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Civil Engineering Journal

Vol. 5, No. 1, January, 2019

Prediction of Fiber Reinforced Concrete Strength Properties by Micromechanics Method

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Received 26 October 2018; Accepted 03 January 2019

Abstract

High strength steel fiber reinforced concrete (HSSFRC) was prepared with the help of steel fiber. 0.5%, 1.0%, and 1.5% steel fiber by volume of concrete specimen was used in concrete for present investigation. Compressive strength test and flexural strength test were conducted on cubical and prismatic specimens respectively.

The main objective of the research work is to validate the experimental out comes by a numerical technique such as micromechanics approach. A high strength steel fiber reinforced concrete whose compressive strength is greater than 60 N/mm2 was prepared and tested on concrete testing machine. Flexural strength test was conducted on universal testing machine to evaluate the bending properties of concrete. It was observed that with increase in the percentage of steel fiber volume the compressive strength and flexural strength also increases. However the workability of concrete declines and concrete is no longer in working condition. Micromechanics technique helps to predict the strength properties which save time required for casting and such technique was found to be beneficial.

Keywords: Flexural Strength; SFRC; Micromechanics Method.

1. Introduction

To predict the strength properties of concrete two classic micromechanics models, rule of mixtures and Mori-Tanaka can be effectively utilized. The rule of mixtures achieves better approximation with results obtained by experimental investigation. Knowing the properties of steel fiber and the matrix (mixture of cement, fine aggregate, coarse aggregate and admixture) properties of steel fiber reinforced concrete can be predicted [1]. Micromechanical model presents overall idea about the behavior of the concrete which help to reduce time required for casting and such model become cost beneficial [2]. The micromechanical model effectively used to envisage the crash surface which was subjected to multi axial compression [3]. The strength properties of concrete composite depend mainly on the strength properties of its ingredients. The properties of matrix were predominant to acquire high stresses in concrete [4]. The behavior of fiber reinforced concrete is also investigated by micromechanical structure. Mori-Tanaka method was used to study the linear elastic behavior of fiber reinforced concrete [5]. To develop steel fiber reinforced concrete model the finite element method and micromechanics method have been applied. To find the effective fiber reinforced concrete modulus the multiphase micromechanics technique was used [6]. For analysis of fiber reinforced concrete stiffness modeling through numerical homogenization was used [7]. During the cracking phase of specimen approximately half of the internal energy dissipated in cracking the matrix and remaining energy dissipated in fiber pull out [8-10]. The stresses at

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http://dx.doi.org/10.28991/cej-2019-03091238

interfacial zone of fiber matrix interface were calculated for various volume fractions for longitudinal loading [11, 12]. Knowing the elastic properties of concrete matrix, volume fraction of ingredient material and grain size curves of aggregates the effective properties of composite material obtained [13].The properties of the ingredient materials were found and properties of cement concrete composite were determined. Therefore the main objective of the study is to validate the experimental results with micromechanics method. Comparison was made between experimentally obtained results with the theoretical micromechanics model.

2. Research Methodology

2.1. Method of Research

Properties of different ingredient materials were found according to IS 2386 and IS 4031. Mix design of high strength steel fiber reinforced concrete was carried out according to ACI 211.4R-93 (Reapproved 1998). Properties of high strength concrete was found in fresh state and hardened state. In fresh state workability of concrete and in hardened state compressive strength and flexural strength of concrete were obtained. The strength properties of concrete obtained from experimental set up was validated with micromechanics technique. A comparison was made between experimental out comes and the results obtained by micromechanics method.

2.2. Material Coarse Aggregates

In present work most of the crushed coarse aggregate of size passing through 16.5 mm sieve and retained on 10mm sieve were used. The specific gravity of coarse aggregate is 2.8, impact value and bulk density is 15.20 % and 1657 Kg/m^3 respectively. Properties of coarse aggregate were confirmed according to IS 2386. Figure 1 shows grading curve for coarse aggregate.

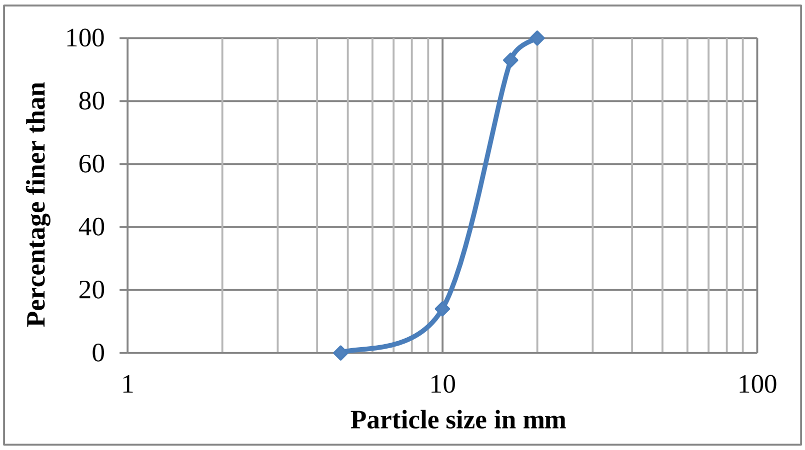

Figure 1. Grading curve for coarse aggregate

2.3. Fine Aggregate

River sand which is available locally free from organic impurities was used for present work. The specific gravity of sand is 2.76. The bulk density and fineness modulus of sand is 1660 Kg/m^3 and 2.83 respectively. Properties of sand were confirmed according to IS 2386. Following Figure 2 shows grading curve for fine aggregate.

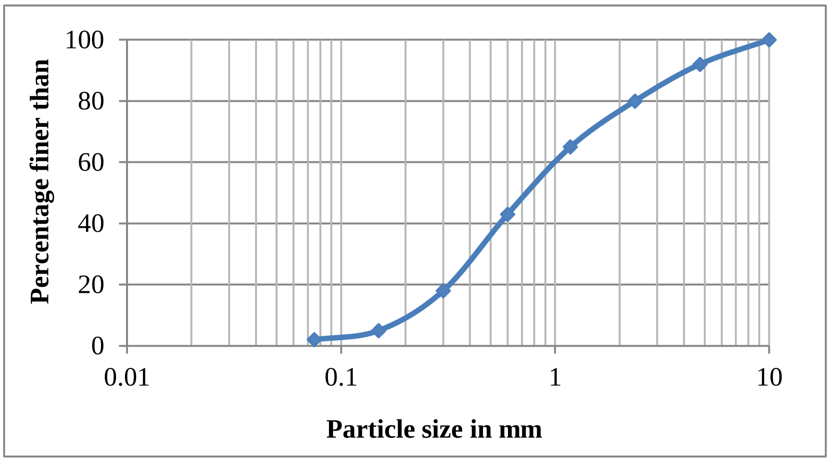

Figure 2. Grading curve for fine aggregate

2.4. Cement

Ordinary Portland Cement of 53 grade (Ultratech cement) confirming to IS 4031-1988 used for the experimental work.

2.5. Steel Fiber

Dramix steel fiber which is glued and hooked end was used for the experimental investigation. The length and diameter of steel fiber is 35 mm and 0.55 mm respectively. The aspect ratio of steel fiber is 65.

2.6. Preparation of Mix

As per IS specifications all ingredients of concrete were selected. A high strength concrete with compressive strength greater than 60 N/mm^2 was prepared by ACI method. Fly ash in concrete helps to improve the strength and durability of concrete without affecting the workability of concrete. High range water reducer (super plasticizer) improves strength by reducing w/c ratio without change in workability. The proportion of ingredients per cubic meter of concrete was as shown in table 1 below [14].

Table 1. Quantity of ingredients of concrete

Cement (Kg)	Fly ash (Kg)	Fine aggregate (Kg)	Coarse aggregate (Kg)	Water (Litter)	Super plasticizer (Litter)
588	65	527	1159	183	5.23

2.7. Micromechanics Technique

The objective of micromechanics approach is to determine the elastic moduli or stiffness of a composite material in terms of elastic moduli of the constituent materials. The elastic moduli of fiber reinforced composite material must be determined in terms of the properties of the fibers and matrix in terms of the relative volumes of fibers and matrix [15].

$$C_{ij} = C_{ij}\,(E_f, \mu_f, V_f, E_m, \mu_m, V_m)$$

Where

E_f = Modulus of elasticity of an isotropic fiber, μ_f = Poisson's ratio for an isotropic fiber

$V_f = \frac{\text{Volume of fibers}}{\text{Total volume of composite material}}$, E_m = Modulus of elasticity of matrix

μ_m = Poisson's ratio for matrix, $V_m = \frac{\text{Volume of matrix}}{\text{Total volume of composite material}}$

An additional objective of micromechanics approaches to composite material analysis is to find the strength of composite material in terms of the strengths of the ingredient materials. The strength of fiber reinforced composite material can be determined in terms of the fiber volume fraction and matrix volume fractions.

3. Results and Discussion

3.1. Workability

It was observed that with increase in the percentage of fiber the workability of concrete declines as shown in Table 2. With greater percentage of fiber more water required for lubrication of steel fiber which is not available in concrete. The concrete become stiff even after addition of superplasticizer with greater percentage of steel fiber [14].

Table 2. Workability test

Mixtures	Controlled concrete	65SF0.5	65SF1.0	65SF1.5
Workability (mm)	55	50	40	35

65 is the aspect ratio of steel fiber, SF indicates steel fiber and 0.5 indicates percentage of steel fiber by volume of concrete specimen.

3.2. Compressive Strength Test

Compressive strength test was conducted on compression testing machine. It was observed that as percentage of the steel fiber increases the compressive strength also increases. Due to more percentage of the fiber propagation of cracks were delayed therefore increase in compressive strength was observed. In compressive loading the cracks were arrested due to presence of fibers which results improvement of compressive strength of concrete. The outcome of the test were summarized as below in table no. 3 [14].

Table 3. Compressive strength test result

Percentage of steel fiber by volume	Compressive strength in N/mm^2 (by experiment)
0.5	63.77
1.0	64.00
1.5	75.55

Figure 3 shows compressive strength test conducted on concrete cubical specimen of size 150mm X 150mm X 150 mm testing machine.

Figure 3. Compressive strength test

3.3. Micromechanics Equation for Compressive Strength

According to micromechanics method from rule of mixtures compressive strength of concrete composite were calculated as below.

Rule of mixtures [1, 16-18]

$\sigma c = \sigma f \ Vf + \sigma m \ Vm$

Where:

σc = Compressive Strength of composite

σf = Tensile Strength of fiber

Vf = Volume fraction of fiber

σm = Compressive Strength of matrix

Vm = Volume fraction of matrix

3.3.1. Prediction of Compressive Strength by Rule of Mixture

Micromechanics method (Upper bound) used for predicting compressive strength as below:

Rule of mixture is $\sigma c = \sigma f \ Vf + \sigma m Vm$ (1)

$\sigma f = 1060 \ N/mm^2$ (2)

To calculate volume fraction Vf,

Volume of steel fiber in cube = 0.5% of total volume of cube = 1.6875×10^{-5} m^3

Total volume of cube = 0.15×0.15×0.15 = 3.375×10^{-3} m^3

Volume fraction $Vf = \frac{\text{Volume of steel fiber in cube}}{\text{Total volume of cube}}$

$$Vf = \frac{1.6875x10^{-5}}{3.375x10^{-3}} = 0.005 \quad (3)$$

$$\sigma m = 64.89 \text{ N/mm}^2 \quad (4)$$

To find volume fraction of matrix

Volume of matrix = $0.15^3 - (1.6875\times10^{-5}) = 3.358125\times10^{-3}$

$$V_m = \frac{3.358125 \text{ x } 10^{-3}}{3.375x10^{-3}} = 0.995 \quad (5)$$

Put values of 2, 3, 4 and 5 in Equation 1:

$\sigma c = (1060\times0.005) + (64.89\times0.995) = 69.86 \text{ N/mm}^2$

Micromechanics method (Lower bound) used for predicting compressive strength as below,

$$\frac{1}{\sigma_c} = \frac{V_f}{\sigma_f} + \frac{V_m}{\sigma_m}; \quad \frac{1}{\sigma_c} = \frac{0.005}{1060} + \frac{0.995}{64.89}$$

$$\sigma c = 65.19 \text{ N/mm}^2$$

For different percentage of steel fiber compressive strength obtained by micromechanics method (upper bound and Lower bound) summarized in Table 4 below.

Table 4. Comparison of compressive strength by expt. and micromechanics method for different percentage of steel fiber

Sr. no.	% of steel fiber	Compressive strength in N/mm²			
		Experimentally	Micromechanics Method		
			Upper bound method	Lower bound method	Experimental Result / lower bound method
1	0.5	63.77	69.86	65.19	0.978
2	1.0	64.00	74.84	65.50	0.977
3	1.5	75.55	79.81	65.81	1.148

Figure 4 shows comparison of compressive strength test results by experimental and micromechanics method. Increasing trend was observed for compressive strength obtained by experimental method. The compressive strength values achieved from micromechanics method (upper bound) shows greater values than experimental values of compressive strength for 0.5%, 1% and 1.5% of steel fiber. With increase in the percentage of fiber more voids are included in the concrete. Experimental results of 0.5% and 1.0% steel fibers are nearer to lower bound method. The ratio of experimental values to lower bound method is nearly equal to one which indicates that experimental values were good fitted with lower bound method.

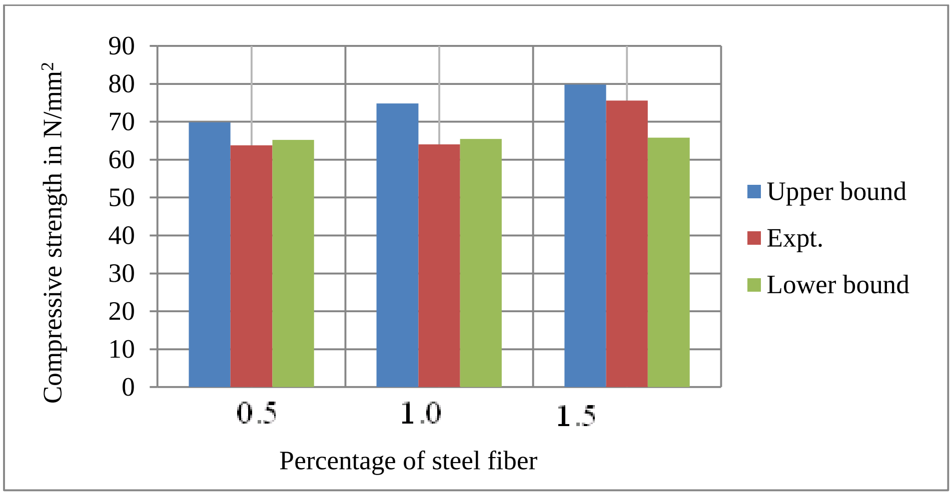

Figure 4. Comparison of compressive strength by experimental and micromechanics method

3.4. Flexural Strength Test

Flexural strength test was conducted on steel fiber reinforced concrete by using universal testing machine. Flexural strength increases with increases in percentage of steel fiber. As percentage of fiber increases more number of steel fiber are available to resist crack propagation and absorb greater energy by deformation. Therefore flexural strength of concrete enhanced with increase in percentage of fiber. For present experimental work steel fiber with aspect ratio 65 were used.

Central displacement of the beam was measured on electronic universal testing machine of capacity 200KN with straining speed at no load is 0-150 mm per minute. This UTM can be connected to any PC using communication port. Load is applied by hydrostatically lubricated ram. Main cylinder pressure is transmitted to the pressure transducer housed in the control panel. The transducer gives the signal to the electronic display unit corresponding to the load exerted by the main ram. Simultaneously the digital electronic fitted on the straining unit gives mechanical displacement to the electronic display unit. Both signals are processed by microprocessor and load and displacement are displayed on the digital readouts simultaneously. The results of the test was summarized as below in Table 5 [14].

Table 5. Flexural strength test result

Percentage of steel fiber by volume	Flexural strength in N/mm^2 (by experiment)
0.5	6.64
1.0	7.15
1.5	7.79

Figure 5 shows flexural strength test conducted on beam specimen of size 150×150×700 mm.

Figure 5. Flexural strength test

3.4.1. Stress Strain Curve

Stress strain curves for different percentage of steel fiber are as shown in Figure 6 below. As the percentage of fiber increases curve becomes more flat. The peak stress increases with increases in the percentage of steel fiber. As the percentage of steel fiber increases the resisting capacity of SFRC also increases.

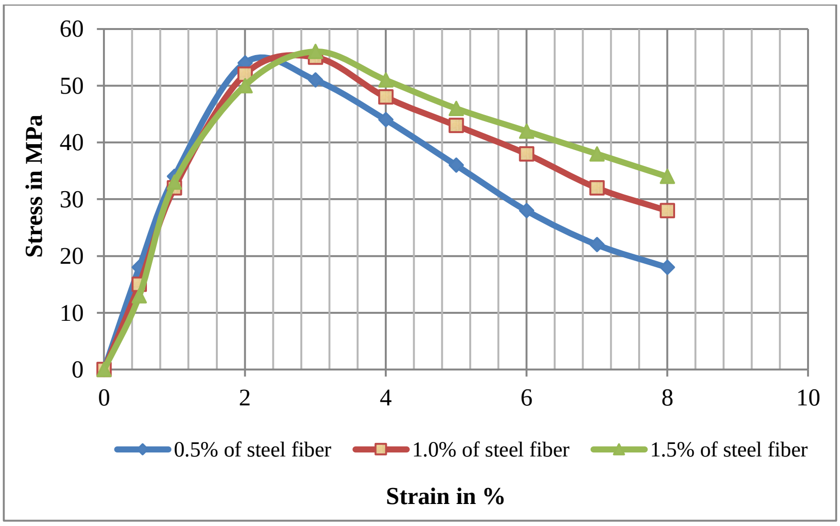

Figure 6. Stress strain curves for SFRC

3.4.2. Crack Analysis

More cracks were observed at 0.5% steel fiber as compared with the specimen 1.5% of steel fiber. Steel fiber acts as crack arrester and helps to resist the crack and dissipate the energy by undergoing greater deflection. With increase in the percentage of steel fiber flexural strength of concrete increases because at greater percentage of fiber, more number of fiber came across the crack which enhance the crack resisting ability of concrete therefore the flexural strength increases. Before failure beam absorb greater amount of energy due to presence of fiber which results in increase in flexural strength of concrete. Due to this phenomenon more cracks were occurred when 0.5% of steel fibers were used in concrete beam as shown in Figure 7 and fewer cracks observed for 1.5% of steel fiber as shown in Figure 8.

Figure 7. More cracks at 0.5% of steel fiber

Figure 8. Fewer cracks at 1.5% of steel fiber

3.5. Micromechanics Equation for Flexural Strength

Rule of mixtures as below

$\sigma c = \sigma \Omega V\Omega + \sigma m Vm$

Where

σc = Flexural strength of composite, $\sigma\Omega$ = Tensile strength of aggregate

$V\Omega$ = Volume fraction of reinforcement, Vm = Volume fraction of matrix

σm = Tensile strength of matrix

3.5.1. Prediction of Flexural Strength by Rule of Mixture

Micromechanics method (Upper bound) used for predicting flexural strength as below:

Rule of mixture is $\sigma c = \sigma \Omega V \Omega + \sigma m Vm$ (6)

$\sigma\Omega = 10.26$ N/mm^2 (7)

To calculate volume fraction of reinforcement $V\Omega$,

Volume of steel fiber in beam = 0.5% of total volume of cube = 7.875×10^{-5} m^3

Total volume of beam = $0.15\times0.15\times0.7$ m^3 = 0.01575 m^3

Volume fraction or reinforcement $V\Omega = \frac{\text{Volume of steel fiber in beam}}{\text{Total volume of beam}}$

$V\Omega = \frac{7.875\text{x}10^{-5}}{0.01575} = 0.005$ (8)

$\sigma m = 5.62$ N/mm^2 (9)

To find volume fraction of matrix

Volume of matrix = $(0.15\times0.15\times0.70) - (7.875\times10^{-5}) = 1.567125\times10^{-2}$

$Vm = \frac{1.567125\times 10^{-2}}{0.01575} = 0.995$ (10)

Put values of 7, 8, 9 and 10 in Equation 6

σc = (10.26×0.005) + (5.62×0.995) = 5.64 N/mm^2

Micromechanics method (Lower bound) used for predicting flexural strength as below:

$$\frac{1}{\sigma_c} = \frac{V_\Omega}{\sigma_\Omega} + \frac{V_m}{\sigma_m}$$

$$\frac{1}{\sigma_c} = \frac{0.005}{10.26} + \frac{0.995}{5.62},$$

σc = 5.63 N/mm^2

For different percentage of steel fiber flexural strength obtained by micromechanics method (upper bound and Lower bound) summarized in table 6 below.

Table 6. Comparison of flexural strength by expt. and micromechanics method for different percentage of steel fiber

Sr. no.	% of steel fiber	Flexural strength in N/mm^2			
		Experimentally	Micromechanics Method		
			Upper bound method	Lower bound method	Experimental Result / lower bound method
1	0.5	6.64	5.64	5.63	1.177
2	1.0	7.15	5.67	5.64	1.263
3	1.5	7.79	5.70	5.65	1.366

Figure 9 shows comparison of flexural strength test results by experimental and micromechanics method. As percentage of fiber increases the flexural strength also increases. Flexural strength of steel fiber reinforced concrete with 0.5, 1.0 and 1.5% steel fiber gives greater values than the flexural strength obtained by upper bound micromechanics method. Experimental values of flexural strength shows greater result than the micromechanics method because the effect of cavities present in concrete not accounted in micromechanics method. The ratio of flexural strength of experimental result to lower bound method is almost equal to one which indicates that the experimental values could be validated with lower bound micromechanics method.

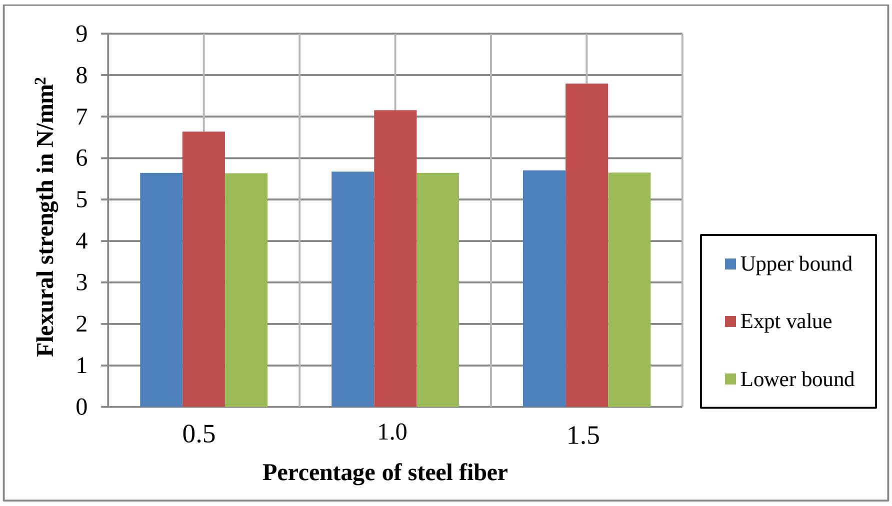

Figure 9. Comparison of flexural strength by experimental and micromechanics method

4. Conclusions

- Micromechanics model can give better estimation for prediction of strength properties of fiber reinforced concrete. In compressive strength test for 0.5, 1.0 and 1.5% of steel fiber results obtained by micromechanics method are similar to that results achieved by experimental investigation. Experimental results are nearer to lower bound method of micromechanics method for 0.5 and 1.0% of steel fiber.
- For flexural strength test at 0.5, 1.0 and 1.5% of steel fiber reinforced in concrete the experimental values greater than upper bound micromechanics method. For flexural strength test with increase in percentage of fiber difference between experimental value and micromechanics value increases.
- At lower percentage of steel fiber better approximation of experimental value with micromechanics method was

obtained. Micromechanics method helps to predict the strength properties of fiber reinforced concrete by knowing the properties of its ingredients. Therefore saving in funds and duration for casting of concrete can be achieved.

5. Conflicts of Interest

The authors declare no conflict of interest.

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