The role of cover and rebar characteristics on load-slip behavior of reinforced concrete members in compression

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Abstract. This paper describes a part of an extensive research work devoted to evaluate the bond strength between rebars and concrete through different testing procedures. Main parameters in this part are the concrete cover and rebar diameter. The tested specimen consisted of a single bar embedded in a concrete block with square cross-sectional area and is being tested under compressive load. Three concrete block sizes were cast to offer three different cover for the embedded rebars. The dimensions of these blocks were; 150×150×135, 100×100×135 and 200×200×185 mm. Three bar diameters, 12, 16 and 20 mm, were investigated. The specimens were water-cured and tested at the ages of 7 and 28 days. A new proposed test set-up was used to monitor the load-slip behavior of the specimens. The test results showed that there is no significant difference in bond energy between the two curing ages, 7 and 28 days. The concrete cover has a significant effect on the bond strength between rebar and concrete. By increasing the cover, the confinement offered by concrete increases, bond strength increases, and slip increases. Based on the present results, a concept of effective cover was developed. This concept showed a high correlation with the mode of failure for the tested specimens.

1 Introduction

The bond between reinforcing bars and concrete has been known as a key parameter to a proper performance of reinforced concrete structures. For many years, bond strength was represented in the term of shear stress at the interface between bar and surrounding concrete. The transfer of axial force from a reinforcing bar to the surrounding concrete results in the development of tangential stress components along the contact surface. The stress acting parallel to the bar along the interface is called the bond stress. The term bond is represented as a structural property [1]. In reinforced concrete structures the real value of force transferred between bars and concrete is required for optimal design [2]. The transfer of forces is depending on the chemical adhesion between bar and concrete, frictional forces and bearing of the front key (concrete between two ribs) against shear forces [3]. The bond behavior is decisively determined by the behavior of concrete close to the rib [4]. The simplest model representing the stress transfer between steel and concrete is so called "friction concept" whereby the shear stress that develops along the lateral surface (bond stress) is a function of the normal confining pressure exerted by the surrounding concrete on the bar surface and concrete cover. Higher the confining pressure higher the frictional force required for bond failure and higher the strength reserves of splitting failure [5]. When the first concrete key fails, there is a sudden drop in bond strength due to the formation of

longitudinal splitting cracks which are visible from the surface of the specimen. Therefore, if there is an adequate confinement (cover) available, the tension stiffening effect reduces the sudden drop in bond strength. As the concrete ages, the compressive strength increases, so the bond stress differs from early ages to later ages. Increasing the concrete compressive strength can improve bond performance. In other words, higher adhesion and friction force between concrete and rebar can be expected for concrete with higher compressive strength [6]. For a given bonded length, larger bars require larger forces to cause either a splitting or pullout failure [1]. For bars not confined by transverse reinforcement, the total force developed at bond failure is not only an increasing function of concrete cover, bar spacing, and bonded length, but also of bar area [7, 8]. The bond strength (stress) can be expressed as:

$$\tau = P_{max} / (\pi d_b l_d) \quad (1)$$

Where:

τ : bond strength (stress), MPa.

P_{max} : the maximum force at failure, N.

d_b : diameter of bar, mm.

l_d : bonded length, mm.

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2 Experimental program

2.1 Materials

Ordinary Portland cement conforming to the ASTM C150 [9] was used throughout this study. The used fine aggregate was natural sand. The fineness modulus, specific gravity (SSD) and sulfate content of this sand were 2.36, 2.6 and 0.09 percent respectively. Crushed gravel with a maximum size of 12.5 mm is the coarse aggregate. The unit weight, specific gravity (SSD) and sulfate content of this gravel were 1640 kg/m³, 2.7, and 0.01 percent respectively. Hot rolled deformed bars with nominal diameters 12, 16 and 20 mm having yield strength of 582, 552 and 559 MPa respectively, were used for bond test specimens.

2.2 Concrete mix

According to the recommendations of the ACI Committee 211 [10], a concrete mix, with proportions of 1: 1.88: 2.63: 0.45 (cement: fine aggregate: coarse aggregate: W/C ratio) by weight, was used to cast the studied specimens. The cement content of this mix was 400 kg/m³. This mix was designed to attain an average compressive strength of 30 MPa at 28 days. Two standard cylinders of 150mm in diameter and 300mm in height were used to determine the compressive strength of concrete and the measured compressive strength values were 23 and 32 MPa at 7 and 28 days respectively.

2.3 Test specimen

The test specimen consisted of a single bar embedded in a concrete block with square cross-sectional area and is being tested under compressive load. Three concrete block sizes, A, B and C were cast to offer three different cover lengths for the embedded rebars. The dimensions of these blocks were; 150×150×135, 100×100×135 and 200×200×185 mm. Size A blocks were reinforced with a single vertically embedded bar with a diameter of 12, 16 and 20 mm (A₁₂, A₁₆ and A₂₀). Meanwhile, size B and C blocks were reinforced with only 16 mm diameter bars (B₁₆ and C₁₆). Figure 1 shows a schematic representation of used test specimen. The bottom end of the rebar was free to move for 15mm to allow the movement of the bar during the test, while the loaded end (top end) was jugged out for 2.5d_b. PVC sleeves with smooth outer and inner surfaces were used as bond breakers to achieve the required embedded (bonded) length for the steel bar. PVC tubes do not restrain the slip of the bars, and do not permit the transfer of force between bar and concrete. The concrete blocks were tested by a universal testing machine in the compression mode applied on the steel bar (push-off mode), and the load-deformation (slip) curves were recorded by the data acquisition system of the UTM.

2.4 Fabrication of test specimen

Wooden molds were fabricated to cast the specimens. Lubricating oil was applied on all the inner sides of the mold. The bar was fixed vertically by using a steel plate at the top and a squared wooden piece at the bottom as shown in figure 2. After the specimens were prepared with bars, the concrete was poured and compacted by a vibrating table machine according to ASTM C192 [11]. After 24 hours, de-molding was carried out and the specimens were placed in a water tank for curing process until the age of 7, or 28 days.

Fig.1. Schematic representation of test specimen

Fig.2. Wooden molds used for specimen fabrication

2.5 Set-up and testing

Displacement control system was used to test the specimens by pushing-off the bar inside the block which was set in the machine on a steel plate with a hole in the middle to permit the free end of the bar to slip down. This bottom bearing plate had a Rockwell hardness of 60 HRC and horizontal dimensions conforming to ASTM C 39 [12]. The effective embedded (bonded) length was kept constant at 100mm. The load was applied vertically on the cross section of the bar (load direction was parallel to the longitudinal axis of the bar) as shown in figure 3. Monotonic load was applied by the actuator and the stroke was maintained at a constant speed of 1.5 mm/min. Each test result represents the average of three tested specimens.

3 Results and discussion

3.1 Basic considerations

Push-off test was carried out on thirty concrete blocks. Strain rate was kept at 1.5 mm/minute. The specimens were tested under push-off test at two ages, 7 and 28 days.

Fig.3. Test set-up of the reinforced concrete block

Fig.4. Schematic representation of the rebar covers C_0 and C_1 .

According to figure 4, two distances could be considered as rebar cover, C_0 and C_1 . Stress-wise, C_0 is considered a more critical stress path than C_1 . This consideration was based on the work of Tepfers [13], to focus on prediction of bond strength for deformed reinforcement. Tepfers was the first to propose an analytical model in which the concrete surrounding a single reinforcing bar is characterized as a thick-walled cylinder subjected to internal shear and pressure. In this analogy the internal shear and pressure correspond respectively to the bond and radial stresses developed at the concrete-steel interface. Thus, it follows that the radial force transfer at the concrete-steel interface determines the tensile hoop stress developed in the concrete surrounding the bar and thus the critical load. Tepfers proposes that bond strength is determined by the capacity of the concrete surrounding the reinforcing bars to carry the hoop stresses, as shown in figure 5. Moreover, the failure

modes of most of the tested specimens have shown that the splitting of concrete block was occurring through C_0 stress path.

The C_0 length was calculated as follows:

$$C_0 = (L_1 - d_b) / 2 \quad (2)$$

Where:

C_0 : rebar cover, mm.

L_1 : lateral dimension of the concrete block, mm.

d_b : nominal diameter of the rebar, mm.

In the present work, the ratio of C_0/d_b is nominated as the *effective cover*. Table 1 lists the values of this ratio for the tested groups.

Fig.5. Schematic representation of internal forces within a reinforced concrete specimen [13]

Table 1. The effective cover for the tested groups

Group	L_1 , mm	d_b (mm)	C_0 , mm	C_0/d_b
A	150	12	69	5.75
		16	67	4.19
		20	65	3.25
B	100	16	42	2.63
C	200	16	92	5.75

3.2 Load-slip relationship

Table 2 lists the maximum load, P_{max} , maximum slip at P_{max} , bond stress (according to Eq. 1) and the bond energy (area under the load-slip curve) which was calculated using Microsoft excel program and trapezoidal rule at ages of 7 and 28 days for specimens A_{12} , A_{16} , A_{20} , B_{16} and C_{16} respectively. Figures 6 -10 show the load-slip curves for the abovementioned specimens.

The bond energy could be considered as an indication to bond development with curing age. It was observed that there is no significant difference in energy between the two curing ages, 7 and 28 days. The only exception to that is the case of specimens A_{16} .

Increasing the bar diameter has a positive effect on the maximum load and associated slip and negative effect on the bond energy for the same age.

The confinement that was offered by the concrete block size (cover) also had a positive effect on load-slip relationship and on the bond-energy values.

Table 2. Push-off test results for the studied specimens at 7 and 28 days.

Group	Specimen	Age, days	P_{max} , kN	Bond stress, MPa	Max. Slip*, mm	Mode of failure**	Bond energy, N.mm	% increase in bond energy
A	A ₁₂	7	28.20	5.16	1.01	P	108.2	8.3
		28	33.27	6.62	1.30	P	117.2	
	A ₁₆	7	53.64	10.67	1.41	PS	79.8	19.3
		28	64.72	12.88	1.53	PS	95.2	
	A ₂₀	7	59.55	11.84	1.63	S	84.6	6.3
		28	81.34	16.18	1.70	S	89.9	
B	B ₁₆	7	47.96	12.72	1.84	S	34.5	6.7
		28	56.72	15.04	2.09	S	36.8	
C	C ₁₆	7	64.16	10.21	2.58	P	164.9	4.1
		28	70.47	11.22	3.21	P	171.7	

*: the max. slip was recorded by a computer program implemented in the testing machine

** : P: push-off, PS: combined, S: splitting

Fig.6. Load-slip curve for specimen A₁₂

Fig.7. Load-slip curve for specimen A₁₆

Fig.8. Load-slip curve for specimen A₂₀

Fig.9. Load-slip curve for specimen B₁₆

Fig.10. Load-slip curve for specimen C₁₆

3.3 Failure modes

Figure 11 displays the observed modes of failure for the push-off test specimens. They failed by the following three modes of failure; push-off failure, P, with pure slippage of the rebar, push-off with splitting of concrete block, PS and only splitting of concrete, S. The push-off failure mode occurred when the concrete block size (cover) provided an adequate confinement, thus preventing a splitting failure of the test specimen. The push-off failure was observed for A₁₂ and C₁₆ specimens. The combined failure was observed only for A₁₆ specimens. The splitting failure was diagnosed in A₂₀ and B₁₆ specimens. This behavior may be explained by that bond strength is inversely proportional to the surface area of the bonded length of the rebar, as shown in Eq.1.

For the smaller one, 12mm, most of the shearing force in the interface is applied on the rebar and that leads to pure slippage of the rebars. Increasing the bar diameter to 16 or 20 mm for the same concrete block size would raise the share of concrete in load carrying thus the failure will change to PS or S. Therefore, it could be concluded that the mode of failure is highly dependent to the bar diameter and concrete confinement (cover).

When relating the mode of failure to the effective cover, C_0/d_b , it could be concluded that higher effective cover causes pure slippage of rebars and lower C_0/d_b values are companions to the concrete splitting mode.

Fig.11. Failure modes a: splitting failure in group A, b: combined failure in group B, c: push-off failure in group C

3.4 The relationship between effective cover and P_{max} and slip

Figure 12 illustrates the variation of P_{max} with the effective cover at the age of 28 days for specimens of different sizes, A, B and C, but with the same bar diameter, 16mm. The increase in the block size makes the concrete stronger and sharing higher percentage of load. In addition to that the confinement becomes higher when the block size increases [14].

Figure 13 shows the variation of P_{max} with effective cover at 28 days for specimens of A size reinforced with different bar diameters, 12, 16 and 20mm. Increasing the bar diameter would cause the effective cover to be reduced but this will improve the bond and makes the rebar to withstand higher load. The change in rebar diameter has the same effect on bond slip as shown in figure 14.

Fig.12. Load-effective cover relationship for specimens A₁₆, B₁₆ and C₁₆ at the age of 28 days

Fig.13. Load-effective cover relationship for specimens A₁₂, A₁₆ and A₂₀ at the age of 28 days

Fig.14. Slip-effective cover relationship for specimens A₁₂, A₁₆ and A₂₀ at the age of 28 days

4 Conclusions

The following are the conclusions reached throughout this research work:

1. For all studied cases, the aging of concrete caused the load at failure and the related slip to increase. This is attributed to the fact that concrete compressive strength increases with time leading to an increase in tensile strength, which means more confining for the steel bar by the surrounding concrete.
2. The concrete cover has a significant effect on the bond strength between rebar and concrete. By increasing the C_0/d_b ratio, the confinement increases, bond strength increases, and slip increases.
3. When relating the mode of failure to the effective cover, C_0/d_b , it could be concluded that higher effective cover causes pure slippage of rebars and lower C_0/d_b values are companions to the concrete splitting mode.
4. The increase in the surrounding concrete size makes the concrete stronger and share higher percentage of load. Meanwhile, increasing the bar diameter would cause the effective cover to be reduced but this will improve the bond and make the rebar to withstand higher load.

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