Studies on Slurry-Infiltrated Fibrous Concrete (SIFCON)

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Slurry-infiltrated fibrous concrete (SIFCON) can be considered as a special type of fiber concrete with high fiber content. The matrix usually consists of cement slurry or flowing mortar. SIFCON has excellent potential for application in areas where high ductility and resistance to impact are needed. Only very limited information is available about its behavior under different types of loading. Tests on 20-mm-thick SIFCON specimens were carried out in the Structural Engineering Research Center (SERC), Madras, India, to study their behavior in flexure and under subjection to abrasion and impact loads. Toughness characteristics of SIFCON were also evaluated by testing another set of specimens 100 × 100 × 500 mm per ASTM C1018. Both strength and deformation characteristics of the specimens were studied. The results obtained from these tests were compared with those carried out on companion plain mortar and conventional fiber-reinforced mortar (FRM) specimens. The investigations confirm the superior characteristics of SIFCON as compared with plain and normal FRM. Major conclusions drawn from the investigations are presented.

Slurry-infiltrated fibrous concrete or mortar (SIFCON) is a relatively new material that can be considered as a special type of fiber-reinforced concrete (FRC). In two aspects, however—namely, fiber content and the method of production—SIFCON is different from normal FRC. The fiber content of FRC generally varies from 1 to 3 percent by volume, but the fiber content of SIFCON varies between 5 and 20 percent. Again, the matrix of SIFCON consists of cement paste or flowing cement mortar as opposed to regular concrete used in FRC. These make the production of SIFCON far different from FRC. Unlike FRC, for which the fibers are added to the wet or dry concrete mix, SIFCON is prepared by infiltrating cement slurry into a bed of fibers preplaced and packed tightly in the molds.

SIFCON has been used successfully for refractory applications (*1*), pavement overlays (*2*), and structures subjected to blast (*3*) and dynamic loading. Because of its highly ductile behavior and far superior impact resistance, the composite has excellent potential for structural applications in which accidental or abnormal loads such as blasts are encountered during service. However, the composite was developed only recently, and only limited data are available on its behavior under different types of loading (*4,5*). Therefore, investigations were undertaken at the Structural Engineering Research Center, Madras, India, to study the relative behavior of SIFCON when subjected to flexure, abrasion, and impact loads. The toughness characteristics of the materials were also investigated. The results of the investigations carried out on a large number of test specimens cast using plain mortar, fiber-reinforced mortar (FRM), and SIFCON are presented.

DETAILS OF TEST SPECIMENS

Materials Used

The materials used in casting the test specimens consisted of portland cement, fine river sand, straight steel fibers, and a high-range water-reducing admixture called CONPLAST-430 (*6*). The cement conformed to Bureau of Indian Standards (IS) 269-1976. The sand was sieved through a 1.18-mm sieve to segregate the coarser particles. Straight round steel fibers of 0.4-mm diameter and a tensile strength of 1000 MPa were used.

Mix Proportions and Casting of Test Specimens

Flexure, Abrasion, and Impact Tests

Details of mix proportions used for making the test specimens intended for flexure, abrasion, and impact tests are given in Table 1. The SIFCON test specimens were cut from previously cast SIFCON slabs of 400 × 400 × 20 mm. The slabs themselves were cast using a wooden mold. A hand-operated steel roller was employed to compact the fibers inside the mold. Cement mortar slurry obtained from an electrically operated mortar mixing machine was poured uniformly over the preplaced fibers in the mold. The slurry consisted of cement and fine sand (passing through a 1.18-mm sieve) mixed in the proportion of 1:1 by weight. Compaction by table vibrator was used to ensure complete penetration of the slurry into the fiber pack. Twenty-four hours after casting, the slabs were demolded and cured in water for 28 days.

FRM and plain mortar test specimens were also prepared in a similar manner from the respective slabs of 400 × 400 × 20 mm.

The dimensions of the test specimens cut from the slabs (with the help of a concrete cutting machine) and used for flexure, abrasion, and impact tests were 400 × 100 × 20 mm, 70 × 70 × 20 mm, and 180 × 180 × 20 mm, respectively. Plain mortar cube specimens 70 × 70 × 70 mm were also cast to ascertain the compressive strength of the mortar used.

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TABLE 1 Details of Mix Proportions and Dimensions of Test Specimens Used for Flexure, Impact, and Abrasion Tests

Specimen identification	Category of specimens	Cube compressive strength of slurry (MPa)	Fibre by volume (%)	Aspect ratio	Water-cement ratio	Super-plasticiser by weight of cement (%)
P	Plain mortar	54.8	-	-	0.30	0.5
F1	FRM	56.0	1	75	0.35	0.5
F2	FRM	56.0	2	75	0.30	1.0
F3	FRM	80.0	3	75	0.32	2.0
F4	FRM	80.0	4	75	0.32	2.0
S1	SIFCON	60.0	6	75	0.38	2.0
S2	SIFCON	62.0	8	75	0.38	1.0
S3	SIFCON	58.5	6	100	0.35	2.0
S4	SIFCON	58.0	8	100	0.32	2.0

(dash) Not Applicable

The two parameters varied in these tests were fiber volume and aspect ratio. Whereas fiber volumes were varied from 1 to 4 percent in casting the FRM specimens, two volume percentages—6 and 8 percent—were used in making the SIFCON specimens. Aspect ratios 75 and 100 were used for SIFCON specimens, and a constant aspect ratio of 75 was maintained for FRM specimens.

Toughness Tests

Table 2 gives the details of the four mix proportions used for casting the SIFCON test specimens. The specimens were flexural prisms 100 × 100 × 500 mm. The prisms were cast using standard steel molds.

Three techniques were used for incorporating the steel fibers in the matrix. In the first case, the fibers were prepacked in the molds and the slurry was allowed to infiltrate the pack, assisted by proper compaction by means of a table vibrator (single-layer technique, designated as SL series). The second technique involved initial placing and packing of the fibers in the mold only up to one-third depth, followed by infiltration of the slurry up to this level. The contents in the mold were then vibrated. The process was repeated until the entire mold was filled and compacted (three-layer technique, designated as TL series). The third technique consisted of filling the mold up to one-third depth by the slurry, implanting the fibers into it immediately thereafter, vibrating the contents, and repeating the process until the mold was full (immersion technique, designated as I series).

The specimens were demolded 24 hr after casting and cured in water for 28 days.

For all the test specimens, the fiber volume and the aspect ratio were kept constant at 8 and 75 percent, respectively. The slurry used for infiltration consisted of portland cement and sand (passing through 1.18-mm sieve) mixed in the proportion of either 1:1 or 1:1.5 by weight (Table 2). Fly ash equal to 20 percent by weight of cement was used in some of the mixes to study its influence on the workability of the mix. The water-cement ratio was kept constant at 0.375, and the percentage by weight of CONPLAST-430 was varied from 1 to 5 percent.

Cylinders 50 mm in diameter and 75 mm high were also made out of SIFCON mixes using the same casting technique as adopted for the test specimens to ascertain the compressive strength of SIFCON. Plain mortar cubes 70 × 70 × 70 mm were also cast in each series to ascertain the cube compressive strength of the mortar used.

TEST PROGRAM

Flexure Test

Static flexure tests were carried out on SIFCON, FRM, and plain mortar test specimens using a universal testing machine with a capacity of 400 kN. The specimens were simply supported over an effective span of 360 mm and tested under constant bending moment over the middle-third portion. The specimens were subjected to a monotonically increasing load until failure. A dial gauge was used to measure the deflections at the midspan section.

Abrasion Test

As explained earlier, the abrasion test was carried out on 70- × 70- × 20-mm test specimens in accordance with IS 1237-1980 and using a standard abrasion testing machine. The specimens were first oven-dried at 100°C for 24 hr and then weighed to an accuracy of 0.001 N (0.1 g). Each specimen was then clamped on top of the disk in the machine and was loaded at its center by a weight of 300 N. Aluminum powder was used as the abrasive agent. After completing 22 revolutions, the rotation of the disk was stopped. The dust resulting from the abrasion of the specimen and the spillover of the aluminum powder was removed. Fresh powder in quantities of 0.2 N (20 g) was then added. After 110 revolutions, the

TABLE 2 Details of Mix Proportions Used for Casting SIFCON Specimens for Evaluation of Toughness Index

Designation of series and number	Mix proportion cement: sand (by weight)	Flyash content by weight of cement (%)	Super-plasticiser by weight of cement (%)	Average strength of SIFCON cubes* (MPa)	Average strength of SIFCON cylinders (MPa)	Average strength of plain mortar cubes (MPa)
**SL-A	***1:1	-	2	112.2	71.6	41.3
SL-B	1:1.5	-	3	22.0	-	39.8
SL-C	1:1	20	4	97.9	70.3	36.0
SL-D	1:1.5	20	5	25.7	-	34.1
TL-A	1:1	-	2	122.6	78.0	40.0
TL-B	1:1.5	-	3	74.4	-	36.0
TL-C	1:1	20	3	99.3	66.5	38.0
TL-D	1:1.5	20	5	119.5	-	26.5
I-A	1:1	-	1	80.8	88.4	42.6
I-B	1:1.5	-	2.5	96.2	89.0	34.4
I-C	1:1	20	3	93.3	97.6	43.4
I-D	1:1.5	20	5	129.3	107.0	26.5
P-A	1:1	-	1	65.0	29.1	35.8
P-B	1:1.5	-	3	63.7	29.0	37.0
P-C	1:1	20	3	59.2	26.6	29.2
P-D	1:1.5	20	5	37.7	25.6	30.0

Notes: * Cubes cut from tested flexural beams

** Each series consisted of three specimens. Values shown here are the average of results obtained for these three numbers.

*** For all the series, the water-cement ratio was kept constant at 0.375 and the percentage volume of steel fibres was kept constant at 8%. The aspect ratio of the fibres was kept as 75 in all cases.

(dash) Not Applicable/Unavailable

specimen was turned about its vertical axis through an angle of 90 degrees, and the test was continued until 220 revolutions were completed. The surface was cleaned, and the specimen was weighed. The test was continued in the same manner until 1,100 revolutions were completed. The loss due to abrasion (abrasion index) was calculated as the difference between the initial weight of the specimen and its weight after a fixed number of revolutions with respect to its initial weight (in this case, 220, 660, and 1,100 revolutions).

Impact Test

The impact test was carried out using the test rig shown in Figure 1. The specimen was placed in the bottom tub and clamped. The weight of drop was 50 N, and the drop height alone was varied from 250 to 1000 mm. Metallic pellets pasted at the bottom surface of the specimen in two mutually perpendicular directions helped to measure the residual strains using a Pfender strain measuring gauge, after the specimen had undergone a prescribed number of drops. For FRM specimens, the test was conducted by dropping the weight from a height of 250, 500, and 750 mm. One specimen was tested in each series. The drop height for SIFCON specimens was kept at 500, 750, and 1000 mm. The dropping of the weight was continued until the failure of the specimen, indicated by excessive cracking at its bottom surface or the formation of an indentation 20 mm in diameter (equal to the diameter of striker) on its top surface. The number of drops it took to cause one of these types of damage was recorded in each test.

Test for Toughness Index

Tests for evaluating the toughness index were conducted on SIFCON flexural specimens only. The toughness index was calculated using the methods prescribed in ASTM C1018 and Japan Concrete Institute (JCI) SF4.

The ASTM procedure involves determining the amount of energy required to deflect the beam to a specified multiple of the first-crack deflection, with the multiple based on functional (e.g., serviceability) considerations. The toughness indexes I_5, I_{10}, and I_{30} are calculated as ratios of the area of the

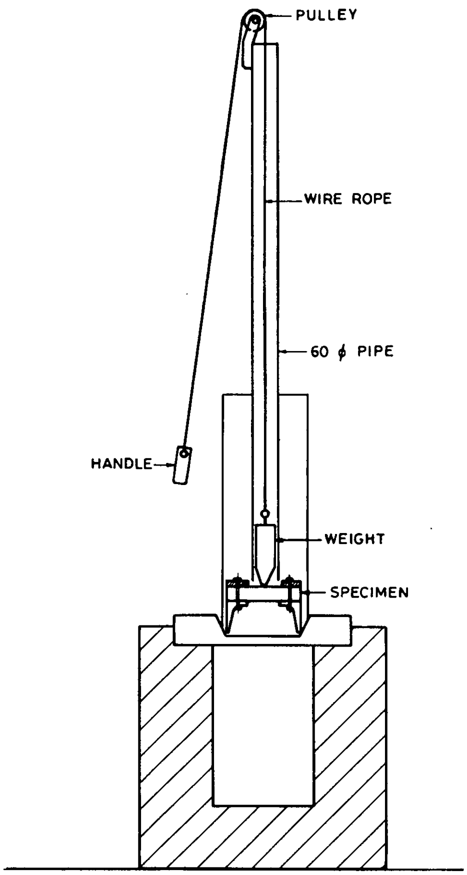

FIGURE 1 **Impact test setup.**

load-deflection curve measured up to deflections of 3, 5.5, and 15.5 times the first-crack deflection, divided by the area of the load-deflection curve up to the first-crack deflection (first-crack toughness), respectively.

In the JCI method, toughness is defined in absolute terms as the energy required to deflect a beam to a midpoint deflection of 1/150 of its span.

The tests were carried out using a universal testing machine with a capacity of 400 kN. A two-point loading system was used in which the specimen was simply supported over an effective span of 300 mm. The point loads were applied 100 mm from each support. A dial gauge having a least count of 0.01 mm and mounted on a specially fabricated steel frame was used for accurate measurement of deflection.

The testing machine was operated in such a manner that the deflection of the specimen at midspan increased at a rate of 0.05 to 0.10 mm/min as specified in IS 269-1976. Deflection measurements were recorded at various stages of loading until failure of the specimen. The cylinder compressive strengths of SIFCON mixes and the cube strengths of plain mortars were obtained by carrying out tests on the respective specimens using the universal testing machine.

Cubes 100 × 100 × 100 mm were also cut from the tested flexural test specimens with the help of a concrete cutting machine; they were subsequently tested for ascertaining the compressive strength of SIFCON mixes.

ANALYSIS OF TEST RESULTS

Flexure Test

The results of the flexural tests are given in Table 3. The load-deflection behavior for the FRM and SIFCON specimens is illustrated in Figures 2 and 3, respectively (*7*).

In Table 3, the hypothetical ultimate flexural strength computed by assuming an uncracked section is tabulated for different test specimens. This strength is taken as an index for comparing the relative performance of the specimens under flexural loading (*8*). It may be seen from Table 3 that SIFCON specimens reinforced with fibers having an aspect ratio of 75 behaved better than those having an aspect ratio of 100. This is true for both the fiber volume percentages (6 and 8 percent). It is also seen that in FRM specimens, there is an increase in the hypothetical flexural strength with the increase in fiber content up to 3 percent. Beyond this, the flexural strength remains almost the same. However, for SIFCON specimens, the improvement in flexural strength is phenomenal as compared with FRM specimens. The improvement is also more

TABLE 3 **Results of Flexure Tests**

Specimen identification (aspect ratio given in bracket)	Cube compressive strength of the slurry (MPa)	Thickness (mm)	Failure load (kN)	Hypothetical ultimate flexural strength (MPa)**
P	54.8	22	0.9	6.7
F1(75)	56.0	21	1.4	11.4
F2(75)	56.0	21	2.3	18.5
F3(75)	80.0	21	2.4	19.5
F4(75)	80.0	21	2.4	19.5
S1(75)	60.0	20	3.6	32.4
S2(75)	62.0	23	6.0	40.8
S3(100)	58.5	25	5.0	28.8
S4(100)	58.0	25	6.4	36.8

** assuming an uncracked section

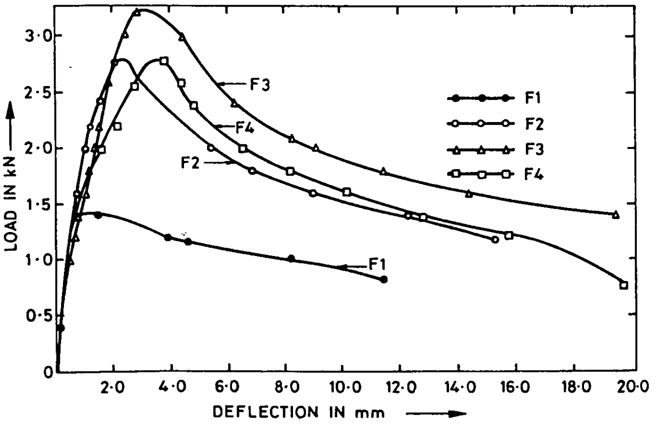

FIGURE 2 **Load-deflection curve for Specimens F1, F2, F3, and F4.**

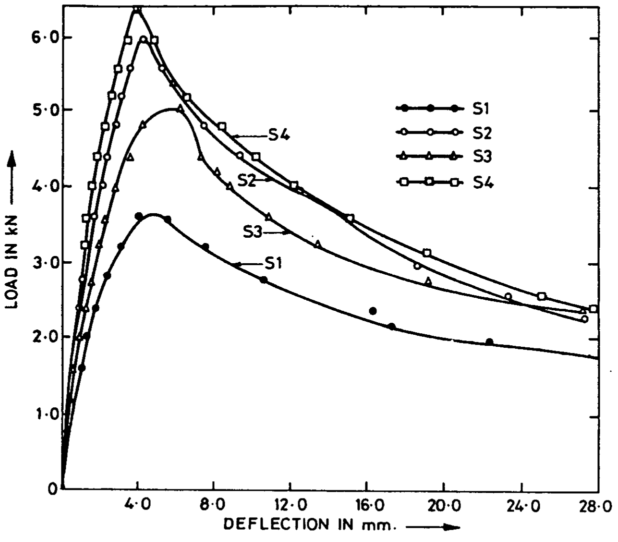

FIGURE 3 Load-deflection curve for Specimens S1, S2, S3, and S4.

with a higher percentage of fiber content. An increase in flexural strength of about 500 percent is shown by SIFCON specimens with 8 percent fiber volume over companion plain mortar specimens. The increase is about 100 percent over normal FRM specimens. From Figures 2 and 3, it is seen that SIFCON specimens exhibit greater ductility, fewer cracks, and less spalling of concrete during the tests than FRM specimens.

It may also be of interest that the ultimate flexural strengths obtained from the current tests are in the range of 35 to 41 MPa, as reported by earlier investigators (*1*).

Abrasion Test

The results obtained from the abrasion tests are given in Table 4. It is clear that SIFCON specimens containing 8 percent fiber content exhibit greater abrasion resistance than other types of specimens. The degree of abrasion, even though high in the initial stages of revolution of the disk (because the outer mortar surface of the specimens wore out faster) is still much lower than plain and FRM specimens.

TABLE 4 Results of Abrasion Tests

Specimen identification	Abrasion index percentage after number of revolutions *		
	220**	660**	1100**
P	10.2	39.0	66.0
F1	9.3	25.3	40.5
F2	8.36	20.6	31.83
F3	6.73	16.25	29.00
F4	6.16	14.00	26.00
S1	4.63	13.10	20.96
S2	4.11	12.26	18.60

*Abrasion index = (weight loss/initial weight of specimen) X 100

**Average of three specimens

Impact Test

The results of the impact tests are given in Table 5. The plain mortar specimen failed even after a single dropping of the weight from a height of 250 mm. Adding fibers to plain mortar greatly improves its impact resistance. More the fiber content, the resistance to impact is higher even for FRM specimens. The results also clearly establish the superiority of SIFCON specimens under impact load over FRM specimens. Here again, the resistance is more pronounced with increasing fiber content. An interesting feature is that SIFCON specimens reinforced with fibers having an aspect ratio of 100 exhibit greater impact resistance than those reinforced with fibers having an aspect ratio of 75. In the flexural tests, however, a reverse phenomenon was noticed, if one goes by the comparison of the respective values of the hypothetical ultimate flexural strength.

The extent of damage in SIFCON specimens during tests was also less than that of FRM specimens.

Test for Toughness Index

The values of the toughness indexes I_5, I_{10}, and I_{30} and the toughness energy of the SIFCON specimens cast using the three techniques described earlier are given in Table 6. The toughness index for plain concrete being equal to unity, because all plain mortar beams failed immediately after first crack, the superior toughness characteristics exhibited by SIFCON are quite evident from the values given in the table. The SL-C, TL-C, and I-D beams gave a higher toughness index, indicating thereby that mixes with a 20 percent fly ash content improve the toughness characteristics. It is also observed that the toughness index is not much dependent on

TABLE 5 Results of Impact Tests

Specimen identification	No. of drops the specimen withstood before failure			
	Weight of drop (N) 50	50	50	50
	Height of drop (mm) 250	500	750	1000
	Impact energy (N mm X 10^3) 12.5	25.0	37.5	50.0
P	1	-	-	-
F1	120	20	10	-
F2	314	33	18	-
F3	600	43	23	-
F4	1000	72	40	-
S1	-	240	43	10
S2	-	625	112	33
S3	-	300	47	20
S4	-	750	130	100

(dash) Unavailable

TABLE 6 Results of Tests for Toughness Index of SIFCON Specimens

Specimen identification*	I_5	I_{10}	I_{30}	I_{10}/I_5	I_{30}/I_{10}	Toughness energy by JCI Method (N mm)
SL-A	6.37	16.25	51.52	2.55	3.17	163540
SL-B	6.43	14.8	45.68	2.3	3.09	100300
SL-C	6.35	16.3	52.99	2.57	3.25	164150
SL-D	6.28	15.13	48.17	2.41	3.18	91250
TL-A	6.9	17.53	60.7	2.54	3.46	168090
TL-B	6.65	16.22	53.32	2.44	3.29	166730
TL-C	6.35	17.52	66.67	2.76	3.81	229600
TL-D	6.98	17.83	66.36	2.55	3.72	180340
I-A	5.89	14.19	46.53	2.41	3.28	134670
I-B	6.55	16.08	54.09	2.45	3.36	177050
I-C	5.86	14.32	47.16	2.44	3.29	144580
I-D	6.78	17.4	65.92	2.57	3.78	227820

*Values shown are the average of results obtained from three specimens

Note: For plain mortar prisms (P-A to P-D), the index is unity.

the method of placing the fibers in the form. From the results obtained by earlier investigators (ASTM C1018; 9), it is concluded that the toughness index of SIFCON is far greater than FRC or FRM. The average I_{30} index for SIFCON observed from the current tests is about 55, while the range observed for FRC and reported in IS 1237-1980 and JCI SF4 is only 6 to 40.

CONCLUSIONS

The following conclusions are drawn from the investigations presented here:

1. SIFCON specimens with 8 percent fiber content showed a fivefold increase in (hypothetical) ultimate flexural strength over companion plain mortar specimens and a twofold increase over normal FRM specimens with 2 to 4 percent fiber content. Fibers with an aspect ratio of 75 were found to contribute more to the hypothetical ultimate flexural strength of SIFCON than those with an aspect ratio of 100. Higher fiber percentages also gave higher ultimate flexural strength for the same aspect ratio.
2. SIFCON specimens exhibited greater ductility and greater resistance to cracking and spalling of concrete than normal FRM specimens.
3. Whereas the abrasion resistance generally improved to a great extent with the addition of fibers, even for FRM specimens, the improvement was phenomenal for SIFCON. This result suggests that SIFCON is ideally suited for applications demanding a high degree of wear and abrasion resistance.
4. The extent of damage in SIFCON due to impact load was found to be far less when compared to plain mortar and normal FRM, confirming thereby the superior impact resistance of SIFCON.
5. The toughness indexes for SIFCON specimens were found to be significantly higher than plain mortar specimens. The values of I_{30} as well as the ratios I_{10}/I_5 and I_{30}/I_{10} given in Table 6 indicate that the behavior of SIFCON is akin to an ideal elasto-plastic material. The range for I_{30} values was observed to be 45 to 60, which is far greater than the range observed for FRC by earlier investigators, namely, 6 to 40.
6. The three techniques used for incorporating fibers in the mortar slurry proved effective during the casting of the SIFCON specimens, but there was not much difference in the toughness indexes obtained from tests on identical SIFCON specimens that were cast differently using any of the three techniques. However, the three-layer and immersion techniques were found to be easier and simpler in actual practice than the single-layer technique.
7. A fiber content of 8 percent was found to be suitable for making SIFCON specimens using the mix proportions reported in the paper from the point of view of workability and strength (flexure, impact, abrasion, and toughness).

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