG10	50.3	66.2
CG20	48.8	59.9
CG30	45.4	51.4
CG40	41.3	48.4

B. Void Ratio Test

The procedures followed in this test complied with ASTM C642 [28], and a total of 36 samples were tested. Cubes with dimensions of 100 × 100 × 100 mm were utilized. Table XIII and Figure 4 show the results of the void ratio test. Mix SS4 exhibited the greatest decrease in void ratio compared to mixes SS2 and SS3. Fibers with different aspect ratios fill gaps more efficiently, leading to a denser and more homogeneous microstructure. This reduction is consistent with the findings reported in [29–30].

TABLE XIII. RESULTS OF SIFCON VOID RATIO TEST

Mix symbol	Void ratio %		
	7 days	28 days	90 days
SS1	8.24	9.33	9.85
SS2	5.92	6.14	6.92
SS3	7.17	7.69	8.52
SS4	4.95	5.75	6.83

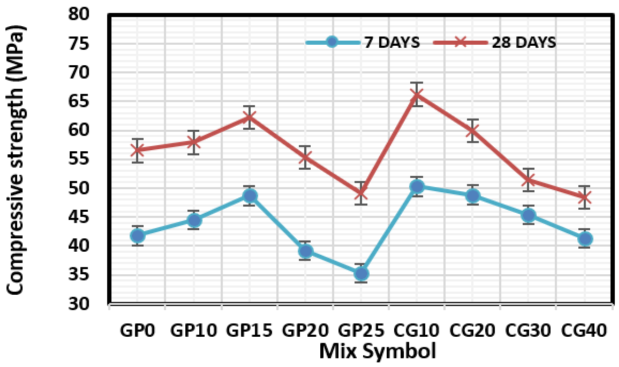

Fig. 3. Results of compressive strength test for slurry with different ratio of GP and CG.

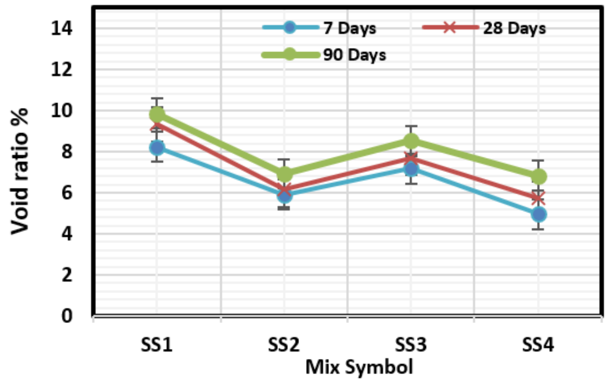

Fig. 4. Results of void ratio test for SIFCON with different ratios of hybrid fibers.

C. Permeability Test

Using cubes of dimensions (150×150×150) mm, this test was conducted according to specification BS EN 12390-8:2019 [31], 8 samples were used during this test, where the mix SS4 showed the most significant decrease in permeability at 60 days. Combining long steel fibers with short polymer fibers may create non-uniform stress distribution, promoting micro-cracks. Permeability increases despite strength gains [32]. Table XIV and Figure 5 present the results of the permeability test on SIFCON.

TABLE XIV. RESULTS OF SIFCON PERMEABILITY TEST

Mix symbol	Water penetration (mm)
SS1	17
SS2	24
SS3	27
SS4	21

The splitting tensile strength of the seven mixes was measured using cylindrical specimens of 200 × 100 mm, in accordance with ASTM C496-17 [33]. A total of 36 samples were tested. Among all mixes, SS4 had the highest splitting tensile strength, as exhibited in Table XV and Figure 6. The rationale for this increase is that the fibers act as bridging agents across micro-cracks, enhancing tensile load transfer and inhibiting crack propagation. This significantly improves the splitting tensile strength [34, 35].

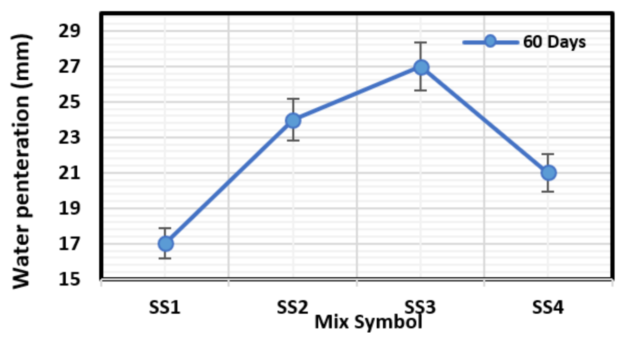

Fig. 5. Results of permeability test for SIFCON with different ratios of hybrid fibers.

TABLE XV. RESULTS OF SIFCON SPLITTING TENSILE STRENGTH TEST

Mix symbol	Splitting tensile strength (MPa)		
	7 days	28 days	90 days
SS1	3.14	4.13	6.04
SS2	8.92	10.52	14.05
SS3	7.35	9.15	12.76
SS4	9.73	11.86	15.24

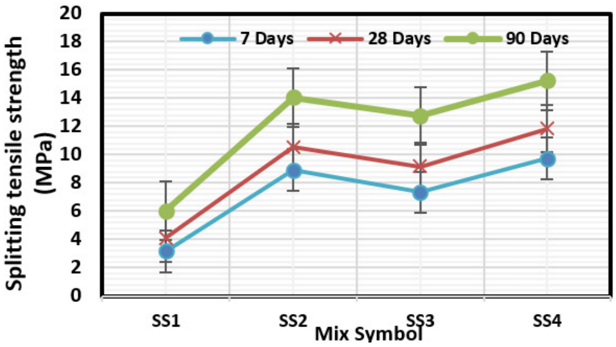

Fig. 6. Results of splitting tensile strength test for SIFCON with different ratios of hybrid fibers.

D. Modulus of Elasticity Test of Slurry Infiltrated Fiber Concrete

This test was conducted according to the ASTM C469 [33], a total of four cylindrical samples of 150 × 200 mm size were tested. Table XVI and Figure 7 demonstrate the results of this test. Mix (SS4) gave the highest increase in the modulus of elasticity compared to the other hybrid mixes. The hybrid mixes create a stiffer network compared to mixes without fibers, due to the higher modulus of elasticity of the fibers, which leads to an overall increase in the modulus of elasticity of the SIFCON mixes, complying with the findings of [29, 30, 36].

TABLE XVI. RESULTS OF SIFCON SPLITTING TENSILE STRENGTH TEST

Mix symbol	Modulus of elasticity (GPa)
SS1	38.52
SS2	43.11
SS3	41.08
SS4	45.37

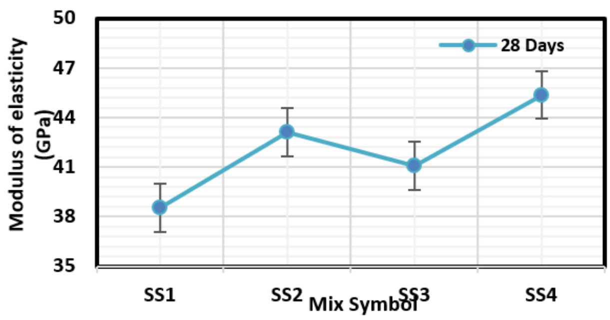

Fig. 7. Results of modulus of elasticity test for SIFCON with different ratios of hybrid fibers.

IV. CONCLUSIONS

Comparing the performance of the reference Slurry Infiltrated Fiber Concrete (SIFCON) mix (SS1), which contained no fibers, with mixes SS2, SS3, and SS4 that contained hybrid fibers consisting of Micro Steel Fibers (MSF), Basalt Fibers (BF), and Polypropylene Fibers (PF), the following conclusions were drawn.

- For the sustainable slurry, the optimum mix was CG10, which incorporated 15% Glass Powder (GP) as a replacement for cement and 10% Crushed Glass (CG) as a replacement for Fine Aggregate (FA).
- The study found that using 2% MSF, 1% PF, and 1% BF in mix SS4 resulted in the highest reduction in void ratio, with values of 39.9%, 38.4%, and 30.7% at 7, 28, and 90 days, respectively. This is because the hybrid fibers effectively filled microscopic voids and pores within the SIFCON matrix, reducing the overall void ratio.
- The permeability test revealed increased water penetration in the SIFCON matrix, with the SS3 mix showing the highest penetration at 58.8% after 60 days. This suggests that fibers can create a deficient interfacial zone, increasing permeability.
- The splitting tensile strength test for SIFCON revealed that the optimal mix (SS4) resulted in a substantial increase in strength of up to 209.9%, 187.2%, and 152.3% at 7, 28, and 90 days.
- The modulus of elasticity increased significantly with the use of 2% MSF, 1% PF, and BF, with a 17.8% increase at 28 days, while the lowest increase was 6.6% with 2% PF, 1% MSF, and 1% BF.

These results revealed that the use of a 2% MSF, 1% PF, and 1% BF as a hybrid SIFCON mix achieved excellent results. The particular finding can lead to a reduction in the density and cost of SIFCON production.

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