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BOND OF REINFORCEMENT IN REACTIVE POWDER CONCRETE: EXPERIMENTAL STUDY

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Abstract: *This study investigates the bond performance of steel rebar embedded in reactive powder concrete(RPC). The assessment of the bond behavior at concrete ages of 7, 14 and 28 days using pull-out specimens was the subject of the investigation. Varying parameters in this research program were embedment length, rebar diameter, concrete age and size of the concrete cover. The concrete compressive and flexural strength were measured at the same test ages. The test results show that with the increase of rebar embedment length and rebar diameter, the ultimate bond stress decreases. This decrease was caused by the nonlinear distribution of the bond stress, voids on the contact surface and the Poisson's ratio effect. When protection layer thickness and standard curing age of reactive powder concrete increases, the ultimate bond stress increase. The bond of reinforcement in RPC is characterized by very high maximum bond stresses, even at early ages. This paper presents the details of the investigation and discusses the results obtained.*

1. INTRODUCTION

Reactive powder concrete (RPC) is one of the newest development in concrete building materials. By adding steel fibers to RPC and its homogenized microstructure, it has many demonstrated advantages such as outstanding mechanical properties, ductility, and durability [1, 2, 3, 4]. In particular, its unique tensile performance, along with its high strength and strain capacity make RPC is very useful in bending structural applications [5, 6].

One of the important aspects of the structural behavior of reinforced reactive powder concrete elements is the development of an appropriate bond capacity. The structural will premature failure for the insufficient bond resistance results. So it is very useful to accurate predict the relative slip between the rebar and concrete in the design and analysis work.

Experimental work had been performed in order to examine the bond of steel bars embedded in RPC [5, 6 ,7, 8, 9]. The main objective was to investigate the bond strength activated in pullout tests and to determine the relationship of bond-slip. Pullout tests were performed to examine the effect of varying parameters such as embedment length, bar diameter, concrete age and concrete cover.

2. EXPERIMENTAL PROGRAM

2.1. Material properties and mix proportion

The mix proportion of RPC used in this study is summarized by the weight in Table 1. The water-to-binder ratio (W/B) used in the test was 0.16. The micro steel fibers having a length of 12 mm to 15mm, a diameter of 0.22mm and the tensile strength is greater than 2800MPa were incorporated by 2% of the total volume. Portland cement and silica fume were used as cementitious materials. Sand with a grain size of 0.16mm to 1.25mm was used as fine aggregate. In addition, the polycarboxylate superplasticizer was added to satisfy the workability, the flow was measured by 270 mm from the flow test in accordance with GB/T 14902-2012 [10].

After casting, the test specimens were placed in the standard curing room and they were cured for 24h before demolding. After demolding, the test specimens were placed in the standard curing room again until reaching the testing concrete age.

Table 1: Mixing ratio of RPC (kg/m^3)

Cement	Silica fume	Sand	Steel fiber	Superplasticizer	Water
920	170	1080	120	22	174

2.2. Mechanical tests

The compressive strength and flexural strength of RPC is the basic mechanical parameters of the analysis and design of RPC structure. The flexure, compression specimens were cast and cured under the same conditions as the Pull-out specimens. Three prism specimens with a dimension of 100mm×100mm×300mm were fabricated and tested for evaluating the compressive behavior in accordance with GB/T 50081-2002 [11]. Compressive strength was measured using universal testing machine (WAW) with a maximum load capacity of 2000kN. To obtain the strain along with the stress, three electronic strain gauges were also installed on the prism specimens. According to the Chinese standard GB/T 50081-2002 [11], a four-point bending test was performed to investigate the flexural behavior. The compressive and flexural strength were measured after 7, 14 and 28 days. The properties of the steel rebars are summarized in Table 2.

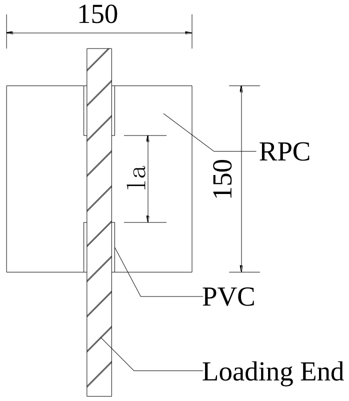
Table 2: Measured strength of rebar

Diameter(mm)	Elastic modulus (GPa)	Yield Strength (MPa)	Ultimate strength (MPa)
16	200	413	587
20	200	430	613

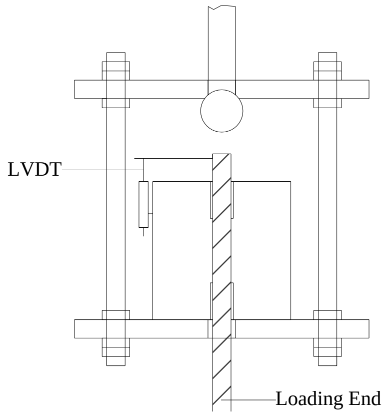
2.3. Pull-out test

To evaluate the bond behaviors of steel rebar embedded in RPC, the pull-out test was carried out in accordance with GB/T 50081-2002[11], the direct pull-out test method was preferred because it is simple and leaves the free end accessible for the slip to be measured.

The nominal diameters of the steel rebar were 16mm and 20mm, the embedded length were 3, 4, 5 and 6 times the bar diameter, the concrete cover were 1, 1.6, 2.5cm and the concrete age were 7, 14 and 28 days to investigate the bond properties. The dimension of Pull-out specimens is 150mm×150mm×150mm. The detailed geometry and test setup are shown in Fig. 1(a). The single bar placed horizontally along the central axis. The unbonded region of the rebar was sheathed with PVC pipe. A pull-out load was applied using a WAW with a maximum load capacity of 1000 kN through the pulling force, with the rate of load increase was 0.1 kN/s during testing. The LVDTs were used to measure the bond slip between the rebar and the concrete at free end, as shown in Fig.1(b).



(a)Dimensions of specimen



(b) Test setup

Fig.1 Pull-out test

3. EXPERIMENTAL RESULTS AND DISCUSSION

The effects of rebar embedment length, rebar diameter, concrete age and size of the concrete cover on the bond behavior is analyzed in this section. The bond-slip curves for the steel rebar embedded in the RPC were plotted using the experimental results obtained directly from the slip measurements at the free end, the bond properties are summarized in Table 3. The bond stress distribution between the rebar and RPC is not constant along the embedment length. For simplification, the average bond stress $\tau$is calculated using Eq. (1).

$$\tau = \frac{F}{\pi d l_a} \tag{1}$$

where F is the pull-out load, l_a is the embedment length of rebar, and d is the diameter of rebar.

The notation adopted for the specimens in Table 3 is as follows: the first number indicates the bar diameter, the next number is the embedment length, the third number is the curing age, and the last number is size of the concrete cover. For example, 16-48-28d-1cm refers to a 16 mm bar with an embedment length 48cm, the concrete cover 1cm, tested after 28 days.

For all test specimens, the whole process of pull-out test is as follows: the bond stress-slip relationship is characterized by an initial increase in the pullout stress with slight slip, followed by softening after the bond strength. As the pull-out load increased, the slip increased and became measurable with crack formation, resulting in the shearing off and crushing of concrete at the bonded region[12]. However, high residual bond strength remains during the bar pullout phase because of friction.

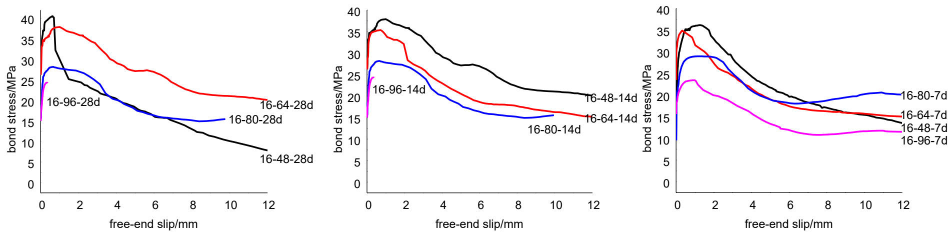
Table 3: Pull-out test results

Specimens	Embedment length(mm)	Concrete age(days)	Maximum average bond strength (MPa)	Slip at maximum average bond strength (mm)
16-48-7d	48	7	35.55	0.55
16-48-14d	48	14	37.89	1.00
16-48-28d	48	28	40.53	0.64
16-64-7d	64	7	33.18	1.25
16-64-14d	64	14	35.36	0.72
16-64-28d	64	28	36.57	1.00
16-80-7d	80	7	27.64	0.40
16-80-14d	80	14	28.54	0.22
16-80-28d	80	28	29.26	0.29
16-96-7d	96	7	20.04	0.99
16-96-14d	96	14	24.11	0.51
16-96-28d	96	28	24.07	0.36
20-80-7d	80	7	26.59	0.27
20-80-14d	80	14	27.72	0.18
20-80-28d	80	28	28.85	0.22
16-48-28d-1cm	48	28	22.45	0.19
16-48-28d-1.6cm	48	28	24.69	0.22
16-48-28d-2.5cm	48	28	33.39	0.23
16-64-28d-1cm	64	28	21.18	0.19
16-64-28d-1.6cm	64	28	25.29	0.06
16-64-28d-2.5cm	64	28	30.64	0.64

3.1. Effect of the embedment length

Fig.2 shows the bond stress and slip relations of different embedment lengths (3d, 4d, 5d and 6d) for steel rebars embedded in RPC. The main findings were as follows:

The results show that with the increase of rebar embedment length, the ultimate bond stress decreases pseudo-linearly[13-14]. The specimens with longer embedment length developed lower bond strength. One reason of this decrease is caused by the nonlinear distribution of bond stresses along the steel bar embedded in concrete. The longer of the rebar embedment length, the shorter and narrower of the high stress region, so specimens with longer embedment length had low average bond stress. The other reason of this decrease is caused by Poisson's ratio effect where the substantial elongation of the bar throughout the embedment length leads to reduction in friction. The bond stress decreased rapid and largely(about 40%) when the local bond stress reach the ultimate bond stress.



(a) 16-28d (b) 16-14d (c) 16-7d

Fig.2 Embedment length effect on the bond-slip relationship

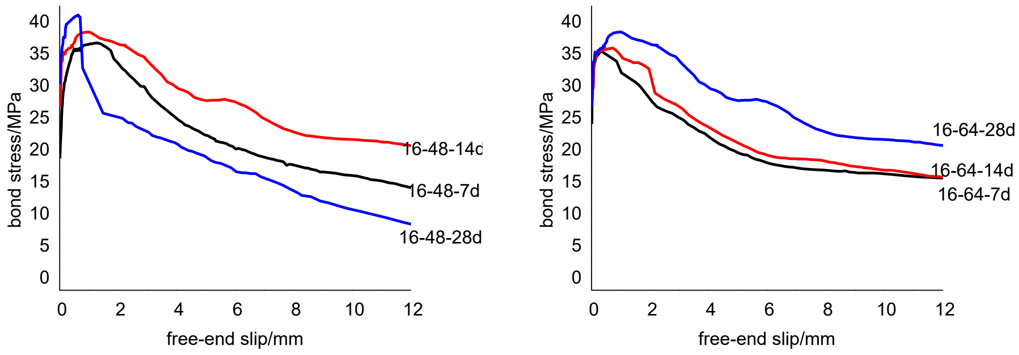
3. 2. Effect of bar diameter

The test results in Table.3 show that with the increase of the diameter of the bars, the ultimate average bond strength decreased slightly. For example, at the embedment length of 80cm, the bond strength of the specimens with a diameter of 16mm were 27.64MPa(7d), 28.54MPa(14d), 29.26MPa(28d), which are about 1.4%-3.9% higher than those of the specimens with a diameter of 20 mm. This decrease is caused by the bleeding of the water in the concrete. The larger the diameter, the more bleed water is trapped beneath the bar, which creates larger voids in the interface [14, 15]. The voids reduce the bond strength on the contact surface between the bar and the concrete. The Poisson's ratio effect also can allow a slight reduction in bar diameter as a result of longitudinal stress. It's more easily to brittle failure in concrete surface when the bars were pulled out as the diameter of the bar increases.

3. 3. Effect of concrete age (confinement effect)

With the growth of the concrete age, the compressive strength and flexural strength of RPC increase. Studying the effect of concrete age amounts to evaluating the effect of the confinement pressure caused by concrete shrinkage on the bond strength[16]. The results obtained from pullout tests performed after 7, 14and 28 days with smooth bars (d=16mm) are displayed in Figs. 3 and Table 3. The following remarks can be made:

- The bond-slip relationship curves were the same shape for all the specimens. The bond-slip relationship become full with the increase of concrete age.
- With the growth of the concrete age, the ultimate bond strength of specimens increase. That because with the growth of the concrete age, the radial confined pressure on the bond strength increased, too.



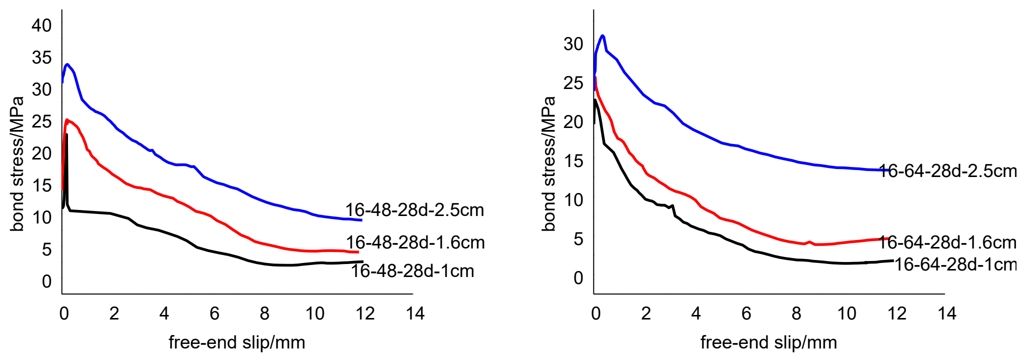
(a) 16-48 (b) 16-64

Fig.3 Effect of concrete age on the bond-slip relationship

3. 4. Effect of concrete cover

Studies have been performed to evaluate the effect on the bond strength of the concrete cover. The results obtained from pullout tests performed after 28 days with the concrete cover (1cm, 1.6cm and 2.5cm) are displayed in Figs.4. The main findings were as follows:

- The bond performance curves were the same shape for all the specimens. The bond-slip relationship become very full with the increase of concrete cover.
- With the growth of the concrete cover, the ultimate bond strength of specimens increased. That is caused as the growth of concrete cover increases the contact surface confinement pressure between the bar and the concrete.



(a) 16-48-28d (b) 16-64-28d

Fig.4 Effect of concrete cover on the bond-slip relationship

3.5 Anchorage length

The force applied in the rebar is resisted by the bond stress acting on the surface of the rebar based on the equilibrium condition. The equilibrium of the forces is expressed by Eq. (2).

$$f_y A_s = \pi d l_a \tau \quad (2)$$

$$l_a = \frac{f_y d}{4\tau} \tag{3}$$

where f_y is steel yield strength, A_s is the area of one rebar, d is the diameter of the steel rebar, l_a is the critical anchorage length, τ is bond strength. By this formula, the adequate anchorage length for bars with the diameters of 16mm is worked out to be 5.5 times of the bar diameters.

4 CONCLUSIONS

- All test specimens failed by pull-out of the rebar with the shearing off and crushing of concrete between the lugs of the rebar. The bond of reinforcement in RPC is characterized by very high maximum bond stresses, even at early ages. High residual bond strength remains during the bar pullout phase because of friction.
- The bond strength was slightly decreased with increasing embedment length due to the nonlinear distribution of the bond stress and the Poisson’s ratio effect. The specimens with longer embedment length developed lower bond strength.
- The average maximum bond strength decreased when the diameter of the bars increased. This decrease is caused by the voids in the interface and the voids reduce bond strength on the contact surface between the bar and the concrete.
- With the growth of the concrete age and the concrete cover, the ultimate bond strength of specimens increase. The reason of this increase is caused by the radial confined pressure on the bond strength increased, too.
- The adequate anchorage length for bars with the diameters of 16mm is worked out to be 5.5 times of the bar diameters.

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REFERENCES

[1] Dugat J, Roux N, Bernier G. Mechanical properties of reactive powder concretes[J]. Materials and structures, Vol. 29, May 1996, 233-240.

[2] Richard P, Cheyrezy M. Composition of reactive powder concretes. Cem Concrres 1995;25(7):1501-11.

[3]Bonneau O, Pouhn C. Reactive powder concrete from theory to practice[J]. Concrete International.1996, 18(4):47-49.

[4]Dallaire S, Korb J P. Analysis of microporsity and setting of reactive powder concrete by proton nuclear relaxation[J]. Magnetic Resonance Imaging. 1998, 16:515-518.

[5] An Mingzhe, Zhang Meng. Experimental research of bond capability between deformed bars and reactive powder concrete[J]. China Railway Science, 2007, 28(2):50-54(in Chinese)

[6]Deng Zongcai, Yuan Changxing. Experimental study on bond capability between high strength rebar and reactive powder concrete[J].China civil engineering journal, 2014, 47(3)：69-78(in Chinese)

[7] Si Jinyan, Fan Xiaoning, Zhou Licheng, Xiao Rui, Yuan Changxing. Research on Bond Behavior of Reactive Powder Concrete and High-strength Reinforcement[J]. Construction Technology, 2013(12)：60-62 (in Chinese)

[8] Tang Hao, Wang Jian. Relationship of bar diameter and bonding performance of reactive powder concrete[J]. Journal of Beijing University of Civil Engineering and Architecture, 2012, 28(3):6-9, 18(in Chinese)

[9]Cosenza E, Manfredi G, Realfonzo R. Analytical modeling of bond between FRP reinforcing bars and concrete. In: Taerwe L, editor. Proceedings of second.

[10]GB/T14902-2012 Code for the ready-mixed concrete[S]. Beijing: China Architecture Building Press, 2012(in Chinese)

[11]GB 50010-2002 Standard for test method of mechanical properties on ordinary concrete[S]. Beijing: China Architecture Building Press, 2002(in Chinese)

[12]Lee JY, Kim TY, Kim TJ, Yi CK, Park JS, You YC, et al. Interfacial bond strength of glass fiber reinforced polymer bars in high-strength concrete. Compos Part B: Eng 2008;39(2):258-70.

[13] Cosenza E, Manfredi G, Realfonzo R. Behaviour and modelling of bond of FRPrebars to concrete. ASCE J Compos Constr 1997;1(2):40-51.

[14] Nanni A, Bakis CE, Boothby TE. Test methods for FRP–concrete systems subjected to mechanical loads: state of the art review. Reinf Plast Compos J 1995;14(6):524-58.

[15] Benmokrane B, Tighiouart B, Chaallal O. Bond strength and load distribution of composite GFRP reinforcing bars in concrete. ACI Mater J 1996;93(3):254-9.

[16] Sayed Ahmad Firas, Foret Gilles *, Le Roy Robert. Bond between carbon fibre-reinforced polymer (CFRP) bars and ultra-high performance fiber reinforced concrete (UHPFRC): Experimental study. Construction and Building Materials 25 (2011) 479-485.

[17] GB 50010-2010 Code for design of concrete structures[S]. Beijing: China Architecture Building Press, 2010(in Chinese)