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MECHANICAL PROPERTIES AND STRESS- STRAIN BEHAVIOUR OF SELF COMPACTING CONCRETE WITH AND WITHOUT GLASS FIBRES

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Abstract

The development of Self Compacting Concrete marks an important milestone in improving the product quality and efficiency of the building industry. Self Compacting Concrete is a recently developed concept in which the ingredients of the concrete mix are proportioned in such a way that it can flow under its own weight to completely fill the formwork and passes through the congested reinforcement without segregation and self consolidate without any mechanical vibration. Several studies in the past have revealed the usefulness of fibres to improve the structural properties of concrete like ductility, post crack resistance, energy absorption capacity etc. Fiber reinforced self compacting concreting combines the benefits of self compacting concrete in fresh state and shows an improved performance in the hardened state due to the addition of fibers. In this investigation Cem-FIL anti-crack high dispersion glass fibres were added to self compacting concrete and Glass Fibre Reinforced Self Compacting Concrete was developed. An attempt has been made to study mechanical properties and stress-strain behaviour of self compacting concrete and glass fibre reinforced self compacting concrete. A strength based mix proportion of self compacting concrete was arrived based on Nan-Su method of mix design and the proportion was fine tuned by using Okamura's guidelines. Five self compacting concrete mixes with different mineral admixtures like fly ash, ground granulated blast furnace slag and rice husk ash were taken for investigation with and without incorporating glass fibres. A marginal improvement in the ultimate strength was observed due to the addition of glass fibres to the self compacting concrete mix. Also incorporation of glass fibres had enhanced the ductility of self compacting concrete. Complete Stress-Strain behaviour has been presented and an empirical equation is proposed to predict the behaviour of such concrete under compression.

Keywords: Self compacting concrete; fibre; glass fibre; fiber reinforced SCC, admixtures; stress-strain behaviour

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1. Introduction

Current scenario in the building industry shows increased construction of large and complex structures, which often leads to difficult concreting conditions. When large quantity of heavy reinforcement is to be placed in reinforced concrete members it is difficult to ensure that the form work gets completely filled with concrete, that is fully compacted without voids or honeycombs. Vibrating concrete in congested locations may cause some risk to labour and there are always doubts about the strength and durability of concrete placed in such locations. One solution for the achievement of durable concrete structures independent of the quality of construction work is the employment of Self Compacting Concrete (SCC) [1,2]. SCC is that concrete which is able to flow under its own weight and completely fill the formwork without segregation, even in the presence of dense reinforcement, without the need of any vibration whilst maintaining homogeneity.

SCC was developed in Japan by Okamura in the late 1980's to be mainly used for highly congested reinforced concrete structures in seismic regions. Since then SCC has generated tremendous interest among the research scholars, engineers and concrete technologists.

Though concrete possesses high compressive strength, stiffness, low thermal and electrical conductivity, low combustibility and toxicity, two characteristics, have limited its use, it is brittle and weak in tension. However the development of fibre-reinforced composites (FRC) have provided a technical basis for improving these deficiencies [3]. Fibres are small pieces of reinforcing material added to a concrete mix which normally contains cement, water and fine and coarse aggregate. Among the more common fibres used are steel, glass, asbestos and polypropylene. When the loads imposed on concrete approach that for failure, cracks will propagate, sometimes rapidly, fibres in concrete provide a means of arresting the crack growth. If the modulus of elasticity of the fibre is high with respect to the modulus of elasticity of the concrete or mortar binder, the fibres help to carry the load, thereby increasing the tensile strength of the material. Fibres improve the toughness, the flexural strength, reduces creep strain and shrinkage of concrete [4].

Glass Fiber Reinforced Concrete (GFRC) is composed of concrete, reinforced with glass fibers to produce a thin, lightweight, yet strong material. Though concrete has been used throughout the ages, GFRC is still a relatively new invention. High compressive and flexural strengths, ability to reproduce fine surface details, low maintenance requirements, low coefficients of thermal expansion, high fire resistance, and environmentally friendly made GFRC the ideal choice for civil engineers [5, 6] . The strength of GFRC is determined by glass content, fiber size, fiber compaction, distribution and orientation [7].

Considering the advantages of SCC and GFRC an attempt has been made to combine these two and to produce Glass Fibre Reinforced Self Compacting Concrete (GFRSCC) and to investigate the stress-strain behaviour and mechanical properties of both SCC and GFRSCC.

2. Research Significance

For new materials like SCC and GFRSCC studies on mechanical properties and stress-strain behaviour are of paramount important for initializing confidence in engineers and builders.

The literature indicates that some studies are available on plain SCC and steel FRSCC but sufficient literature is not available on the stress-strain behaviour and mechanical properties of GFRSCC and SCC with different mineral admixtures. Hence considering the gap in existing literature an attempt has been made to study the mechanical properties and stress-strain behaviour of both SCC and GFRSCC.

3. Experimental Program

Five SCC Mixes with different types of admixtures were developed in the laboratory and Cem-FIL anti-crack high dispersion glass fibres of 600 grams/m^3 of concrete were added to these SCC mixes and glass fibre reinforced self compacting concrete was developed. The experimental programme consisted of casting and testing of SCC and GFRSCC elements(3 specimens each for each mix of SCC and GFRSCC) in compression , tension and in flexure. Cubes of 100mm size and cylinders of 150 mm diameter and 300 mm long were cast for testing in compression and in tension. Prisms of 100 × 100 × 500 mm were cast for testing in flexure. 100 ×500 mm were cast for testing in flexure.

3.1 Materials used

Cement	Ordinary port land cement of 53 grade confirming to IS-12269 having specific gravity of 3.15
Fine Aggregate	Natural river sand confirming to IS-383 zone II having specific gravity 2.63
Coarse Aggregate	Crushed granite angular aggregate of size 12.5 mm passing confirming to IS-383 having specific gravity 2.67
Mineral admixtures	Fly ash confirming to IS 3812-1981 Ground granulated blast furnace slag (GGBS) confirming to BS 12089-1987 Rice husk ash Properties of mineral admixtures are given in Tables 1 - 6
Chemical admixtures	Super plasticizer Conplast SP430 Viscosity modifying agent (VMA) Glenium stream 223
Water	Confirming to IS 456.
Glass Fibres	Cem-FIL anti-crack high dispersion glass fibres Properties of glass fibres are given in Table 7

3.2 Properties of Materials

Table 1. Physical properties of Fly ash

S.No	Characteristics	Properties
1	Specific gravity	2.3
2	Specific surface area	420m^2/kg

Table 2. Chemical composition of Fly ash

S.No	Characteristics	Percentage contents	Percentage (range)
1	Silica, Sio_2	68	35-67
2	Alumina Al_20_3	23	16-28
3	Iron oxide Fe_20_3	4	4-10
4	Lime CaO	1.1	0.7-3.6
5	Magnesia Mgo	0.5	0.3-2.6
6	Sulphar Trioxide So_3	0.03	0.1-2.1
7	Loss on Ignition	0.3	0.4-1.9

Table 3. Physical properties of GGBS

S.No	Characteristics	Properties of slag used
1	Specific gravity	2.91
2	Fineness (Blaine's) m^2/kg	330
3	Glass content percent	93
4	Bulk Density Kg/m^3	1100
5	Color	Dull white

Table 4. Chemical composition of GGBS

S.No	Characteristics	Requirement (BS:6699)	Percentage contents
1	SiO_2	32-42	33.2
2	Al_2O_3	7.16	18.3
3	CaO	32-45	41.00
4	Fe_2O_3	0.1-1.5	1.3
5	MgO	14 Max.	11.6
6	SO_3	2.5 Max.	1.0
7	CaO/SiO_2	1.4 Max.	1.23
8	Loss on Ignition	3 Max.	0.5

Table 5. Physical properties of RHA

S.No	Characteristics	Properties
1	Specific gravity	2.3
2	Loss on ignition	3.6%
3	Fineness Blains	16000 cm^2/gm

Table 6. Chemical composition of RHA

S.No	Characteristics	Percentage contents
1	Sio_2	84.00
2	Al_20_3	0.90
3	Fe_20_3	0.45
4	Mgo	0.40
5	Cao	3.15
6	Ko	1.6

Table 7. Properties of glass fibres

1	Trade name	Cem-FIL anti-crack high dispersion glass fibres
2	Number of fibres	212 million/kg
3	Aspect ratio	857:1
4	Specific surface area	105 m^2/kg
5	Typical addition rate	0.6 kg/m^3 of concrete
6	Tensile strength	1700 MPa
7	Modulus of elasticity	73 GPa
8	Corrosion resistance	Excellent
9	Specific gravity	2.6
10	Density	26 KN/m^3
11	Filament diameter	14 μ
12	Filament length	12 mm

3.3 Mix proportion

To start with a M 30 grade SCC mix was designed based on Nan Su method of mix design[8], and was further modified by fine tuning the relative proportions of fine and coarse aggregate, filler material like fly ash, GGBS and RHA along with super plasticizers and viscosity modifying agents[9]. The guide lines given by Professor Okamura&Ozawa [10], Takada [11], Gibbs [12], Nan Su, Subramanian [13] and EFNARC specifications [14] were taken as references and the final SCC mix proportion was arrived.

3.4 Development of scc and gfrscc

Number of attempts were made in the laboratory to get optimum dosages of mineral and chemical admixtures to produce M 30 grade SCC without segregation and bleeding with satisfying the properties both in fresh and hardened states. From these trials five SCC mixes shown in Table 8 with different types of admixtures like fly ash, GGBS and RHA with different dosages which had given relatively high compressive strengths were selected for the investigation and to these mixes, Cem-FIL anti-crack high dispersion glass fibres of 600 grams/m^3 of concrete were added to get GFRSCC shown in Table 9.

Table 8. Mix proportions of SCC

Sl. No	Design -ation	Cement in Kg	C.A Kg	F.A Kg	Fly–Ash %Kg	GGBS %Kg	RHA %Kg	Water Kg	S.P %bwc	VMA %bwc
1	SCC 1	240	700	900	----	260	----	199.5	2.50	--
2	SCC 2	240	700	900	-----	100%=2 60	1% (addition) =2.6	199.5	2.50	--
3	SCC 3	240	700	900	-----	97%= 252.2	3% (Replacement) =7.8	199.5	2.50	--
4	SCC 4	240	700	900	49.5%=1 28.7	49.5%= 128.7	1% (Replacement) =2.6	199.5	2.50	--
5	SCC 5	240	700	900	60% =144.0	40% =96.0	1% (addition) =2.4	198.5	2.50	0.35%

Table 9. Mix proportions of GFRSCC

Sl. No.	Designation	Mix proporton
1	SCC 1 F	SCC 1 + 600 grams/m^3 of Cem-FIL HD Glass Fibre
2	SCC 2 F	SCC 2 + 600 grams/m^3 of Cem-FIL HD Glass Fibre
3	SCC 3 F	SCC 3+ 600 grams/m^3 of Cem-FIL HD Glass Fibre
4	SCC 4 F	SCC 4 + 600 grams/m^3 of Cem-FIL HD Glass Fibre
5	SCC 5F	SCC 5 + 600 grams/m^3 of Cem-FIL HD Glass Fibre

4. Testing of SCC in Fresh State

Slump flow, V-funnel and L-box tests were performed in the laboratory on fresh SCC and GFRSCC to find filling ability, passing ability and segregation resistance. The prescribed limits of the tests as per the EFNARC specifications are as shown in Table 10. The fresh properties of SCC and GFRSCC are shown in Tables 11 and 12

Table 10. EFNARC specifications for fresh properties of SCC

Name of the test	Property	Unit	Min.	Max.
Slump flow	Filling Ability	mm	650	800
T 50cm Slump Flow	Filling Ability	sec	2	5
V- Funnel	Filling Ability	sec	6	12
V- Funnel 5sec	Seg. Resistance	sec	6	15
L-Box	Passing Ability	H_2/H_1	0.8	1.0

Table 11. Fresh concrete properties of SCC

Sl. No.	Designation	Slump Cone Test		V Funnel Test		L Box Test		
		Horizontal Slump (mm)	T 50 (time in Sec)	Time for complete discharge	T 5 min in Sec	Time for 0-200mm spread	Time for 0- 400mm spread	H_2/H_1
1	SCC 1	690	3.0	7.0	9.5	2.5	5.0	0.81
2	SCC 2	680	4.0	8.0	10.5	4.0	6.5	0.81
3	SCC 3	690	3.5	7.5	9.0	3.0	5.5	0.80
4	SCC 4	685	3.0	7.0	9.0	3.5	5.0	0.82
5	SCC 5	690	3.5	7.5	10	3.5	6.0	0.83

Table 12. Fresh Concrete properties of GFRSCC

Sl. No.	Designation	Slump Cone Test		V Funnel Test		L Box Test		
		Horizontal Slump (mm)	T 50 (time in Sec)	Time for complete discharge	T5min in Sec	Time for 0–200mm spread	Time for 0–400mm spread	H_2/H_1
1	SCC 1 F	680	4.0	9.0	10.5	4.0	7.0	0.81
2	SCC 2 F	675	4.0	9.5	11.5	5.0	7.0	0.80
3	SCC 3 F	680	4.5	8.0	10.0	4.0	5.5	0.80
4	SCC 4 F	680	4.0	8.0	10.0	4.5	7.0	0.82
5	SCC 5F	690	4.0	7.0	9.5	4.0	5.0	0.82

5. Specimen Preparation

After testing the SCC and GFRSCC in fresh state the concrete was poured in moulds of cubes, cylinders and prisms. After the concrete has set in moulds the cylindrical specimens which were to be tested in axial compression were capped with a thin layer of stiff neat Portland cement paste. After 24 hours of casting the specimens were de-moulded and placed in water for curing. After 28 days of curing the specimens were taken out from water and allowed the surfaces for drying. For each SCC and GFRSCC mixes 3 cubes, 6 cylinders and 3 prisms were cast.

6. Tests on SCC and GFRSCC in Hardened State

i. Compressive strength tests were carried out on cubes of 100 mm size using a compression testing machine of 1000 KN capacity as per IS 516:1959.
ii. Split tensile strength tests were carried out on cylinders of 150 mm diameter and 300 mm height using a compression testing machine of 1000 KN capacity as per IS 516:1959.
iii. Flexural strength tests were carried out on prisms of size 100×100×500 mm on flexure testing machine of capacity 100 KN as per IS 516:1959.
iv. The cylinders which were capped, were tested in compression using 1000 KN capacity computer controlled UTM under strain rate control as per IS 516:1959 to get the stress-strain characteristics.

After testing SCC and GFRSCC in hardened state , the hardened properties of SCC and GFRSCC are shown in Tables 13 and 14.

Table 13. Hardened concrete properties of SCC at 28 days

Sl. No.	Designation	Cube compressive strength in N/mm^2	Split tensile strength in N/mm^2	Modulus of rupture N/mm^2
1	SCC 1	31.8	3.112	5.4
2	SCC 2	40.0	3.324	5.2
3	SCC 3	43.0	3.423	5.4
4	SCC 4	37.0	2.829	5.0
5	SCC 5	40.0	3.607	5.0

Table 14. Hardened concrete properties of GFRSCC at 28 days

Sl. No.	Designation	Cube compressive strength in N/mm^2	Split tensile strength in N/mm^2	Modulus of rupture N/mm^2
1	SCC 1 F	32.5	3.324	6.0
2	SCC 2 F	41.5	3.423	5.8
3	SCC 3 F	44.2	3.567	6.0
4	SCC 4 F	37.8	3.112	5.8
5	SCC 5F	39.0	3.607	6.0

7. Analytical Stress-Strain Curves for SCC and GFRSCC

A number of empirical equations have been proposed to represent uniaxial stress-strain behaviour of concrete [15], but most of them can be used for only ascending portion of the curve. In 1985 Carriera and Chu [16] extended the empirical equation proposed by Popovics [15] to include both ascending and descending portions of complete stress-strain curve. Recently Hsu and Hsu [17] proposed an empirical equation which includes the effects of steel fibres in concrete. NRD Murthy [18] also proposed an empirical equation which includes the effects of steel fibres in concrete.

This paper proposes an equation in the form of $Y=Ax/1+Bx^2$ for both SCC and GFRSCC mixes.

Where x is the normalized strain: Y- normalized stress: A, B are constants for ascending portion and A_1, B_1 are constants for descending portion.

For SCC a set of constants A, B and A_1, B_1 are determined.

Similarly another set of constants are determined for GFRSCC

Constants are determined based on the boundary conditions of normalized stress-strain curves for both SCC and GFRSCC.

The boundary conditions are

i. The strain ratio and stress ratio at the peak of the non-dimensional stress-strain curve is unity

$$i.e \quad \frac{\varepsilon}{\varepsilon_u} = 1 \text{ and } \frac{\sigma}{\sigma_u} = 1 \tag{1}$$

ii. The slope of non-dimensional stress-strain curve at the peak is zero.

$$i.e \text{ at } \frac{\varepsilon}{\varepsilon_u} = 1 \qquad \frac{d\left(\frac{\sigma}{\sigma_u}\right)}{d\left(\frac{\varepsilon}{\varepsilon_u}\right)} = 0 \tag{2}$$

The peak stress, strain at peak stress and normalised stress-strain values for both SCC and GFRSCC are shown in Tables 15 and 16.

Table 15. Peak stress values and strain values corresponding to peak stress

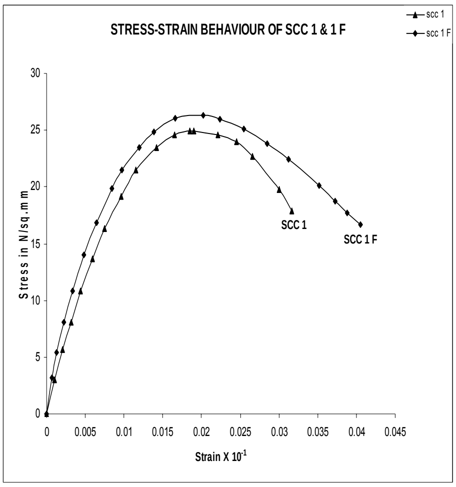
Sl. No	Designation	Peak stress	Strain at peak stress in N/mm^2
1	SCC 1	24.955	0.001905
	SCC 1.F	26.300	0.002025
2	SCC 2	31.0 0	0.002070
	SCC 2 F	32.52	0.002183
3	SCC 3	31.500	0.00209
	SCC 3 F	32.832	0.002205
4	SCC 4	25.763	0.00199
	SCC 4 F	26.920	0.002027
5	SCC 5	28.000	0.00203
	SCC 5 F	29.21 0	0.00205

Table 16. Normalized stress-strain values for SCC and GFRSCC

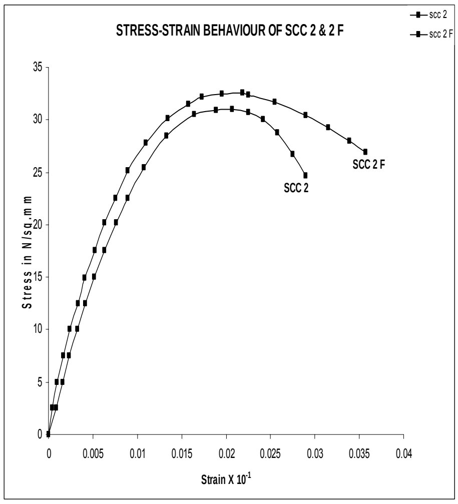
Normalized stress-strain values for SCC				Normalized stress-strain values for GFRSCC			
actual values		equation values		actual values		equation values	
$\varepsilon / \varepsilon_u$	σ / σ_u	$\varepsilon / \varepsilon_u$	σ / σ_u	$\varepsilon / \varepsilon_u$	σ / σ_u	$\varepsilon / \varepsilon_u$	σ / σ_u
0	0	0	0	0	0	0	0
0.036	0.1	0.05	0.1	0.0379	0.1	0.045	0.1
0.0785	0.2	0.095	0.2	0.07	0.2	0.09	0.2
0.1338	0.3	0.15	0.3	0.104	0.3	0.125	0.3
0.1892	0.4	0.2	0.4	0.15956	0.4	0.186	0.4
0.2538	0.5	0.26	0.5	0.217	0.5	0.23	0.5
0.3254	0.6	0.33	0.6	0.287	0.6	0.2972	0.6
0.4092	0.7	0.4	0.7	0.36	0.7	0.3738	0.7
0.509	0.8	0.5	0.8	0.46288	0.8	0.456	0.8
0.64615	0.9	0.63	0.9	0.6308	0.9	0.6	0.9
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.392	0.9	1.373	0.9	1.5743	0.9	1.594	0.9
1.581	0.8	1.5	0.8	1.8143	0.8	1.809	0.8
1.7	0.7	1.62	0.7	2.0097	0.7	2.08	0.7

8. Results

Fresh and hardened properties of SCC and GFRSCC are shown in Tables 11 to 14. Peak stress values and strain values corresponding to peak stress for both SCC and GFRSCC are shown in Table 15. The Normalized stress-strain values for both SCC and GFRSCC are shown in Table 16. Young's Modulus (E_c) values for SCC and GFRSCC are shown in Table 17. Stress-strain curves for different mixes of SCC and GFRSCC are shown in Figures 1(a) to 1(e). Normalized stress-strain curves for M 30 grade SCC and GFRSCC for experimental values and the values obtained from the equations developed are given in Figures 2(a) and 2(b).



(a)



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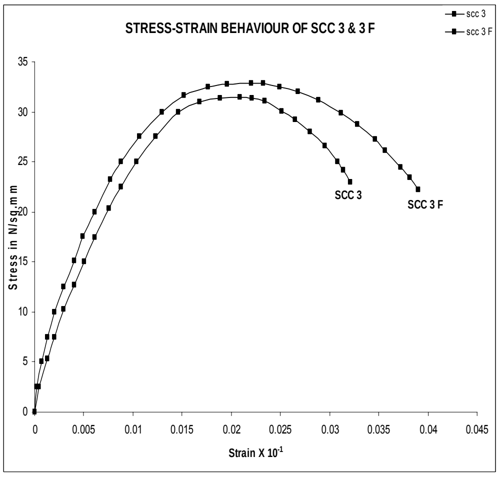

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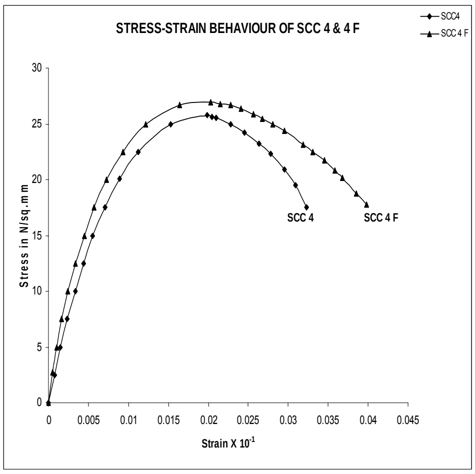

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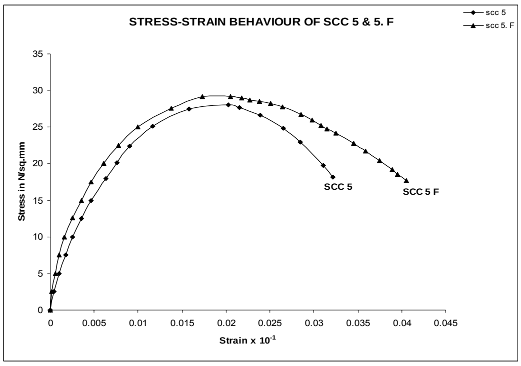
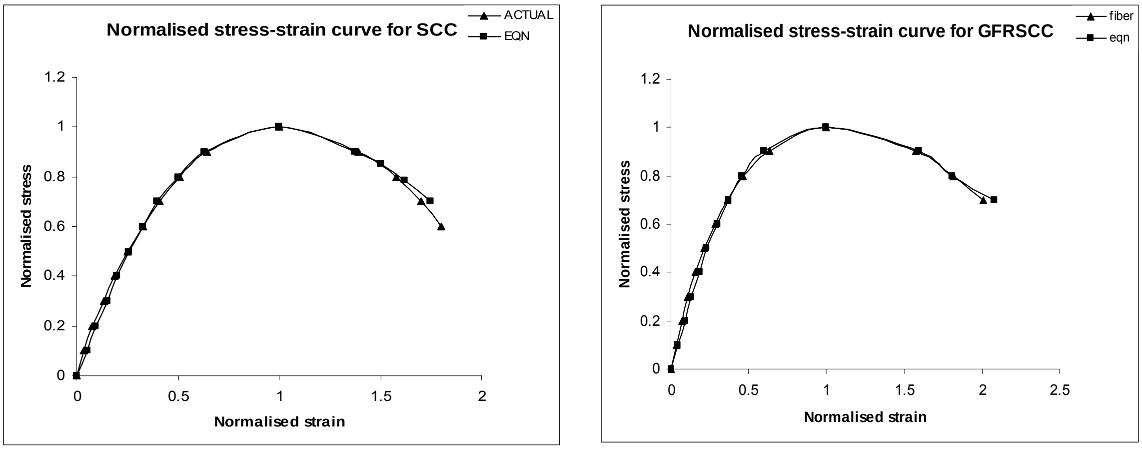


(e)

Figure 1. Stress-Strain curves for SCC and GFRSCC



(a) (b)

Figure 2. Normalized stress-strain curves for SCC and GFRSCC

10. Discussion of Test Results

Results of experimental investigations are discussed in the following sections with respect to the characteristics of self compacting concrete mixes in the fresh and hardened states.

11. Characteristics of SCC Mixes in Fresh State

Properties such as filling ability, passing ability etc. of the SCC and GFRSCC mixes in the fresh state are given in Tables 11 and 12. These values on comparison with EFNARC specifications given in Table 10, indicate that the mixes possess the self compacting characteristics.

The filling ability and passing ability values of GFRSCC mixes compared to SCC mixes given in Tables 11 and 12 indicate that the presence of glass fibres did not have any pronounced effect. This may be due to the low dosage of fibre addition (0.03%) and also may be due to the high dispersing nature of the fibres.

12. Characteristics of SCC Mixes in Hardened State

Efect on

12.1 Compressive Strength

The compressive strength values obtained by testing standard cubes made with different SCC and GFRSCC mixes are tabulated in Tables 13 and 14. All the mixes have shown strength above 30 MPa, which is the required strength. The mix, with or without glass fibers, containing the mineral admixture combination of GGBS (97%) and RHA (3%) has shown higher compressive strength compared to other SCC mixes. Further the GFRSCC mixes compared to normal SCC mixes have shown an improvement in compressive strength by 2.0 to 5.5%.

12.2 Tensile strength

The tensile strength of mixes is obtained (i) by conducting split tensile test on standard cylindrical specimens and also by (ii) by conducting three point bend test on standard prisms. The results are tabulated in Tables 13 and 14. The results indicated that the incorporation of glass fibres in to the SCC mixes, increased the split tensile strength and flexural strengths by 3.0 to 7.0 % and 11.0 to 20.0 % respectively. The increase is significant and it may be due to high tensile strength (1700MPa) of glass fibres. Also the observations were in conformity with the observations made by Building Research Establishment, England and BS 1881.

12.3 Young's modulus (E_C)

The values of Young's Modulus (E_C) are calculated from the stress-strain curves of SCC and GFRSCC and are shown in Table 17. The average value of Young's modulus (E_C) obtained for SCC mix is 25.74 GPa. This is found to be about 6.0% less than normal concrete of similar strength (27.4 GPa). An equation relating Young's modulus (E_C) of SCC and its compressive strength (f_{ck}) is obtained as $E_C = 4700 \sqrt{f_{ck}}$.

Addition of glass fibres to SCC mixes has improved the Young's modulus and its average value is 31.29 GPa, which is about 14% more compared to normal concrete of similar strength. The Young's modulus of GFRSCC follows the relationship $E_C=5700\sqrt{f_{ck}}$. The high elastic modulus and high density of glass fibres may be responsible to increase the E_C of SCC.

Table 17. Young's modulus (E_C) values for M 30 grade SCC and GFRSCC

Designation	Young's modulus	Designation	Young's modulus
SCC 1	22,916 N/mm^2	SCC 1 F	25300 N/mm^2
SCC 2	26,350 N/mm^2	SCC 2 F	32,500 N/mm^2
SCC 3	25,800 N/mm^2	SCC 3 F	31,630 N/mm^2
SCC 4	24,900 N/mm^2	SCC 4 F	32,560 N/mm^2
SCC 5	28,735 N/mm^2	SCC 5 F	34,485 N/mm^2

Average value: 25,740 N/mm^2 31,295 N/mm^2

$E_C = 4700 \sqrt{f_{ck}}$ For $f_{ck} = 30$ N/mm^2 $E_C = 25{,}743$ N/mm^2 For SCC
$E_C = 5700 \sqrt{f_{ck}}$ For $f_{ck} = 30$ N/mm^2 $E_C = 31{,}220$ N/mm^2 For GFRSCC

12.4 Energy absorption

Energy absorption capacity expressed in terms of area under stress-strain diagram of SCC mixes have shown an improvement of 30% due to the addition of glass fibres. The high tensile strength of glass fibres have increased the strain capacity in the descending portion of the stress-strain curves of SCC mixes and resulted in increase in the area of stress-strain diagram and energy absorption capacity.

12.5 Ductility

Ductility (μ) which indicate the deformable characteristic of material and is expressed as the ratio of strain in the descending to that in the ascending portion of stress- strain curves. From the normalized stress- strain curves shown in Figures 2(a) and 2(b) it is observed that the improvement of ductility at 90%, 80% and 70% stress levels is 21%, 25% and 27% respectively due to the addition of glass fibres to SCC mixes. This may be attributed to the high tensile strength and high elastic modulus of glass fibres added to the SCC mixes.

12.6 Stress-Strain response

The Stress-Strain behaviour of both SCC and GFRSCC mixes shown in Figures 1(a) to 1(e) is observed to be almost similar. The only a difference is that the GFRSCC mixes have shown improved stress values for the same strain levels compared to that of SCC mixes. The Empirical equations for the stress-strain response of SCC and GFRSCC have been proposed in the form of $Y = Ax/1+Bx^2$. The same empirical formulae are valid for both ascending and descending portions with different values of constants as shown in Table 18.

Table 18. Proposed empirical equations and constants for the stress-strain response of SCC and GFRSCC

Type of concrete	Equation	Constants	
		For ascending portion	For descending portion
SCC	$Y = \frac{AX}{1 + BX^2}$	A=2.0, B=1.0	A=2.24, B=1.24
GFRSCC	$Y = \frac{AX}{1 + BX^2}$	A=2.61, B=1.61	A=1.78, B=0.78

The proposed emperical equations can be used as stress block in analyzing the flexural behaviour of sections of SCC and GFRSCC structural elements. The proposed equations have shown good correlation with experimental values.

Conclusions

- All the SCC and GFRSCC mixes developed satisfied the requirements of self compacting concrete specified by EFNARC
- Addition of 0.03% high dispersion glass fibres to SCC mixes did not have any pronounced effect on the filling and passing ability when compared to SCC mixes.
- Incorporation of glass fibres by 0.03% *ie* 600 grams / m^3 of concrete has increased the strengths at 28 days by 2.0 to 5.5 % in compression,3.0 to 7.0 % in tension, and 11.0 to 20.0 % in flexure.
- Average value of Young's modulus (E_C) obtained for M_{30} grade SCC is 6.0% less than ordinary concrete and follows the relationship $E_C = 4700\sqrt{f_{ck}}$,
- Addition of glass fibres have increased the E_C value by 14.2% when compared to ordinary M30 grade concrete and by 21.5% when compared with SCC and follows the relationship $E_C = 5700\sqrt{f_{ck}}$
- Energy absorption capacity of SCC has increased to an extent of 30% due to the addition of glass fibres
- Addition of 0.03% of high dispersion glass fibres increases the ductility from 21% to 27% at 70% to 90% stress levels.
- More ductility *i.e* 27% is imparted to SCC at 70% stress level and as stress levels increases the gain in ductility decreases.
- The empirical equations proposed here depict the complete stress-strain behaviour of SCC and GFRSCC mixes under compression. The equations are valid for M30 grade concrete.

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