Research Article

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The effect of using different fibres on the impact-resistance of slurry infiltrated fibrous concrete (SIFCON)

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Abstract: Slurry infiltrated fibrous concrete (SIFCON) is a modern type of fibre reinforced concrete (FRC). It has unique properties; SIFCON is superior in compressive strength, flexural strength, tensile strength, impact resistance, energy absorption and ductility. Because of this superiority in these characteristics, SIFCON was qualified for applications of special structures, which require resisting sudden dynamic loads such as explosions and earthquakes. The main aim of this investigation is to determine the effect of fibre type on the apparent density of SIFCON and on performance under impact load. In this investigation, hook-end steel fibre and polyolefin fibre were used. Purely once and hybrid in different portions again. After reviewing previous research, including [1–3] references three trail mixes were tested with a volume fraction of fibres (4, 6 and 8)%, and after testing them, a volume fraction of 6% was chosen. We chose the volume fraction of 6% and made the type of fibre the variable for comparison in this research. In hybrid fibres this fraction was divided once 2/3 steel fibres with 1/3 polyolefin fibres and vice versa. The specimens of the Impact resistance test were made with two specimens for each series, which are panels with dimensions of 50×50×5 cm. Three cubes were made for each series in the SIFCON apparent density test. Test results prove SIFCON produced from 2/3 polyolefin and 1/3 steel fibres achieved a good density reduction that contributes to reducing the self-weight of the structural element, which is a major aim in this investigation, reducing cost and maintaining high impact resistance.

Keywords: SIFCON; Silica fume; density; impact resistance

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1 Introduction

Slurry infiltrated fibrous concrete (SIFCON,) is a high strength composite material. SIFCON is a modern type of fibre reinforced concrete (FRC) and differs from it in two essential factors: the amount of fibre it contains and how it's manufactured. SIFCON was developed to get a very high strength property, and the reason for this high strength is the high content of fibres. Some researchers are beginning to use widely different types of fibres. SIFCON is characterised by great ductility and high strength and can be widely applied to structural applications. Mortar does not consist of the coarse aggregate because it cannot penetrate the small spaces within a net of dense fibres. In addition, it is characterised by containing a high proportion of cement. It also contains fine or very fine sand and mineral additives such as fly ash, silica fume and slag. The mortar (slurry) must be designed precisely and be suitable for infiltration into the dense net of fibres inside the mould [4]. The technology of SIFCON was developed as an outcome of the cement packing process, pozzolana, fine sand, chemical additive mixture and water as a fluid mortar (slurry), poured into the mould in which a high volume fraction of fibres (5–30%) has been placed [5]. SIFCON has excellent application potential in the areas where impact and blast resistance and superior ductility are particularly required in the design of seismic resistance requirements and in structures subjected to impact [6]. For engineering applications, concrete structures may be exposed to dynamic loads generated from the effect of loads resulting from winds, storms, explosions, external projectiles, impulsive and sea waves. Characteristics of these loads are height-loading rate, very little period, and frequent root causes of a lot of stress in the structures. The resistance of materials varies under the influence of dynamic loading compared to static load. This is because differences in the dynamic retort of concrete structures, conventional calculation methods, and traditional design approaches are probably not very useful for understanding and analysing the behaviour of elements under dynamic loading. In the past few years, several researchers have been interested in addressing this deficiency. They conducted investigations to understand the behaviour of concrete and concrete based compounds that affected impact load [7]. In recent years, interest has increased in using SIFCON in explosion-proof containers, repairing structural components, and explosion-proof safety cabinets. SIFCON has high impact resistance it has high energy absorption. For SIFCON being a relatively modern building material, there is slight knowledge about the property of SIFCON that are susceptible to impact load and were identified from previous research. From this particular point of view, researchers proposed an examination to provide experimental information about performing (SIFCON) under the influence of impact loads by recognising the type of slurry SIFCON. In addition, the outcome of different volumetric fractures of steel fibre and geometric of this fibre is considered one of the greatest significant factors that influence the characteristics of the SIFCON manufactured product [8]. The real work in the sites and the rapid development witnessed by life in various aspects caused an urgent need to find new types of concrete. That serves the practical work at a lower cost and faster time. So theoretical research worked using the materials of building sustainable. In addition, additives material of all kinds to develop also find kinds other than normal concrete. slurry infiltrated fibre concrete (SIFCON) is one of these kinds [9]. Some researchers studied the effect of adding different volumetric ratios of steel fibre. They examined the properties of concrete using a volume fraction (1/2, 3/4 and 1) percentage by the concrete volume and length/diameter ratio of 100. Samples were tested (cubes and prisms) of blain concrete and reinforced concrete with steel fibres. For comparison, the best increase in compressive strength was when using the largest volume fraction of 1% of the fibres and the best flexural strength [10]. Reinforcing concrete resistance is not limited to using steel fibres only. Researchers have proven that other fibres, such as polypropylene increase concrete's resistance to impact loads [11].

Aim of study: Traditionally, steel fibres are used in the manufacture of SIFCON, which leads to a raised density and then raises the self-weight of the structural member made of it. In this investigation, a new type of fibre was tested. The aim was to reduce the density while maintaining the superiority of mechanical properties, especially impact resistance. The polyolefin fibres were not previously used in SIFCON, but were used in fibre reinforced concrete. It was used for the first time in a SIFCON by researchers of this investigation.

Figure 1: Steel fibre

Figure 2: Polyolefin fibre

Table 1: Physical properties of cement

Test type	Property		Test results	Limits of (IQS No. 5, 2019) for OPC
Physical tests	Setting time	Initial (minutes)	135	Min. 45
		Final (minutes)	207	Max. 600 Min.
	Compressive strength (MPa) at age	2 days	21	≥ 20
		28days	42.70	≥ 42.5
	Specific surface area	m^2/kg	398.9	≥ 300
	Soundness Le-Chatelier	mm	3	≤ 10

Table 2: Chemical composition of cement

Test results	Component		Test result	Limits of (IQS No. 5, 2019)
Chemical Tests	SiO_2 (%)		19.73	Not limited
	Al_2O_3 (%)		4.62	Not limited
	Fe_2O_3 (%)		3.64	Not limited
	CaO (%)		61.87	Not limited
	MgO (%)		2,97	Max. 5
	SO_3 (%) Max.	C3A ≤ 3.5%	—	2.5
		C3A > 3.5%	2.48	‘2.80
	Loss on ignition (%)		2.2	Max. 4
	Insoluble residue (%)		0.44	Max. 1.50
	C3S (%)		58.53	Not limited
	C2S (%)		12.43	Not limited
	C3A (%)		5.12	Not limited
	C4AF (%)		11.07	Not limited

Table 3: Fibres properties

Fibre type	Length [cm]	D [mm]	Aspect ratio	Density [kg/m^3]	Tensile strength MPa
Steel	3.5	0.55	64	7850	1650
Polyolefin	6	0.9 equivalent	66.7	910	>500

2 Experimental work

This investigation used “Ordinary Portland Cement” [type I] grade 42.5 R, conforms to (Iraqi specifications limits No. (5) – 2019) [12]. Tables 1 and 2 detail the physical properties and chemical composition. Fine aggregate (Sand) taken from Karbala desert, south Iraq. The sieve analysis test shows it falls under gradient zone 4 and has been sieving on a 1.18 mm sieve to pass finer sand. The sand conforms to (Iraqi specification limits No. (45) – 1984) [13]. Silica fume agreeing to the specifications of (ASTM C1240, 2015) [14]. Used steel fibres with length of 3.5 cm and 0.55 mm in diameter, aspect ratio 64 product by BUNDREX company / South Korea (Figure 1), also used Synthetic polyolefin have a length of 6 cm, a diameter of 0.9 mm and have density of 910 kg/m^3 (Figure 2) the properties of two type fibre listed in Table 3. Used a high-performance super-plasticiser concrete admixture type (Sika Viscocrete 5930) that conforms to ASTM C494 / C494M-15 [15].

2.1 Mix proportion

After conducting several trail mixes and obtaining the best slurry flowability, it was within the common limits of SIFCON production based on previous research. The following mixing proportion was also selected. Quantities to produce one cubic meter of slurry: 885 kg of binder (90% cement, 10% silica fume), which means 796.5 kg cement and 88.5 kg silica fume, the sand to binder ratio was 1:1 means 885 kg sand, the water binder ratio was 0.31 that means 274 kg water and the weight S. P to cement ratio 1.6% (12.7 kg). A fibre volume fraction of 6% of the concrete volume was used for all SIFCON models. Based on the change in the type of fibre, five series of SIFCON were produced: SFO as a reference mixture without fibres, SFS with 6% steel fibre only. SFP with 6% polyolefin fibre only. SFS2P1 with 4% steel fibre and 2% polyolefin fibre (total 6%). SFS1P2 with 2% steel fibre and 4% polyolefin fibre.

2.2 Mixing procedure and casting samples

1. Mix the dry ingredients, which are cement, sand and silica fume, with an electric mixer, for 2 minutes.
2. Add 65% of water and mixing for 3 minutes.
3. Leave the mixture to rest for 3 minutes.
4. Add the 35% of the water that was mixed with SP and continue mixing for 2 minutes.

For determining the flow-ability, a slurry micro-flow test was carried out according to ASTM C-1437, 2007 [16] to ensure a homogeneous mixture with desirable flow characteristics and to ensure no segregation or agglomeration in the mixture and efficiently infiltrated through the dense fibre net. All the moulds 10×10×10 cm cubes and 50×50×5 cm panels were cleaned and lubricated before casting. The fibre amount was placed at once before pouring the slurry to infiltrate through the fibres, as shown in Figure 3. The mould was knocked lightly with a hand rod to achieve good penetration, based on previous research [9]. Afterwards, 24 hours after the pouring process, the samples are taken out of the moulds and placed in water basins for curing until the age required for testing. According to the specification. ASTM C192/C192M-07 [17].

Figure 3: Casting the slurry in moulds

2.3 Testing samples

2.3.1 Strength-activity index (S.A.I.)

The strength activity index (S.A.I.) for silica fume used in this study was conducted according to the (ASTM C1240, 2020) [14].

2.3.2 Flow test

Slurry must be liquid and fine adequate to flow through the condensed steel fibres. Therefore, according to ASTM C-1437, 2007, [16] a flow test was conducted for the slurry. A flow test is an easy test for a fresh slurry state. It estimates the filling ability and horizontal flow; in addition, it indicates the uniformity of the slurry and its resistance to segregation from the visual observation through conducting the test. The test is shown in Figure 4.

Figure 4: Flow test of slurry

2.3.3 Apparent density

The apparent density investigation was done on the (15 specimens) 10×10×10 cm cubes in accordance with ASTM C642-13 [18]. This test was carried out using an oven, balance and immersion basins in tap water, and immersion basins for boiling water. Eq. (1) provided in the above specification was used to calculate the apparent density.

$$\text{Apparent-density}\,[\mathrm{g/cm^3}] = \frac{A}{(A-D)} \times \rho \tag{1}$$

A – mass of sample after oven dry
B – the mass of sample after Immersion (saturated)
D – Immersed apparent mass,
ρ – Density of water g/cm^3

2.3.4 Impact resistance test

A low-velocity impact device consisting of:

1. A rigid steel frame. The measurements of the testing steel frame allowed holding the specimens (50×50×5 cm)
2. The vertical guide (2400 mm in high 110 mm in diameter) for the falling body was used to ensure impact in the middle of the sample. This was a tube of circular sections.
3. The steel ball of a mass of 3.75 kg.

Samples were in their location in the testing frame. Mass was then dropped at a high of 1.5 m, and the number of required blows to cause the first crack was recorded. The number of blows required to cause failure (no rebound) was also recorded. Figure 5 shows the impact test device. To calculate the energy of blows, we used the Eq. (2).

Figure 5: Impact resistance device

$$E = h \times g \times M \times N \quad (2)$$

E – Energy of blows (N·m).
N – Blows number.
M – Dropping body mass (kg).
g – Ground acceleration (m /Sec^2).
h – The height in meter of the dropping body (m).

3 Result and discussion

3.1 Strength activity index (S.A.I.)

The test result was 182%. As the specification, limits should be greater than 105%.

3.2 Flow test

The test result was that the slurry achieved a horizontal spread with an average diameter of 27 cm, which is a very good result compared to a lot of previous research on SIFCON (see reference [5]).

3.3 Apparent density

The results are detailed in Figure 6 and Table 4. It results from the average of three specimens for all mixture types. Using steel fibres in SFS mixes increased the density compared with SFO mix that does not contain fibre. The reason for the increase in the density in the presence of steel fibres is the very high density of the steel, 7850 kg/m^3, which is higher than the density of the mortar, which occupied an alternative space in the SIFCON. where it replaced a volumetric part of 6% of the mortar. The reason for the decrease in the density in the series that replaced the steel partially or completely with polyolefin fibre (SFP, SFS2P1, and SFS1P2) is the low density of polyolefin fibre, only 910 kg/m^3. It is much lower than the density of steel fibres. We mentioned the effect of the type of fibres on the density in other literature [19, 20].

Table 4: Apparent density results

mix	Apparent density kg/m^3
SFO	2252
SFS	2764
SFP	2348
SFS2P1	2759
SFS1P2	2361

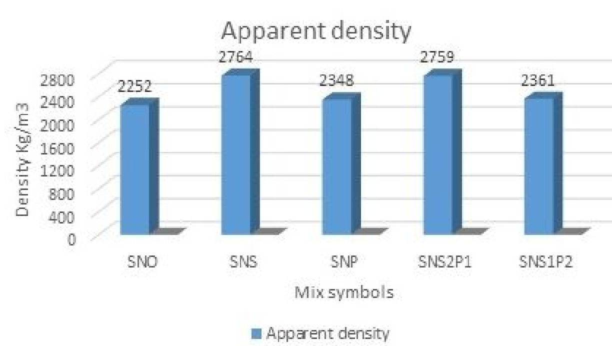

Figure 6: Apparent density results

3.4 Impact resistance and energy test result

The impact resistance test was carried out after 60 days of curing for two samples of each mix. Table 5 and Figures 7 and 8 describe the impact test results. From the Table, it is clear that the impact resistance increases when using the

Table 5: The results of impact resistance

mix	Number of blows caused first crack	Energy N. m	Number of blows caused failure	Energy N. m	Residual energy	Increasing in energy in failure
SFO	5	275.9	15	828.6	552.7	0%
SFS	135	7457	800	44190	36733	5331.2%
SFP	30	1657.1	150	8285.7	6628.6	999.9%
SFS2P1	95	5247.6	770	42532.9	37285.3	5133.1%
SFS1P2	67	3701	650	35904.31	32203.3	4333.1%

fibre (the number of strikes to first crack and failure occurs) compared with the reference mix SFO. When taking (SFO) as a reference sample, the increment of impact is (5331.1%) for failure when using 6% steel (SFS). When taking (SFO) as a reference sample, the increment of impact is (4333.1%) for failure when using 2% steel and 4% polyolefin (SFS1P2). The impact resistance raises because of the interlocking of the fibre network in the mortar, which increases the absorption energy because of its high tensile strength. Both types of fibres in the reinforced SIFCON series caused a significant increase in the impact resistance, the absorbed energy, and the residual energy between the first crack and failure compared to the fibre-free reference mixture (SFO). The reason for this is that each fibre worked as a small mechanism to absorb energy, and when the first crack occurred, it worked to prevent the expansion and spread of the crack and transfer those loads to the fibre network and from there to the matrix. This mechanism of fibres relieved the stress on the edge of the crack and prevented the cracked SIFCON panels from failing. This is clear from the amount of residual energy, the difference in energy between the failure and the first crack. Thus, improving the performance of SIFCON panel's samples under impact loading compared to reference samples SFO. These conclusions are consistent with what we mentioned in previous literature [4, 6].

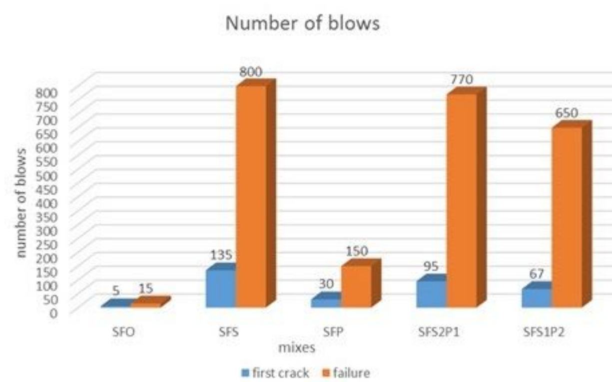

Figure 7: Number of blows caused first crack and failure

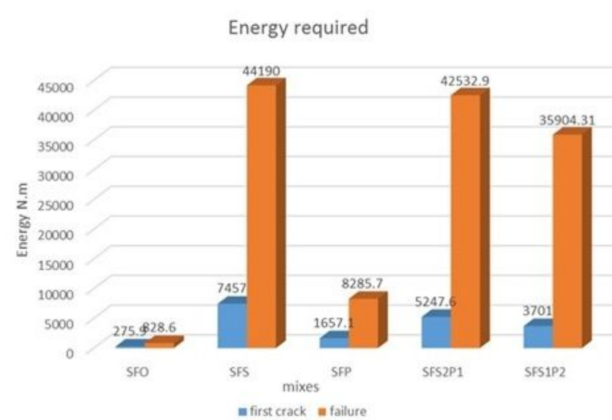

Figure 8: Energy required to first crack and failure

3.5 Investigation of cost

We made a simple comparison of reducing the cost by using polyolefin fibres and steel fibres. The prices listed in Table 6 below are the purchase prices in the local markets when purchased by the authors to complete the research. The quantities listed are for the production of one cubic meter of SIFCON.

Table 6: Comparison of the cost of fibres

Type of fibre	Volume m^3	Density kg/m^3	Weight $kg/1m^3$	Price for 1kg fibre	Total price for 1 m^3	Reduction in cost
Steel	0.06	7850	471	5 $	2355 $	0
polyolefin	0.06	910	54.6	9 $	491.4 $	79.1%

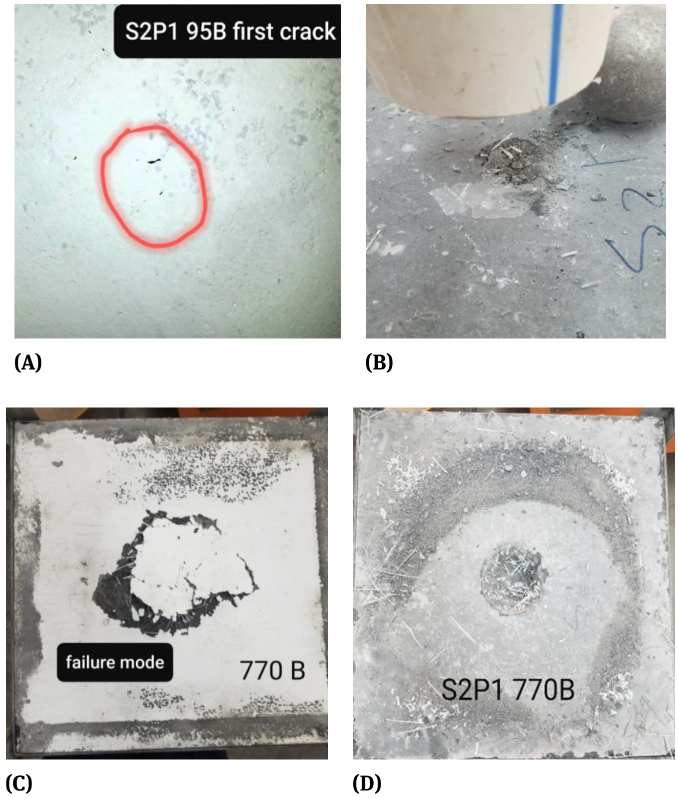

Figure 9: Face and back of impact resistance, test samples: [A] The back of SFS2P1sample in first crack; [B] The face of SFS2P1sample in first crack; [C] The back of SFS2P1sample in failure; [D] The face of SFS2P1sample in failure

4 Conclusion

1. When performing a flow test, it was observed that the inclusion of silica fume in SIFCON slurry improves workability and flowability. Strength development with age was also observed. It enhances the strength of the mortar, due to the reaction of the pozzolanic by making an additional C-S-H gel.
2. SIFCON mix SFS exhibits maximum resistance to impact and energy to whole failure greater by (53) times the reference-mix (60 days) curing.
3. The use of polyolefin fibres reduced the apparent density of SIFON by (17.7%) in a mix SFP compared to a mix SFS because the density of polyolefin is only equivalent (11.6%) to the density of steel fibre.
4. We find that the mix SFS1P2 achieved a significant decrease in density (17.7%). And achieved an excellent impact resistance, not much less than the maximum impact resistance in the mix SFS. In addition, it achieved an increase in the impact resistance by (4233.3%) to the reference mixture.
5. Since the mixture contains 65% polyolefin and 35% steel fibres from the total volume fraction of the fibres, it will lead to a significant cost reduction based on what has been proven above.
6. Because the polyolefin fibres are of low density, the weight sufficient to reinforce one m^3 of SIFCON with a volume fraction of 6% is 54.6 kg, while it needs 471 kg of steel fibres to achieve a volume fraction of 6%. After calculating the price per kilogram for both types, it was proven that using polyolefin fibres reduces the cost by 79.1% as shown in Table 6.

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