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Behavior of High-Performance Pull-out Bond Strength of Fibers Reinforced Concrete Structures

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ABSTRACT

The influence of steel fibers in bond strength attributes of fiber reinforced concrete is examined in this research. Concrete specimens with fiber contents of 0%, 1.0%, 2.0% and 2.5% by volume were tested. Thirty pull-out bond half-cylinder concrete mixes were prepared in order to examine the discrepancy in bond resistance owing to the disparity in percentage volume of steel fibers and the aspect ratio of the fibers. Each of the 30 half-cylinders were comprised of two matching half-cylinders; one with steel-fiber reinforced concrete containing different volumes of fibers with various aspect ratios and one containing plain concrete using reinforcement by placing a medium tensile steel bar in the center. Employing fiber-reinforced concrete instead of plain concrete showed a tangible increase in the interfacial force at the surface of the steel bar. The influence of steel fibers in augmenting the interfacial forces is assessed in percentage increase over plain concrete. A thorough experimental scheme has confirmed the proposed method using several variations of steel-fiber reinforced concrete samples.

KEYWORDS: Steel fibers, Plain concrete, Pull-out, Bond strength, Aspect ratio, Half-cylinder.

INTRODUCTION

The American Concrete Institute (ACI) has defined steel fiber reinforced concrete as: “concrete made of hydraulic cements containing fine or coarse aggregate and discontinuous discrete steel fibers” (ACI, 2009). Reinforcing concrete with steel fibers results in a useful construction material, especially when utilizing deformed steel fibers with an aspect ratio under 100 (Trottier and Bantha, 1994; Bentur and Mindess, 2009; Tsai et al., 2009). Steel fiber reinforced concrete can be a long-lasting material if correctly mixed and poured, which can improve the durability of structural members (ACI, 2009). In addition, this type of concrete has better flexural toughness (Wegian et al., 2011), is impact resistant and has the capability to endure more flexural fatigue and more fire resistance than ordinary concrete (Haddad and Ashour, 2008).

In general, fiber reinforced concrete has been used in a range of structures, including thin bridge deck overlays, marine structures and tunnel linings. Since it can reduce the thickness of construction members, which results in lighter structures, steel fiber reinforced concrete is a cost-effective building material (ACI,

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2009). Accordingly, this type of concrete is very suitable in constructions where permanent tensile reinforcement is not essential, such as in floor construction on grades, pavement, overlays, ground support and shotcrete linings.

Assessing the strength of flexural members supposes a seamless bond between concrete and its reinforcing steel. Usually, the tension stiffening capacity of concrete on the steel is neglected when evaluating the tensile strength of concrete. Tension stiffening is the capability of concrete to encompass tensile stress between two successive cracks and is related to the bond between concrete and steel. For plain concrete, the aspect of tension stiffening has been extensively researched. However, a bond phenomenon is complicated and equations for predicting theoretical bond strength are vague (Dei Poli et al., 1992). Empirical relations are available in the code and in literature involving bond strength and its relation to the compressive strength of concrete (ACI Committee, 2008; Haddad and Smadi, 2004; Haddad and Ashteyate, 2001).

It has been established that the presence of steel fibers in concrete will increase its tensile strength. It has been found that steel fibers arrest concrete crack and will markedly advance its static and dynamic properties (Soranakom et al., 2008). In addition, other properties of fiber reinforced concrete like fire resistance, flexural strength, compressive strength, fatigue endurance, impact resistance, ductility, abrasion resistance, deflection, … etc. have been extensively researched (Dejke, 2001; Wang and Lee, 2007). However, studies involving bond strength are few in literature (Chao, 2005; Harajli, 2010).

In spite of the research involved in the study of bond-slip behavior of fiber reinforced concrete, the processes of bond action and de-bonding which encompass both concrete and steel are still not entirely implicit. Thus, there is little agreement regarding method and model to describe the bond-slip behavior in structural analysis. As a consequence, there are insufficient design guidelines for bond behavior of rebars to fiber reinforced concrete and this is one of the reasons limiting their use in the field. In order to evaluate this bond behavior, experimental investigations using pull-out tests are commonly performed. These tests, using a strength testing machine, measure the force required to pull a steel rod insert from a concrete surface.

The bond strength is usually studied using the pull-out and flexural four-point load tests. The flexural four-point load test is more representative for the study of the overall bond behavior of the steel bars in structural members subject to moments. In this study, the bond strength of steel-fiber reinforced concrete using pull-out bond half-cylinders was experimentally studied. The experiment replicated concrete adjoining the reinforcing bar in the tension zone of flexural member flanked by two consecutive cracks. The length of the pull-out bond half-cylinder is defined as the distance between two consecutive cracks at the time when there is stable crack formation or when no more cracking transpires with additional loading. Further dimensions of the pull-out bond half-cylinder are contingent upon the effective cover adjusted to the reinforcing bar.

EXPERIMENTAL REGIMEN

The experimental regimen entailed casting and then testing 30 pull-out bond half-cylinders of steel-fiber reinforced concrete of even cross-sections with changing volume percentages of steel fibers and with several values of aspect ratios of the same fibers. A control short cylinder of 150 mm length and 150 mm diameter was separated into two matching test samples of half-cylinders of 150 mm length and 150 mm diameter with a half-circle cross-section. Steel fibers with a diameter of 0.5 mm with aspect ratios [Ar = fiber (length/diameter)] of 0, 30, 60 and 90 were used. In addition, four different volume percentages of steel fibers [Ff = weights of (fibers/cement)] were used as shown in Fig. 1. These percentages were 0%, 1.0%, 2.0% and 2.5%. The steel fibers used had a yield strength of 250 MPa and a modulus of elasticity of

194.2 GPa. A high tensile strength steel bar was used for reinforcement. The bar, which was 10 mm in diameter and 450 mm in length, was placed in the center of the specimen. The bar extended outside the specimen by 15 mm at the bottom and by 285 mm at the top. This extension outside the specimen was necessary for fixing the specimen in the testing machine and for measuring strain. The remaining 150 mm bar length was covered inside the specimen. The modulus of elasticity of the high tensile strength steel bar was 206 GPa and its proof strength was 358 MPa. Table 1 lists the specifics of each test specimen.

Figure 1: Steel fibers

Table 1. Pull-out bond half-cylinder details

Specimen #	Half-cylinder details			Steel fibers	
	Length (mm)	Radius (mm)	Reinforcement (mm)	Volume fraction (%)	Aspect ratio
P0.0-00 (control)	150	75	10	0.0	0.0
P1.0-30	150	75	10	1.2	30
P1.0-60	150	75	10	1.2	60
P1.0-90	150	75	10	1.2	90
P2.0-30	150	75	10	2.4	30
P2.0-60	150	75	10	2.4	60
P2.0-90	150	75	10	2.4	90
P2.5-30	150	75	10	3.0	30
P2.5-60	150	75	10	3.0	60
P2.5-90	150	75	10	3.0	90

SPECIMEN CASTING

The steel molds of the control short cylinders were 150 mm in length and 150 mm in diameter. The molds were prepared using a 25 mm-thick wooden base. Two holes were drilled in the wooden base with a diameter of 11 mm, a depth of 15 mm and 75 mm apart and the center of gravity was coincident with the center of gravity of the circular mold base. These holes were drilled in order to support the two bars when casting the two adjacent specimens and allowed the embedded bar to extend 15 mm beyond the bottom in order to take strain measurements. To obtain equal half-cylinder specimens, 150 mm x 150 mm x 6 mm Perspex sheets were placed vertically in the mold in order to divide the cylindrical space into two equal partitions. To ensure that reinforcing bars inside the specimens were completely vertical, a 350 mm x 50 mm x 6 mm mild steel clamping plate was used with two drilled holes of 10 mm diameter and 75 mm apart to support the bars at the top during casting.

The concrete mix used for casting the test specimens had a weight proportion of 1: 1.75: 3.5 (ordinary Portland cement: fine aggregate sand: crushed granite coarse aggregates). The aggregate used had a maximum nominal size of 12.5 mm and a water-cement ratio of 0.47. The steel fibers were added to the dry mix while mixing thoroughly to make sure that there was uniform distribution. To this mixture, water was later added while mixing manually. The steel-fiber reinforced concrete was then poured in the molds and compacted manually with a compacting rod. Supplementary specimens comprising of 150 mm cubes were cast at the same time for each concrete mix batch in order to establish the compressive strength of the mixes. The cubes were then manually compacted. Then, 24 hours after casting, the specimens were removed from their molds and immersed in a curing tank holding potable water for 28 days. After curing, the specimens were removed and white washed in preparation for testing.

SPECIMEN TESTING

Using a tensile testing machine with a 50 kN capacity, the specimens were tested under direct tension with a minimum force of 0.5 kN. A custom steel frame layout was used that cosisted of two square, mild-steel plates (400 mm x 400 mm x 20 mm) and four custom bolts with a diameter of 25mm and had a length of 400 mm. Two of the plates had four holes drilled in the corners in order to connect the two plates with four bolts. The bottom plate had a distinct design so it could be attached to the fixed capping of the machine. The top plate had an extra hole drilled in the center in order to allow free movement of the reinforcing bar used in the specimen. This top plate was attached to the flexible capping of the testing machine. The steel frame was designed with adequate stiffness so as not to indicate relative displacement under the applied load. The entire layout was safeguarded from any vibration.

The vertical deformation of the concrete was monitored at two different points using two mechanical dial gauges with a 25 mm travel. In order to measure the extension strain of the reinforcing bar, two Demec gauges were attached to the reinforcing bar, close to the upper face of the specimen. To detect any crack formation, a magnifying glass was used. After fastening the rebar in the chuck of the tensile testing machine, the load was enforced on the reinforcing bar. The tensile force was applied in increments of 0.5 kN. The Demec and dial gauge readings at each load increment were logged. For every variation in parameter, the readings for three specimens were averaged. Elongation of the embedded steel bars, concrete deformation and the slip values for the specimens were inferred from the averaged readings. From the start of the loading until collapse, the appearance and performance of the specimens were scrutinized. At the same time the pull-out testing was being conducted, the previously cured concrete cubes were tested in compression. This was carried out to determine the compressive strength of the concrete mix batch that was used for the specimens.

RESULTS AND DISCUSSION

Table 2 and Figure 2 show the results gathered from experimental tests to investigate the pull-out bond strength of steel-fiber reinforced concrete in contrast to the control specimens. By dividing the load needed to induce a precise amount of slip caused by the surface area of the bar in contact with the concrete, a bond force per unit area of rebar surface is attained. From the test results, it can be seen that the failure values of the pull-out bond loads were found to increase with increasing values of steel-fiber volumes (Ff), the aspect ratios of the fibers (Ar) increase as well. As the volume of steel fibers increased, the failure values of the pull-out bond loads were found to increase for the same value of aspect ratio. As shown in Table 3, for an aspect ratio of 30, the increase ranged from 23% to 75%, for a ratio of 60, it ranged from 28% to 120% and for a ratio of 75, it ranged from 34% and 149%. It can clearly be seen from these results that the rate of pull-out bond strength is increasing as the aspect ratio increases.

In addition, the failure pull-out bond loads were detected to increase for the same volume of steel fibers as the aspect ratio increased. As shown in Table 3, the increase ranged from 23% to 34% for a steel fiber volume of 1.0%, from 53% to 96% for a volume of 2% and from 75% to 149% for a volume of 2.5%.

An empirical model for the relationship between the bond strength (Fb), the percentage fiber (Ff) and the fiber aspect ratio (Ar) can be written as follows:

$$Fb = A * Ff^{3} + B\, Ff^{2} + C\, Ff + 2.7948$$

Table 2. Test result details

Specimen #	Failure Bond Loads (kN)				Bond strength (MPa)	Max. slip (mm)	Comp. strength (MPa)
	P1	P2	P3	Pavg			
P0.0-00 (control)	13.50	13.00	13.00	13.17	2.7948	0.094	23.556
P1.0-30	16.20	15.60	16.80	16.20	3.4378	0.116	28.090
P1.0-60	16.80	18.00	15.60	16.80	3.5651	0.120	28.445
P1.0-90	16.80	18.60	17.70	17.70	3.7561	0.126	28.622
P2.0-30	20.10	20.40	19.80	20.10	4.2654	0.144	29.333
P2.0-60	22.20	22.20	23.40	22.60	4.7959	0.161	30.400
P2.0-90	26.40	25.20	25.80	25.80	5.4750	0.185	30.934
P2.5-30	22.80	23.40	22.80	23.00	4.8808	0.164	30.578
P2.5-60	27.60	30.60	28.80	29.00	6.1541	0.208	31.466
P2.5-90	34.20	31.20	33.00	32.80	6.9605	0.234	31.289

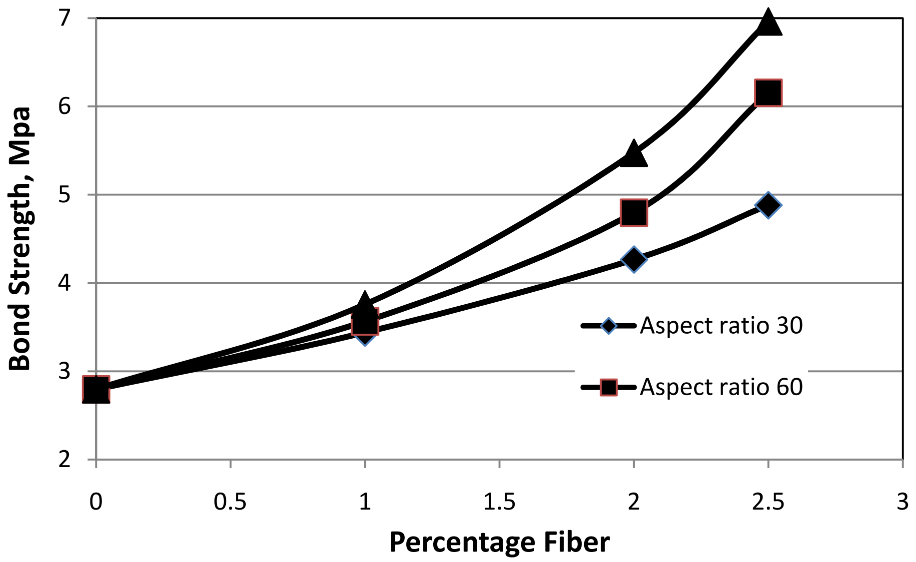

Figure 2: Effect of fiber content on bond strength

where the parameters A, B and C are functions of the fiber aspect ratio (Ar) as follows:

$A = -0.0002\ Ar^2 + 0.0255\ Ar - 0.5181$

$B = -0.0006\ Ar^2 + 0.0725\ Ar - 1.5189$

$C = -0.0004\ Ar^2 + 0.0481\ Ar - 0.4217$

This model fully represents the above data and can be used to estimate the bond strength at any percentage of fiber and aspect ratio.

It is also apparent from these results that the pull-out bond strength between the reinforcing bar and the adjacent concrete depends on the bond between the steel fibers and concrete. The capacity of the steel fibers to allocate tensile forces between cracks increases as the aspect ratio of the fibers (length of the fibers) increases. There is a substantial increase in the bond strength of steel-fiber reinforced concrete with increasing volumes of steel fibers regardless of the aspect ratio. Although still increasing, the increase in the cube compressive strength is not as pronounced for all the variants of the steel fiber volumes or the aspect ratios of the fibers. Comparing the pull-out bond strength values to the cube compressive strength in Table 3 shows that as the steel fiber volumes increase, the aspect ratios of the fibers increase for the same concrete batch. The pull-out bond strength to the cube compressive strength ratios range between 12% to 22%. Consequently, it can be deduced that the increase in the pull-out bond strength of the half-cylinder specimens is due to the increase in the volume of steel fibers and the increase in the aspect ratio of the fibers.

Slip is attained by measuring the variance in deformation of the concrete and the reinforcing bar. Certain slip resistance characteristics can be observed from the recorded values; as the aspect ratio of the fibers and the volume of the fibers increase, the slip resistance increases inducing greater bond strength. The addition of steel fibers undoubtedly causes this increase in the bond strength of concrete. Functioning as crack arrestors, the steel fibers strengthen the concrete by transferring stress across any occurring crack. This phenomenon consequently leads to a stronger clasp of concrete on steel and an increase in bond strength. Ultimately, the experiments showed that all the pull-out specimens failed by slippage of the reinforcing bar from the concrete due to bond failure.

Table 3. Influence of steel-fiber reinforced concrete on f_b, f_c and slip

Specimen #	Increase in Fb (%)	Increase in Fc (%)	Fb/Fc (%)	Increase in slip (%)
P0.0-00 (control)	0.0	0.0	11.9	0.0
P1.0-30	23.0	19.2	12.2	23.4
P1.0-60	27.6	20.8	12.5	27.7
P1.0-90	34.4	21.5	13.1	34.0
P2.0-30	52.6	24.5	14.6	53.2
P2.0-60	71.6	29.1	15.8	71.3
P2.0-90	95.9	31.3	17.7	96.8
P2.5-30	74.6	29.8	16.0	74.5
P2.5-60	120.2	33.6	19.6	121.3
P2.5-90	149.1	32.8	22.2	148.9

CONCLUSIONS

Based on the results of this study, an empirical model was developed to describe the relationship between the bond strength, the percentage fiber and the fiber aspect ratio. The model shows the following conclusions:

1. The addition of steel fibers to concrete strengthens the bond between the reinforcing bar and the concrete.
2. Increasing the volume of steel fibers increases the bond strength between the concrete and the reinforcing bar.
3. Increasing the aspect ratio of fibers for a given volume of fibers increases the bond strength of steel-fiber reinforced concrete.

In addition to the above-mentioned points, the following conclusions can also be drawn:

4. The compressive strength of concrete increases by adding steel fibers to the concrete.
5. The pull-out bond strength to the cube compressive strength ratios range between 12% and 22%.

Abbreviations

Ar: Aspect ratio of steel fibers (length/diameter).

Ff: Volume of steel fibers (by percentage weight of [fibers/cement]).

Fb: Pull-out bond strength.

Fc: Cube compressive strength.

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