Materials Research, Vol. 11, No. 4, 453-457, 2008

Analysis of the Relative Rib Area of Reinforcing Bars Pull Out Tests

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Received: June 23, 2008; Revised: December 11, 2008

The good performance of reinforced concrete structures is ensured by the transfer of stress linking a reinforcing bar and the surrounding concrete. The bond steel-concrete is a very complex phenomenon. This paper presents the experimental results of a program with specimens used in the pull out test with concrete strength of 20, 40, 60, 80 and 100 MPa and four different steel diameters: 12.5, 16.0, 20.0 and 25.0 mm. The test results indicated that the bond stress varied with the bars rib face angle, rib spacing, and rib height. The trends of the results were independent of the concrete strength with the test results, and design recommendations made as regards optimum rib geometries of deformed bars with high bond-slip characteristics.

Keywords: *bond stress, pull out test, reinforcing steel, rib geometries*

1. Introduction

The behavior of the bond between the steel reinforcement and the concrete enveloping the bar is of fundamental importance in relation to the load capacity of the structural concrete. Knowledge of this is imperative to ascertaining anchorage lengths, the lap splices, tension stiffening between cracks and other important factors for the structures[1,2,3,9].

The concrete strength is the main parameter that influences the anchorage length and the transmission of tensions concentrated on the bars ribs. Other factors that influence the bond stress are the roughness and/or irregularities on the bar surface; the diameter of the bars; type and positioning of the ribs.

1.1. Factors that influence the bond

The main factors that influence the steel-concrete bond[1]:

- **Strength of the concrete:** The analyses of fly ash conducted by most authors indicate that its presence increases the strength and the bond of the concrete. The increase of the strength of the bond is attributed to the compacted concrete and the reduced thickness of the transition zone between the concrete and the reinforced concrete.
- **Diameter of the bars:** An increased diameter of the reinforcement reduces the maximum bond stress. Such fact is explained by the thickness of the transition zone, thicker on the bars of larger diameter. The diameter, along with larger dimensions of the ribs holds more water under the bar providing a thicker transition zone, making it more porous and facilitating the crushing for rib compression. This variable is considered less important since the thickness and the anchorage length are multiples of the bar diameter[11,12].
- **Loading Age:** The loading age influences the bond in the same way as the mechanical strength of the concrete[4].
- **The Production of the Concrete:** The production influences the bond in the same way as the strength of concrete.

This paper presents the results of pull out tests of different concrete strengths: 20, 40, 60, 80 and 100 MPa and four different steel diameters: 12.5, 16.0, 20.0 and 25.0 mm and design recommendations were made concerning optimum rib geometries of deformed bars with high bond-slip characteristics.

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2. Studying the Bond

The bond is the connection between the reinforcement and the concrete which prevents slipping between these two materials. Therefore, the materials are deformed together resulting in the effort being transferred from one to the other, that is to say, whenever the stress in the bar varies, be it due to compression or due to traction, and supposing the bond stress is developed throughout the bar, there will be a transfer of effort between the bar and the concrete.

For smooth bars, where rupture from slipping occurs, the bond is mainly consists of chemical adhesion between the cement paste and the bar; when that connection is broken, strength appears in the slipping due to friction, the intensity of which depends on the surface type of the bar. In these kinds of bars, a mechanical bond can appear between the concrete and the steel due to the irregularities on the surface. Therefore, the force capable to break the bond is proportional to the area of the bar in contact with the concrete where the adhesion occurs; friction and surface type are verified.

In the case of other bars (rib bars) the strength in the slipping is due, mainly, to the strength that the concrete offers to the pressures exercised on it by the ribs, that means, to the mechanical action between the concrete and the ribs. The effect of the chemical adhesion, in this case, is minor and the friction does not occur until the reinforced steel is displaced.

When traction efforts are applied to reinforced steel, traction and compression efforts are produced in the concrete that become a main stress of traction and of compression, respectively. Therefore, the maximum value of the bond stress is limited by the smallest value of the main stress (traction or compression). When one of those stresses is exceeded in the concrete due to the application of a traction effort in the reinforcement, this ruptures the mechanical bond.

In ribs bars the traction force in them is transferred to the concrete by the ribs. The radial components of the forces of the ribs spread along the concrete perpendicular to the axis of the bar increase with the bond stress that can be regarded as the longitudinal component of the resulting force exerted by the ribs in the concrete. The resulting force forms an angle in relation to the axis of the bar (see Figure 1). The radial component of the force exerted in the concrete generates internal pressure-inducing traction tensions, in the form of rings, that cause bursting fissures along the anchored bar. When the rings are loaded to the point of rupture, longitudinal fissures appears. However, these can begin as longitudinal fissures invisible on the surface of the concrete before the maximum capacity of load is reached. As a longitudinal fissure appears, they increase the displacement between the bar and the concrete and the bond stress is transferred along the anchorage length to where the fissures appear. The radial components of the strength of the bond impose a load and when they are loaded to maximum capacity, they break suddenly[14].

The bond can be described ideally as a shearing stress between the surface of the reinforcement and the concrete that surrounds it. That mechanism is determined by means of the relative displacement between the reinforcement and the concrete.

3. Experimental Investigation

The study of the bond is presented by the relationship between the bond stress and the slipping of the reinforcement. The former is identified by the shearing stress in the intercession reinforced-concrete and, the latter, by the relative displacement between the reinforcement and the concrete.

The experimental program with specimens used in the pull out tests with concrete strengths: 20, 40, 60, 80 and 100 MPa and four different steel diameters: 12.5, 16.0, 20.0 and 25.0 mm[2,3] were made.

The pull out test is the most traditional bond test and it consists of the extraction of a bar, usually positioned in the center of a specimen test cubic of concrete. This method enables calculation, according to RILEM (CEB (1983)), of the values of the medium and maximum bond stress for each bar diameter used in the different strength concretes, so as to compare them with the values of given standards, as well as to trace curves representing the characteristics of bond stress x slipping.

3.1. Materials

Concrete: The chemical and physical analyses of the cement are listed in Table 1. River sand and gneiss gravel aggregate are used. The fineness modulus of aggregate is 2.52 (for river) and 5.75 (for gneiss); and the maximum diameters are 2.4 and 9.5 mm, respectively. The superplatifized are used RX 4000 REAX. Table 2 shows the mixture proportions of concrete (cement: sand aggregate: gravel aggregate: water/cement factor) are used in order to obtain an approximate compressive concrete strength at 28 days of 20, 40, 60, 80 and 100 MPa. The concrete specimens undergo the pull out test at the age of 90 days.

Steel bars: Table 3 and Table 4 show the characterization of reinforcing steel for all steel bar diameters. The relative rib area reinforcing bars are prescribed in CEB[5,6,7] and EUROCODE[8]. If relative rib area reinforcing bars (f_R= 0.056)) attain the minimum prescribed value in the standardizations[5,8], the steel bars are considered to be of high bond stress.

3.2. Items of investigation

Tests were conducted on concrete of four different reinforcement diameters and five different concrete strengths according to the pull out test[5]. As many as eight specimens are made for each diameter and concrete strength. At the age of 90 days, concrete specimens are tested and medium bond stress, rupture bond stress and maximum slipping are obtained, as illustrated in Table 5 and Figures 2 to 5.

4. Experimental Results and Discussion

The ribs angle of reinforcement bars proposes[6,7] between 55° and 65° but several authors give the value 55°. For Brazilian steels with nominal diameters 12.5, 16.0, 20.0 and 25.0 mm, this angle is 46°, 46°, 45° and 50°, respectively. The angle of the 25.0 mm bar is better than when one considers the rib spacing and rib height for such high strength concrete.

In order to obtain an equation that represents the results for relative rib area reinforcing in function of the rib angle, the rib spacing and of the rib height for the higher bond stress a regression was used. Equation 1 represents the analysis.

Equation 1: Relative Rib Area Reinforcing Bars

$$f_R = -0.0274 - 0.0049\phi + 0.0024\beta + 0.0028h_R - 0.0091S_R \quad (1)$$

(Error = 0.0, R^2 = 1.0)

The data of Table 5 shows:

- If the strength of concrete increases, the bond stress increases because there is a decrease in the porosity to transition zone between aggregate/paste - reinforcement/paste;

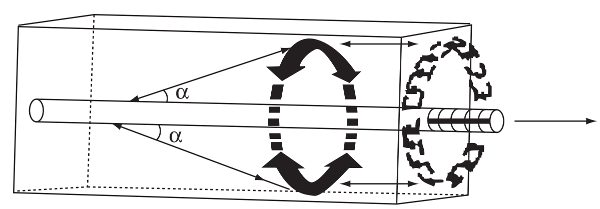

Figure 1. Representation of the radial component of by strength bond in the anchorage zone (Tepfers, 1979).

Table 1. Physical and chemical compositions of Portland cement – type V.

Properties	CPV
Specific gravity (mm)	4.6
Fineness modulus	4.59
CaO/SiO_2	2.67
CaO (%)	60.56
SiO_2 (%)	22.68
MgO (%)	1.94
Al_2O_3 (%)	6.53
SO_3 (%)	0.14
K_2O (%)	0.73
Fe_2O_3 (%)	2.58

Table 2. Concrete mixture proportions and the strength of concrete.

f_c, MPa	Mixture proportions	Silica fume	SP (%)	f_c28, MPa	f_c90, MPa
20	1: 2.927: 3.933: 0.786	0	0	33.44	33.63
40	1: 1.682: 2.631: 0.523	0	0	51.71	54.77
60	1: 1.219: 1.828: 0.392	0	0	61.49	63.31
80	1: 1.219: 1.828: 0.391	0.12	2.5	79.98	83.24
100	1: 0.884: 1.542: 0.348	0.12	2.5	100.89	105.44

- Slipping had been a strong influence of strength of concrete[10,13] and if the diameter of steel bar increases, the slipping increases, see Figure 6.

In order to obtain an equation that represents the results for medium and maximum bond stress in function of the concrete strength and of the diameter of the bar, for Brazilians materials, a regression was used resulting in Equations (2) to (5).

Strength of concrete ≤ 50 MPa (7.25 ksi):

$$\tau_M = 0.663e^{0.086\phi}e^{0.006f_c} \text{ (Error = 1.1 MPa; R² = 0.9317)} \quad (2)$$

$$\tau_R = 0.774e^{0.115\phi}e^{0.029f_c} \text{ (Error = 1.1 MPa; R² = 0.9820)} \quad (3)$$

Strength of concrete > 50 MPa (7.25 ksi):

$$\tau_M = 3.377e^{0.059\phi 0.005f_c} \text{ (Error = 1.1 MPa; R² = 0.9492)} \quad (4)$$

$$\tau_R = 2.519e^{0.114\phi 0.006f_c} \text{ (Error = 1.1 MPa; R² = 0.9653)} \quad (5)$$

5. Conclusions

Based on the analysis of the test results of pull out specimens, it is concluded that:

- If the strength of concrete increases, bond stress increases because there are reductions in the transition zone with the silica fume addition;
- Slipping was proportionally relative to the strength of the concrete and the bar diameter, i.e., when concrete strength and bar diameter increase the slipping increases;

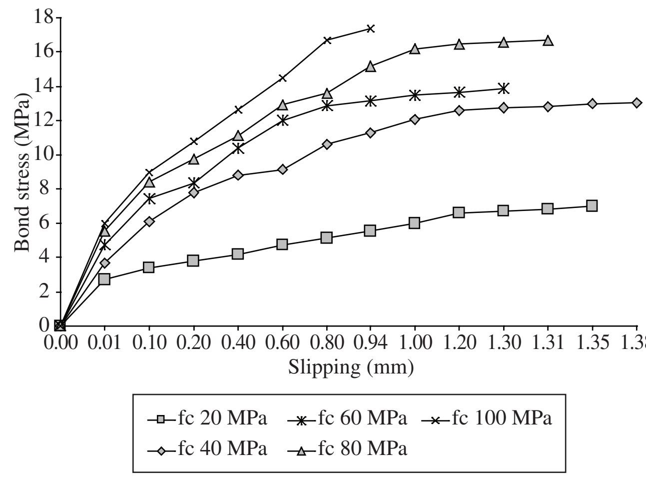

Figure 2. Bond Stress vs. Slipping (ϕ = 12.5 mm).

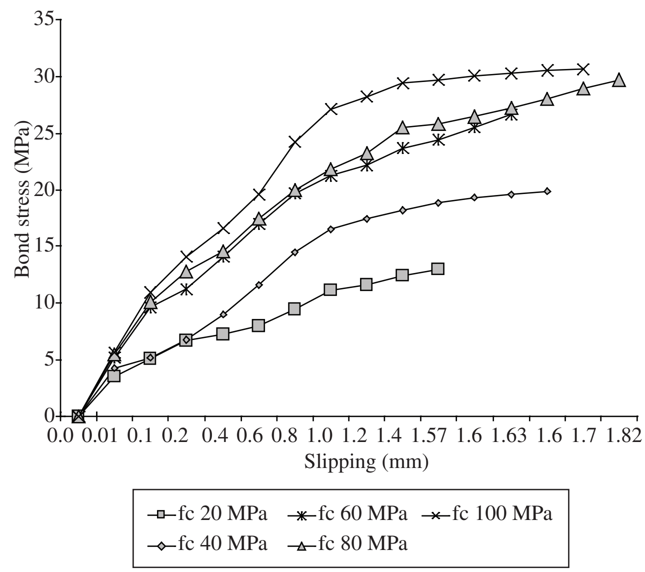

Figure 3. Bond Stress vs. Slipping (ϕ = 16.0 mm).

Table 3. Characterization of steel bars.

ϕ (mm)	f_y,MPa	f_{yd},MPa
12.5	565.3	782.5
16.0	626.9	744.8
20.0	529.0	841.8
25.0	618.6	721.6

Table 4. Characterization of steel bars (rib's bar).

ϕ (mm)	β (°)	h_R, cm (% ϕ)	S_R, mm (% ϕ)	f_R calculated	f_R minimum
12.5	46	0.12 (9.0%ϕ)	0.84 (70%ϕ)	0.071	0.056
16.0	46	0.16 (9.0%ϕ)	0.92 (62%ϕ)	0.082	0.056
20.0	45	0.18 (9.0%ϕ)	0.17 (64%ϕ)	0.077	0.056
25.0	50	0.25 (9.0%ϕ)	1.57 (70%ϕ)	0.079	0.056

Table 5. Medium bond stress, rupture bond stress (MPa) and maximum slipping (mm) in the pull out test.

f_c (MPa)	Diameter of bar, mm											
	12.5			16.0			20.0			25.0		
	τ_M	τ_R	S	τ_M	τ_R	S	τ_M	τ_R	S	τ_M	τ_R	S
20	4.03	6.98	1.35	6.59	12.9	1.57	7.17	16.8	2.10	13.2	32.0	2.21
40	7.27	13.0	1.38	8.65	19.9	1.66	12.7	36.7	2.12	18.6	52.5	2.32
60	8.56	13.9	1.30	12.0	26.6	1.63	15.5	40.0	1.55	19.6	x	2.00
80	10.0	16.7	1.31	12.5	29.7	1.82	17.6	46.0	1.80	19.9	x	2.01
100	10.8	17.4	0.94	14.6	30.6	1.70	19.4	48.5	1.70	21.5	x	2.20

x – Not rupture with 60 MPa is the maximum capacity of equipment.

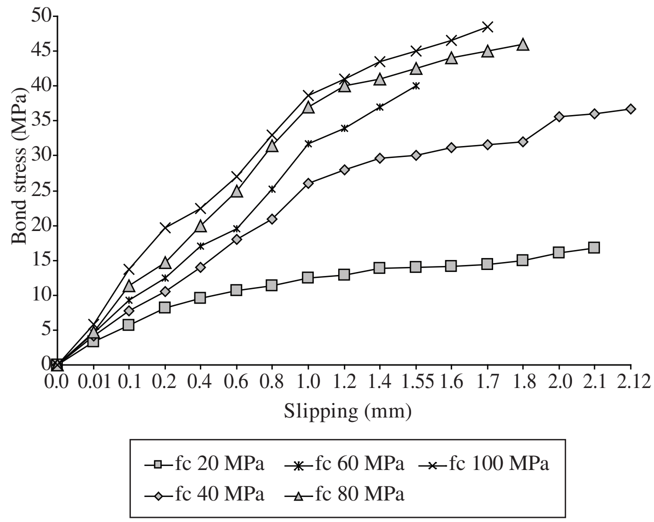

Figure 4. Bond Stress vs. Slipping (ϕ = 20.0 mm).

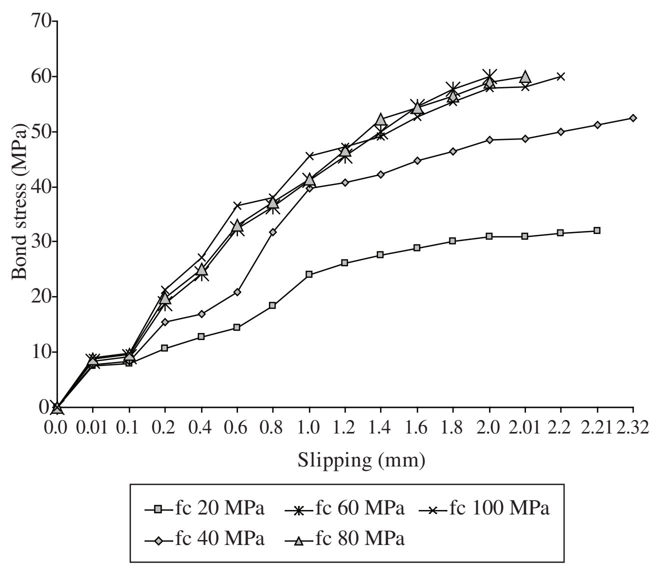

Figure 5. Bond Stress vs. Slipping (ϕ = 25.0 mm).

- The bar with a rib angle of 47° developed the greatest bond stress for Brazilian materials. The others authors obtained 55°;
- The bar with a rib spacing of 70%ϕ and a rib height equal to 9%ϕ developed greater bond stress, according the results obtained in this research;
- Equation (1) identified good results for bond stress, especially for high strength concrete. It's possible to substitute the terms prescribed in the international and Brazilian standard;
- If the diameters of the bars and strength of the concrete increase, the bond stress increases. In this case, concrete vibration is the most important factor. Many authors'[11,12] state the opposite because their research was concerned with the transition zone between aggregate/paste – reinforcement/paste. The high performance concrete tends to entrap large air pockets and bubbles that must be eliminated by internal or external vibration;

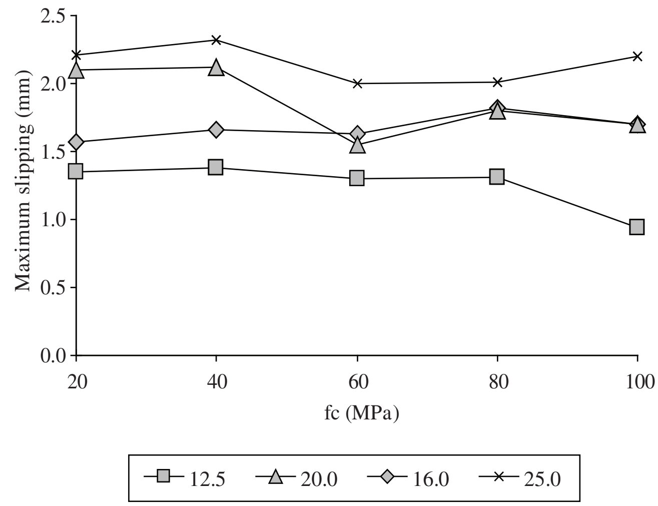

Figure 6. Maximum slipping vs. strength of concrete.

- The equation for medium bond stress and maximum bond stress are proposed in virtue of the bar diameter and the concrete strength for Brazilian materials.

Acknowledgements

The authors would like to thank the Brazilian HOLCIM for their financial assistance during the construction and testing of the specimens.

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Nomenclature

CPV = Portland cement type V (Brazilian standard);
ϕ = diameter steel bar;
f_R = relative rib area;
f_c = compressive strength of concrete;
f_c28 = compressive strength of concrete at 28 days of age;
f_c90 = compressive strength of concrete at 90 days of age;
h_R = rib height;
S_R = rib spacing;
S = maximum slipping;
SP = superplastized;
β = rib face angle;
τ_M = medium bond stress (Equation (2) and (4));
τ_R = rupture bond stress (Equation (3) and (5)).