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Eco-friendly modified weight SIFCON production: The role of glass waste and hybrid fibers

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ABSTRACT

SIFCON is a type of high-performance concrete distinguished by its exceptional strength-to-density ratio. This study achieved significant density reductions by incorporating single and hybrid fibers to develop modified-weight SIFCON. However, the production and use of SIFCON involve substantial amounts of cement and fine aggregates, which have environmental repercussions. Substituting cement and fine aggregates with glass waste contributes to enhancing environmental sustainability by lowering cement consumption, thereby reducing CO_2 emissions associated with its production. Eco-friendly SIFCON was evaluated through three tests: compressive strength, ultrasonic pulse velocity, and density. These tests were conducted on six different mixes, all containing a 4% fiber volume fraction in single and hybrid configurations, along with a reference mix. Among the formulations, the hybrid combination of 1% basalt fibers, 2% micro steel fibers, and 1% polypropylene fibers demonstrated the best performance in compressive strength and ultrasonic pulse velocity. On the other hand, the use of polypropylene fibers alone resulted in the decrease in density, the decreases of 0.73% after 7 days, 1.1% after 28 days, and 0.76% after 90 days. Meanwhile, the hybrid composition of 1% basalt fibers, 1% micro steel fibers, and 2% polypropylene fibers showed the lowest density growth in hybrid mixes, with increases of 2.5% at 7 days, 2% at 28 days, and 2.4% at 90 days.

Keywords: eco-friendly SIFCON, glass waste, hybrid fibers, density.

INTRODUCTION

The strength and performance of SIFCON are perceived as being higher than those of steel fiber-reinforced concrete. The term SIFCON was initially introduced by Prof. Lankard in 1979, and it is also known as volume fiber concrete due to the high volume of fiber in the matrix. His experiments, conducted in his labs in Columbus, Ohio, USA, demonstrated that materials with a high percentage of steel fiber by volume exhibit exceptional strength. (Dagar, 2012). As a distinct variety of high-fiber-content concrete, slurry infiltrated fiber concrete (SIFCON) is both strong, unusual and has high ductility (Najeeb and Fawzi, 2021; Jerry and Fawzi, 2022).

Compared to SIFCON, the volume proportion of fiber in conventional and high-performance fiber reinforced concrete is 1-3%, whereas in SIFCON it ranges from 3-20%. The tensile strength and flexibility of the cementitious matrix are both greatly enhanced by this proportion. Flexural strength and toughness are both enhanced by SIFCON's greater strength, which has been the subject of extensive investigation into its mechanical characteristics (Farnam et al., 2010), Also, unlike conventional and high-performance fiber-reinforced concrete, SIFCON doesn't have coarse aggregate; it consists of a slurry containing cement and fine aggregate in addition to fiber (Lankard, 1984).

In fiber-reinforced concrete, SIFCON can also use single or hybrid fiber. Hybrid fiber consists of two or more fibers incorporated into concrete. To enhance concrete's performance, it uses the fibers' unique properties. Combining the strengths of many fiber types, hybrid fibers enhance concrete's performance throughout loading stages, serve as a "positive confounding effect" for the material, and outperform doped single-fiber reinforced concrete. Nevertheless, hybrid fiber reinforced concrete has been made using a variety of fiber blends, including carbon and polypropylene, glass and polypropylene, and carbon and glass fibers (He et al., 2017; Abdulhameed et al., 2022).

SIFCON is utilized in the construction sector for many applications, particularly for the repair and reinforcement of existing buildings, especially in seismic regions. SIFCON is utilized in buildings necessitating resistance to blast loads, collisions, or explosions due of its superior energy absorption capability. This include military bunkers, defensive obstacles, and essential infrastructure such as nuclear power facilities. SIFCON is utilized in industrial floors and pavements that need exceptional wear resistance, durability, and load-bearing capability. SIFCON's corrosion resistance and endurance in harsh settings render it appropriate for marine and coastal constructions, including piers, seawalls, and offshore platforms (Naaman and Reinhardt, 2003; Song and Hwang, 2004; Bentur and Mindess, 2006).

The creation of SIFCON and other forms of sustainable concrete is made possible by recycling materials such as glass waste. Produced at a pace of more than one million tons annually, glass is notoriously difficult to dispose of due to its resistance to atmospheric decomposition. Significant amounts of carbon dioxide gas are emitted during cement production, which is harmful to the environment. Conversely, the pozzolanic qualities of glass – improved by its high silica content – lead to higher strength and durability, making waste glass a viable alternative to fine aggregate or cement powder.(Lepech et al., 2008; Gahoi and kansal, 2015; Islam et al., 2017; Hussain and Aljalawi, 2022), it was crucial to create concrete that helps lower atmospheric CO_2 levels because high-strength concrete is made from industrial waste, which contains silica fume and other minerals like calcium and silica (Abdullah and Fawzi, 2024).

Many research studies on SIFCON were investigation. Najeeb and Fawzi (2022) conducted research on the impact of crimped steel fiber on compressive and flexural strengths with two different volume fractions (7% and 9%), using either randomly distributed or orderly distributed fibers. The results showed that at a 7% fiber use volume fraction, randomly scattered fibers had a 1.5% increase in compressive strength and a 6.9% increase in flexural strength, compared to ordered distributed fibers. Increases of 23% in compressive strength and 6.5% in flexural strength were seen at a fiber use volume fraction of 9%.

The effect of single and hybrid fiber use on SIFCON was investigated by Abdulbaqi and Abdulrehman (2024). Researchers tested a variety of combinations of the two types of fibers – first, hooked steel fiber and second, micro steel fiber – in varying proportions by volume fraction (5%, 10%, and 15% in a single state, and also hybrids with 2.5% hooked + 2.5% micro, 5% hooked + 5% micro, and 7.5% hooked + 7.5% micro). The results showed that adding 10% micro steel fiber increased compressive strength and abrasion resistance, but negatively affected water absorption.

Other types of fibers studied in SIFCON by researchers, such as polypropylene, basalt and glass fiber. Thomas and Mathews (2014) tested three different proportions of steel and polypropylene fiber (4%, 5%, and 6% by weight) to determine their impact on SIFCON's compressive, flexural, and tensile strengths. The experimental study demonstrated that steel fiber had a greater impact on SIFCON properties than polypropylene fiber. Specifically, a volume of 5% fiber produced better results in compressive strength, flexural strength, and tensile strength compared to 4% and 6% of fiber, respectively. When comparing the compressive strength of cube specimens made of steel and polypropylene fiber to that of cylinder specimens, the former proved to be superior. Evidence from experiments suggests that using polypropylene fiber can reduce fracture width. The polypropylene fiber's bridging action is to blame for this.

Glass fiber use in SIFCON with steel fiber was studied by (Indhirani et al., 2019) with a volume fraction of 2% of glass fiber and (6%, 8%, 10% and 12%) of steel fiber, using proportions of cement, sand, and fly ash 1:1:0.5. According to the results, the compressive strength is much greater when steel and glass fibers are used together compared to other SIFCON mixtures and regular concrete. The increase in compressive strength was 28.73 %, and also flexural strength increased.

Algın et al. (2022) investigated the volumetric replacement rates of 0%, 25%, 50%, 75%, and 100% using basalt fiber in lieu of steel fiber. In connection to the variation in basalt fiber replacement, laboratory research have established the specific compressive strength, flexural strength, sorptivity, water absorption, acid attack resistance, and Bohme abrasion resistance. The findings showed that compressive strength and capillary water absorption both reduced with increasing amounts of basalt fiber, whereas water absorption increased. One of the problems of SIFCON is its high density. This is due to the high weight and content of the fiber used (Vijayakumar and Kumar, 2017). Naser and Abeer (2020) to assess the efficacy of the SIFCON weight modification, they employed three distinct fiber types – micro steel fiber, macro hooked end steel fiber, and polypropylene fiber – with volume fractions of 7%, 4%, and 3%, consecutively. Furthermore, two distinct fiber types are combined to form hybrid fibers, where each kind makes up half of the total. The results demonstrated that combining three fibers produced a dense material with a specific density of 18.66 kN/m^3 and a flexural strength of 8.09 MPa. However, when comparing compressive and flexural strengths, the SIFCON of micro and macro steel fibers performed better than other combinations of fibers. Additionally, using polypropylene fiber resulted in better water absorption than that of another type of fiber. In summary, the presence of fibers demonstrated that the fibers are an important component of SIFCON, contributing to their exceptional strength (Jerry and Fawzi, 2023). The study delves into the use of glass waste in SIFCON and environmentally conscious slurry manufacturing. A more eco-friendly alternative to cement is waste glass powder. As a substitute for fine aggregate, crushed waste glass is used for its silica content. Steel, polypropylene, and basalt fibers are mixed in various quantities to create modified weight SIFCON, which improves its mechanical qualities and performance.its mechanical qualities and performance.

MATERIALS AND METHODS

Materials

Cement

This study utilized OPC CEM I (42.5 R), which complies with (IQS No. 5, 2019) the results of the cement's chemical and physical evaluation, demonstrated in Table 1 and 2, respectively.

Fine aggregate

According to Iraqi standards (IQS No. 45, 1984), the fine aggregate employed in this study is zone 4. Tables 3 and 4 display the physical and chemical characteristics, as well as the analytical parameters of the fine aggregate sieve.

Table 1. Chemical composition and main compound of OPC

Oxide composition		Content %	The IQS No. 5 2019 limitations
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	C3A < 3.5%	Not applicable	2.5
	C3A > 3.5%	2.13	2.8
L.0.I		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 2. Physical tests of OPC

Physical properties		Test result	The IQS No. 5 2019 limitations
Setting time	Initial (hrs:min)	1:35	Min. 45 (min)
	Final (hrs:min)	4:25	Max 10 (h)
Compressive strength (MPa)	2 days	23.8	Min. 20
	28 days	45.5	Min. 42.5
Specific surface area (m^2/kg)		380.5	Min 280
Soundness (%)		0.42	Min 0.8

Water

This project makes use of tapped water. And all mixes and conforms with (IQS No. 1703, 2018).

Superplasticiser

The superplasticiser utilised was Hyperplast PC175. A dose of between 0.4 and 2.5 liters per 100 kilograms of cement was suggested by the manufacturer. According to ASTM C494, 2019 types F and G, this admixture is suitable. According to the manufacturer, these are the major qualities of this superplasticiser (Table 5).

Glass waste

Glass waste bottles were collected, washed, and then crushed using a Los Angeles machine shown in Figure 1. After the grinding process, the particles that passed through the 600-micron sieve were used as crushed glass instead of fine aggregate. In contrast, the remaining particles on the 600-micron sieve were ground until they produced powdered glass and were used instead of cement. Results of the tests of crushed glass and glass powder shown in Tables 6, 7 and 8 conform to (IQS No. 45, 1984) and (ASTM C618, 2015), respectively.

Micro steel fiber

The investigation utilized straight micro steel fiber, as illustrated in Figure 1a, and its attributes are listed in Table 9, according to the data sheet manufacture.

Polypropylene fiber

Polypropylene fibers were used for reinforcement. The experimental work used fibers with precise specifications and qualities, as shown in Table 10, according to data sheet manufacturing, and Figure 1b.

Table 3. Sieve analysis of fine aggregate

Sieve size (mm)	Passing (%)	Limitations of 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 4. Chemical and physical properties of fine aggregate

Properties	Tests result	Limitations 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/m³)	1620	-

Table 5. Properties of superplasticiser

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

Table 6. Sieve analysis of crushed glass

Sieve size (mm)	Passing (%)	Limitations of 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 7. Chemical and physical properties of crushed glass

Properties	Tests result	Limitations 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 8. Chemical and physical properties of glass powder

Composition	Result (%)	(ASTM C618, 2015) class N specification
SiO_2	69.3	Min 70
AL_2O_3	10.4	
Fe_2O_3	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 (No. 325)	25	Max 34(%)
Strength activity index at 7 days	89.1	Min 75
Strength activity index at 28 days	93.3	Min 75

Table 9. Properties of Micro steel fibers

Description	Specification	Description	Specification
Surface	Brass coated	Aspect ratio	83.3
Shape	Straight	Bulk density (kg/m³)	7860
Length (mm)	25	Tensile strength (MPa)	2800
Diameter (mm)	0.3	Melting point	1500 °C

Table 10. Properties of polypropylene fiber

Description	Specification
Length (mm)	12
Diameter (μm)	18
Density (kg/m³)	910
Tensile strength (MPa)	300–400
Modulus of elasticity (MPa)	4000

Table 11. Properties of basalt fiber

Description	Specification
Length (mm)	12
Diameter (μm)	13
Density (kg/m³)	2650
Tensile strength (MPa)	2600–4840
Modulus of elasticity (GPa)	80–115

Basalt fiber

The properties of basalt fiber shown in Table 11 according to data sheet manufacturing, and Figure 1c.

Design and procedure for SIFCON mixes

The first step in developing SIFCON involves formulating a sustainable slurry using recycled glass. Following trial mixing, a cement-to-fine aggregate ratio of 1:1 is adopted, along with a water-to-cement ratio of 0.33 and the addition of 1.4 liters of superplasticizer per 100 kg of cement.. This will produce a slurry free of glass waste. Next, replace some of the cement with glass powder at varying weight ratios (10%, 15%, 20%, and 25%), with 15% being the optimal choice. Finally, replace some of the fine aggregate with crushed glass, using 10% as the best option. The mixed design of SIFCON is shown in Table 12, which was created after the sustainable slurry was prepared. SIFCON, which has a volume percentage of 4% in both single and hybrid forms, is made using three kinds of fiber: micro steel, polypropylene, and basalt. SIFCON specimens were created by filling molds with fibers and a slurry to penetrate the thick matrix. The two-layer method was chosen for high volume fibers, partially filling the mold with slurry, inserting fibers halfway, shaking the mold, and building the second layer using a table vibrator to ensure all SIFCON soaked into the fiber pack, this method was used by (hamed and Abass, 2022). Figure 2 shows the cubes used in casting, which have dimensions of (100×100×100) mm.

EXPERIMENTAL WORK

Dry bulk density test

The procedure followed for the test was ASTM C642. At7, 28, and 90 days of age, it

Figure 1. Fibers: (a) micro steel fiber, (b) polypropylene fiber, (c) basalt fiber

Table 12. Mix design of SIFCON

Mix symbol	Cem. (kg/m³)	F.A (kg/m³	Glass powder (kg/m³)	Crushed glass (kg/m³)	Water (kg/m³)	SP (1 L/100 kg cement)	Micro steel fiber	Polypropylene fiber	Basalt fiber
							By volume %		
RS	680	720	120	65.5	264	1.4	-	-	-
SSF	680	720	120	65.5	264	1.4	4	-	-
SPF	680	720	120	65.5	264	1.4	-	4	-
SBF	680	720	120	65.5	264	1.4	-	-	4
SH1	680	720	120	65.5	264	1.4	1.5	1.5	1
SH2	680	720	120	65.5	264	1.4	1	2	1
SH3	680	720	120	65.5	264	1.4	2	1	1

Figure 2. Cubes (100×100×100) mm after casting

was carried out on samples with dimensions of (100×100×100) mm.

Compressive strength test

Cubes with dimensions (100×100×100) mm were used to conduct the test of compressive strength in accordance with the standard (BS EN 12390-4). The compressive strength test is seen in Figure 3.

Ultrasonic pulse velocity test

In accordance with ASTM C597, the ultrasonic pulse velocity test was performed using cubes with dimensions of (100×100×100) mm. To ensure proper contact and accurate transit time measurements, grease was applied between the specimen's tested surfaces and the transducer contact faces. The instrument's settings were regularly verified using the provided reference bar. The results of the experiment, conducted using the direct method, are illustrated in Figure 4. The pulse velocity was calculated as follows:

$$V = \frac{L}{T} \quad (1)$$

Figure 3. Compressive strength test

where: V – pulse velocity (m/sec), L – displacement between the center of transducer face (m) and T – transit time (sec).

RESULTS AND DISCUSSION

Dry bulk density test

In this investigation, dry density is a key metric. The goal of this test is to find out which fiber type will make the SIFCON a modified weight, which will allow it to be lighter. The dry bulk density data at 7, 28, and 90 days are shown in Table 13, Table 14 and Figure 5, respectively.

The data show that the density of each mixture increases as it ages. The mixture without fibers had the lowest density, followed by the one with steel fibers, and the one with polypropylene fibers the lowest. The density of the mix with micro steel fibers increased by 12.7%, 11.2%, and 13.3% at 7, 28, and 90 days compared to the control mix without fibers; the density of the mix with polypropylene fibers decreased by 0.73%, 1.1%, and 0.76% at the same time intervals; and the density of the mix with basalt fibers increased by 5.4%, 4.7%, and 4.5% at the same time intervals. The lowest increase in density in terms

Figure 4. Ultrasonic pulse velocity test

Table 13. Results of compressive strength test

Mix symbol	Dry bulk density (kg/m³)		
	7 days	28 days	90 days
RS	2054	2091	2113
SSF	2315	2326	2398
SPF	2039	2068	2097
SBF	2165	2189	2209
SH1	2133	2156	2188
SH2	2106	2132	2164
SH3	2155	2196	2215

Table 14. Results of increasing in dry bulk density test

Mix symbol	Increasing % at 7 days	Increasing % at 28 days	Increasing % at 90 days
RS	-	-	-
SSF	12.7	11.2	13.3
SPF	-0.73	-1.1	-0.76
SBF	5.4	4.7	4.5
SH1	3.8	3.1	3.5
SH2	2.5	2	2.4
SH3	4.9	5	4.8

of hybrid mixtures was the one that contained 1% basalt fibers, 1% micro steel fibers, and 2% polypropylene fibers, where the percentage of increase was 2.5%,2%, and 2.4% at 7,28, and 90 days. The reason for the increase and decrease in density is due to the difference in the density of the fibers used, as polypropylene fibers have the lowest density, which is listed in Table 9,10 and 11. Also, using basalt and polypropylene fibers leads to an increase in the percentage of voids, so the density is lower compared to steel fibers (Algın et al., 2022).

Compressive strength test

All of the fiber types tested showed an increase in compressive strength, however the exact percentage of improvement varies by kind. These outcomes are displayed in Figure 6 and Table 15 and Table 16, when applied to a cube size (100×100×100) mm. In comparison to the control mix that did not contain fibers, the reference mix that did contain micro steel fibers increased the compressive strength by 32.8% after 7, 28 days, and 21.7% after 90 days. Because adding tiny steel fibers to concrete greatly increases it's compressive and tensile strengths, this is the case. After7,28, and 90 days of utilizing polypropylene fibers, the compressive strength increases by 14.7%, after 30 days it rises by 7.9%, and after 60 days it rises by 5.4% due to the effective transfer of loads made possible by the strong link between the steel fibers and the cement matrix (Ali and Riyadh, 2018). Incorporating polypropylene fibers into concrete enhances its strength by inhibiting the formation and propagation of micro cracks. (Hasan et al., 2019). However, when basalt fibers were used, the increase in compressive strength was 10.7%,3.5%, and 3% at 7,28, and 90 days, respectively. By filling small cracks in the concrete, basalt fibers increase their strength and

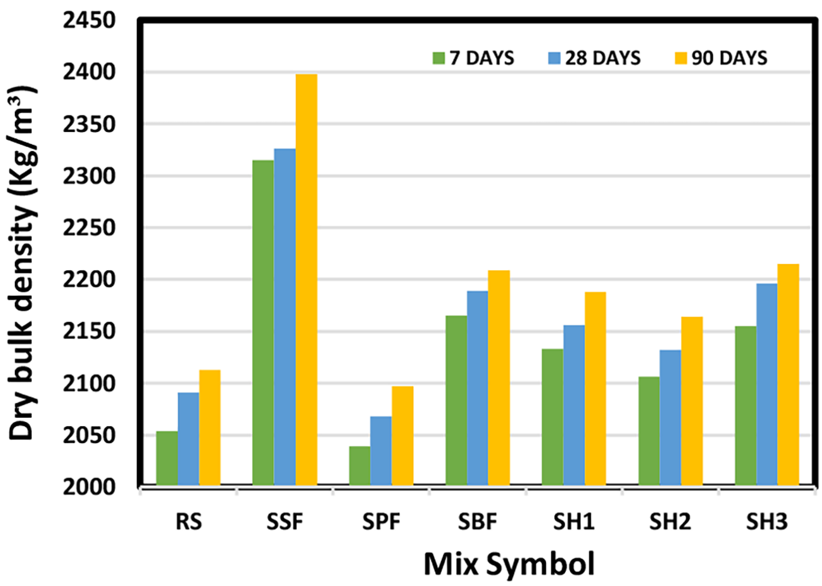

Figure 5. Relationship between dry bulk density and mixes at 7, 28 and 90 days

Table 15. Results of compressive strength test

Mix symbol	Compressive strength (MPa)		
	7 days	28 days	90 days
RS	50.3	66.2	74.3
SSF	66.8	81.4	90.4
SPF	57.8	71.4	78.3
SBF	55.7	68.5	76.5
SH1	63.1	78.1	89.4
SH2	60.4	76.7	86.4
SH3	68.2	86.8	95.2

Table 16. Results of increasing in compressive strength test

Mix symbol	Increasing % at 7 days	Increasing % at 28 days	Increasing % at 90 days
RS	-	-	-
SSF	32.8	22.7	21.7
SPF	14.9	7.9	5.4
SBF	10.7	3.5	3
SH1	25.4	17.9	20.3
SH2	20.1	15.9	16.3
SH3	35.6	31.1	28.1

prevent them from spreading. Under load, this crack-filling process helps maintain the integrity of the concrete (Algın et al., 2022) when using hybrid fibers, the best result for compressive strength was when using 1% basalt fibers, 2% steel fibers, and 1% polypropylene fibers, where the percentage of increase was 35.6%,31.1%, and 28.1% at 7,28, and 90 days, due to different of aspect ratio and large aspect ratio lead to increase strength (Abdullah and Fawzi, 2024; Hendi and aljalawi 2024).

Ultrasonic pulse velocity test (UPV)

This test evaluated the quality of SIFCON both with and without fiber in single and hybrid states, with velocity findings presented in Table 17, Table 18 and Figure 7 at 7, 28, and 90 days. This test evaluated the quality of SIFCON both without and with fiber in single and hybrid states, with velocity findings presented in Table 15 and Figure 11 at 7, 28, and 90 days. The results indicated a speed enhancement with the incorporation of steel fibers, with percentage increases of 21.7%, 20.2%, and 13.9% at 7, 28, and 90 days, respectively, in comparison to the reference mix

Table 17. Results of ultrasonic pulse velocity test

Mix symbol	Velocity (MPa)		
	7 days	28 days	90 days
RS	4.32	4.70	5.02
SSF	5.26	5.65	5.72
SPF	4.91	5.21	5.43
SBF	4.75	5.06	5.33
SH1	5.17	5.71	5.79
SH2	4.88	5.17	5.56
SH3	5.53	5.83	5.94

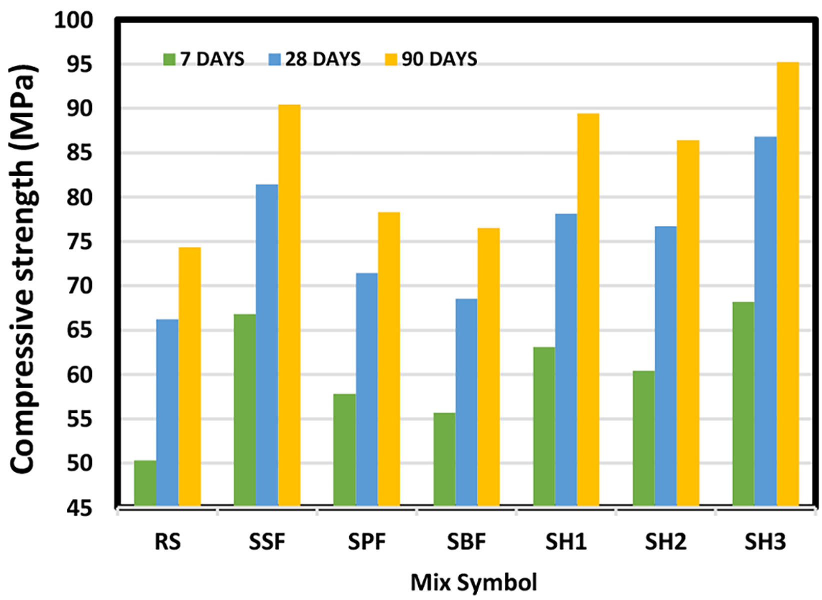

Figure 6. Relationship between compressive strength and mixes at 7, 28 and 90 days

Table 18. Results of increasing in ultrasonic pulse velocity test

Mix symbol	Increasing % at 7 days	Increasing % at 28 days	Increasing % at 90 days
RS	–	–	–
SSF	21.7	20.2	13.9
SPF	13.6	10.6	8.2
SBF	9.9	7.7	6.2
SH1	19.7	21.5	15.3
SH2	12.6	10	10.8
SH3	28	24	18.3

devoid of fibers. The velocity increase was reduced with polypropylene and basalt fibers compared to micro steel fibers. The optimal composition of the hybrid fiber mix consisted of 1% basalt fibers, 2% micro steel fibers, and 1% polypropylene fibers, resulting in increasing percentages of 28%, 24%, and 18.3% at 7, 28, and 90 days, respectively. Adding steel fibers improves the homogeneity of the mix, reducing voids and other factors that could hinder wave propagation. The presence of micro steel fibers can also increase

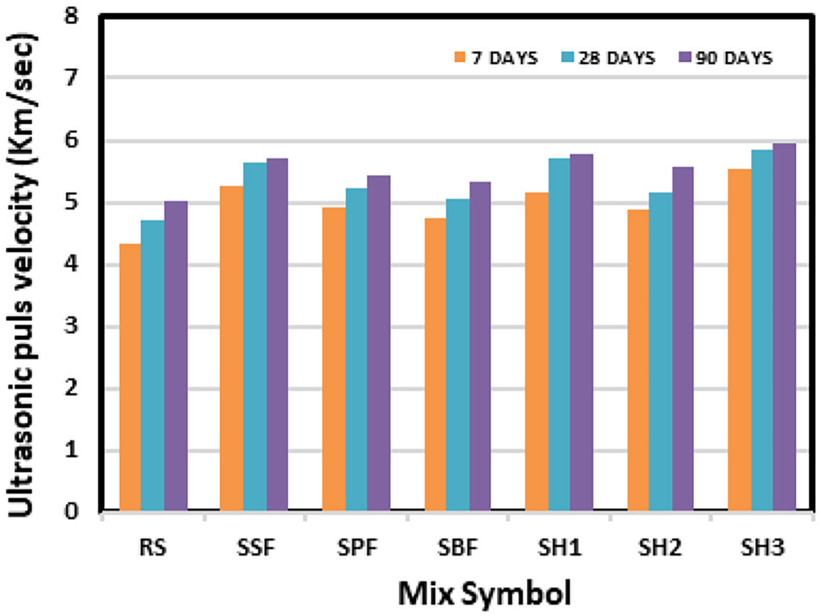

Figure 7. Relationship between ultrasonic pulse velocity and mixes at 7, 28 and 90 days

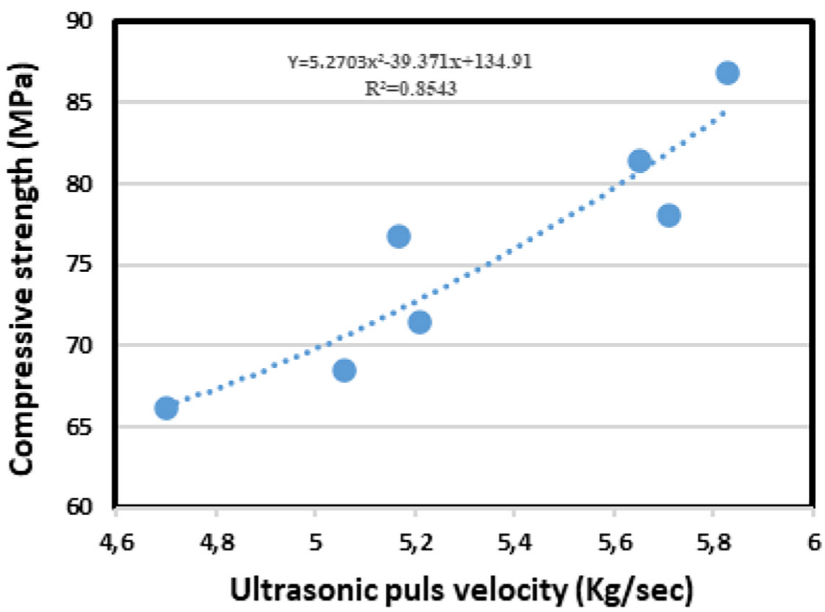

Figure 8. The relationship between compressive strength and ultrasonic pulse velocity for all mixes after 28 days

the modulus of elasticity of the concrete, leading to a higher wave velocity (AL-Ridha et al., 2017).

Relationship between compressive strength test and ultrasonic pulse velocity test

Figure 8 illustrates the correlation between compressive strength and velocity for all mixtures after 28 days, allowing for the calculation of strength based on velocity using the equation provided below:

$$Y = 5.2703x^2 - 39.371x + 134.91 \quad (2)$$

CONCLUSIONS

The most effective combination of SH3, consisting of 1% basalt fiber, 2% polypropylene fiber, and 2% micro steel fiber, resulted in the greatest compressive strength measurements. When compared to the reference mix, the compressive strength rose by 35.6% after 7 days, 31.1% after 28 days, and 28.1% after 90 days.

In the test measuring ultrasonic pulse velocity, the SH3 mixture did the best. After 7 days, the velocity was 28% higher than the reference mix; after 28 days, it was 24% higher; and after 90 days, it was 18.3% higher.

The addition of micro steel fibers increased the density of SIFCON by 12.7% after 7 days, 11.2% after 28 days, and 13.3% after 90 days. In contrast, when polypropylene fibers were used, the density decreased by 0.73% after 7 days, 1.1% after 28 days, and 0.76% after 90 days compared to the reference mix without fibers. The SH2 hybrid fiber mix resulted in density increases of 2.5% after 7 days, 2% after 28 days, and 2.4% after 90 days compared to the reference mix. This increase was the lowest compared to the SH1 and SH3 hybrid fiber mixes.

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