Effects of slag on flexural strength of slurry infiltrated fibrous concrete

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Abstract. Slurry infiltrated fibrous concrete is one of the new advanced concrete composite which differs from method of fabrication and composition of the matrix. Extensive research is being carried out on alternative binders or supplements to cement aiming to reduce environmental impact. However, little has been published to investigate the structural behaviour of SIFCON incorporating with mineral admixtures, particularly as regards its ultra-high ductility, which may alter the mode of failure from brittle to the more desirable ductile. An experimental study was carried out to investigate the flexural behavior of SIFCON containing three different percentage of fibre content 6%,8% &10% with incorporation of optimum dosage of blast furnace slag replaced by cement. Strength characteristics such as Compressive strength and splitting tensile strength test were carry out for SIFCON incorporating 10% of fibre content and different percentage of slag (0, 15, 30, 45, 60%&75%) to optimize the replacement level. The test results found that the maximum strengths were attained at 30% of blast furnace slag replaced by cement. To study the flexural behavior of SIFCON beam of size 1.2x0.1x0.2m containing different percentages (6%, 8% & 10%) fibre content incorporating with and without the optimum percentage of slag were cast and tested. Both flexural strength and Load displacement characteristics of the specimens were studied under flexure. The outcomes presented from test results have been compared. The test results reveals that the flexural strength, toughness, ductility and stiffness characteristics were significantly improved due to incorporation of optimum dosage of slag enhancing when compared to without mineral admixtures also compared to conventional concrete(RCC). Major conclusions were drawn from the investigations which are presented.

Keywords: SIFCON, GGBFS, Flexural strength, Ductility, Stiffness, Toughness.

1. Introduction
Slurry-infiltrated fibrous concrete (SIFCON) is a high strength composite material originated by Lankard. It possess superior mechanical properties and toughness characteristics. SIFCON can be considered as steel fibre reinforced concrete (SFRC) with high volume of fibre content which differs from the conventional SFRC in terms of volume of fibre content and method of fabrication. The matrix consists of cement mortar or slurry without containing course aggregates. In most cases, SIFCON is prepared by infiltrating the cement slurry into a pre-packed fibre bed. Even though SIFCON is a new construction material, it has found many applications in the areas of rehabilitation of pavements, prefabricated products, coatings, bridge decks and safety vaults, seismic and explosive-resistant structures, military applications such as anti-missile hangers, under-ground shelters, sea-protective
works, shielding of nuclear containment, platforms for aerospace repair and rehabilitation of air-field, solar tower, mega structures like long span structures and offshore structures etc.

It is already established by many researchers concluded that the SIFCON composites exhibit excellent performance in static loading such as shear strength and flexural strength compared to plain cement concrete(PCC), reinforced cement concrete(RCC) and fibre reinforced concrete(FRC). Also the structures subjected to impact and dynamic loading gaining excellent ductility and energy absorption characteristics. The strength of the composite depends upon four main design factors such as slurry strength, fiber volume, fiber alignment, and fibre type and aspect ratio. The fiber content by volume fraction is based on the fiber type, aspect ratio and the vibration effort needed for proper compaction. [1] revealed the basic mechanical properties of SIFCON like load-deflection response, ultimate compression and flexural strengths, impact and abrasion resistance. [2,3] studied the effect of incorporation of high volume class C fly ash on mechanical strength of SIFCON and conclusions have been made that the flexural strength and toughness characteristics were improved with higher amount of mineral admixtures and increased percentage of fibre content by volume fraction. [4] investigated the behaviour of slurry infiltrated fibrous concrete slabs subjected to impact loading and reported that the energy absorption capacity of SIFCON exhibits excellent performance compared to fibre reinforced concrete(FRC), reinforced cement concrete (RCC) and plain cement concrete (PCC). The test result revealed that SIFCON slabs with 12 % fiber content performed well in strength and toughness characteristics compared to all other SIFCON specimens. Energy absorption capacity of SIFCON slabs were increases with increasing fiber volume and also from visual observation the level of damages less when compared with SIFCON slabs without conventional reinforcement. [5] investigated the performance of restrained SIFCON two way slab was subjected to flexure and found that SIFCON slab containing 12% of fibre content yielding higher ultimate load with lesser deflection and became reported that the increased percentage of fibre content increases the stiffness of SIFCON slabs. And also observed the first crack load was higher than all other specimens. [6] investigated the simply supported two way SIFCON slab containing different percentage of fibre content(8%,10% &12%) under flexure and reveals that the SIFCON slabs exhibit excellent toughness characteristics and spacing of cracks have been minimized with increased volume of fibre content in SIFCON compared to Fibre reinforced concrete and plain cement concrete slabs. [7] studied the relative behaviour of SIFCON subjected to abrasion, flexure, and impact loads and also studied the toughness characteristics. The test results reveals that the SIFCON specimen exhibit superior ductility behavior and greater spalling and crack resistance. [8] the pull-out behavior was studied and indicated that increasing pull out strength depends on the fiber type, length of fibre, condition of curing, geometry of fibre and matrix strength and also increasing diameter increases the matrix-fibre bond. It was concluded that the pullout toughness increased due to increasing length of fibre and also observed that the hooked end fibre shows better bond strength when compared with straight smooth fibre. [9] investigated experimentally the triaxial compressive behavior of SIFCON with 10% of fibre content increases the higher tri-axial compressive strength and poisons ratio with increasing confining pressure and fibre content compared to high strength concrete (HSC), HPFRC. [10] investigated experimentally the shearing properties of SIFCON specimens with two different diameters and aspect ratio of fibres using cored cylindrical specimens subjected to pure torsion and concluded that the SIFCON beam shows more ductile, stable, post yielding cyclic behavior compared to reinforced cement concrete(RCC). [11] investigated the durability characteristics of ground granulated blast furnace slag (GGBFS) concretes and reinforced concrete beams were affected by corrosion under various loading conditions. The test results found that the slag was partial replacement by cement has the effects of arresting on both permeability and total charge-pass and also significant effects on corrosion rate and flexural rigidity of RCC beams. [12,13] examined the durability characteristics of alkali-activated slag(AAS) concrete subjected to acid attack and revealed that both the strength and durability characteristics of AAS shows better performance when compared to plain cement concrete using the same grade of ordinary Portland cement(OPC). [14] investigated the reported the efficiency of GGBFS
in concrete observed that increasing the strength up to 80% replaced by cement for getting required design strength. [15] investigated on optimum percentage of ground granulated blast furnace slag (GGBFS) on mechanical property of concrete and the test results concluded that the presence of GGBFS in the matrix acting as filler material enhancing the strength characteristics were improved up to 55% subsequently causes reducing strength. [16] investigated experimentally studied the stress–strain characteristics SIFCON composites in tension and compression and concluded that the elastic modulus of SIFCON increases due to the fibre volume, fibre alignment and orientation, aspect ratio and method of testing etc. [17] found that the incorporation of the mineral admixtures decreases permeability of chloride ion, thus improved durability of concretes and also found that the incorporation of ground granulated blast furnace slag (GGBFS) gives better durability characteristics when compared to flyash and silica fume. [18] investigated experimentally the effect of slag on strength and durability properties of concrete and reported that the concrete containing slag exhibits lower early strength and higher later strength were attained when compared to conventional concrete.

However, literature review reveals that a very little work has been carried out on SIFCON to determine the durability characteristics. Hence there is a need to conduct experiments to study the durability characteristics of SIFCON. Further more, the utilization of higher amount of cement in slurry not only influenced the cost of production, but also has an unfavorable effects on releasing enormous amount of heat causes shrinkage problems. Substitution of ground granulated blast furnace slag by cement suggest to solve these complications.

2. Experimental Investigations
An experimental program was designed to produce a slurry infiltrated fibrous concrete made with binary cementitious blend of blast furnace slag. For optimizing the slag was replaced different percentage (0%, 15%, 30%, 45, 60% & 75%) with constant a fibre content (10%) by volume fraction on compressive strength and split tensile strength. An optimum dosage of slag is to be found experimental results.

To study the ductility, ultimate load carrying and stiffness characteristics of beams are to be evaluated on two point bending test using loading frame testing setup. It comprises of casting of six reinforced SIFCON beams (1200 x 100 x 200 mm) with varying fibre content (6%, 8% & 10%) with and without incorporating optimum percentage of slag and one conventional concrete (RCC) for comparison. The materials used, mix proportions and the test methods are illustrated in the following headings.

2.1 Materials used
Grade 53 ordinary Portland cement was used to IS: 12269. The specific gravity of cement was found to be 3.15. The binary cementitious blend of slag conforming to ASTM C 989 was partially replaced by cement for improving strength characteristics and its specific gravity was found to be 2.91 was used. Locally available river sand of particle size less than 4.75mm having a specific gravity of 2.71 and fineness modulus of 2.43% was used for preparation of slurry. Hooked end steel fiber having a circular cross section of 1mm diameter, tensile strength of 1056MPa and aspect ratio 30 was used. Fibers were randomly oriented in all directions. For casting and curing of the specimens a fresh portable water which is available from local source. In addition to water a high range water reducing admixture (Superplasticizer CONPLAST 430) was added to improve the workability and flow ability of slurry into the fibre bed.
### Table 1. Chemical constituents of Cement and Slag

| Chemical Constituents | Cement (%) | Slag (%) |
|-----------------------|------------|----------|
| Silica (SiO₂)         | 21.8       | 39.18    |
| Alumina (Al₂O₃)       | 6.6        | 10.18    |
| Ferric oxide (Fe₂O₃)  | 4.1        | 2.02     |
| Calcium oxide (CaO)   | 60.1       | 32.82    |
| Magnesium oxide (MgO) | 2.1        | 8.52     |
| Sodium oxide (Na₂O)   | 0.4        | 1.14     |
| Potassium oxide (K₂O) | 0.4        | 0.30     |
| Sulphuric anhydride (SO₃)| 2.2   | -        |
| Loss on Ignition (LOI)| 2.4        | 1.0      |
| Specific gravity      | 3.1        | 2.56     |

2.2 Mix proportions

The slurry mix consisted of partial replacement of cement with different percentage of slag (15, 30, 45, 60%, & 75%) for getting an optimum dosage of slag in the matrix and rich mix proportion of 1:1 with water binder ratio of 0.4 were maintained for fabrication of the SIFCON specimens containing a constant 10% of fibre content was adopted. During mixing of slurry a high range water reducing admixture (Superplasticizer) was added for improving more workable and easy infiltration capacity into the packed of fibre. The matrix was compacted well manually to verify the complete penetration of the slurry into the pre-packed fibre bed.

To study the flexural behaviour of reinforced SIFCON beam with varying fibre content (6%, 8% &10%) and incorporation of an optimum dosage of slag (30%) for enhancing the ductility, stiffness and toughness characteristics. Reinforced cement concrete specimen of mix proportion 1:1:2.8 and water cement ratio of 0.39 was adopted for comparison. The mix ratio of different mixes were presented in Table 2.

### Table 2. Mix ratio of SIFCON specimens

| S. No. | Nomenclature of mix | Cement content (%) | Slag (%) | Fine Aggregate (%) | Fibre content (%) | W/B ratio | SP (%) |
|--------|---------------------|--------------------|----------|--------------------|-------------------|-----------|--------|
| 1.     | RCC                 | Mix proportion 1:1:2.8 |          | -                  | 0.39              | -         |        |
| 2.     | SIF6(S0)            | 100                | -        | 100                | 6                 | 0.40      | 2      |
| 3.     | SIF6(S30)           | 70                 | 30       | 100                | 6                 | 0.40      | 2      |
| 4.     | SIF8(S0)            | 100                | -        | 100                | 8                 | 0.40      | 2      |
| 5.     | SIF8(S30)           | 70                 | 30       | 100                | 8                 | 0.40      | 2      |
| 6.     | SIF10(S0)           | 100                | -        | 100                | 10                | 0.40      | 2      |
| 7.     | SIF10(S30)          | 70                 | 30       | 100                | 10                | 0.40      | 2      |

2.3 Casting of specimens

For investigating the flexural behavior of SIFCON incorporating with an optimum dosage of blast furnace slag containing different percentage of fibre content (6%, 8%, & 10%) were fabricated by adopting three layer techniques. Hand compaction have been done to assure the slurry is infiltrated into full depth of packed bed of fibres. After casting the specimens were demoulded after 24 hours and cured in water for 28 days. The reinforcement details were shown in figure 1.
2.4 Testing of specimen

The flexural performance of SIFCON containing three different percentage of fibre content with and without an optimum percentage slag were conducted on a computerized loading frame test setup as shown in figure 3. The beam specimens were erected and static load was applied gradually increasing the rate of loading till the specimens were collapsed. Mid span deflections at the initiation of first crack, yield point and ultimate stage were measured by a dial gauge with an accuracy of 0.01mm was used. To obtain an optimum dosage of blast furnace slag in SIFCON was also carried out on compression and split tensile strength by using compression testing capacity of 3000kN at constant rate of loading.

3. RESULTS AND DISCUSSIONS

3.1 Compressive and split tensile strength

The compressive and splitting tensile strength of SIFCON specimens containing 10% of fibre content were increased with increasing the replacement level of slag 30% and 45% respectively. One drawback of using slag solidification of the concrete is delayed causes strengths were attained on later stage due to incorporation of slag in SIFCON specimens. The test results were given in Table 3.

| S. No. | Mix type | Compressive strength (N/mm²) | Split tensile strength (N/mm²) |
|-------|----------|-----------------------------|-------------------------------|
| 1.    | SIF10(CS) | 65.50                        | 11.03                         |
| 2.    | SIF10(S15) | 65.85                        | 12.67                         |
| 3.    | SIF10(S30) | 66.97                        | 13.08                         |
| 4.    | SIF10(S45) | 64.85                        | 13.78                         |
| 5.    | SIF10(S60) | 61.97                        | 12.06                         |
| 6.    | SIF10(S75) | 59.73                        | 11.98                         |
3.2 Flexural strength
The flexural behaviour of SIFCON specimens containing different fibre content of 6%, 8% and 10% were tested and shown in Fig.4. The test results reveals that the flexural performance was gradually improved with increasing fibre content (SundarsanaRao et al. 2008) in the matrix with and without slag. Due to the incorporation of slag the strength was increased by 12.05%, 13.37% & 11.63% in SIFCON containing 6%, 8% and 10% respectively when compared to without slag in SIFCON.

3.3 Ultimate load
The ultimate load carrying capacity and first crack loads were presented in table 4 observed that load carrying capacity was improved due to incorporation of blast furnace slag and increasing percentage of fibre content and also the displacement of slag based SIFCON specimens were decreased with increasing load. The ultimate load carrying capacity increases also depend on the fibre alignment and orientation, method of production (Homrich et.al, 1987).

| Mix type       | First crack Load (kN) | First crack Deflection (mm) | Yield Load (kN) | Yield Deflection (mm) | Ultimate Load (kN) | Ultimate Deflection (mm) |
|----------------|-----------------------|----------------------------|-----------------|-----------------------|---------------------|--------------------------|
| RCC(CS)        | 29.6                  | 3.4                        | 51.7            | 4.75                  | 73.8                | 6.25                     |
| SIF6(0)        | 52.3                  | 3.9                        | 85.5            | 6.6                   | 127.6               | 12.5                     |
| SIF6(S30)      | 57.2                  | 1.5                        | 96.1            | 2.94                  | 142.8               | 7.83                     |
| SIF8(0)        | 54.95                 | 4                          | 87.65           | 6.5                   | 129.25              | 15.5                     |
| SIF8(S30)      | 61.1                  | 2.1                        | 101.8           | 3.24                  | 146.5               | 10.1                     |
| SIF10(0)       | 56                    | 7.6                        | 90.4            | 7.3                   | 133.2               | 16.16                    |
| SIF10(S30)     | 64                    | 1.2                        | 102.5           | 1.86                  | 148.9               | 6.08                     |

3.4 Stiffness
The stiffness behaviour of different mixes were shown in fig.5. The ultimate stiffness of slag based SIFCON mixes were increased by 78.7%, 74.75% and 197% in 6%, 8% and 10% of fibre content. Whereas in SIFCON without mineral admixtures, it was decreased with the addition of fibre content. The ultimate stiffness was increased due to increasing load carrying capacity without increasing displacement (Gnaneswar et al. 2009).

3.5 Ductility factor
Figure 6 shows the ductility factor of various mixes. The SIFCON specimens were more ductile than RCC. Among the SIFCON without blast furnace slag shows the ductility factors were improved with increasing fibre content by volume fraction. It was observed that the incorporation of slag in SIFCON the ductility were increased upto 8% , beyond it was decreased because the load carrying capacity was increased without increasing displacement.

3.6 Toughness
The toughness characteristics found from the experimental test results were shown in figure 7. It was calculated the area under load deflection curve. When compared to RCC specimen SIFCON mixes were more toughness value. Among the SIFCON beam without incorporation of slag the toughness was gradually increased with increased percentage of fibre content. Due to incorporation of slag enhancing the stiffness characteristics were improved with decreasing toughness.

3.7 Failure pattern
The first crack loads and failure loads were observed for all specimens were presented in table 3 and failure pattern was shown in figure 3(b). The failure pattern was observed that all the specimens were getting flexure failure and the cracks spacing have been decreased with addition of fibre content and
also the deformation was quite less in SIFCON incorporated with slag when compared to without slag, it became reported that the stiffness was increased due to slag which is present in the mix and also the growth of cracks were not extended into the entire depth of the beam.
4. Conclusions

Based on the investigations have been done experimentally the following inferences were drawn from test results:

- It is observed that the utilisation of ground granulated blast furnace slag (GGBFS) is well accepted as an alternative source for cement thereby reducing the consumption of cement which will cause saving energy, construction cost and also protect our environment from pollution.

- The impact of ground granulated blast furnace slag (GGBFS) increases the mechanical properties such compression and splitting tension were attained at 30% compared to other replacement level.

- The flexural strength and ultimate load carrying capacity of slag based SIFCON specimens were increased by 12.05%, 13.37% & 11.63% in SIFCON containing 6, 8 and 10% of fibre content respectively compared with SIFCON specimens without incorporation of slag.

- The load carrying capacity and ultimate stiffness of SIFCON specimens were shows better performance in SIFCON containing higher volume of fibre content (10%) with incorporation of slag when compared to SIFCON without slag.

- The toughness characteristics were also improved due to increasing fibre content in SIFCON without blast furnace slag, whereas in slag based SIFCON containing 10% was decreased due to arresting the displacement.

- The ductility performance was improved with increased amount of fibre content containing an optimum dosage slag in SIFCON compared to without inclusion of slag. The incorporation of slag enhancing the ductility behaviour.

- It was concluded that the replacement of slag by cement shows better ultimate load carrying capacity and excellent stiffness characteristics. The addition of slag in SIFCON improving the flexural properties and also modifying the microstructure of concrete by means of reducing pores which is present in the composites arrested the deformation and also reduce its permeability thereby reducing the intrusion of water.

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