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ANALYTICAL MODELLING ON THE STRESS-STRAIN BEHAVIOR OF HYBRID FIBRE REINFORCED SELF COMPACTING CONCRETE

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ABSTRACT: Professor Okamura proposed a concept for a design of concrete independent of the need for compaction. Ozawa and Maekawa produced the first prototype of SCC at the University of Tokyo in 1988. Since that time SCC has gone from a laboratory novelty to practical applications all over the world. The behavior of self compacting concrete (SCC) as a structural material can be improved if adequate fibre reinforcement is added to SCC mix composition. The use of fibre reinforced cementitious composites (FRCC) in structural applications is relatively a novel approach in order to overcome the weakness of concrete in tension and its brittle behavior from the structural design point of view. Past researchers have developed SCC using steel and glass fibres independently and the use of fibres is attracting keen interest among several researchers in view of very encouraging performance of FRSCC due to enhanced ductile behaviour and increased resistance to tensile and flexural failure. In the present work, an effort is made to make a comparative study of stress-strain behaviour of M30 grade Hybrid Fibre Reinforced Self Compacting Concrete (HFRSCC) using mix of steel and glass fibres. Analytical stress-strain models are proposed to predict the stress-strain behaviour of HFRSCC based on the results of experimental investigations.

KEY WORDS: Glass fibre, Steel fibre, Hybrid Fibre Reinforced Self Compacting Concrete (HFRSCC), stress-Strain, Ductility factor.

INTRODUCTION:

The self compacting concrete (SCC) which was developed by Prof Hajime Okamura in the year 1986, to address some durability problems, was received very well all over the world. The mechanical and durability characteristics can be further enhanced if adequate fibre content is added to SCC. The introduction of glass fibres and steel fibres not only reduces crack propagation, but also enhances the tensile strength, toughness, compressive strength and energy absorption capacity. Infact introduction of fibres converts the brittle behaviour of the concrete into pseudo-ductile behaviour up to a crack width that is of acceptable limits. In the present investigation, an effort has been made to study the fresh and hardened properties of M30 grade hybrid fibre reinforced self compacting concrete (HFRSCC). The stress-strain behaviour of HFRSCC was completely studied and two analytical models were proposed in the form of polynomial equations. A comparison of the behaviour of Plain SCC and HFRSCC is made.

EXPERIMENTAL AND ANAYLITICAL PROGRAMME:
In the first phase of the investigation, 30MPa self compacting concrete (SCC) with hybrid fibres (i.e., both steel fibres and glass fibres) was developed satisfying all the basic requirements of fresh SCC. In the second phase, the mechanical behaviour of HFRSCC was studied. Using the stress-strain results under axial compression, mathematical models were developed and compared.

MATERIALS USED:
53 grade ordinary Portland cement confirming to IS 12269, river sand confirming to zone II and coarse aggregate confirming to IS 2386 were used in the present investigation. Type II fly ash obtained from Vijayawada thermal power plant confirming to IS 3812 was used. Superplasticizer (SP) and viscosity modifying agents (VMA), with 'poly carboxylic ether' based were used in the development of SCC. Anti crack high dispersion glass fibres with aspect ratio of 857 with a filament length of 12 mm and specific gravity of 2.68 was used, the steel fibres of 0.4 mm diameter, 12 mm length with an aspect ratio of 30 were used in developing HFRSCC. The mix details are shown in Tables 1 and 2. All the SCC mixes satisfied the EFNARC guidelines.

SPECIMEN PREPARATION AND TESTING:
Cubes of 100 mm size and cylinders of 150 mm diameter and 300 mm length were cast for studying the compressive strength and stress-strain behaviour of M30 grade concretes with hybrid fibres (i.e., both glass fibres and steel fibres). The specimens were cured as per BIS specifications and tested in 1000 kN strain controlled universal testing machine under 0.02mm/s strain rate.

TEST RESULTS AND DISCUSSION:
Different trial mixes were investigated in the laboratory and the concrete mix with following constituents, as shown in Table 1 and 2 was arrived at and used in the further investigation. The compressive strength of cubes and cylinders for the SCC with different types of fibres are shown in Table3. The optimum fibre dosages are arrived at based on trial mixes.

Table 1 Details of M30 grade plain mix

Grade of concrete	Cement kg/m^3	Fine Aggregate kg/m^3	Coarse Aggregate kg/m^3	Fly Ash kg/m^3	Water kg/m^3	SP lt/m^3	VMA lt/m^3
M30	330	860.6	794.4	150	186	6.75	0.33

Table 2 Details of M30 grade HFRSCC mix

Grade of concrete	Cement kg/m^3	Fine Aggregate kg/m^3	Coarse Aggregate kg/m^3	Fly Ash kg/m^3	Steel Fibre kg/m^3	Glass Fibre kg/m^3	Water kg/m^3	SP lt/m^3	VMA lt/m^3
M30	330	860.6	794.4	150	31.42	0.63	186	6.75	0.33

Table 3 Compressive Strength for M30 plain and M30 HFRSCC

Sl.No	Designation	Cube compressive strength (MPa)	Cylinder compressive strength (MPa)
1	Plain M30	35.31	26.82
2	HFRSCC M30	39.49	32.47

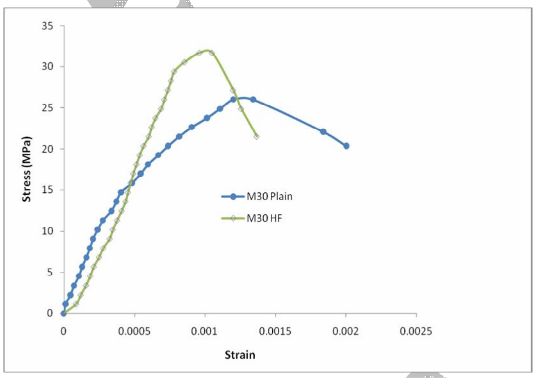

Fig. **1** Stress-Strain behavior of different types of SCC

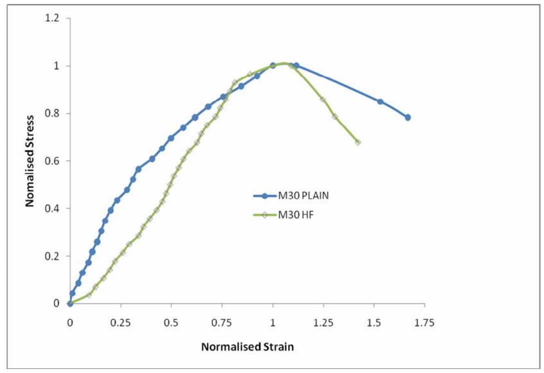

Fig. **2** Normalised Stress-Strain behavior of different types of SCC

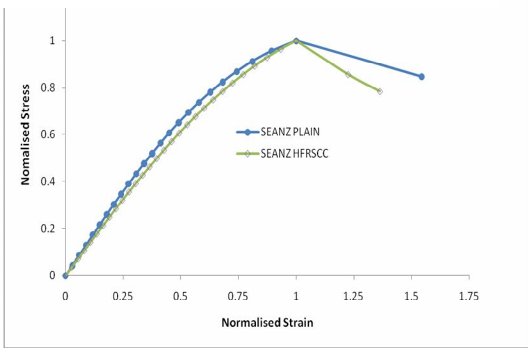

Fig. **3** Normalised Stress-Strain behavior of different types of SCC using Seanz model

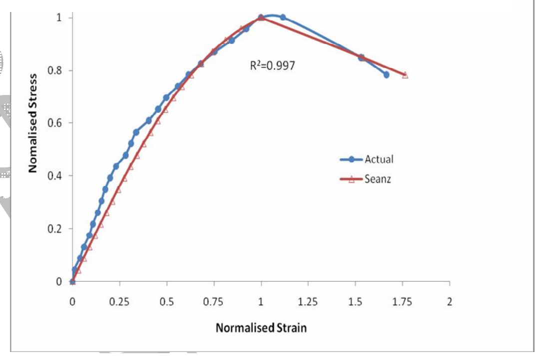

Fig. **4** Comparison of actual and Seanz model Stress-Strain curves for Plain SCC

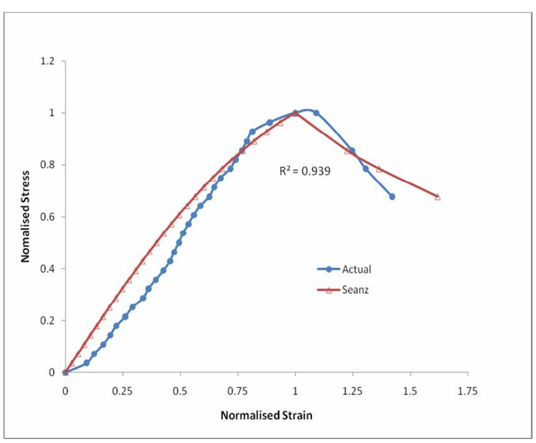

Fig. **5** Comparison of actual and Seanz model Stress-Strain curves for HFRSCC

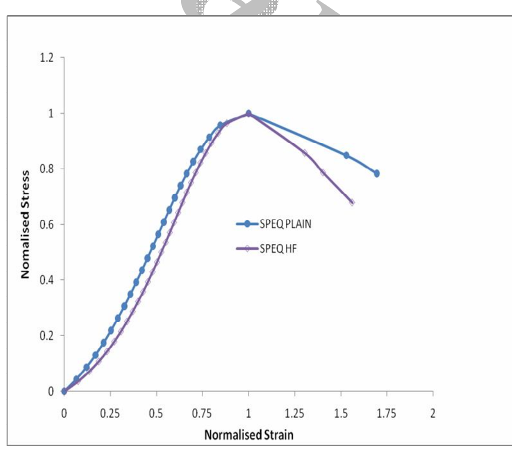

Fig. **6** Normalised Stress-Strain behavior of different types of SCC using SPEQ model

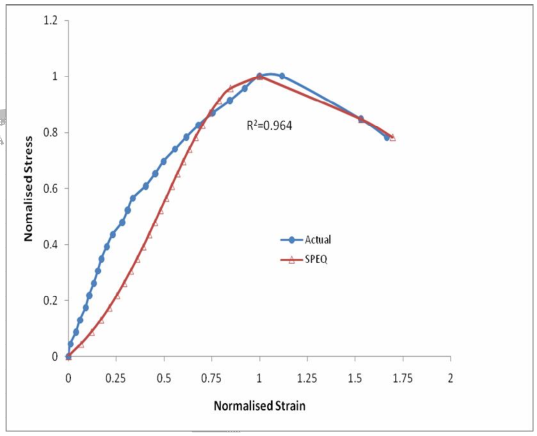

Fig. **7** Comparison of actual and SPEQ model Stress-Strain curves for Plain SCC

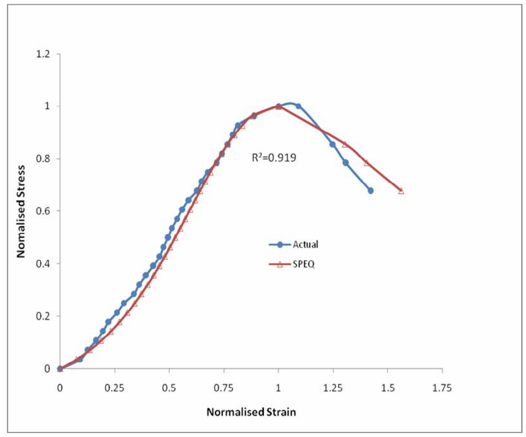

Fig. **8** Comparison of actual and SPEQ model Stress-Strain curves for HFRSCC

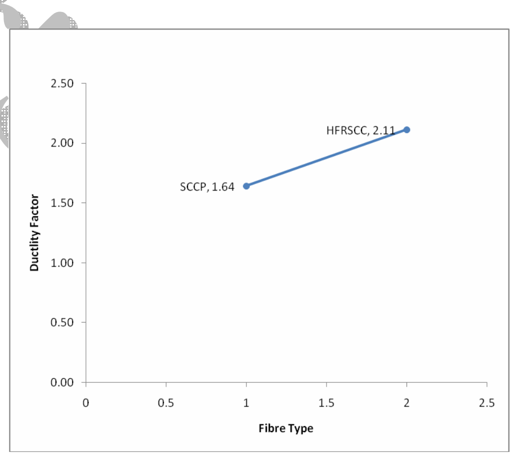

Fig. **9** Variation of ductility factor for different mixes

From the stress-strain curves from Fig 1 the values of ultimate strength (f_u), strain at ultimate strength (ε_u), and strain at 85% for ascending ($\varepsilon_{0.85u}$ Asc) and descending portion ($\varepsilon_{0.85u}$ Dsc) were obtained and ductility factors were calculated for different SCC mixes which are shown in Table 4. From the Table 4 it can be observed that the ductility factors were improved by 22.27% in HFRSCC.

Table 4: Stress ratio (f_u / f'), strain ratio (ε_u /ε') and ductility factors for different mixes

Sl. No	Designation	Peak stress N/mm^2	f_u/f'	Strain at peak stress	ε_u/ε'	$\varepsilon_{0.85u}$ Asc x 10^{-6}	$\varepsilon_{0.85u}$ Dsc x 10^{-6}	Ductility Factor
1	SCCP	26.0202	1.2174	0.0012	1	734	1206	1.64
2	HFRSCC	31.67677	1.0000	0.00096	1.25	867	1833	2.11

Stress-Strain behaviour: From the Fig.2, it can be observed that the behaviour is almost similar for plain SCC and HFRSCC for the given grade of concrete. However it is observed that stress and corresponding strain increases with the introduction of fibres. Further it is also observed that the increase in stresses and strains are more in HFRSCC. It is observed that the non-dimensional stress-strain behaviour in the post peak region up to 85% of ultimate stress level is almost similar. Fig.2 shows the normalised stress-strain behaviour for different mixes. A single equation proposed based on Seanz model is proposed to explain the stress-strain behaviour as shown below

$$f/f_u = \frac{A(\varepsilon/\varepsilon_u)}{1+B(\varepsilon/\varepsilon_u)^2} \qquad \text{-------------------} \quad (1)$$

The boundary conditions are:

1) At $\varepsilon/\varepsilon_u = 1$; $f/f_u = 1$ ----------------- (2)
2) At $\varepsilon/\varepsilon_u = 1$; $d(f/f_u)/d(\varepsilon/\varepsilon_u) = 1$

By satisfying the boundary conditions, constants for ascending and descending portions are obtained. Based on the above conditions, the constants for ascending and descending portions of the curve are as follows:

For M30 Plain concrete:
A=1.486 and B=0.486 for ascending portion and A=2.462 and B=1.462 for descending portion.
For M30 HFRSCC:
A=1.331 and B=0.331 for ascending portion and A=6.91 and B=5.91 for descending portion.
The stress-strain diagram obtained from the above equation and experimental data is given by Fig 4, 5. The regression coefficients for SCC, HFRSCC are 0.997, 0.939 respectively.

Model based on single polynomial empirical equation:

The model is taken in the form of

$$f = \frac{(A\varepsilon+D)}{(1+B\varepsilon+C\varepsilon^2)} \qquad \text{-----------} \quad (3)$$

where f is the stress and ε is the strain at different levels. The non dimensional stress strain equation is given in the form

$$f/f_u = \frac{A_1(\varepsilon/\varepsilon_u)+D_1}{1+B_1(\varepsilon/\varepsilon_u)+C_1(\varepsilon/\varepsilon_u)^2} \qquad \text{----------} \quad (4)$$

The boundary conditions for ascending and descending portion of the stress – strain curve are
At $\varepsilon/\varepsilon_u=0$; $f/f_u=0$; At $\varepsilon/\varepsilon_u=1$; $f/f_u=1$; At $\varepsilon/\varepsilon_u=1$; $d(f/f_u)/d(\varepsilon/\varepsilon_u)=1$
Additional boundary conditions used for ascending portion are as follows:
For M30 Plain concrete: at $\varepsilon/\varepsilon_u=0.85$; $f/f_u=0.7135$;
For M30 HFRSCC: at $\varepsilon/\varepsilon_u=0.85$; $f/f_u=0.7610$.
Additional boundary conditions used for descending portion of stress-strain curve are
For M30 Plain: at $\varepsilon/\varepsilon_u=0.85$; $f/f_u=1.536$;
For M30 HFRSCC: at $\varepsilon/\varepsilon_u=0.85$; $f/f_u=1.239$.
Based on the above conditions, the constants for ascending and descending portions of the curve are as follows:
For M30 Plain concrete:
A=0.652; B=-1.347; C=1; D=0 for ascending portion and A=1.0798; B=-0.920; C=1; D=0 for descending portion.
For M30 HFRSCC:
A=0.425; B=-1.5747; C=1; D=0 for ascending portion and A=0.26; B=-1.7418; C=1; D=0 for descending portion.
The stress-strain diagram obtained from the above equation and experimental data is given by Fig 7, 8. The regression coefficients obtained for SCC, HFRSCC are 0.964, 0.919 respectively.

Equation for static Modulus of elasticity

Based on the stress-strain curves for M30 grade SCC and HFRSCC secant moduli of elasticity were obtained and empirical equations relating the secant modulus of elasticity (Es) and characteristic mean strength were arrived which are as follows.

(1) $E= 5431.24\sqrt{f_{ck}}$ for SCC

(2) $E= 5959.732\sqrt{f_{ck}}$ for HFRSCC

where Es and f_{ck} are in N/mm^2

CONCLUSIONS:

Based on the experimental studies on the Hybrid Fibre Reinforced Self Compacting Concrete under axial compression, the following conclusions are arrived.

1. HFRSCC of M30 grade satisfying EFNARC guide lines can be prepared with improved performance.
2. It is observed that there is improvement in ductility factor for HFRSCC.
3. The compressive strength of concrete was improved by 10.58% for HFRSCC.
4. In the case of HFRSCC there is a gradual reduction in stress with increase in strain when compared to plain SCC indicating more strain absorbing capacity.
5. The empirical equation between E(MPa) and f_{ck}(MPa), are as follows

   $E= 5431.24\sqrt{f_{ck}}$ for SCC

   $E= 5959.732\sqrt{f_{ck}}$ for HFRSCC
6. Two analytical models were proposed for the stress-strain behaviour of Plain SCC and HFRSCC. It is observed that the model based on single polynomial equation is closely agreeing with experimental results for HFRSCC where as Seanz model is giving better results for plain SCC.

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