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Development of Analytical Stress-Strain Model for Glass Fiber Reinforced Self Compacting Concrete

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Abstract

The development of Self-Compacting Concrete (SCC) marks an important milestone in improving the product quality and efficiency of the building industry. SCC improves the efficiency at the construction sites, enhances the working conditions and the quality and appearance of concrete. Use of glass fibers in SCC bridge the cracks and enhance the performance of concrete by not only avoiding the propagation of cracks but also contribute to an increased energy absorption compared with plain concrete. Glass Fiber Reinforced Self-Compacting Concrete (GFRSCC) combines the benefits of SCC in the fresh state and shows an improved performance in the hardened state compared with conventional vibrated concrete. In the present work, the stress-strain curve for GFRSCC has been suggested and an analytical stress-strain model was developed based on the experimental results.

Introduction

Self Compacting Concrete (SCC) facilitates and ensures proper filling and good structural performance in restricted areas and heavily reinforced structural members. Developed by Professor Hajime Okamura [1] in Japan during the 1980s, it has gained wide acceptance in today’s concrete works. SCC can be considered as an engineered composite material, tailor made to achieve performance related properties to suit specific applications [2, 3]. The mechanical properties of the brittle SCC under axial loading may be improved by introducing randomly oriented short discrete fibers, which prevent or control initiation and propagation or coalescence of cracks [4]. Glass

Fiber Reinforced Self Compacting Concrete (GFRSCC) is one such composite, developed with an idea of modifying the other wise inferior properties of Self Compacting Concrete (SCC) alone [5]. The properties of fibers that are usually of interest are fiber concentration, fiber geometry, fiber orientation and fiber distribution. Glass fibers have very good applications in changing the behavior of the material by bridging of fibers across the cracks. In other words, ductility is provided with fiber reinforced cementitious composites, because fibers bridge crack surfaces and delay the onset of the extension of localized crack [6]. In the present work an analytical stress-strain model was proposed of this wonderful composite viz., Glass Fiber Reinforced Self Compacting Concrete (GFRSCC).

Research Significance

An effort has been made in the present investigation to develop an analytical stress-strain model for SCC & compare the mechanical properties of SCC without and with glass fibers. The mix proportion suitable for Glass Fiber Reinforced Self Compacting Concrete (GFRSCC) accommodating finer filler materials was developed modifying the existing Nansu's method of mix design [7]. This study examines and compares the mechanical properties and the stress-strain behavior of self compacting concrete for no fiber and GFRSCC. The present work provides very useful information for the practical use of fibrous self-compacting concretes. An analytical model was suggested for fibrous SCC and the stress-block parameters are proposed. The relationship between no fiber and fibrous SCC with respect to stress, strain at 85% and ductility is proposed.

Experimental Program

The experimental program was done in two phases. In the first phase the aim was to develop GFRSCC and come out with an optimum GF content based on fresh and hardened properties. In the second phase the mechanical behavior of the optimized GFRSCC was investigated and the stress-strain curve was established and model was proposed.

Materials used

Ordinary Portland cement with a compressive strength not less than 53 MPa [named 53 grade cement], at the end of 28 days was used in the study. The Fine Aggregate (F.A) used was standard river sand confirming to Zone-II as per IS-2386 [8]. Crushed granite was used as Coarse Aggregate (C.A). The aggregate was properly graded through standard sieves [9] before using in the concrete works. The fly ash available locally was used as a partial replacement for cement, Conplast SP 337 superplasticizer (water reducing admixture) and Viscosity Modifying Agent (VMA) were added in optimum dosages for improving the properties of SCC. Two concrete strengths Viz., M20 (compressive strength not less than 20 Mpa at the end of 28 days) & M40 (compressive strength not less than 40 Mpa at the end of 28 days) were tested in the study. Nansu method [7] of mix design was followed for the designing the above mixes with some modifications. The details of the mix proportions adopted are shown in **Table-1**. The glass fiber used in the study was Cem-Fil Anti Crack with a specific gravity of 2.6, the length of the fiber is close to 12 mm, and the specific surface area is 105 m^2 /kg. It can be noted in the **Table-1** that the different proportions of glass fiber was considered to optimize the dosage of the same from the fresh and hardened properties.

Table 1: Details of Mix Proportions for M20 and M40 grade concrete.

No.	**Desg.**	**Concrete Grade**	**Cement (Kg/m^3)**	**C.A (Kg/m^3)**	**F.A (Kg/m^3)**	**Flyash (Kg/m^3)**	**Glass Fiber (Kg/m^3)**	**Water (Lit)**	**S.P (Lit)**	**VMA (Lit)**
1	SCC 1	M20	257	815	970	173	0	197	8.63	0.42
2	SCC 2		257	815	970	178	0.25	197	9.28	0.42
3	SCC 3		257	815	970	183	0.50	197	9.93	0.43
4	SCC 4		257	815	970	188	0.75	197	10.58	0.44
5	SCC 5		257	815	970	194	1.00	197	11.32	0.45
6	SCC 6		257	815	970	199	1.20	197	11.50	0.45
7	SCC 7	M40	365	781	964	156	0	182	13.00	0.46
8	SCC 8		365	781	964	162	0.25	182	13.80	0.46
9	SCC 9		365	781	964	169	0.50	182	14.70	0.47
10	SCC 10		365	781	964	175	0.75	182	15.50	0.47
11	SCC 11		365	781	964	182	1.00	182	16.40	0.48
12	SCC 12		365	781	964	188	1.20	182	17.20	0.48

Development of Glass Fiber Reinforced Self Compacting Concrete (GFRSCC)

Fresh SCC must possess the key properties including filling ability, passing ability and resistance to segregation at required level. To satisfy these conditions EFNARC [10] has formulated certain test procedures. The fresh properties of SCC without and with glass fiber are shown in **Table 2**. Companion cube specimens of standard dimensions 150mm x 150mm were also cast and tested for the strength. The results of the compressive strength are also presented in **Table 2**. From the above study the optimum mix proportions were SCC 5 and SCC 11 for M20 grade and M40 grade concrete respectively on the basis of fresh properties and the corresponding compressive strength of cube specimens presented in **Table 2**. Thus, the optimum mix proportions for GFRSCC were arrived at the end of this phase of study.

Table 2: Fresh and Hardened properties of SCC with Glass Fiber.

No.	**Desg**	**Slump Cone Test**		**V- Funnel Test**		**L Box Test**			**Comp. Strength (Mpa)**
		H-Flow (mm)	**T_{50} (time in Sec)**	**Time for complete discharge Sec**	**T_5 min in Sec**	**Time for 0-200 mm spread**	**Time for 0- 400 mm spread**	**H_2/H_1**	
1	SCC 1	725	4.00	6.15	8.45	2.45	4.95	0.92	31.64
2	SCC 2	720	4.15	6.80	8.73	2.58	5.21	0.89	31.87
3	SCC 3	720	4.14	7.00	9.20	2.62	5.47	0.88	32.14
4	SCC 4	715	4.20	8.65	10.75	2.65	5.63	0.88	32.28
5	SCC 5	680	4.50	9.72	11..26	3.10	6.34	0.82	32.87
6	SCC 6	640	5.80	12.50	15.48	3.28	6.49	0.75	32.20
7	SCC 7	710	4.12	6.79	9.00	2.56	5.00	0.91	52.90
8	SCC 8	710	4.23	7.81	10.51	3.00	5.60	0.85	53.44
9	SCC 9	690	4.50	8.94	11.62	3.60	5.50	0.83	53.76
10	SCC 10	695	4.53	9.00	11.85	4.20	6.10	0.83	54.05
11	SCC 11	675	4.61	10.50	13.20	4.40	6.60	0.82	54.26
12	SCC 12	640	5.40	12.80	15.68	5.20	7.10	0.74	53.52

Mechanical Properties of optimized Glass Fiber Reinforced Self Compacting Concrete (GFRSCC)

The influence of fiber on the behavior of compressive strength, split tensile strength, flexural strength and the stress-strain behavior is investigated. 150x150mm cubes for compressive strength, 150mm diameter and 300mm height cylinders for split tensile strength and 100x100x400mm prism specimens were adopted for studying the modulus of rupture [11]. 150x150x300mm prisms were tested in axial compression for developing the complete stress-strain curves. The program consisted of casting and testing a total number of 48 cubes, 48 cylinders and 48 prisms cast in 4 batches for M20 & M40 grades of concrete. Of these 48 cubes, 24 cubes correspond to M20 & M40 grades of concrete. Of these 24 cubes, 12 cubes each correspond to no fiber and with GF additions. Similarly, additional 60 prisms of size 150 x 150 x 300mm (30 for M20, and 30 for M40) were cast and tested after 28 days curing for examining the stress-strain behavior of M20 & M40 grades for no fiber and optimum glass fiber contents. The mix was designed as per modified Nansu method of mix design [7]. 1000 KN Servo Controlled Dynamic Testing Machine was used for testing the specimens under displacement control. While testing, precautions were taken to ensure axial loading. For flexural strength, standard three point loading was adopted [11].

Discussion of Test Results

Table 3 shows the details of various mechanical properties viz., compressive strength, split strength, flexural strength and modulus of elasticity for SCC without fiber (NF) and SCC with glass fiber (GF). The optimum fiber content utilized throughout the experimentation was based on initial strength and flow studies as explained earlier (Clause 3.0). The dosage of Glass fiber maintained is 0.038 % uniformly through out the experimental study.

Compressive Strength of Glass Fiber Reinforced Self Compacting Concrete (GFRSCC)

It can be noted from **Table 3**, that the addition of fibers has definitely increased the compressive strength, though marginally. The variation of compressive strength with fiber addition is shown in **Table 3** and the percentage increase in strength with fiber addition is plotted in **Fig 1**. It can be noted that the percentage increase is marginal ie; 3.89 % in M20 grade concretes & 2.57% in M40 grade with the addition of Glass Fibers in Self-Compacting Concrete. It can hence be concluded at this stage that fiber additions do not increase the compressive strength much.

Table 3: 28 Day strength results of M20 & M40 grade SCC.

Mix	**Comp. Strength (Mpa)**		**Split Tensile Strength(Mpa)**		**Flexural Strength(Mpa)**		**Split / $\sqrt{Comp}$)**		**Flexure/ $\sqrt{f_{ck}}$**		**Modulus of Elasticity x 10^3 Mpa**	
M20	**NF**	**With GF**	**NF**	**With GF**	**NF**	**With GF**	**NF**	**With GF**	**NF**	**With GF**	**NF**	**With GF**
	31.64	32.87	3.05	3.37	3.20	3.50	0.54	0.59	0.72	0.78	25.95	27.09
M40	52.90	54.26	4.97	5.43	4.13	4.48	0.68	0.74	0.65	0.71	30.29	32.73

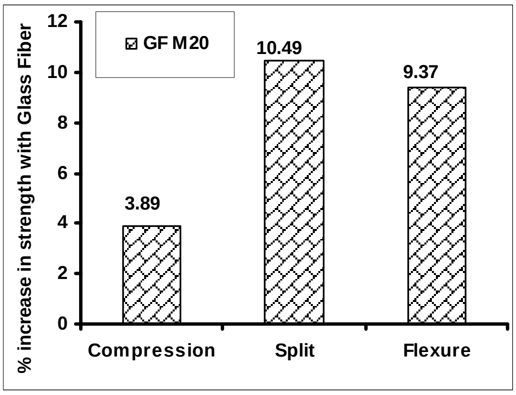

Figure 1: Effect of Glass Fiber on strength (M20).

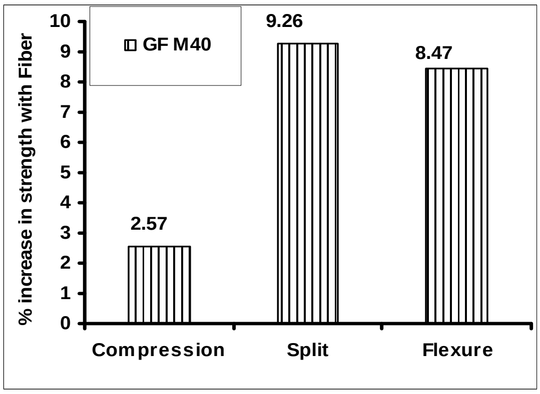

Figure 2: Effect of Glass Fiber on Strength (M40).

Influence of Glass Fiber on split tensile strength of SCC

The tensile strength of SCC is relatively much lower than its compressive strength because, it can be developed more quickly with crack propagation. Hence, it is important to improve the tensile strength of such a concrete. The variation of split tensile strength with fiber additions is shown in **Table 3**. It can be noted from **Figs 1 & 2** that the percentage increase with fiber addition is 10.49 % in M20 & 9.26 % in M40 Grade concretes.

Effect of Glass Fiber addition on Flexural Strength of SCC

Table 3 shows the details of flexural strength for no fiber (NF) and glass fiber (GF) additions in M20 & M40 grades of SCC. There is an increase in flexural strength of 9.37 % in M20 concrete and it is 8.47 % in the case of M40 grade concrete fibrous concretes (GF) as compared to no fiber concretes (NF). At this stage it may be concluded that the tensile and bending behavior is greatly improved with glass fiber additions in self compacting concrete.

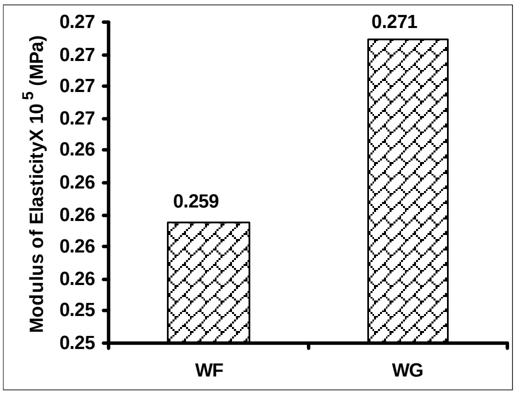

Figure 3: E-Value Vs WF & with GF (M20).

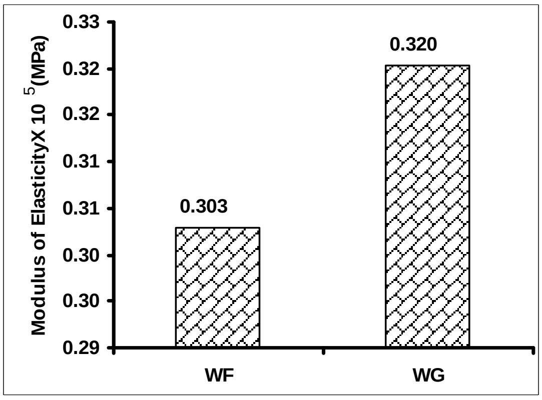

Figure 4: E-Value Vs WF & with GF (M40).

Effect of Glass Fiber addition on Modulus of Elasticity of SCC

The brittle behavior of self compacting concrete is known. The fiber addition in such concretes certainly modifies the stress-strain behaviour of concrete. The Modulus of Elasticity (E) was calculated, following the specifications as laid by IS Code 516-1999[11]. **Table 3** shows the details of the values of modulus of elasticity for self compacting concrete without and with fiber respectively. From **Figs 3** and **4,** it may be concluded that the addition of fiber in general increased the value of modulus of elasticity of self compacting concrete.

Stress-Strain Behaviour of Gfrscc

The effect of glass fiber in SCC under axial compression was examined for the stress-strain behavior of GFRSCC. Prism specimens of size 150 x 150 x 300mm were cast for different dosages of fiber (0, 250, 500, 750, 1000 gm/m^3) and tested by using a standard 1000kN dynamic compression set up. An average of six specimens was taken to obtain the stress-strain curve for each Fiber Index (F_i), the definition of which is given else where by the authors [12, 13].The specimens were tested under a strain rate control of 0.1mm/min. The stresses and strains thus obtained for different fiber concentrations (0-1000gm/m^3) were plotted as shown in **Fig 5** for M20 grade and **Fig 6** for M40 grade concretes respectively.

Effect of fiber on ultimate Strength and Strain

From the stress-strain curves explained in **Figs 5** and **6**, the ultimate strength(f_u), Strain at ultimate strength(ε_u), strain at 85% of the ultimate on the ascending portion ($\varepsilon_{0.85u}$ asc) and 85% of ultimate on the descending portion ($\varepsilon_{0.85u}$ des) are obtained. These are shown in **Table 4**. From these values the stress ratio (f_u / f'), the strain ratio ($\varepsilon_u / \varepsilon'$) and the Ductility Factor (DF) [14], were obtained for different Fiber Index values (corresponding to different fiber concentrations).

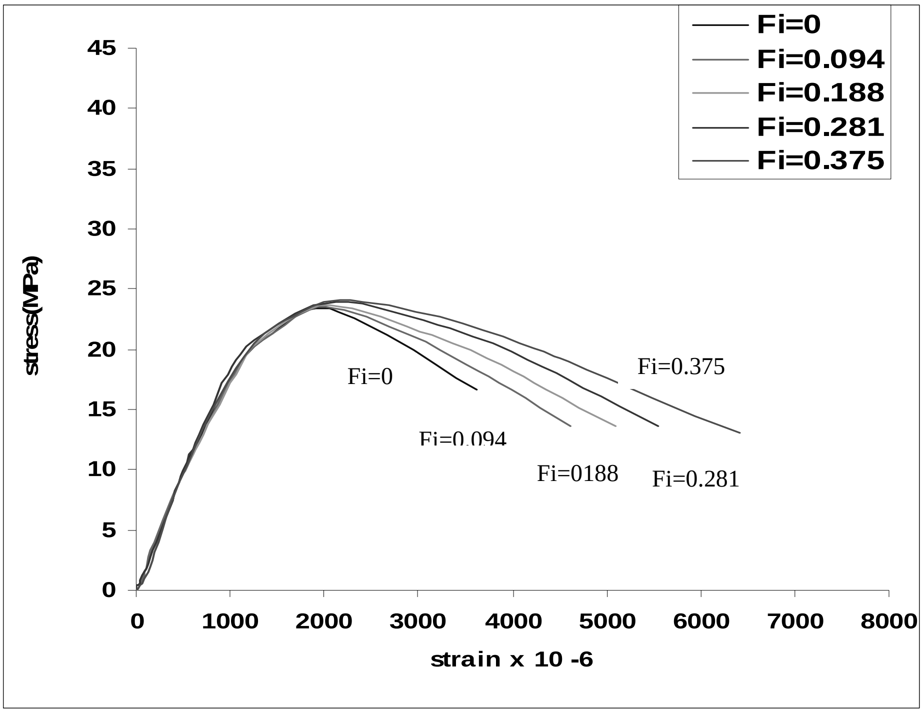

Figure 5: Stress Vs Strain with different F_i (M20 grade GFRSCC).

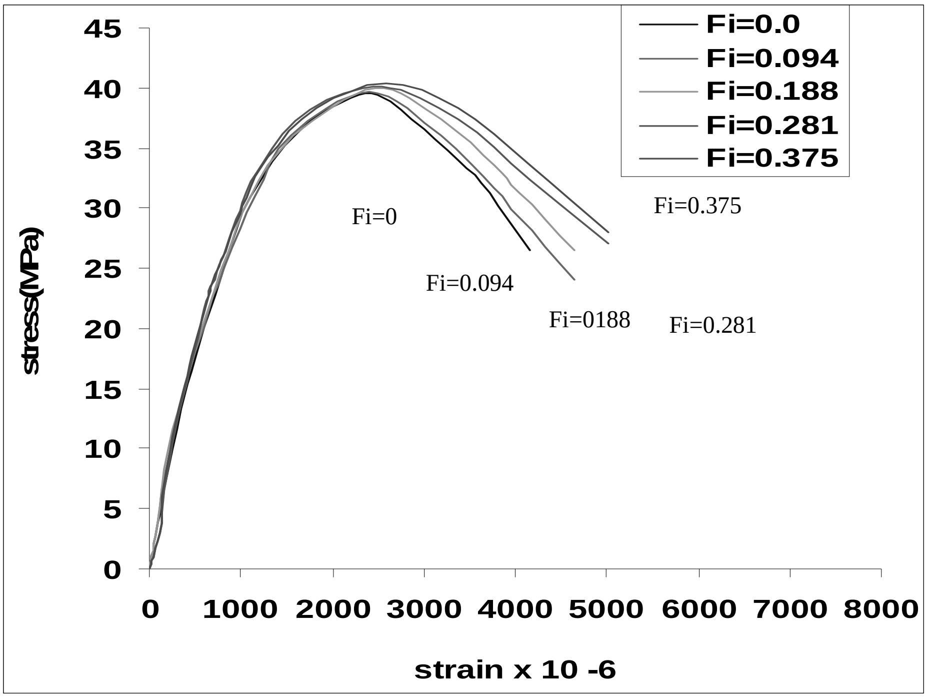

Figure 6: Stress Vs Strain with different F_i (M40 grade GFRSCC).

Table 4: Peak Stress and Peak Stain Values of SCC with Fiber Variation.

No	**Desg**	**Fiber Index** F_i	**Peak Strength** f_u	f_u / f'	**Peak Strain** ε_u	$\varepsilon_u / \varepsilon'$	$\varepsilon_{0.85u}$ **asc x 10^-6**	$\varepsilon_{0.85u}$ **desx 10^-6**	**Ductility Factor**
1	NAP0	0.000	23.33	1.000	0.00197	1.000	1188	2970	2.50
2	NAG1	0.094	23.42	1.004	0.00202	1.025	1208	3208	2.66
3	NAG2	0.188	23.71	1.016	0.00207	1.050	1226	3461	2.82
4	NAG3	0.281	23.96	1.027	0.00212	1.074	1214	3806	3.14
5	NAG4	0.375	24.08	1.032	0.00217	1.099	1229	4085	3.32
6	NBP0	0.000	39.56	1.000	0.00235	1.000	1373	3380	2.46
7	NBG1	0.094	39.84	1.007	0.00241	1.027	1340	3530	2.63
8	NBG2	0.188	39.95	1.010	0.00248	1.053	1310	3620	2.76
9	NBG3	0.281	40.17	1.015	0.00254	1.080	1270	3900	3.07
10	NBG4	0.375	40.32	1.019	0.00260	1.106	1300	4082	3.14

Relationship between Fiber Index, stress ratio and strain ratio:

The relationship between Fiber Index (F_i) vs stress ratio and Fiber Index (F_i) vs strain ratio for Glass Fiber Reinforced SCC is shown below.

$$\frac{f_u}{f'} = 1 + 0.1074 F_i \tag{1}$$

$$\frac{\varepsilon_u}{\varepsilon'} = 1 + 0.3732 F_i \tag{2}$$

The plots for the above are shown in **Figs 7** and **8** respectively. It can be noted that there is an increase in stress ratio and strain ratio with increase in Fiber Index (F_i). The strain ratio is more predominant than the stress ratio. The glass fibers hence improve the deformation capacity significantly in the structural members.

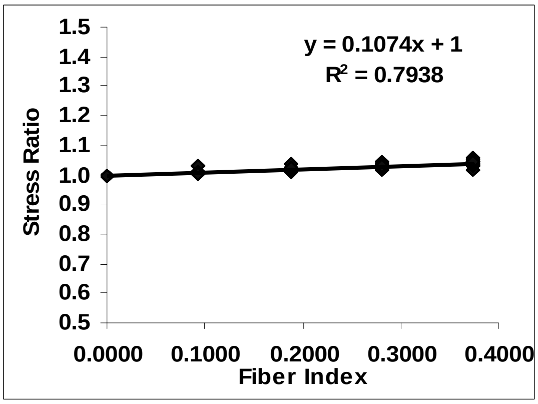

Figure 7: Stress ratio (f_u / f') vs Fiber Index (F_i).

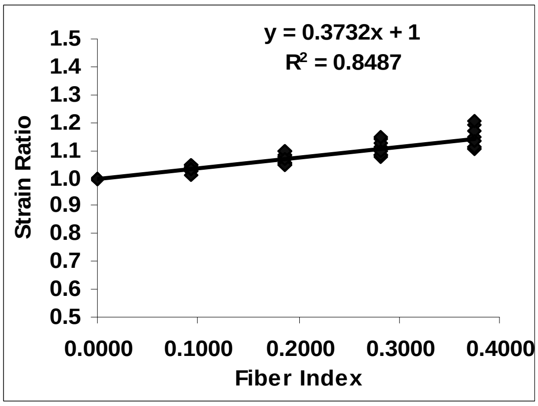

Figure 8: Stain ratio ($\varepsilon_u / \varepsilon'$) vs Fiber Index (F_i).

Ductility Factor Vs Fiber Index

The ratio of strains at 85% of the ultimate strength in the descending portion to that of 85% in the ascending portion gives the Ductility Factor (DF)[14]. A plot of Fiber Index vs Ductility Factor indicates an increase in Ductility with increase in the Fiber Index. This is shown in **Fig 9**.

The equation for the same is given below

$$\text{DF} = 2.4577 + 2.0912\ F_i \tag{3}$$

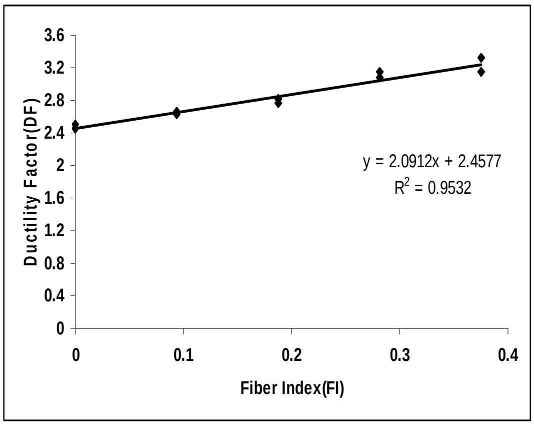

Figure 9: Fiber Index vs Ductility Factor.

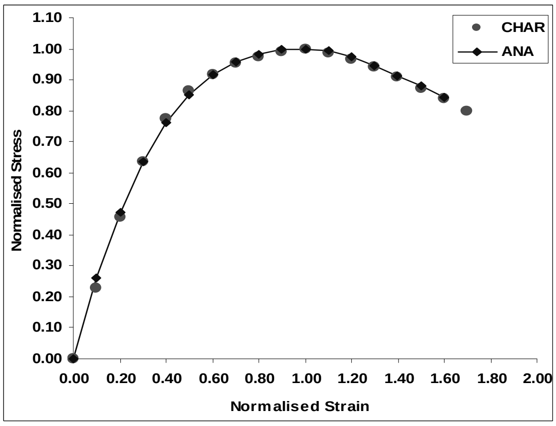

Figure 10: Normalised Stress vs Normalised Strain.

Non-Dimensionalised Stress-Strain Curve

An examination of the curves in **Figs 5** and **6** indicates that the behaviour is similar for all the grades, meaning that the stress-strain behaviour is linear upto 80-90% of the ultimate and non linear beyond this. The post peak stress-strain response for all the GFRSCC specimens is gradual and appears to have a consistent and constant gradient. This similarity leads to the conclusion that if the stress is expressed as stress ratio by dividing the stress at any level by the corresponding stress at ultimate and the strain ratio obtained by dividing the strain at any level by the corresponding to the strain at ultimate strength, the plot of these two ratios falls into the same pattern. Thus by non-dimensionalising the stresses and strains as explained above the effect of Fiber Index (F_i) can be eliminated. **Fig 10** shows the values of the non-dimensionalised stress as ordinate and the normalized strain as abscissa. The characteristic values and the analytical values are plotted in the figure. The stress-strain behavior can be represented by a general curve, which functions as a stress block. A single polynomial of the form shown in equation 4 is used in the current investigation.

The model is of the form

$$f = \frac{A\varepsilon + D}{1 + B\varepsilon + C\varepsilon^2} \tag{4}$$

where, f is the stress at any level and ε is the strain at any level. To express in non-dimensional stress-strain curves the following form is proposed.

$$\frac{f}{f_u} = \frac{A1(\varepsilon/\varepsilon_u) + D1}{1 + B1(\varepsilon/\varepsilon_u) + C1\left(\frac{\varepsilon}{\varepsilon_u}\right)^2} \tag{5}$$

where, f_u and ε_u are the ultimate stress and strain of the GFRSCC specimen in compression. A single equation to predict the entire behaviour was not giving good correlation. Hence, the constants based on the following boundary conditions were obtained separately for ascending and descending portions.

The boundary conditions common for both ascending and descending portions of stress-strain curve

At $\frac{\varepsilon}{\varepsilon_u}$ = 0; $\frac{f}{f_u}$ =0; At $\frac{\varepsilon}{\varepsilon_u}$ =1; $\frac{f}{f_u}$ =1; and At $\frac{\varepsilon}{\varepsilon_u}$ = 1; $d(f/f_u)/d(\varepsilon/\varepsilon_u)=0$; (6)

Additional Boundary Condition for ascending portion of stress- strain curve

At $\frac{\varepsilon}{\varepsilon_u}$ = 0.637; $\frac{f}{f_u}$ = 0.3; (7)

Additional Boundary Condition for descending portion of stress- strain curve

At $\frac{\varepsilon}{\varepsilon_u}$ = 0.85; $\frac{f}{f_u}$ = 1.58; (8)

satisfying the above boundary conditions the constants for ascending and descending portions of the curve were obtained.

The values were A1 = 2.8662, B1= 0.8662, C1= 1.0, D1 = 0.0 (for Ascending Portion) and A1= 1.206, B1= -0.794, C1= 1.0, D1=0.0 (for Descending Portion)

Thus, the stress-strain equations for the ascending portion of the GFRSCC is

$$\frac{f}{f_u}=\frac{2.8662(\varepsilon/\varepsilon_u)}{1+0.8662(\varepsilon/\varepsilon_u)+1.0\left(\varepsilon/\varepsilon_u\right)^2} \tag{9}$$

While the stress-strain equation for the descending portion of the GFRSCC is

$$\frac{f}{f_u}=\frac{1.206(\varepsilon/\varepsilon_u)}{1-0.794(\varepsilon/\varepsilon_u)+1.0\left(\varepsilon/\varepsilon_u\right)^2} \tag{10}$$

Conclusions

Based on experimental study on Glass Fiber Reinforced Self Compacting Concrete (GFRSCC) the following conclusions can be drawn.

(1) Self Compacting Concretes satisfying the specifications laid by EFNARC could be developed for non fibrous and fibrous concretes. There is a marginal increase in compressive strength of self compacting concrete with glass fiber additions. There is a very good increase in the split tensile strength and the flexural strength of FRSCC with glass fiber additions.

(2) Glass Fiber inclusion in Self Compacting Concrete improved the peak strain and strain at 85% of the ultimate strength in descending portion. The improvements in strains are pronounced than improvement in strength.

(3) The ultimate compressive strength varied linearly with Fiber Index and can be expressed by a relationship that includes the Fiber Index. The prediction equation for ultimate strength is

$$f_u = f'\{(1.0 + 0.1074F_i)\}$$

(4) The strain at peak stress varies linearly with Fiber Index and can be expressed by a relationship that includes Fiber Index. The equation obtained by regression analysis is

$$\varepsilon_u = \varepsilon'\{(1.0 + 0.107F_i)\}$$

(5) The ductility factor (D_F) of standard concrete given by the ratio of the strain at 85% of the peak stress on the descending portion of the stress strain curve has improved with specific surface factor.

$$DF = 2.4577 + 2.0912\ F_i$$

(6) The experimental values compared well with analytical model developed. A non-dimensionalised stress–strain equation proposed in this investigation can be used to predict the behaviour of Glass Fiber Reinforced Self Compacting Concrete(GFRSCC). The stress block parameters presented in this paper can be used to determine the ultimate moment and corresponding curvature of GFRSCC.

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