IMPACT AND BLAST RESISTANCE OF SLURRY INFILTRATED FIBER CONCRETE (SIFCON): A COMPREHENSIVE REVIEW

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The construction field developed Slurry Infiltrated Fiber Concrete (SIFCON) to improve mechanical properties considerably. The durability and ductility of this unique kind of concrete have significantly improved as well, and it has a higher energy absorption capacity. SIFCON differs from other fiber-reinforced concretes because it is produced in a different process, and finally, it contains a significant quantity of fiber, up to 20% or even more. In recent years, several research studies have been conducted on SIFCON, mainly focusing on the performance under impact and blast loading. Although this type of concrete is currently being utilized for significant structures, such as energy plants and military buildings, little is known about how it will respond to blast loads. The aim of this study is to analyze the research findings on enhancing the characteristics and toughness of SIFCON during impact and explosion situations. The review provides essential details about SIFCON that specialists in this field would need to know.

Keywords: Slurry Infiltrated Fiber CONcrete, SIFCON, impact, blast resistance, fibers

1. INTRODUCTION

Since the 1970s, fiber-reinforced cementitious composite (FRCC) has advanced significantly. It is well recognized that FRCC improves the properties of normal concrete, such as its tensile strength, stiffness, and fracture resistance. These benefits have led to the use of FRCC in civil engineering construction. Slurry infiltrated fiber concrete (SIFCON), a variation of traditional FRCC, was created by Lankard in 1984. The mechanical properties of SIFCON and its applications have been the subject of several investigations (Naaman and Najm, 1992; Naaman et al., 1993; Wang and Maji, 1994; Shannag et al., 2001; Mohammed et al., 2009; and Farnam et al., 2010). According to these studies, SIFCON is more ductile and capable of absorbing more energy than traditional FRCC. Due to these qualities, SIFCON is utilized for significant constructions such as military complexes, runway precast pavements, and underground shelters.

Steel fibers are covered with a slurry of Portland cement, fine sand, pozzolanic products, water, and superplasticizer to make SIFCON. SIFCON contains a high-volume ratio of fibers (up to 20%), significantly higher than that of regular steel FRCC (containing less than 2%), which sets it apart from conventional steel FRCC (Pang et al., 2013).

Many concrete buildings are frequently subjected to impact loads throughout their service lives. Today, much civil infrastructure is subject to impact loads, which can seriously harm the buildings. Therefore, extra consideration must be given to safety and technical solutions so that these structures can withstand impact loads. The kinds of impact situations include vehicular accidents on concrete systems, ships crashing into bridges, falling objects impacting concrete slabs, planes taking off and landing on airport runways, constructions exposed to wind and explosions, etc. (Bambach et al., 2008; and Abirami et al., 2019).

Due to the significant growth in nuclear power plants, terrorist threats, and military threats over the past few decades, the behavior of building materials under blast loading has become a topic of growing interest. With the abovementioned features, SIFCON has much potential as a blast-proof material. However, because of the complexity of blasting experiments, relatively few investigations have been reported on the behavior of SIFCON during blast loading (Pang et al., 2013).

Blast-resistant constructions must be strong to ensure switch load ways in the event of localized failures. If the structural details cannot function as intended, toughness may not be feasible to guarantee. It has been demonstrated that structural features have a considerable behavioral impact on buildings subjected to blast loads. Therefore, it is essential to better understand how structural details behave when subjected to blast stresses. Several sources (Baker et al., 1983; American Society of Civil Engineers, 1985; HQ Dept. of Army, 1986; Drake et al., 1989; Department of Army, 1990; Department of Energy, 1992; and Krauthammer, 1999) contain a lot of details on this subject.

In this review, we attempt to summarize what has been discussed in earlier studies related to the resistance of SIFCON to the impact and blast and the materials used to increase its strength to the influence of those loads.

2. REVIEW OBJECTIVES

This review explores the properties of slurry infiltrated fiber concrete when subjected to the influence of impact and blast. This study focuses on two main themes: (1) the impact response of SIFCON and (2) the blast resistance of SIFCON.

Emphasis is placed on studying how SIFCON is affected by impact load and explosion compared to other types of concrete. Previous studies and their summary of how to enhance the properties of SIFCON to resist blast and collision are also discussed.

3. IMPACT RESPONSE OF SIFCON

For concrete constructions like bridges, ordinary buildings, and other secure structures, strength against impact is necessary. Examples include an airplane landing impact on a runway, a highway barrier against a random vehicle hit, an accidental ship impact on a bridge pier, a boulder falling on a concrete building, and an offshore structure affected by a sea wave (Murali and Ramprasad, 2018). Because of this, there is an increasing demand for the development of building materials, especially concrete, vulnerable to impact loads. The distortion in regular concrete is nonetheless low. The insufficient impact energy absorption capacity makes it difficult to guarantee the safety of buildings that are subject to impact loads (Li et al., 2020). Several procedures can improve the resistance of concrete to impact loads and significantly reduce damage. Among these techniques, adding fibers to concrete can improve its tensile properties and ability to absorb impact energy compared to ordinary concrete (Abid et al., 2020). Steel fibers can efficiently prevent fracture development and spread, increase energy absorption, and enhance ductile behavior in concrete (Nili and Afroughsabet, 2010).

This section discusses previous research dealing with the SIFCON response to impact load. As well as the types of mineral admixtures used in SIFCON and the range of their influence on this aspect. Also, the extent of the action of impact load is explored through a comprehensive review of the previous literature to gain the most benefit from this study and save effort for researchers in this field. In most previous studies, the drop weight impact testing setup has been fabricated following the guidelines of ACI Committee 544.2R-89.

Table 1. presents details on the number of blows required to cause the first crack (N1) in SIFCON and other types of concrete specimens under impact loading tested in past investigations. Additionally, the number of blows required to cause the ultimate failure stage (N2) was documented.

The same table also includes a comparison of total energy-absorption capacities at the first crack (E1) and ultimate impact strength stages (E2). The energy absorption is obtained by using the following formula (Sudarsana et al., 2010):

$$E = m \cdot g \cdot h \cdot N, \qquad (1)$$

where:

E	is the energy absorption capacity.
m	is the mass of the ball (kg),
g	is the acceleration due to gravity (9.81 m/s^2),
h	is the height of falling (mm), and
N	is the number of blows.

Based on the results of *Table 1*. SIFCON specimens were highly effective against the impact load compared to other types of concrete. SIFCON was more intact because it has a higher fiber content. Its property of increasing tensile strength and ductility when loaded beyond the elastic limit caused energy dissipation in the slab and increased the stiffness of the specimens against the impact load.

Table 2. shows the figures of failure patterns for the tested specimens. Note from it an improvement in the impact resistance of the specimens using SIFCON compared with other types of concrete.

4. BLAST RESISTANCE OF SIFCON

In recent times, terrorism and explosion accidents have been increasing worldwide. The design of blast-resistant structures is a challenge in modern days. With the latest research in the field of fiber-reinforced concrete, SIFCON is now considered one of the best materials. The need for reinforced concrete buildings as physical protection grows as the threat of international terrorism increases. The protection systems must endure sudden dynamic loads, such as explosion strikes, terrorist attacks, and military accidents.

Fiber-reinforced concrete is now regarded as one of the best materials due to recent industry studies, and it is better to use it in this field (Haekook et al., 2017).

This section discusses previous research dealing with the SIFCON resistance to blast loading. The details of the type of fibers and mineral admixtures used, explosive material (type, quantity, and location for the tested specimen), and the damages (crater diameter or fragment weight in the tested specimen) under blast loading for SIFCON and other types of concrete specimens tested in previous investigations are presented in *Table 3*.

The results of the blast behavior of SIFCON for many previous papers were recorded in *Table 3,* investigated, and compared to other types of concrete. A series of blasting tests was conducted with varying amounts of explosive materials. It was found that SIFCON has much higher blast resistance than other types of concrete.

During the test, it was observed that the SIFCON specimens expanded, proving the superior ductility and energy absorption of SIFCON. It is considered that these characteristics are due to the bridging effect of steel fibers in SIFCON, which transfers the stress across cracks.

Table 4. shows the failure patterns of the samples subjected to blasting. The SIFCON concrete proved its effectiveness in resisting blasting compared to the other concrete types, which were completely destroyed in some cases. Therefore, SIFCON is suitable for structures that may be subject to blast loading. These achievements will help us to design and provide safer structures with SIFCON.

5. CONCLUSIONS AND FUTURE RESEARCH NEED

The purpose of the current study was to critically analyze relevant papers in the published literature on the two factors that directly influence of slurry infiltrated fiber concrete (SIFCON). The impact loading and resistance of SIFCON to blast are discussed. This comprehensive review leads to the following conclusions:

1. When compared to other types of concrete, SIFCON specimens were more efficient against the impact load. Because SIFCON has more fibers, it was less damaged (see *Table 1*). SIFCON achieved high results in energy absorption compared to conventional FRC and other special types of concrete.

Table 1: Summary of impact response of SIFCON

No.	Type of concrete	Dimension of specimens (cm) L	W	T	Type of fiber	Volume fiber fraction Vf. (%)	Type of mineral admixtures	Number of blows N1	N2	Energy absorption (kJ) E1	E2	References
1	SIFCON	60	60	5	Steel D=1 mm L=50 mm	8	--	7516	40700	169	915	(Sudarsana et al., 2010)
						10		13750	67466	309	1517	
						12		26950	82133	606	1848	
	SIFCON with steel bar					8		94600	162800	2128	3663	
						10		111100	192500	2499	4331	
						12		137500	242000	3093	5445	
	FRC with steel bar					2		213	40150	4	903	
	FRC					2		100	7406	2	166	
	RCC				--	--		27	11550	0.600	259	
	PCC							--	10	--	0.220	
2	SIFCON	--			Hooked end steel D=1 mm L=30 mm	10	--	246	1005	4.988	20.355	(Elavarasi, and Saravana, 2018)
							SF-15%	273	1032	5.527	20.894	
							GGBS-30%	303	1112	6.130	22. 512	
	SIFCON with steel bar						--	715	2364	14.491	47.854	
							SF-15%	742	2572	15.031	52.101	
							GGBS-30%	836	2740	16.918	55.457	
	RCC				--	--	--	10	117	--	--	
	PCC							--	10			
3	SIFCON	Cylindrical disc, D=150 mm H=64 mm			Hooked end steel D=0.9 mm L=60 mm	10	--	619	2074	--		(Abirami et al., 2019)
	FRC					1.5		172	374			
	TSFRC					5		428	1358			
	LFRC					T, M, B 2, 1, 2		450	1394			
4	FRC	Cylindrical disc, D=152 mm H=63 mm			Hooked end steel D=0.7 mm L=35 mm	2	--	33	127	2396	9220	(Manolia et al., 2020)
	SIFCON					11	--	200	923	14519	67004	
							SF-10%	365	1385	26497	100543	
							SF-10% FA-20%	470	1508	34120	109472	
5	FRC	50	50	4	Micro steel L/D = 65	2	--	44	133	2158	6524	(Nadia et al., 2020)
	SIFCON					6	SF-10% FA-20%	430	1327	21091	65089	
6	SIFCON	Cylindrical disc, D=152 mm H=63.5 mm			Hooked end steel D=0.5 mm L=30 mm	8	--	74	614	--		(Ramakrishnan et al., 2021)
					Polypropylene D=0.8 mm L=45 mm			43	480			
	PAFC					2.5		32	241			
					Hooked end steel D=0.5 mm L=30 mm			46	450			
	PAC				--	--		15	17			
7	SIFCON	--			Hooked end steel D=1 mm L=30 mm	10	--	--	--	605	1130	(Sumathi et al., 2022)

8	SIFCON	50	50	5	Hooked end steel D=0.55 mm L=35 mm	6-S	SF-10%	135	800	7457	44190	(Ali and Nada, 2022)
						4-S,2-P		95	770	5248	42533	
					Polyolefin D=0.9 mm L=60 mm	4-P,2-S		67	650	3701	35904	
						6-P		30	150	1657	8286	
9	SIFCON	Cylindrical disc, D=100 mm H=64 mm			Hooked end steel D=0.6 mm L=35 mm	4	--	--	--	--	2329	(Shelorka and Jadhao, 2022)
							MK-10%				3863	
							FA-10%				3540	
10	SIFCON	90	90	6	Hooked end steel D=0.55 mm L=35 mm	6	SF-10%	--	1086	--		(Mohammed et al., 2023)
					Micro steel D=0.2 mm L=13 mm				1075			
					Hybrid fiber Hooked end steel + Micro steel				1324			
	NSC				--	--	--		580			

Remark: Data should be evaluated according to varying parameters such as mixture proportions, curing conditions, and mechanical properties

2. SIFCON has shown much higher blast resistance than other types of concrete (see Table 3). Samples of concrete types, such as HSC and NSC, were destroyed compared to the fragmentation of very small parts of SIFCON samples.
3. The failure patterns of the samples that were subjected to blast and impact loading show that SIFCON is more successful at withstanding against them than other concrete types, some of which were destroyed (see Tables 2 and 4).
4. For future research, a few studies have examined how SIFCON is affected when exposed to various factors that reduce its service life, specifically when SIFCON is subjected to blasts and impact loads. Nevertheless, there is a need for more studies on the resistance of SIFCON to impact and blast resistance and the use of fibers of different lengths or different aspect ratios in it.

6. TERMINOLOGY

SIFCON	slurry infiltrated fiber concrete
NSC	normal strength concrete
HSC	high strength concrete
FRCC	fiber reinforced cementitious composite
FRC	fiber reinforced concrete
RCC	reinforced cement concrete
PCC	plain cement concrete
TSFRC	two stage fiber reinforced concrete
LFRC	layered fiber reinforced concrete
PAFC	preplaced aggregate fibrous concrete
PAC	preplaced aggregate concrete
HPFRCC	high performance fiber reinforced cementitious composite
UHPFRC	ultra high-performance fiber reinforced concrete
SF	silica fume
GGBS	ground granulated blast furnace slag
FA	fly ash
MK	metakaolin

7. REFERENCES

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Table 2: *Failure patterns for the impact-tested specimens*

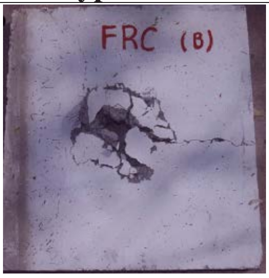
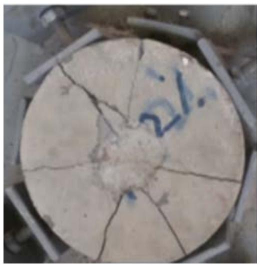
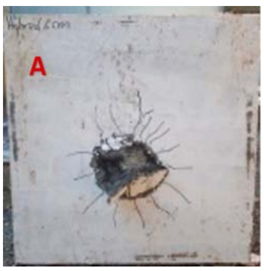
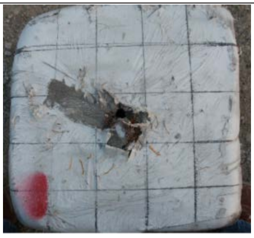
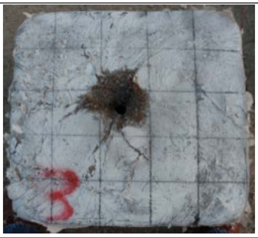
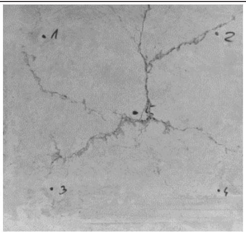
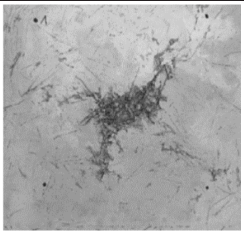
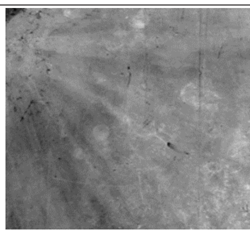
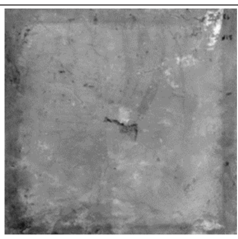
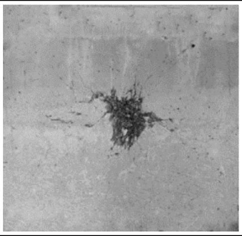
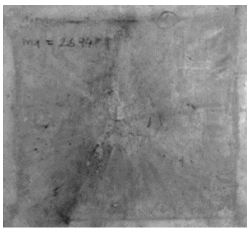
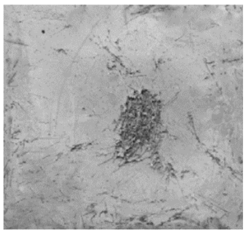
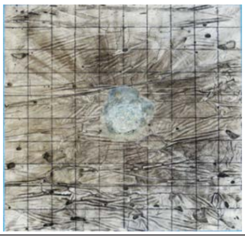
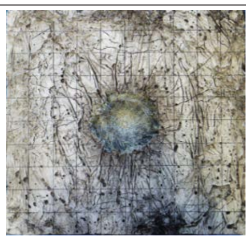
No.	Figures of specimens of all concrete types after the impact test				References
1					(Sudarsana et al., 2010)
	SIFCON with steel bars and 8% fibers	SIFCON with 12% fibers	FRC with 2% fibers	RCC	
2					(Elavarasi, and Saravana, 2018)
	SIFCON with steel bars, 10% fibers, and 30% GGBS	SIFCON with 10% fibers and 15% SF	RCC	PCC	
3					(Abirami et al., 2019)
	SIFCON	LFRC	TSFRC	FRC	
4					(Manolia et al., 2020)
	SIFCON with 6% fibers	SIFCON with 8.5% fibers	SIFCON with 11% fibers	FRC with 2% fibers	
5					(Mohammed et al., 2023)
	SIFCON with hybrid steel fibers	SIFCON with hooked-end steel fibers	SIFCON with microsteel fibers	NSC	

Table 3: Summary of blast load resistance of SIFCON

No.	Type of concrete	Dimension of specimens (cm) L	W	T	Type of fiber	Volume fiber fraction Vf. (%)	Type of mineral admixtures	Explosive material: Type	Quantity (g)	Place	The damages: A- Crater diameter (cm) or B- Fragment weight (g)	References
1	SIFCON	50	50	30	Steel D=0.5 mm L=30 mm	9	--	Gelignite	3	Inside the center of slab	A/8.82	(Pang et al., 2013)
									27		A/21.38	
	HSC				--	--	FA GGBS		3		A/22.2	
									9		Destroyed	
2	SIFCON based HPFRCC	190	190	10	Steel D=0.75 mm L=60 mm	5	SF	TNT	100000	5 m of away	Remained intact, but some permanent damage was observed	(Haekook et al., 2017)
					Basalt sheet (surface wrapping)	--						
	NSC				--	--	--				Destroyed	
3	SIFCON	50	50	4	Waste steel fibers from tires	10	SF	Semtex 10	150	1 m of away	B/23.9	(Martina et al., 2018)
					Steel D=0.5 mm L=30 mm	10					B/84	
	UHPFRC					4					B/232	
4	SIFCON	50	50	40	Steel D=0.8 mm L=50 mm	9	SF	Semtex 10	150	1 m of away	B/192	(Drdlová et al., 2018)
					Aramid D=12 μm L=1 mm	0.5 + 9 steel					B/20	
					AR glass D=12 μm L=1.3 mm	0.7 + 9 steel					B/50	
					Polypropylene D=15 μm L=2.2 mm	0.5 + 9 steel					B/166	
					Carbon PAN D=12 μm L=2 mm	0.5 + 9 steel					B/30	
					Wollastonite D=9 μm L=0.3 mm	2 + 9 steel					B/126	
5	SIFCON	50	50	8	Steel D=0.62 mm L=30 mm	11.5	GGBS	SEP	130	Inside the center of slab	A/14.7	(Shintaro et al., 2020)
					Polypropylene D=0.53 mm L=30 mm	10.5					A/18.4	
					Polyethylene D=0.7 mm L=30 mm	15					A/22.2	

Remark: Data should be evaluated according to varying parameters such as mixture proportions, curing conditions, and mechanical properties

Table 4: Failure patterns for the blast-tested specimens

No.	Quantity of explosive material (g)	Figures of specimens of all concrete types after the blasting test				References
		Concrete specimens 1		Concrete specimens 2		
		Types	Figures	Types	Figures	
1	3	SIFCON		HSC		(Pang et al., 2013)
	9	SIFCON		HSC		
2	100000	SIFCON based HPFRCC		NSC		(Haekook et al., 2017)
3	150	SIFCON with Waste steel fibers from tires		UHPFC		(Martina et al., 2018)
4	150	SIFCON with 9% steel fibers		SIFCON with 9% steel + 0.5% Aramid fibers		(Drdlová et al., 2018)
		SIFCON with 9% steel + 0.7% AR glass fibers		SIFCON with 9% steel + 0.5% Polypro-pylene fibers		
		SIFCON with 9% steel + 0.5% Carbon PAN fibers		SIFCON with 9% steel + 2% Wollast-onite fibers		
5	130	SIFCON with 11.5% steel fibers		SIFCON with 15% Polyethy-lene fibers		(Shintaro et al., 2020)

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