論文 Prediction for the Stress-Strain Curve of Steel Fiber Reinforced Concrete

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ABSTRACT: In order to use steel fiber reinforced concrete in structural applications, the whole stress-strain behavior of the material in compression is needed. The ductile failure of steel fiber reinforced concrete in compression, comparing with plain concrete show the flexibility improve in the failure. On the other hand, the steel fibers confined the material and delayed the crack propagation, thus producing an increase in the peak strain and the postpeak ductility. Analyzing experimental results of this investigation and others were led to establish empirical equations to predict the stress-strain diagram of steel fiber reinforced concrete by knowing maximum compressive strength, steel fiber's characteristic and strain corresponding to maximum compressive stress.
KEYWORDS: Steel fibers, stress-strain diagram, aspect ratio, volume fraction of steel fibers, peak compressive stress, peak compressive strain, ductile failure.

1. INTRODUCTION

In recent decades, considerable developments have taken place in the field of steel fiber reinforced concrete (SFRC). The current field applications include: highway, airport pavements, bridge decks, hydraulic structures, and tunnel lining as shotcrete. Crack resistance, restrain crack propagation, energy absorption properties, high impact resistance, decreasing temperature gradient stresses in cold region and corrosion resistance behaviors of steel fiber reinforced concrete were increased to use the steel fiber cement-based composites in engineering construction in compression zones and has made it more important to understand the behavior of this structural material. Besides, recently, one of the main objectives of adding steel fibers to a concrete matrix is to increase its toughness or energy absorbing capability to make it more suitable for use in structures subjected to impact and earthquake loads. Design of structures and analyzing the elements using steel fiber reinforced concrete, the stress-strain behavior of material in compression is needed. While the compressive strength is used for strength calculations of the structural components, the stress-strain curve is needed to evaluate deformability which is important for ductility and toughness resistance of structures. For this purpose, material properties can best be described by their stress-strain relationships.

Many researchers have studied the mechanical properties of steel fiber reinforced concrete. They reported effect of steel fibers on the compressive strength ranges from negligible to marginal. Typical stress-strain curves of SFRC in compression show an increase in the strain at peak stress and substantially higher toughness, where toughness is a measure of the ability to absorb energy during deformation and can be estimated using the area under the stress-strain curves or load-deformation diagrams.

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A number of empirical expressions for the stress-strain diagram of plain concrete have been proposed. However, they cannot represent fiber reinforced concrete behavior. An analytical model which was proposed by Fanella and Naaman [1] predict the whole stress-strain curve of fiber reinforced mortar taking into account fiber shape, volume fraction, and fiber geometry. They used different parameters to define the ascending and the descending branches of the stress-strain curve. Four constants were used to represent the ascending part and four more to determine the descending segment. The constants were determined using the characteristics of the curve such as modulus of elasticity and empirical relationships obtained using the experimental curves.

This study attempts to obtain a perfect stress-strain curve in compression and to develop empirical equations in terms of this measured curve for SFRC.

2. EXPERIMENTAL PROGRAM

Experimental data which initially isolated the important factors were obtained using a mixture proportions with 350 kg/m^3 of portland cement Type I, 1057 kg/m^3 of 9.5 mm crashed stone, 715 kg/m^3 of sand from local sources, and tap water with 0.4 of **W/C** (water to cement ratio). The steel fibers used in this investigation were made from low carbon steel and was machined steel fibers with one roughness surface and the others smooth surface. The equivalent aspect ratio of fibers was 50 with 40 mm length. Steel fiber reinforcement consisted of three fiber contents of 50kg/m^3, 100kg/m^3 and 150 kg/m^3.

All fibers in the all series of specimens were space-oriented within the matrix and each series were 3 specimens. All specimens were left inside the mold for 24 hours after casting, then stripped off the mold and placed in the curing room for an additional 27 days. The plain concrete mix yielded an average of concrete compressive strength f'_c=280.8 kgf/cm^2 (cylinder ϕ 15x30 cm). In order to avoid the stress concentration at the ends of cylinder specimens, and considering JSCE-SF2 by using horizontal cylinder molds (cylinder ϕ 15x30 cm) the top surface of specimens had plainness about 0.05 mm or less and capping was not needed. Other consideration were selected based on JSCE-SF2 and JSCE-SF5 .

3. EXPERIMENTAL RESULTS

The typical stress-strain curves which are plotted in Fig. 1 clearly shows that the post-peak segment of the stress-strain curves are effected by the addition of fibers. An increase in the slope of the descending part of stress-strain curve was also observed by increasing the fiber volume fraction. The addition of steel fibers increase the strain corresponding to the peak stress. Hence, the strain capacity of the concrete matrix in the prefailure zone is increased with the inclusion of the steel fibers.

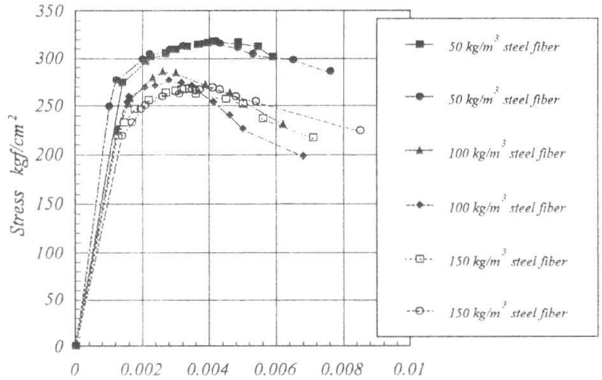

Fig. 1: Typical stress-strain diagram of SFRC

The contribution of fibers to the strain capacity at the peak stress is more effective when using higher fiber content but does not produce any significant changes in the compressive strength (peak stress). This may be attributed to the reduced workability caused by adding fibers to a lower water-cement ratio matrix. This reduced workability causes more air to become entrapped after compacting. Another possible cause may be the aggregate. In the concrete matrix, the aggregate may effect fibers orientation, and the fibers parallel to the loading direction may even produce lower strength due to buckling of the fibers [5]. The fibers perpendicular to the loading direction, however, can increase the compressive strength, because the fibers tend to confine the lateral expansion of specimen, thereby reducing crack propagation. Another advantages of addition the steel fibers is providing an uniform matrix which is an important factor in designing and serviceability of SFRC structures. According to experimental results, also there are marginal increase or decrease in the compressive strength, but uniformity of matrix as a composite material was increased very well which is shown by decreasing the coefficient of variation, Fig. 2. The toughness of a concrete is related to its ability to absorb energy. It can be estimated using the area under a stress-strain curve or load-deformation curve. A convenient way to quantify the toughness is to use the toughness index and in this study according to JSCE-SF5 it has been determined and studied as a compressive toughness index of SFRC.

4. EQUATIONS FOR STRESS-STRAIN CURVE OF *SFRC*

The following conditions must be considered when equations are proposed to represent the stress-strain relationship of steel fiber reinforced composites.

1 : The equation or equations should compare favorably with all experimental data.

2 : Ascending and descending branches of the stress-strain curve should be implied, and the equation or equations should represent both ascending and descending branches of the curve.

3 : The mathematical form should be as simple as possible and easily used in any analysis.

4 : The equation should be based on physically significant parameters that can be experimentally determined. At the point of origin, $f_{sf}=0.0$ and $d(f_{sf})/d\varepsilon_{sf}=E_{itf}$, where f_{sf} is the SFRC stress, ε_{sf} is the SFRC strain, and E_{itf} is the initial tangential modulus of SFRC. At the point of peak or maximum stress, $d(f_{sf})/d\varepsilon_{sf}=0.0$

The most common parameters which physically significance used to define the stress-strain relationship of SFRC include f'_{sf} , which is the maximum stress of SFRC, usually considered as the material strength, ε'_{sf} which is corresponding strain to the maximum stress and E_{itf} as slope at the inflection point of the descending branch. Furthermore, $I_{sf}=V_f.l/d$ as *Index of steel fibers* is defined which V_f and l/d are volume percent and the aspect ratio of steel fiber respectively.

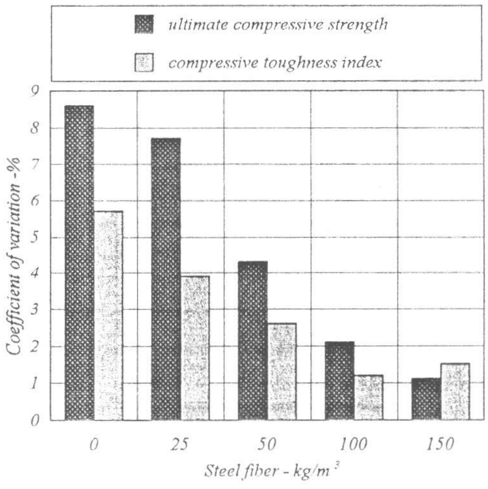

Fig. 2: Decrease dispersion of behavior of SFRC by addition of steel fibers

After investigating several empirical expressions available in the literature, the expression proposed by Carreira and Chu and S. Popovics [2, 6] are modified here to investigate the stress-strain characteristics for steel fiber reinforced concrete. The expression for complete stress-strain relationship under uniaxial compression can be represented by the following equations:

$$\eta_f = \frac{\mu \times r_\varepsilon}{\mu - 1.0 + r_\varepsilon^{\mu}} \qquad (1)$$

Where:

$$\eta_f = \frac{f_{sf}}{f'_{sf}} \quad \text{normalized stress} \qquad (2)$$

$$r_\varepsilon = \frac{\varepsilon_{sf}}{\varepsilon'_{sf}} \quad \text{normalized strain} \qquad (3)$$

f'_{sf} : peak stress of steel fiber reinforced concrete

f_{sf} : stress in general

ε'_{sf} : strain at peak stress

ε_{sf} : strain in general

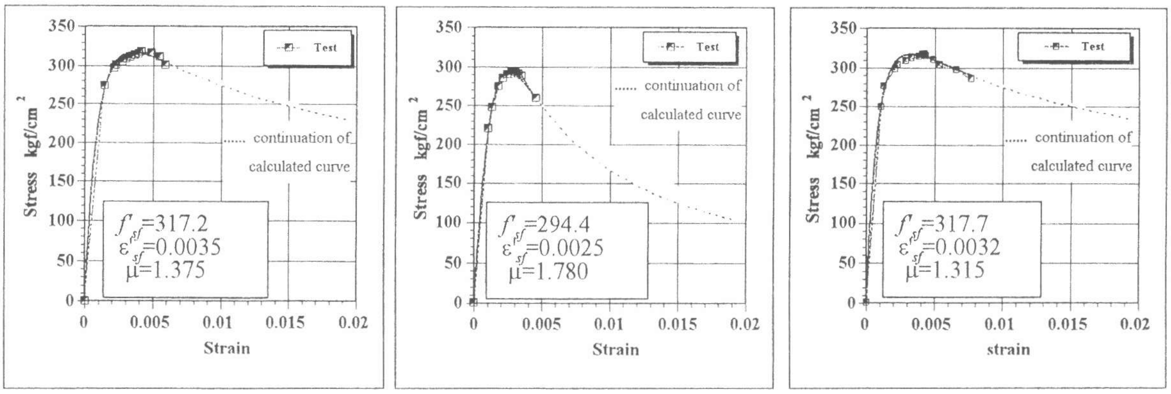

Fig. 3: Analytical stress-strain diagram of SFRC based on proposed equations; steel fiber 50kg/m^3

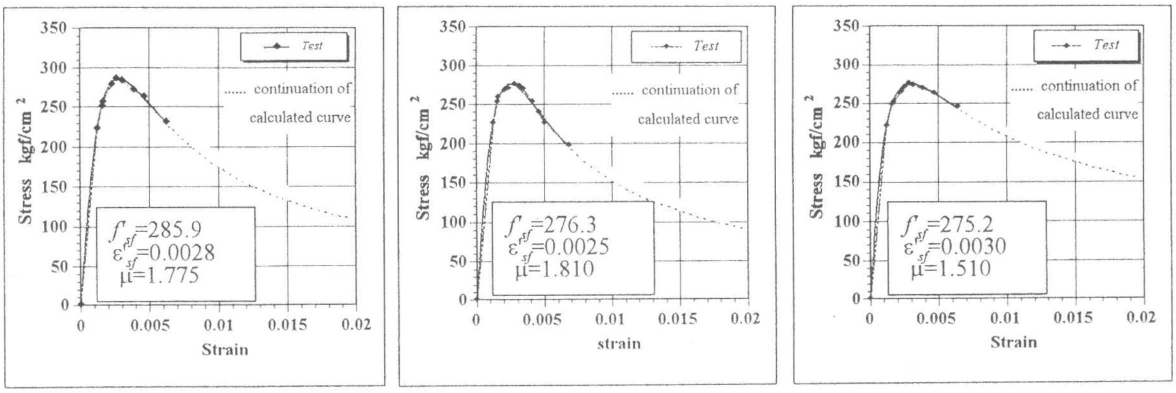

Fig. 4: Analytical stress-strain diagram of SFRC based on proposed equations; steel fiber 100kg/m^3

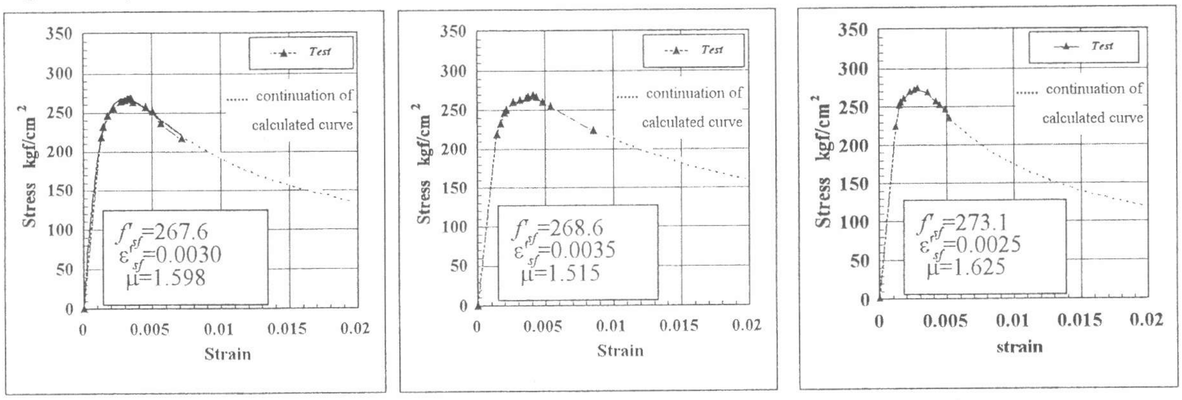

Fig. 5: Analytical stress-strain diagram of SFRC based on proposed equations; steel fiber 150kg/m^3

and **μ** defines as a matrix parameter which is function of $V_f, l/d, f'_{sf}, \varepsilon'_{sf}$ and shape of **σ–ε** curves.

Eq. 1 generates the compressive stress-strain curve in which only two values are needed, namely, ε'_{sf} and μ. These parameters can be determined from compressive tests in which the strain rate is controlled. For design purpose, an ultimate strain ε_u is specified to limit the degree of failure allowed in the concrete. According to proposed equation and regression analysis the stress-strain curves were showed a best-fitting with the experimental results, Figs. 3 to 5. The main problem in using eq. 1. is specifying the values of μ and ε'_{sf}. There is strong relationship between the stress-strain curve and values of the μ and the ε'_{sf}. Thus their effects could not be separately discussed. According to Fig. 6, Fig. 7 and Table 1. can be concluded that, in comparative, effects of ε'_{sf} values in the descending branch of stress-strain curves are less than the μ values. It means, the best fitting diagrams by using regression methods for different values of ε'_{sf} showed about 12% difference in the area under stress-strain curves in the descending branch when the ratio of ε'_{sf} values were increased 150%.

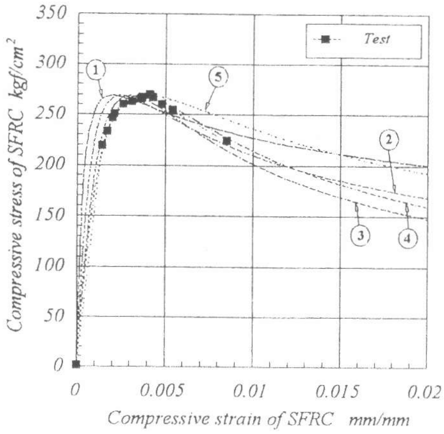

Fig. 6: Effect of peak strain ε'_{sf} on σ–ε curve

Table 1. Interaction results between μ and ε'_{sf} in σ–ε curves

Fig.	Curve Number	f'_{sf}	ε'_{sf}	μ	Chi-Squared	Regression Coefficient
Fig. 6	1	268.6 kgf/cm²	0.0020	1.2	4,811	0.96
	2		0.0025	1.36	3,082	0.98
	3		0.0030	1.52	805	0.99
	4		0.0035	1.52	119	1
	5		0.0040	1.38	756	0.99
Fig. 7	a		> 0.0	1	7,933	0.08
	b		0.00344	1.5	113	1
	c		0.00336	2	3,145	0.98
	d		0.00356	3	21,040	0.85
	e		0.00375	4	42,339	0.74
	f		0.00396	6	76,885	0.61

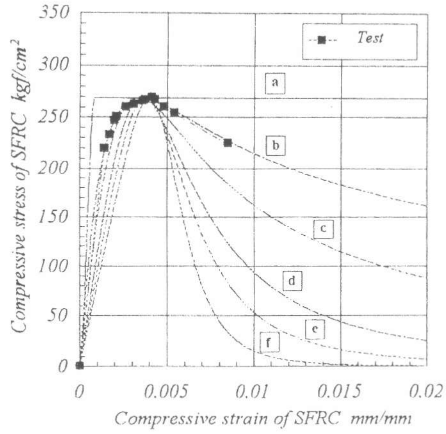

Fig. 7: Effect of matrix parameter μ on σ–ε curves

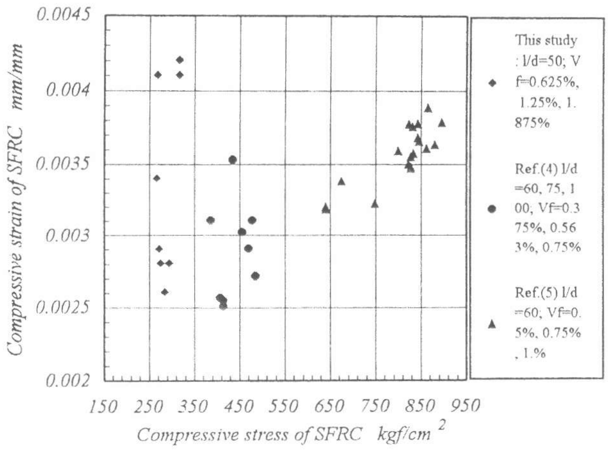

Fig. 8: Relationship between f'_{sf} and ε'_{sf}

However, this difference for different values of the μ showed big differences in the descending branch of stress-strain curves. Consequently the stress-strain curves of SFRC are effected by the matrix parameter μ, more than the ε'_{sf} . The interesting property of the μ as shown in the curve **a** Fig. 7, is perfectly plastic behavior of SFRC when $\varepsilon'_{sf} \rightarrow 0.0$ and the value of μ becomes 1.

When using the steel fibers in concrete for structural applications, the fiber content, length and diameter are usually known. These terms can be combined in one constant as the index of steel fibers I_{sf} , as explained previously. Also, it has been noticed from the experimental results that fibers have more effective contribution on the compression stress-strain curve in postfailure region. Hence, using the experimental results, a best-fitting statistical analysis was performed to obtain a relationship between the parameter μ and the index of steel fibers, I_{sf}. This relationship is based on a physical property of the stress-strain curve, which is the slope at the inflection point at the descending segment. To generate the complete stress-strain curve of steel fiber concrete the proposed equation requires the knowledge of the index of steel fibers, the maximum stress of steel fiber concrete f'_{sf} and the corresponding strain to this stress, ε'_{sf}. Usually, the value most difficult to accurately determine is ε'_{sf} . Besides, it is well-known that by addition of steel fibers to concrete the flexibility of matrix is increased and therefore the strain corresponding to the peak stress will be increased, too. Thus below equation according to the experimental results of this study, the others' experimental results and a best-fitting analysis were proposed to determine ε'_{sf}. The following equations were found to best describe that relationship for the SFRC, Fig. 8 and Fig. 9.

$\varepsilon'_{sf} = 0.00131 f'^{0.147}_{sf}$ (4)

$\mu = 0.794 \times [f'_{sf}(1. + I_{sf})]^{0.113}$ (5.a)

$I_{sf} = V_f \times l/d$ (5.b)

Where:

f'_{sf} : maximum compressive stress of SFRC for ϕ15x30 cm cylinder specimens kgf/cm^2

ε'_{sf} : strain corresponding to maximum compressive stress

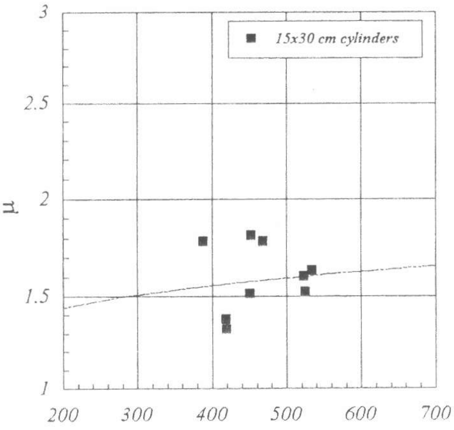

Fig. 9: Relationship between f'_{sf}, I_{sf} and μ

Eq. (5.a) in the power function form was found to have good correlation for the relation between f'_{sf}, I_{sf} and μ comparing to other functions. However, dispersion of the data regarding the regression lines indicate that some other important testing variables and material characteristics were not included in the analysis. It must be emphasized that due to changes of steel fibers specifications, e.g. sizes, type, shape and directions in the matrix, besides the many parameters affect in the matrix of concrete e.g. cement content, **W/C** ratios, aggregates, curing conditions, method of testing, size of specimens, and so on, establishing an empirical relationship for determining the value of f'_{fs} is difficult. This means that, according with the results of this study and the other researchers results there were some differences in the compressive strength of SFRC in the similar conditions which confirmed above subject. Thus, the value of f'_{fs} as an important value in the design process and plotting the stress-strain curves, based on laboratory tests must be determined.

5. CONCLUSIONS

According to proposed equations and based on this experimental investigation, the following observations can be drawn regarding the compression behavior of steel fiber reinforced concrete.

The addition of steel fibers to concrete effectively increase the uniformity of matrix. A marginal increase in the compressive toughness, compressive strength and the strain corresponding to maximum stress were obtained. Proposed equations to generate the complete stress-strain curves for steel fiber reinforced concrete by relating steel fibers specifications, provided a good correlation between experimental results and proposed equations. Consequently, proposed equations can be used for obtaining stress-strain diagram of SFRC in the design of steel fiber reinforced concrete members and predicted the behavior of matrix.

REFERENCES

1: Fanella, D., and Naaman, A. E., "Stress-Strain Properties of fiber reinforced mortar in Compression" ACI Journal V. 82-4, pp. 475-583

2: Carreira, D. and Chu, K., "Stress-Strain Relationship for Plain Concrete in Compression" ACI Journal, Nov.-Dec. 1985, pp. 797-804.

3. Keyvani Someh, A. and Saeki, N., " Ultimate Strength of Steel Shaving Fiber Reinforced Concrete", Proceedings of the Japan Concrete Institute, Vol. 17, No. 1, June 1995, pp. 433-438.

4: Elzeldin, A.S. and Balaguru, P.N., " Normal-And High strength Fiber Reinforced Concrete Under Compression", Journal of Materials in Civil Engineering, Vol. 4, No. 4, November, 1992, pp. 415-429.

5: Hsu, L.S. and Hsu. C.T., " Stress-Strain Behavior of Steel Fiber High Strength concrete Under Compression", ACI Structural Journal/July-August 1994, pp. 448-457.

6: Popovics, Sandor, "A Numerical Approach to The Complete Stress-Strain Curve of Concrete", Cement and Concrete Research , Vol. 3, 1973, pp. 583-599.