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Behavior of Compressive Strength of Steel Fiber Reinforced Concrete

Abdullah KEYVANI SOMEH	S. M. of JSCE	Dept. of Civil Engg., Hokkaido University
Noboru SAEKI	M. of JSCE	Dept. of Civil Engg., Hokkaido University
Kazunori SHIMURA	M. of JSCE	Dept. of Civil Engg., Hokkaido University

ABSTRACT

Steel fiber reinforced concrete demonstrates better deformational and cracking characteristic in comparison to plain concrete and is used in structures where significant tensile stresses are encountered. In order to use steel fiber reinforced concrete in structural applications, the complete stress-strain behavior of the material in compression is needed. The influence of the fiber reinforcing parameters on the peak stress, corresponding strain, the toughness of concrete and the curve shape were discussed. The ductile failure of steel fiber reinforced concrete in compression, comparing with plain concrete show the flexibility improve in the failure. Analyzing experimental results were led to establish empirical equations to draw the stress-strain diagram of steel fiber concrete by knowing maximum compressive strength, steel fiber's characteristic and strain corresponding to maximum compressive stress.

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. As noted by ACI Committee 544, the composite has potential for many other applications, especially in the area of structural elements.

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 and toughness resistance those are important for ductility of structures.

The use of fibers to improve the behavior of concrete after cracking is well established. Several types of fibers, of which steel fibers are the most common, have been used in various construction works overs the past two decades. The inclusion of steel fibers is especially beneficial in structures where significant tensile stresses are encountered and the sole of the reinforcing bars would lead to an undesirable congestion.

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 diagram..

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 predict the complete 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 paper presents the experimental stress-strain behavior of steel fiber reinforced concrete with compressive strength. The matrix consisted of concrete and the strain values were measured at the middle half of cylinders. The influence of the fiber reinforcing parameters on the peak stress, corresponding strain, the toughness of concrete and the curve shape were investigated.

2 RESEARCH SIGNIFICANCE

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 use of steel fiber cement-based composites in engineering construction in compression zones and has made it more important to understand the behavior of these structural materials. For this purpose, materials properties can best be described by their stress-strain relationships. This study attempts to obtain experimentally a complete stress-strain curve in compression and to develop empirical equations in terms of this measured curve.

3 EXPERIMENTAL PROGRAM

The authors' experimental data which initially isolated the important factors were obtained using a mix with 350 kg/m^3 Type I cement satisfying ASTM C150, 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'_{cu}= 434.8 kg/cm^2 (cube 15x15x15 cm) and f'_c=280.8 kg/cm^2 (cylinder ϕ 15x30 cm). The tests were conducted using 400,000 lb capacity universal testing machine of Soiltest INC. Co. with a rate of loading controller. 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. The specimen deformation measurement apparatus was a strain gauge with precision of 10^{-4} inch. Other consideration were selected based on JSCE-SF2 and JSCE-SF5 .

4 EXPERIMENTAL RESULTS

Fig. 1 shows the typical complete stress-strain curves. It is 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 is 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 and the elastic deformation capability of the concrete matrix in the prefailure zone is increased with the inclusion of steel fibers. The contribution of fibers to the strain capacity at 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. 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.

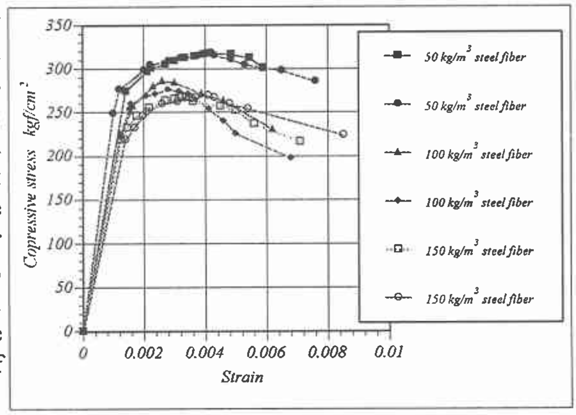

Fig. 1: Typical stress-strain diagram of SFRC

Another advantages of addition of 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. According to JSCE-SF5 the compressive toughness index of steel fiber reinforced concrete were calculated by the equation below:

$$\sigma_c = 4T_c / \pi d^2 \delta_{tc} \qquad (1)$$

Where : σ_c : Compressive toughness index kgf/cm²

T_c : Compressive toughness kgf.cm

δ_{tc} :Deformation corresponding to 0.75% converted to strain (mm) which is 0.75 mm when specimen dimensions are ϕ10x20 cm and 1.125 mm when specimens dimensions are ϕ15x30 cm.

d : Cylinder diameter cm

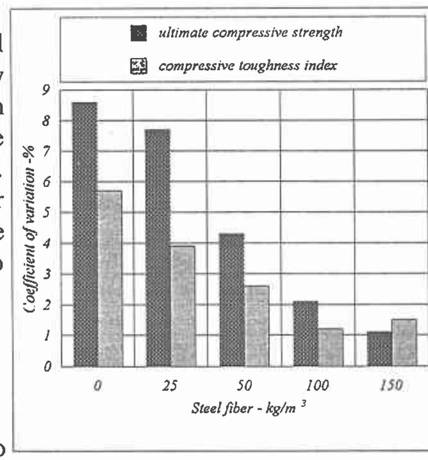

Fig. 2: Decrease dispersion of behavior of SFRC by addition of steel fibers

The calculated results are shown in Table 1.

Using steel fiber in concrete, although has not big effect in compressive strength or compressive toughness, but existence of steel fibers as already mentioned, provided a uniform matrix without big scattered in behavior and results.

5 ANALYTICAL EQUATIONS FOR COMPLETE 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.

Table 1: Compressive toughness index of SFRC

steel fiber content kg/m³	compressive toughness T_c ; kgf-cm	compressive toughness index σ_c ; kgf/cm²	coefficient of variation %	standard deviation kgf/cm²
0.0	4562.5 4156.3 4668.8	224.4 205.5 229.0	5.7	12.5
50	4937.5 4900.0 4700.0	242.8 240.7 231.1	2.6	6.22
100	4650.0 4531.3 4600.0	229.9 224.3 226.8	1.2	2.8
150	4437.5 4475.0 4562.5	218.8 221.5 225.3	1.5	3.24

4: The equation should be based on physically significant parameters that can be experimentally determined. At point of origin, f_{sf}=0 and $d(f_{sf})/d\varepsilon_{sf}=E_{itf}$, where f_{sf} is the concrete stress, ε_{sf} is the concrete strain, and E_{itf} is the initial tangential modulus of SFRC. At point of maximum stress, $d(f_{sf})/d\varepsilon_{sf}$=0.

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

After investigating several empirical expressions available in the literature, the analytical expression proposed by Carreira and Chu is modified here to investigate the stress-strain characteristics for steel fiber reinforced concrete. The expression for complete stress-strain relationship under uniaxial compresssion can be represented by the following equations:

$$\eta_f = \frac{\mu \times r_\varepsilon}{\mu - 1.0 + r_\varepsilon^{\mu}} \qquad (2)$$

where:

$$\eta_f = \frac{f_{sf}}{f'_{sf}} \quad \text{and} \quad r_\varepsilon = \frac{\varepsilon_{sf}}{\varepsilon'_{sf}} \qquad (3)$$

$$\mu = F(V_f, l/d, f'_{sf}, \varepsilon'_{sf})$$

The μ is the material parameter and depends on the shapes of stress-strain diagram. It means ultimate compressive strength, corresponding strain and steel fibers contents and geometry specification of fibers are effective in the values of μ.

To use Eq. 2 for a given f'_{sf} to generate the compressive stress-strain curve, 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.

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}, based on a physical property of the stress-strain curve, which is the slope at the inflection point at the descending segment. The following equation was found to best describe that relationship for steel fiber reinforced concrete, Fig. 3.

$$\mu = 1.647 \times I_{sf}^{0.0756} \quad \text{and} \quad I_{sf} = V_f \times l/d \qquad (4)$$

During the design stages of most structures, only the specified compressive strength f'_{sf} is known. Therefore, for ϕ15x30 cm cylinder specimens, when only f'_{sf} is known, μ may be estimated using Eq. 5 and Fig. 4.

$$\mu = 275.38 \times f'^{\,-0.913}_{sf} \qquad (5)$$

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 to this stress, ε'_{sf}. Usually, the value most difficult to accurately determine is ε'_{sf}. Slight variations may be attributed to the concrete curing conditions prior to testing; namely, moist cured up to testing versus having been allowed to dry prior to testing. But 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. So, below equations according to the experimental results and a best-fitting analysis were proposed to obtain a relation between f'_{sf} and ε'_{sf}, Eq. 6 and Fig. 5 .

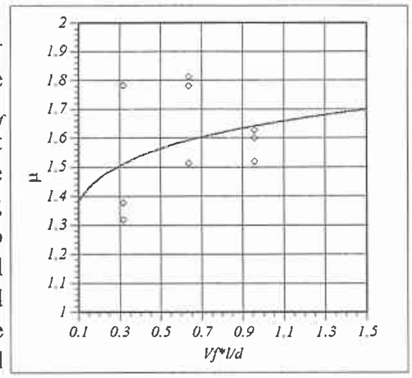

Fig. 3: Index of steel fiber and μ

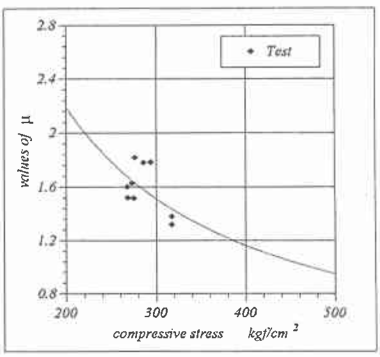

Fig. 4: Diagram of f'_{sf} and μ for SFRC

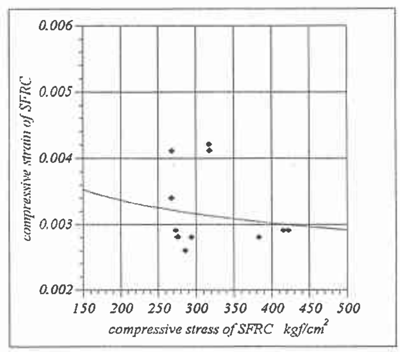

Fig. 5: Relationship between f'_{sf} and ε'_{sf}

$$\varepsilon'_{sf} = 0.00781 f'^{\,-0.158}_{sf} \qquad (6)$$

It must be emphasized that the values for plain concrete can be computed by using the following equations proposed by Hognestal, E. et. al. for ε'_c and Carreira and Chu for μ .

$$\varepsilon'_c = (0.071 f'_c + 168) \times 10^{-5} \qquad (7)$$

$$\mu = \left(\frac{f_c}{330}\right)^3 + 1.55 \qquad (8)$$

Where:

f'_c : maximum compressive stress of plain concrete for φ15x30 cm cylinder specimens kgf/cm²

ε'_c : strain corresponding to maximum compressive stress

μ : material parameter for plain concrete (330 has the same units as f'_c).

6 CONCLUSION

According to analytical results of 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

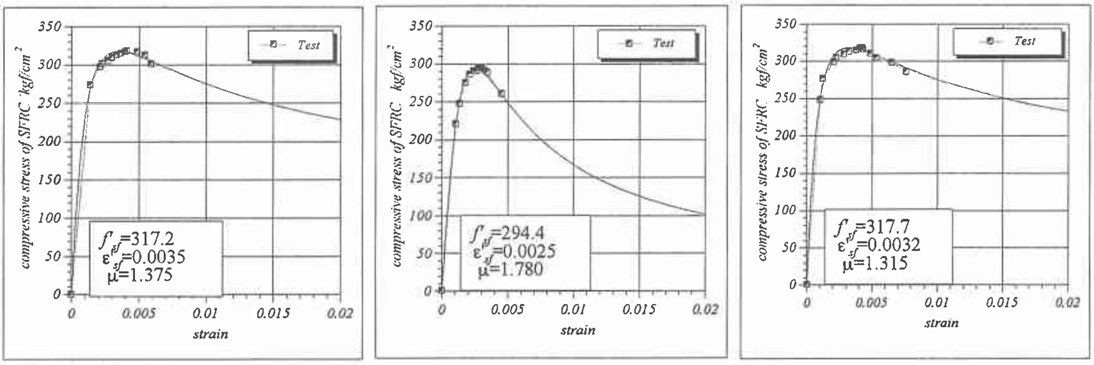

Fig. 6: Analytical stress-strain diagram of SFRC based on proposed relations; steel fiber 50kg/m³ ; φ15x30 cm cylinder specimens

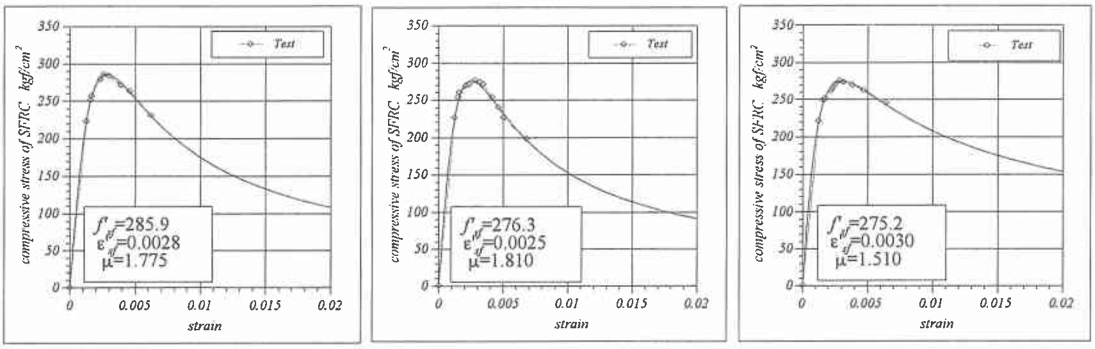

Fig. 7: Analytical stress-strain diagram of SFRC based on proposed relations; steel fiber 100kg/m³; φ15x30 cm cylinder specimens

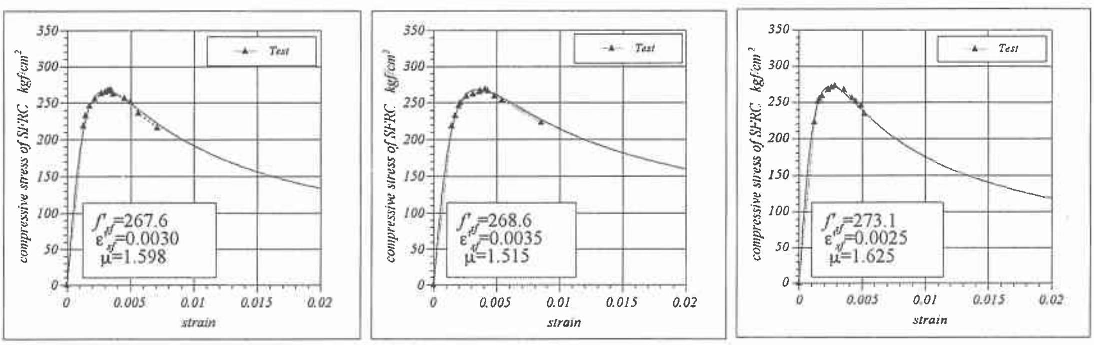

Fig. 8: Analytical stress-strain diagram of SFRC based on proposed relations; steel fiber 150kg/m³; φ15x30 cm cylinder specimens

relating steel fibers specifications, provide a good correlation between experimental results and proposed equations, Fig. 6, 7, 8.

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