Effect of cover on bond behaviour of fiber reinforced high strength concrete

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Abstract—Inclusion of steel fibers reduces the brittleness of high strength concrete. These fibers carry the circumferential tensile stresses, arrest the longitudinal bond splitting cracks and increase the bond strength. Experimentation was carried out to study the effect of increase in cover on bond strength of steel fiber reinforced concrete. It involved Pullout tests for different cover to bar diameter ratios. The steel bars of different diameters were selected for this study. Embedded length was kept constant for all the samples. Tests were conducted using linear variable displacement transducers and strain controlled universal testing machine. The results of the experimentation concluded that by increasing the (c/d_b) ratio bond strength increases for all the bar diameters. This increase was from 50% to78 % for pullout samples of 13.0 mm, 19.0 mm and 25.0 mm steel reinforcing bars. Moreover the failure was ductile showing a post peak bond yielding zone. The test results may have an implication of on cover provisions of fiber reinforced concrete in the building codes

Key words. Concrete key, Bond splitting cracks, Fracture process zone, Circumferential tensile bond stress, Cover to bar diameter ratio.

1 INTRODUCTION

Reinforced concrete can perform its intended structural function only when there is adequate bond between steel reinforcement and adjoining concrete. Shearing stresses at the bar concrete interface is transferred by this bond [1,2,3]. This bond strength depends upon a number of parameters. These include, cover to reinforcement, development length, concrete compressive strength and bar geometry [4,5,].

Cover to the reinforcement is an important parameter that affects the bond performance of plain and fiber reinforced concrete. [3,4]. When a structural member is loaded, due to difference of the stiffness, steel bar tries to slip relative to the concrete. As the adhesion and friction bond between steel and adjoining concrete fails, cracks develop along the steel bar and steel slips relative to the concrete[6,7] . In front of the ribs of the deformed steel bar, the concrete is crushed due to confinement provided by the cover and fiber reinforcement. This crushed concrete forms a wedge on which concrete key slips, experiencing a circumferential strain as shown in Fig.1 [8,9]. Tangential stress and circumferential tensile bond stress develop in the concrete key as shown in Fig.2[9].

Adequate cover to the steel reinforcement, reduces the magnitude of these circumferential tensile bond stresses. However, when these stresses exceed the tensile strength of the concrete, splitting cracks are initiated [9]. The propagation of these cracks depends upon the inclusion of steel fibers that arrest the splitting cracks through bridging action. Therefore, further bond energy is required for the propagation of these bond splitting cracks and post cracking resistance of the concrete increases. When the cover to the reinforcement is increased, then crack initiation load increases and subsequently bond strength improves. Inclusion of steel fibers also produces the post peak bond yielding. Therefore the brittleness of the bond failure of high strength concrete is reduced [12]. Moreover increased confinement reduced the uneven bond stress distribution along the short embedment length. Stress concentration on the front keys is reduced. Hence bond strength improves even before the fibers perform their function. As the first concrete key fails there is not a sudden drop in bond strength as incase of high strength concrete (HSC) [3].

Davies concluded that use of fibers (90.0 mm) result in higher average bond strength. The increase was less than the increase in $(fc')^{1/2}$ due to increase in fiber volume. Ezeldin and Balaguru concluded that bond strength increases when steel fiber volume is greater than 0.5% to 0.75%. Moreover, improvement was more for large diameters bars than smaller diameters bars. Soroushian concluded that there is 30.0% increase in bond strength for 0.5% by volume addition of steel fibers. However further increase in fiber volume does not increase the bond strength significantly. Harajli concluded that fibers have little effect on bond strength when specimen fail by pullout [10]

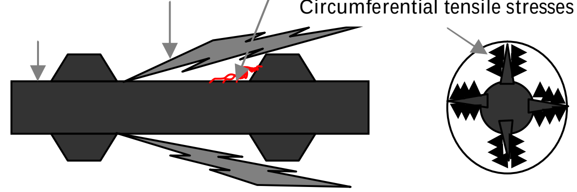

Fig.1. Longitudinal splitting crack formation [8,9,10]

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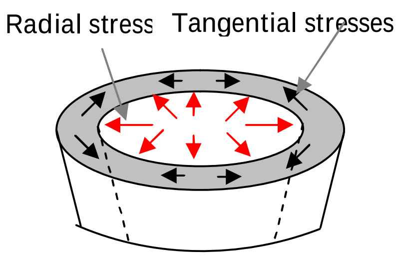

Fig.2 Stresses in concrete key

The objective of this research was to study the effect of confinement on bond strength of fiber reinforced high strength concrete (FRHSC) with small embedded lengths. Experimentation was carried out to determine bond strength of FRHSC. Since tensile strength is a direct function of bond strength, therefore its improvement due to fiber reinforcement was required to be determined. Pull out samples were used to study the bond strength. Steel fibers 1.0% by volume were used in the experimentation The cover/bar diameter (c/ d_b) ratio was varied for 13.0 mm, 19.0 mm and 25.0 mm bars. The results showed that by the inclusion of steel fibers, the bond strength of FRHSC increased from 50% to 78%

2. Fracture Mechanics Approach

The bond stress and slip relationship exhibited by high strength concrete samples showed an initial stiff response. This behavior is close to linear elastic fracture mechanics due to absence of strain softening and stress redistribution in high strength concrete. In pull out samples longitudinal splitting cracks initiate at much higher bond stress.

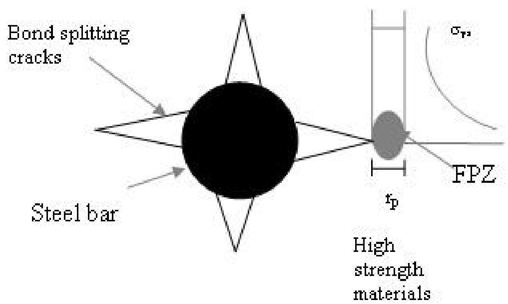

Fig.3: Fracture process zone in high strength concrete pullout samples [13]

This results in accumulation of a lot of strain energy in the material. The fracture process zone in front of these longitudinal splitting bond cracks would be small as shown in Fig.3 [13].

$$\sigma_{ys} = \frac{ki}{\sqrt{2 \pi rp}} \quad (1)$$

$$r_p = \frac{Ki2}{2\pi\sigma_{ys2}} \quad (2)$$

$$r_p \ \alpha \ \frac{Ki2}{\sigma_{ys}2} \quad (3)$$

σ_{ys} = Yield strength of material
r_p = Size of fracture process zone
K_I = Stress intensity factor

Once a crack forms at the interface due to slip between steel and concrete, all the accumulated strain energy is poured into it for the propagation of the crack. As this energy is more than the fracture energy required to create new surface, The crack propagates in unstable manner and leads to longitudinal splitting cracks This behavior of high strength material is mathematically given by David and Broek (1979) where size of fracture process zone is inversely proportional to square root of the yield strength of the material as shown by the equations given below [14,15,16]. However, with the inclusion of steel fibers, more bond energy is required to propagate these bond splitting cracks as these fibers stop the advancing cracks and increases the bond strength.

3. Methodology

In order to study the effect of steel fiber confinement on bond behaviour, pullout tests were planned. Embedded lengths, and compressive strengths of concrete, were kept constant and cover was changed. The steel fibers were added to the concrete during mixing. After testing the effect of steel fibers on bond behaviour of deformed steel bar was evaluated.

4. Experimentation

High strength concrete of compressive strengths 60.0 MPa was used in the experimentation. The compressive strength test of fiber reinforced concrete sample is shown in Fig.4 and the result is given in Fig.5. Micro silica and polycarboxylate ether were used to produce high strength concrete. PVC pipes were used to debond steel from concrete as shown in Fig.6. Hot rolled deformed steel bars as per ASTM A 36, having 420.0 MPa yield strength, were used in the experimentation. The geometric properties of these bars are shown in Tables 1 and 2. The testing scheme is shown in Table.3 Short embedded length of 4.5d_b was provided keeping in view the findings of a number of researchers, working on bond behaviour of high strength concrete. During concreting steel fibers were added after the addition of coarse aggregates and sand. These were distributed slowly and gently to avoid any ball formation. Immediately after pouring samples were covered with polyethylene sheets to avoid the loss of moistureSamples were cured in water and tested at 7, 14 and 28 days. Temperature of the water was 25^{o}C. The pullout sample before testing is shown in Fig.7.
Samples were gripped in a specially designed assembly having a hinge at the bottom to accommodate any eccentricity formed during pouring of the samples. This assembly is shown in Fig. 8. The testing was done in strain controlled ma-

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chine as shown in Fig.9. The post peak response was also recorded. All the samples failed by splitting as shown in Fig.10. Data was recorded at 50milli second interval.

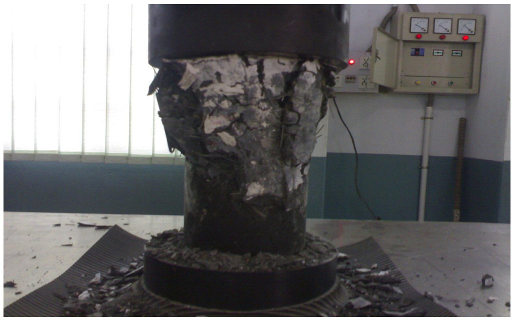

Fig.4. Compression test in UTM

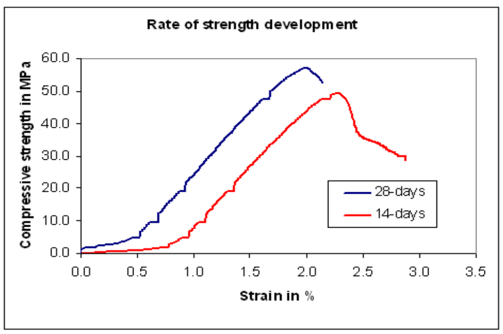

Fig.5 Compressive strengths of concrete

Fig.6. Steel bars for pull out test

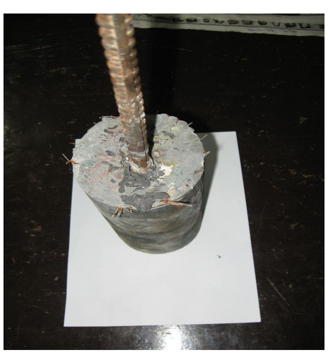

Fig.7.Pullout sample for test

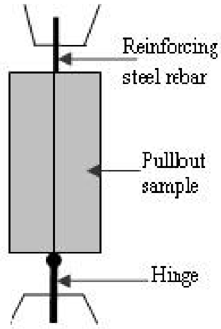

Fig.8 The pullout test assembly

Fig.9. Compression test in UTM

Fig.10. Formation of longitudinal splitting cracks

Table 1
Properties of13mm steel bar used

Bar Dia meter mm	Rib Height 'a' mm	Avg. Rib Width 'b' mm	Avg. c/c Rib spacing 'c' mm	Clear distance between ribs mm	a/c
13	1.2	1.905	7.39	4.944	0.16
13	1.36	1.86	7.97	5.029	0.17
19	1.48	1.79	7.97	4.944	0.18
19	1.51	1.83	8.02	5.573	1.08

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Table 2
Properties of pullout samples

S. No	Properties of pullout sample			
	Bar Diameter mm	Cover "c" mm	c/d$_b$	Development length
1	13	31.0	2.38	4.5d$_b$ = 58.5
2	13	43.5	3.35	4.5d$_b$ = 58.5
3	19	40.5	2.13	4.0d$_b$ = 78.0
4	19	40.5	2.13	4.5d$_b$ = 85.5
5	25	62.5	2.5	4.5d$_b$ = 85.5

5. Analysis of Results and Discussion

The bond stress was calculated by using the formula as shown below. The force required for the given slip in the strain controlled testing machine was measured from the data acquisition system of the machine. Then this force was divided by the bonded area of the steel bar present over the development length or embedded length.

$$\frac{A_b f_s}{\pi d_b l_d} = U_b \quad (4)$$

f_s = Steel Stress A_b = Area of steel bar
d_b = Bar Diameter l_d = Development length

The results of the pullout tests are given in Table 4. The bond behaviour of 13.0mm, 19.0mm and 25.0mm pullout sample is shown in Fig.11 to Fig. 14. It is clear from the results that for 13.0 mm bar, the bond strength increased by 50 % when cover was increased from 2.38 c/d$_b$ to 3.34 c/d$_b$ and there is further 50 % increase when cover was increased from 3.34 c/d$_b$ to 5.27 c/d$_b$. Incase of 19.0 mm bar, the bond strength increased by 75 % when cover was increased from 1.47 c/d$_b$ to 2.13 c/d$_b$ and there is further 42 % increase when cover was increased from 2.13 c/d$_b$ to 3.45 c/d$_b$. There is 78 % increase in bond strength when cover was increased from 1.0 c/d$_b$ to 1.5 c/d$_b$ and there is further 46 % increase when cover was increased from 1.5 c/d$_b$ to 2.5 c/d$_b$. It is concluded that bond strength increased by increasing the cover of pullout samples of steel fiber reinforced concrete.

Table 3
Increase in bond strength with increase in confinement

13.0 mm bar		19.0 mm bar		25.0 mm bar	
c/d$_b$	Bond strength MPa	c/d$_b$	Bond strength MPa	c/d$_b$	Bond strength MPa
2.38	12.15	1.47	7.2	1	5.4
3.34	18.34	2.13	12.6	1.5	9.63
5.28	24.88	3.45	18	2.5	14.1

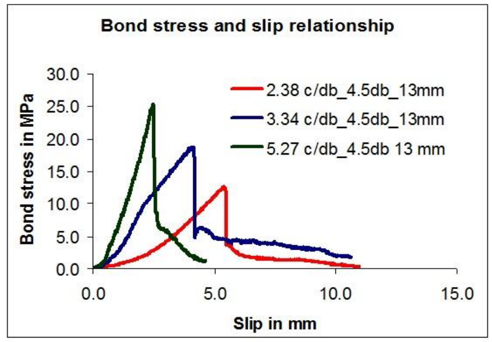

Fig.11. Bond behaviour of 13.0 mm bar samples

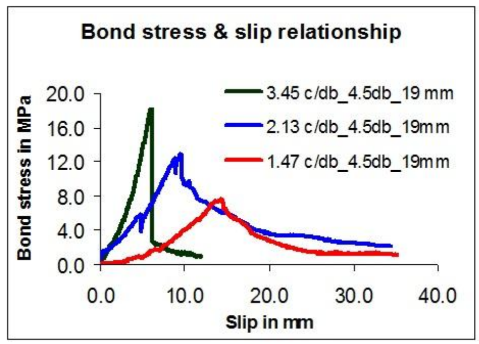

Fig.12. Bond behaviour of 19.0 mm bar samples

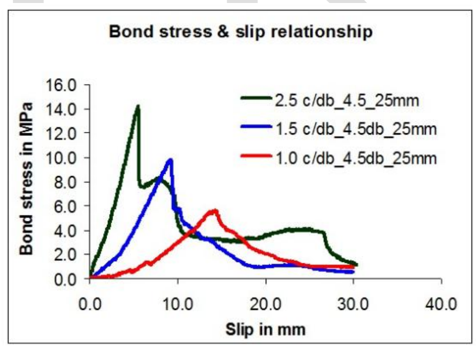

Fig.13. Bond behaviour of 25.0 mm bar samples

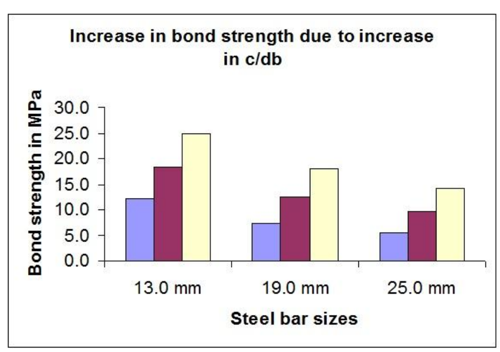

Fig.14 Bond strength for different bar diameters

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The initial bond response of the fiber reinforced concrete is linear however after the peak value it dropped. The mathematical equation to describe the initial response of the bond stress and slip relationships is given below. The values of the coefficients and co-efficient of co relation are given in the Table

$$u_c = \alpha s^2 + \beta s \qquad (5)$$

u_c = Bond Stress
s = Slip of the steel
α , β = Coefficients

Table 5
The vales of the co efficient for the pullout bond behaviour

S.No	Bar Dia meter	Co-efficient				Co-efficient of co-relation
	φ	"α"		β		R
		Min	Max	Min	Max	
1	13	0.01	0.40	0.04	1.0	0.9994
2	19	0.03	0.40	0.04	0.6	0.9990
3	25	0.02	0.20	0.005	1.5	0.9970

6. Comparison with Local Bond Constitutive Model

The post peak response represent the bond failure as given by the bond constitutive model given by Eligehausen et al (1983) (ascending part adopted by Comite- International du Beton- Federation International de la Precontrainte Model Code 1990). It shows that the response of the pullout samples is close to splitting bond failure and not to pull out bond failure. The reason for this behavior is that crushing of concrete in front of the ribs of the steel bar is insignificant and mainly the splitting of the concrete due to circumferential tensile bond stress took place. This local bond model is shown in Fig.27. This ascending part is mathematically given by Eligehausen et al (1983) and shown below. The descending part could not be determined in this set of experimentation[10].

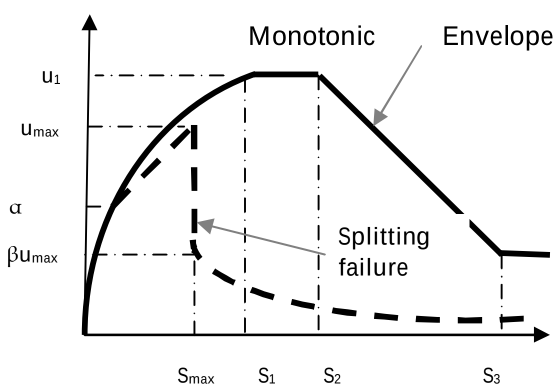

Figure 15. Bond constitutive model given by Eligehausen et al (1983)[10]

$$\frac{u}{u_1} = \left(\frac{s}{s_1}\right)^{\alpha} \qquad \text{For Ascending part of the curve (6)}$$

$$\frac{u}{\beta u_{max}} = \left(\frac{s}{s_{max}}\right)^{\alpha} \qquad \text{For descending part of the curve (7)}$$

u_{max} = maximum bond stress in splitting failure
S_{max} = maximum slip in splitting failure

α=0.7 For High strength concrete [6]
β=0.3 to 0.5 For High strength concrete [6]

Inclusion of the steel fibers increases the post cracking resistance of concrete in splitting bond failure. These fibers arrest the longitudinal splitting bond cracks and therefore increase the bond strength. In case of pullout bond failure, inclusion of fibers does not affect the bond performance because longitudinal splitting cracks are not formed in this type of failure. In all the above mentioned tests, confinement by the fibers increased the bond strength and changed the mode of failure of HSC from brittle to ductile.

7. Conclusions

1-In fiber reinforced high strength concrete, bond strength increases by increasing the cover of the concrete.
2-The increase in bond strength was up to 50% in 13.0mm bar pullout samples, 42% to 75% for 19.0mm bar samples and 46% to 78% for 25.0mm bars samples.
3-The mathematical model is given to describe this behaviour of fiber reinforced high strength concrete pullout samples of 13.0mm, 19.0mm and 25.0mm steel bar samles.3- The failure was ductile due to energy absorbed by the fibers while arresting the cracks.
4- When the results are compared with the bond constitutive model given by Eligehausen et al (1983) (ascending part adopted by Comite- International du Beton- Federation International de la Precontrainte Model Code 1990) for plain high strength concrete then it can be seen that for 13 mm bar, 19.0 mm bar and 25.0 mm bar splitting bond failure took place for the given confinements .

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