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SHEAR STRENGTH OF HIGH – STRENGTH STEEL FIBRE REINFORCED CONCRETE RECTANGULAR BEAMS

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ABSTRACT

In IS 456-2000, the design equation proposed for shear strength of concrete beam does not consider the effect of steel fibres. In this paper, the experimental shear strength by various authors and the predicted shear strengths using the proposed equations in the literatures were reviewed and also experimental investigations were carried out on the shear strength of High Strength Steel Fibre Reinforced Concrete rectangular beams of characteristic compressive strength 80MPa. The ratio between the experimental and theoretical strength possess wide variation, so an equation is suggested for shear strength by comparing the experimental results with that of the theoretical results. Six beams were tested with varying fibre content and shear-span to effective depth ratios. The experimental results were compared with the strengths obtained using the equations proposed in the literature and also with the analytical results. This study reports that the ultimate strength increases significantly as the fibre content increases.

Key words: High Strength Concrete, Steel Fibres, Beam, Shear Strength, Analytical Model.

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1. INTRODUCTION

High strength concrete is a concrete of characteristic compressive strength more than 60 mPa. Use of High strength concrete in construction industry increases significantly over the past few years since it reduces the dead weight of the structure and increases the functional space. This in turn leads to earthquake resistant structures. High strength fibre reinforced concrete is one of the special concrete which is in use. Many Research works has been carried out to study the mechanical properties and strength characteristics of fibre reinforced concrete. High strength concrete of 80MPa compressive strength is made by adopting appropriate mix design procedure. High strength concrete can be achieved by decreasing water cement ratio which leads to low workability. This is overcome by using High range water reducing admixtures (Superplasticizers). High strength concrete is a brittle material and the post-peak portion of the stress-strain diagram almost vanishes or descends steeply as the strength of the concrete increases. Higher the strength of the concrete, lower is the ductility and this is a major drawback for the use of high strength concrete. This can be overcome by using discrete discontinuous fibres. In the shear region of the beam, diagonal cracks develop when the principal tensile stress exceeds the tensile strength of reinforced concrete, thereby causing failure. After the first crack, the unreinforced beam collapses due to its brittle nature. When steel fibres are added to the concrete, they get distributed randomly throughout the mix at a closer spacing compared to conventional reinforcement. The stress intensity at the tip of the internal crack depends on the aspect ratio of the fibres. The presence of fibres in concrete increases the shear friction, tensile strength, ductility and hence controls cracking. These characteristics depends upon bond in the matrix- fibre interface, ductility and volume of fibres, spacing between the fibres, position and orientation, aspect ratio. Many studies have been conducted to determine the shear strength of steel fibre reinforced concrete beams. A Number of equations are developed to predict the shear strength of steel fibre reinforced concrete. It was observed from the shear test on fibre concrete beams that about 30 percent increase in shear strength of slender beams is due to fibre reinforcement. (Batson,Jenkins and spatney ,1972). Increase in shear strength were proportional to flexural strength of conrcrete due to addition of fibres (Swamy and Bahia, 1985). Testing slender beams (d=130mm) showed increase in shear strength with 1% crimped steel fibres and a/d of 2 and 2.5.Mode of failure of these beams were studied and equations for estimating shear strength of beams. (Narayanan and Darwish[4], 1987). Shear strength of beams increases with increase in fibre content and decreases with aspect ratio. Equations were developed for a/d>2.5 and for a/d <=2.5 (Samir A.Ashour et al. [6], 1992). Mechanical behaviour of reinforced concrete beams in shear was found to be influenced Increase in fibre content from 0 to 2% (B.H.Oh et al.[5], 1998). Equation for evaluating the ultimate shear strength of steel fibre reinforced concrete beams based on shear transfer mechanism were suggested. (Madhusudan Khuntia et al.[3], 1999). Equation for calculating the shear strength of steel fibre reinforced concrete beams and the procedure for measurement of properties of FRC were outlined. (ACI Committee544[1], re approved 1999). Normal strength concrete converted failure mode of the beam from shear to flexure completely at a quantity of 2% fibres. (Soon-Ho Cho and Yeon –II Kim[9], 2003).

Effect of variables such as compressive strength, shear span-depth ratio, vertical shear reinforcement ratio were studied and strength were compared with the ACI Equation (Sung-Woo Shin, 1999). Three series of reinforced concrete beams without shear reinforcement were tested for shear capacity. It was found that for longer beams, ACI equations were conservative and for shorter beams, ACI equations for shear strength were underestimated by 71% (Andrew G. Mphonde, 1984). Singly reinforced beams of normal and high strength concrete were studied for their flexural behavior and flexural ductility. Formula for predicting the flexural ductility of normal and high strength concrete were developed (Pam, 2001). Experimental and Analytical investigation were done to assess the shear resistance of high strength concrete beams. Results were compared with selected codes. (Raghu S. Pendyala, 2000)

This paper deals with the study of shear strength of High Strength Steel Fibre Reinforced Concrete (HSSFRC) rectangular beams. Results of experimental investigations on the shear strength of HSSFRC rectangular beams of 80mpa characteristic compressive strength are summarized in this study. A total of 6 beams were tested without web reinforcement in the form of vertical stirrups. The equation for ultimate shear strength of HSSFRC beams suggested in this paper depends on compressive strength of concrete, fibre effects, shear span to depth ratio and longitudinal reinforcement ratio.

2. EQUATIONS PROPOSED IN PUBLISHED LITERATURES

Manny studies have been conducted to determine the shear strength of steel fibre reinforced concrete beams. Number of equations are developed to predict the shear strength of steel fibre reinforced concrete.

ACI 544 – 88 Equation

The ACI Building Code presents the following equation for computing the shear strength of steel fibre reinforced concrete beam.

$$V = k f_t' \left[\frac{d}{a}\right]^{0.25}$$

$$k = \text{constant} \begin{cases} 1 \text{ if } f_t' \text{ obtained by direct tension test} \\ 0.667 \text{ if } f_t' \text{ obtained by indirect tension test} \\ 0.444 \text{ if } f_t' \text{ obtained using modulus of rupture} \end{cases} \quad (1)$$

Equation proposed by R.Narayanan et al

Testing slender beams (d=130mm) showed increase in shear strength with 1% crimped steel fibres and a/d of 2 and 2.5.Mode of failure of these beams were studied and equations for estimating shear strength of beams. By using steel fibres as shear reinforcement, Narayan and Darwish have represented the shear stress as,

$$V = e\left(0.24\, f_{spfc} + 80\, \rho \left[\frac{d}{a}\right]\right) + 0.41\, F\tau \quad (2)$$

e = 1.0 when a/d = 2.8

e = 2.8 (d/a) when a/d ≤ 2.8

τ = Average fibre matrix interfacial bond stress = 4.15 N/mm^2

F = (L_f/ D_f) $v_f d_f$

$$d_f = \text{bond factor} \begin{cases} 0.5 \text{ for circular fibres} \\ 0.75 \text{ for crimped fibres} \\ 1.0 \text{ for indented fibres} \end{cases}$$

Equation proposed by Shin et al.

By shear behaviour of laboratory – sized High strength beams reinforced with bars and steel fibre, they have proposed the following equation for determining the shear stress of fibre reinforced concrete as,

$$v = 0.22\, f_{sp} + 217\, \rho \left[\frac{d}{a}\right] + 0.34\, \tau f \qquad \text{for } (a/d) < 3 \qquad (3)$$

$$v = 0.19\, f_{sp} + 93\, \rho \left[\frac{d}{a}\right] + 0.34\, \tau f \qquad \text{for } (a/d) \geq 3 \qquad (4)$$

τ = Average fibre matrix interfacial bond stress = 4.15 N/mm^2

Equation proposed by Madhusudan Khuntia et al.

Equation for evaluating the ultimate shear strength of steel fibre reinforced concrete beams based on shear transfer mechanism were suggested. By strength of Normal and High strength Fibre reinforced concrete beams, they have represented the shear stress of fibre reinforced concrete as,

$$v = (0.167\, \alpha + 0.25\, F)\, \sqrt{f_c'} \qquad (5)$$

Here α = arch action factor $\begin{cases} 1 \text{ for } a/d \geq 2.5 \\ 2.5d/a \leq 3 \text{ for } a/d < 2.5 \end{cases}$

$$F = (L_f / D_f)\, v_f d_f$$

Equation proposed by Samir A.Ashour et al

Shear strength of beams increases with increase in fibre content and decreases with aspect ratio. Equations were developed for a/d>2.5 and for a/d <=2.5 By shear behaviour of high strength fibre reinforced concrete beams, they have represented the ultimate shear stress of fibre reinforced concrete as,

$$v = \left(0.7\, \sqrt{f_c'} + 7F\, \frac{d}{a} + \right) 17.2\, \rho\, \frac{d}{a} \qquad (6)$$

In IS 456 – 2000, the shear strength is given by,

$V_{us} = 0.87 f_y\, A_{sv}\, d/s_v$

This equation does not account the amount of steel fibres to be used.

3. COMPARISON OF EXPERIMENTAL AND PREDICTED SHEAR STRENGTH IN PUBLISHED LITERATURES

The experimental values by various investigators were compared with the predicted shear strength values by the ACI, Narayanan, Shin, Madhusudan and Samir A.A.Shour equations proposed in the published literatures. From these comparisons, the equation that gives comparatively better strength was suggested to calculate the shear strength of steel fibre reinforced concrete beams. From the comparison with ACI equation, found that the mean value as 1.56 and the variance as 0.404. Similarly, the mean of 1.077, 1.36. 1.227, and 1.045 was obtained for comparison with Samir A.A.Shour, Shin, Madhusudan and Narayanan equation respectively.

Comparison chart

The comparison chart was plotted for the experimental value and the theoretical value by the proposed equation. The graph is plotted with the f_c' values and the $\boldsymbol{V_{Exp} / V_{Pred}}$ values. The f_c' values is plotted in X-axis and the $\boldsymbol{V_{Exp} / V_{Pred}}$ value in Y-axis. Fig .1 shows that the comparison of experimental value with the predicted value estimated using the ACI equation (Eq.1). Similarly Fig. 2, Fig. 3, Fig. 4, Fig. 5 represent comparison of the experimental value and the theoretical value by Samir et al. (Eq.6), Madhusudan et al.(Eq.5), Shin et al.(Eq.3 & 4), and Narayanan et al.(Eq.2) equations respectively.

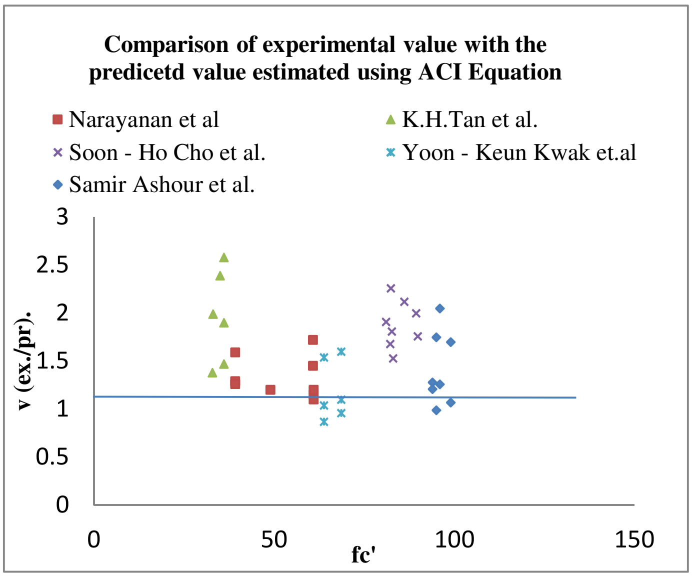

Figure 1 Comparison of experimental value with the predicted value estimated using ACI Equation

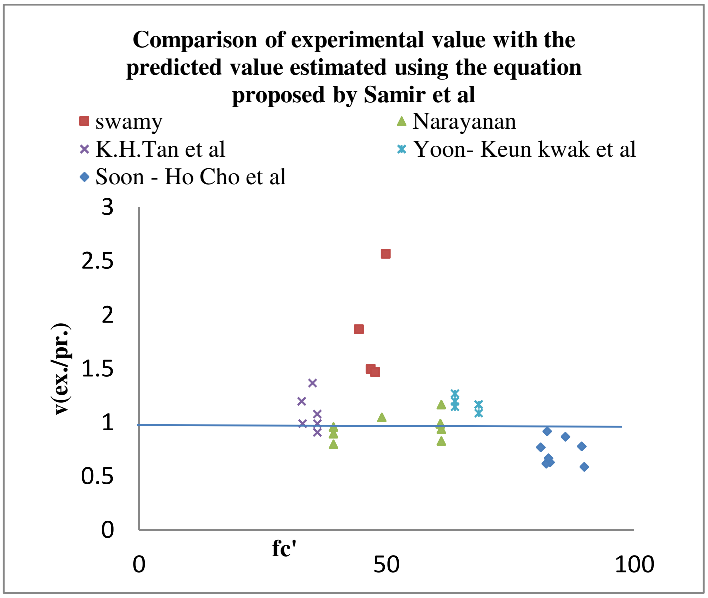

Figure 2 Comparison of experimental value with the predicted value estimated using the equation proposed by Samir et al

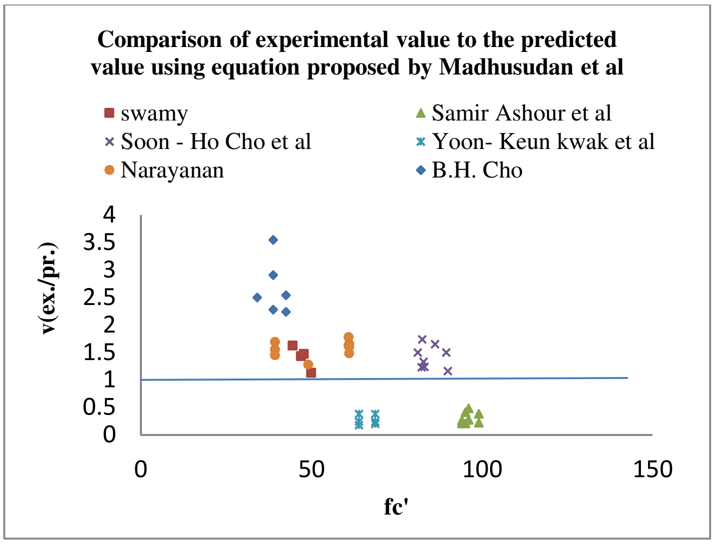

Figure 3 Comparison of experimental value to the predicted value using equation proposed by Madhusudanet al

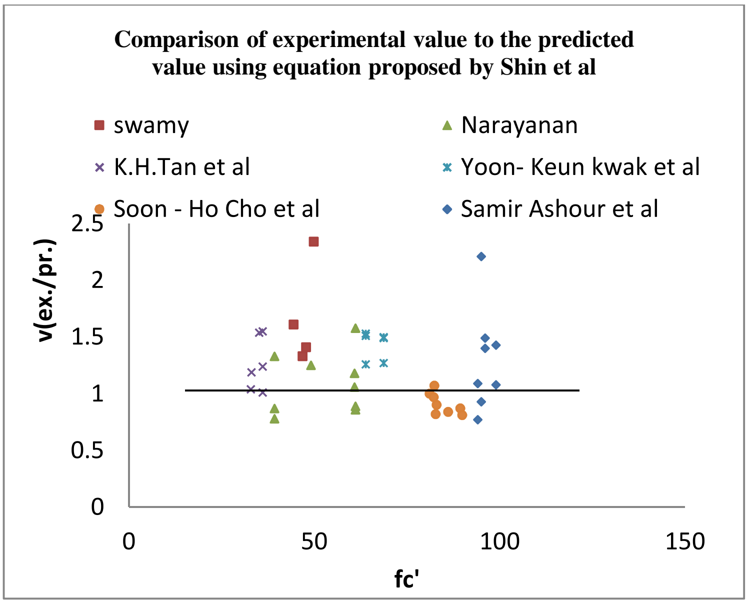

Figure 4 Comparison of experimental value to the predicted value using equation proposed by Shin et al

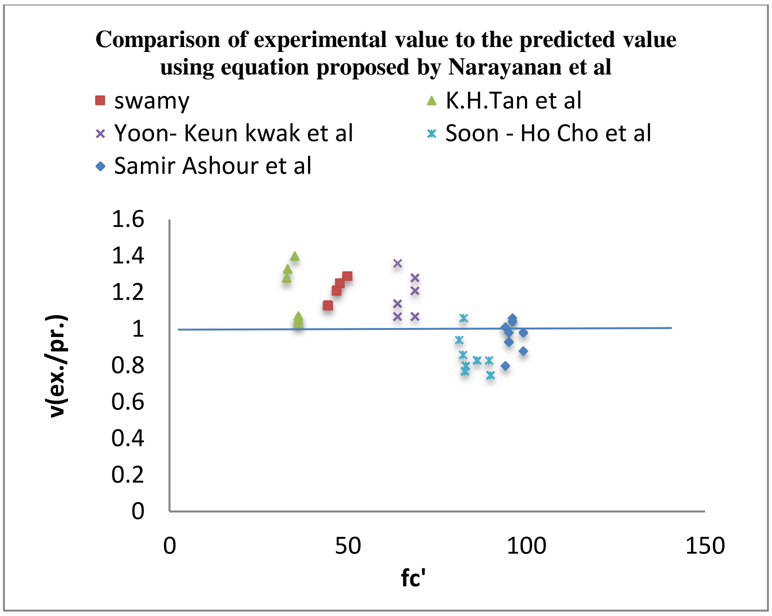

Figure 5 Comparison of experimental value to the predicted value using equation proposed by Narayanan et al

4. DISCUSSION

In the figures the horizontal line V_{Exp} / V_{Pred} =1 represents the actual shear stress equals the shear stress predicted using the proposed equation. The points fall above this line represents the beam that had measured shear stress that was greater than the predicted by the proposed equations. This comparison states that experimental strength is higher than the proposed equations in the literature. The theoretical strength obtained using the equation proposed by Narayanan et al gives comparatively better results than other equations to calculate the shear strength of steel fibre reinforced concrete beams. This equation is suited low strength and high strength concrete beams and also suited for all types of fibres.

5. EXPERIMENTAL PROGRAMME

In this work, the experimental programme consisted of casting and testing six High Strength Steel Fibre Reinforced Concrete (HSSFRC) rectangular beams of identical cross section (140 x 220mm) the span length of the beam was 2000 mm. All the beams were singly reinforced. The mix was designed to resist the cylinder compressive strength of 80Mpa.

6. MATERIALS USED

The maximum size of the aggregate used in this study is limited to 12mm. A superplasticizer Conplast – SP 430, 2% by weight of cement was used to improve the workability. Mild steel deformed steel bars of aspect ratio 80 are used. Volume fractions of the fibres used in this investigation were 0.5%, 1.0% and 1.5% of volume of concrete. The mix proportion used was 1: 0.8: 1.8: 0.3 (Binder: Fine aggregate: Coarse aggregate: water/binder ratio), 10% of the cement replaced by silica fume. The materials used is listed in Table 1.

Table 1 Materials used

MATERIAL	QUANTITY	
Ordinary portland cement(53 grade)	624kg/m^3	
Fine aggregate	450 kg/m^3	
Coarse aggregate	1123kg/m^3	
Micro silica	62.4kg/m^3	
Water	187.2lit/m^3	
Plasticizer(CONPLAST – SP 430)	12.48 lit/m^3	
Water / binder ratio	0.3	
Reinforcement	4 Nos- 10mm # bars (Fe415)	
Testing condition	Two point loading	
Fibres	Mild steel deformed steel fibres	
	Aspect ratio	80(36mm length and 0.45mm diameter)
	Volume fractions of fibre used in investigation	0.5%, 1.0%, 1.5% of volume of concrete

(150mm diameter and 300mm height cylindrical specimens were tested to determine the compressive and split tensile strength).

7. TESTING PROCEDURE

All the six beams were tested at the age of 28 days in two point loading conditions, with load applied to the test beam as the two equal concentrated loads by means of a steel beam with shear-span to effective depth ratio of 1.5 and 2.5. Two point loads were applied to the beams by 500kN by hydraulic testing machine, up to the failure. The deflection was measured at the three points using dial gauge, one at the mid span and other at the loading points. Fig. 6 shows the set up for testing beams for deflection.

The loads were applied in small increments and at every increment of loading, the deflection. Strain gauge readings, were recorded. Cylinder specimen of 300mm height and 150mm diameter with volume fraction of 0.5, 1.0, 1.5 were tested to determine the compressive and split tensile strengths of the concrete and 150mm cube were used to calculate the cube compressive strength of the concrete. Experimental shear strength values were calculated as shown in Table 2.Crack pattern for 1% steel fibre fraction is shown in Fig.7.

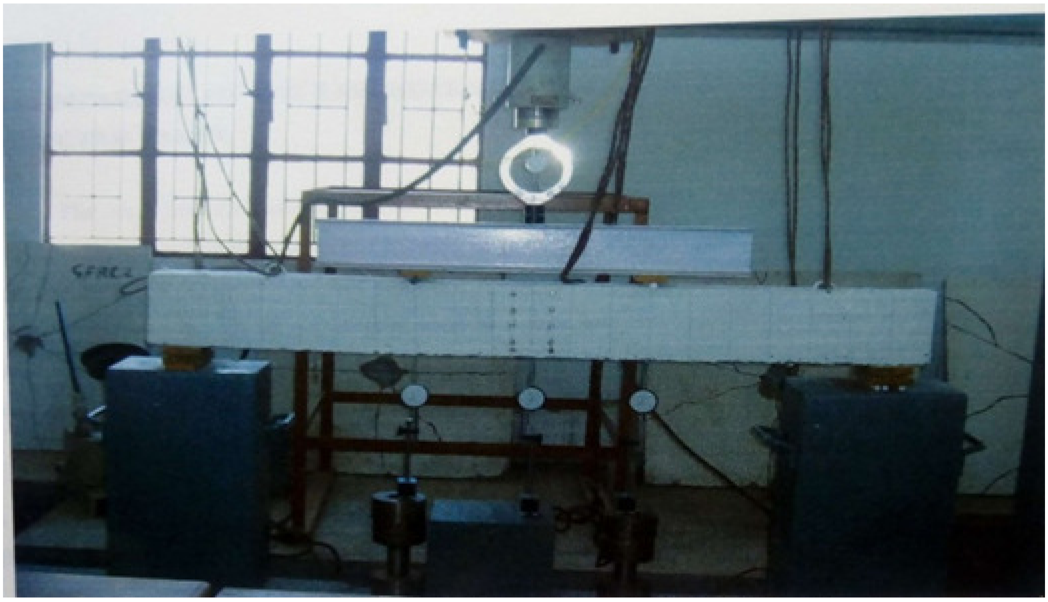

Figure 6 Testing arrangement of beams

8. EXPERIMENTAL RESULTS

150mm cube were used to determine the cube compressive strength of the concrete. Experimental shear strength values were calculated as shown in Table 2. Experimental shear strength depends on the volume of fibres, aspect ratio, shear span to effective depth ratio (**a/d**) and amount of longitudinal reinforcement (ρ). Crack pattern for 1% steel fibre fraction is shown in Fig.7.

Table 2 Experimental test results

Beam	v_f	L_f/D_f	ρ	a/d	f_{cuf}	f_c' N/mm^2	f_{sp} N/mm^2	V_{Exp} N/mm^2
SH1	0.5	80	0.01	1.5	94.11	82.0	7.2	4.81
SH2	1.0	80	0.01	1.5	95.20	83.2	8.8	6.32
SH3	1.5	80	0.01	1.5	96.10	83.8	9.5	7.61
SH4	0.5	80	0.01	2.5	94.11	82.0	7.2	2.56
SH5	1.0	80	0.01	2.5	95.20	83.2	8.8	3.24
SH6	1.5	80	0.01	2.5	96.10	83.8	9.5	5.51

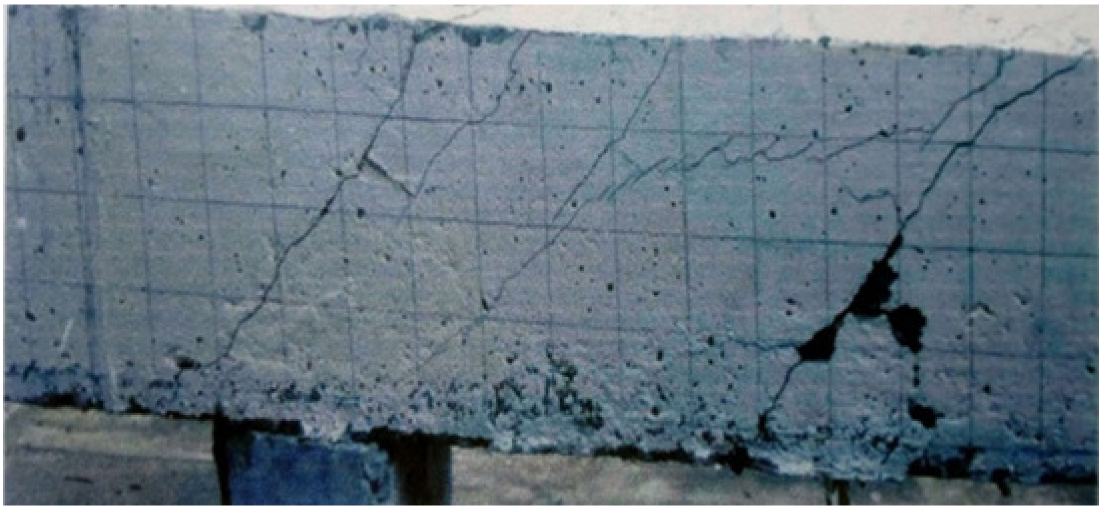

Figure 7 Crack Pattern of beam with 1% steel fibres.

9. COMPARISON OF THE EXPERIMENTAL VALUE WITH THE PREDICTED VALUE

The experimental value of the present study is compared with the theoretical strength calculated using equations available in published literatures. Graph is plotted with the 'f_c' values and the v_{exp}/v_{pred} that is presented in Fig. 8. The 'fc' value is plotted in the x-axis and the v_{exp}/ v_{pred} value in y-axis. The effects of fibre content v_f and shear span to effective depth ratio (a/d) on experimental shear strength is shown in Fig. 9.

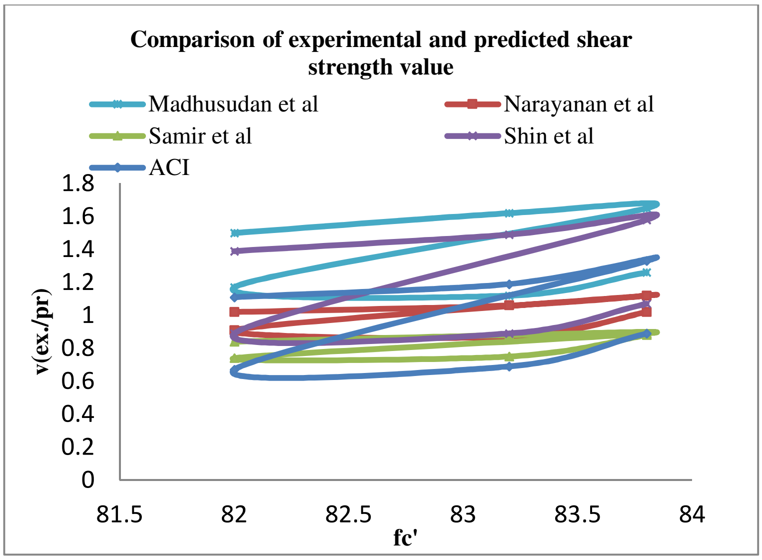

Figure 8 Comparison of experimental and predicted shear strength value

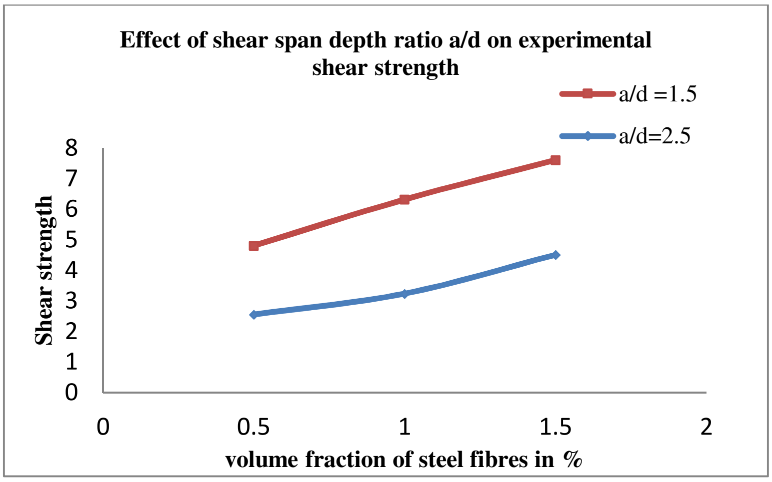

Figure 9 Effect of shear span depth ratio a/d on experimental shear strength

10. ANALYTICAL MODELING OF BEAMS

The aim of this study was to understand the structural behavior of HSSFRC beams under two point loading condition. The model utilized to compute the shear strength of steel fibre reinforced concrete beams must reflect the configuration of the structure under consideration, elastic and inelastic behaviour must be realistically represented in the model. The beam is meshed and the stress intensity pattern of the beam were studied as shown in Fig. 10 and Fig. 11.

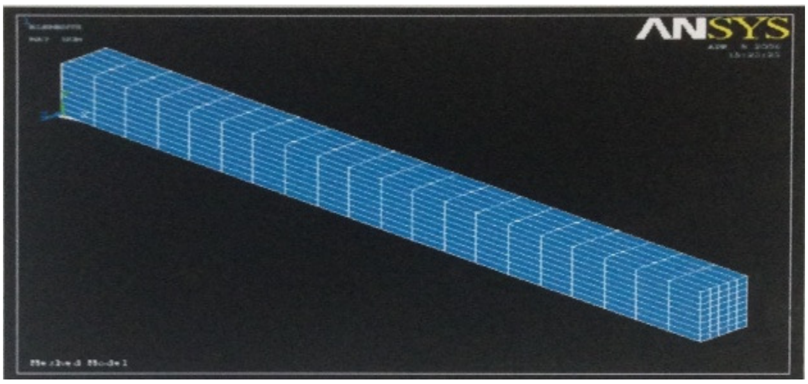

Figure 10 Meshed view of the beam

11. ANALYTICAL RESULTS

The shear strength of the analytical model depends on the non-linear analysis done. In this method, Newton – Raphson method of iteration is used. The shear strength of the beams using analytical method is listed in Table 3. With volume fraction of 0.5, 1.0, 1.5% steel fibres, compressive strength, split tensile strength were found and shear strength is found analytically as shown in table 3.

Table 3 Analytical results

Beam	v_f	ρ	a/d	$f_c{}'$ N/mm^2	f_{sp} N/mm^2	Analytical value using ANSYS N/mm^2
SH1	0.5	0.01	1.5	82.0	7.2	4.440
SH2	1.0	0.01	1.5	83.2	8.8	5.446
SH3	1.5	0.01	1.5	83.8	9.5	5.690
SH4	0.5	0.01	2.5	82.0	7.2	2.520
SH5	1.0	0.01	2.5	83.2	8.8	2.926
SH6	1.5	0.01	2.5	83.8	9.5	4.002

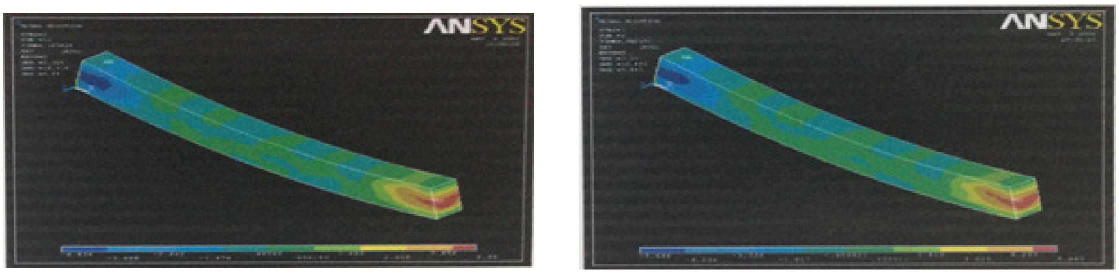

Figure 11 Stress Intensity pattern for ANSYS Model

12. RESULT AND DISCUSSIONS

The beam SH3 with volume fraction of fibres 1.5 and shear span to effective depth ratio(a/d) 1.5 gives high shear strength both experimentally and analytically and the beam SH4 with volume fraction of fibres 0.5 and shear span to effective depth ratio(a/d) 2.5 has lower shear strength both experimentally and analytically. Comparatively, the shear strength of beam SH3 is three times higher than SH4.

13. LOAD DEFLECTION CURVE

The deflection was measured at three points using the dial gauge, one at mid span and other two at nearer to the support. The deflection increased as the load increases. Deflection of 1.5% volume fraction beam is more compared to 0.5% and 1.0%. The maximum of 9.9mm deflection was obtained for the beam SH5, which is for 1.5% fibre content and shear – span to effective depth ratio of 2.5. Similarly, the deflection of 5.8mm and 7.2mm were obtained for beam SH3 and SH4 respectively as shown in Fig.12.

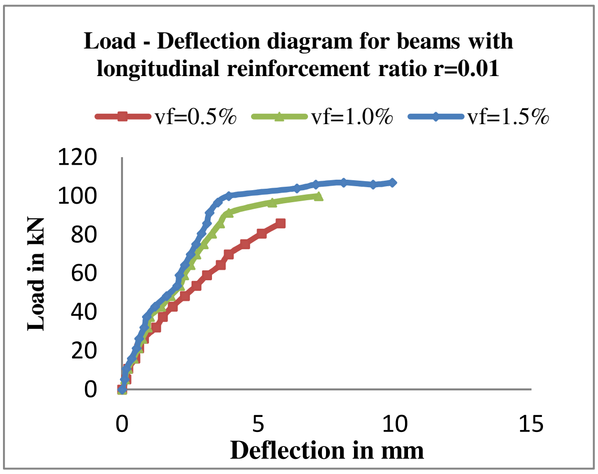

Figure 12 Load - Deflection diagram for beams with longitudinal reinforcement ratio r=0.01

Comparison of Analytical result with Experimental result

Experimental and Theoretical shear strengths were compared and its mean and variance is found as shown in Table.4. Variations of results of the six beams were plotted as shown in Fig. 13. The experimental shear strength is higher than analytical results.

Table 4 Comparison of Analytical result with Experimental result

Beam	v_f	a/d	V_{Exp} N/mm^2	Analytical value using ANSYS V_{anly} N/mm^2	V_{Exp} / V_{anly}
SH1	0.5	1.5	4.81	4.440	1.083
SH2	1.0	1.5	6.32	5.446	1.160
SH3	1.5	1.5	7.61	5.690	1.337
SH4	0.5	2.5	2.56	2.520	1.016
SH5	1.0	2.5	3.24	2.926	1.107
SH6	1.5	2.5	5.51	4.002	1.127
				MEAN	1.138
				VARIANCE	0.099

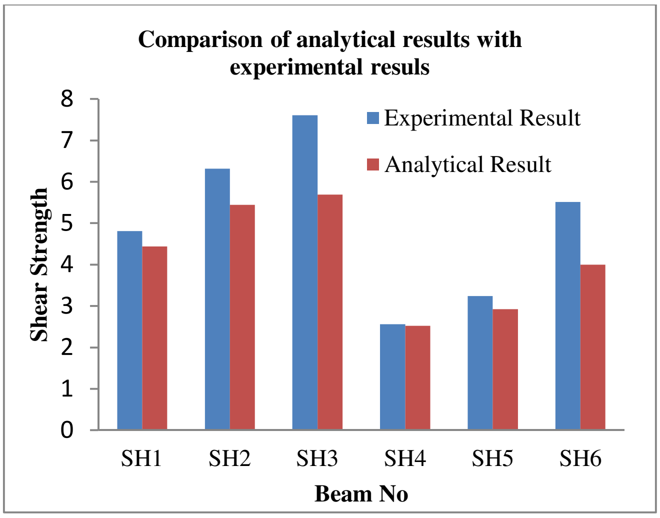

Figure 13 Comparison of analytical results with experimental results

14. CONCLUSIONS

From the above discussions, the following conclusions were made,

- The experimental strengths by various investigators with theoretical strengths calculated using the ACI equation were compared and the variance is equal to 0.404. Similarly, the variance of 0.376, 1.22, 0.352 and 0.182 were obtained by comparison with Samir A.Ashour, Shin, Madhusudan and Narayanan equations respectively.
- Results of experimental study on shear strength of HSSFRC beams are compared with the theoretical strength obtained using the proposed equations. The variances observed in the ratio between experimental to theoretical strengths are 0.248, 0.194, 0.28, 0.22 and 0.085 for ACI, Samir A.Ashour, Shin, Madhusudan, and Narayanan equations respectively.
- The equation developed by Narayanan et al. gives comparatively better theoretical strength than the other equations.
- Steel fibres are effective in increasing the shear strength of concrete. The ultimate shear strength of HSSFRC beams increases with increase in fibre content and concrete strength. Increasing fibre content 0.5% to 1.5% causes an increase in shear strength of 58% and 115% for shear span to effective depth ratio (a/d) = 1.5 and 2.5 respectively.
- Shear strength of beams increases with an increase of fibre content and decreases with shear span to depth ratio.
- Fibre addition in concrete restricts the propagation of cracks.
- Experimental shear strengths were compared with the strength obtained using ANSYS software. The mean and variance obtained for ratio between analytical and experimental strengths are 1.38 and 0.099 respectively.

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