

## STUDY ON BONDING PROPERTY OF POLYURETHANE CEMENT (PUC) TO STEEL BAR

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### ABSTRACT

The pull-out test of the bar and PUC is carried out in this paper, the effects of protective layer thickness, reinforcement anchorage length, diameter and shape of reinforcement on bonding properties were studied. The results show that the bond strength between reinforcement and PUC material increases with the increase of the thickness of the protective layer but decreases with the increase of the anchorage length and diameter of reinforcement. The bond strength of bare round steel is significantly lower than that of ribbed steel, and the maximum bond strength is about 47.4% of ribbed steel. By analyzing the bond slip curve obtained from the pull-out test, the stress process of bond anchorage between reinforcement bar and PUC material is mainly summarized into three stages: the rising stage, the falling stage and the residual stage. The characteristics of the curve, the stress process and the failure mode of specimen at each stage are analyzed.

### KEYWORDS

Polyurethane cement (PUC) material, Steel bar, Bond stress, Pull-out test, Bond-slip curve

### INTRODUCTION

The bond between steel bar and concrete is a complex interaction between steel bar and peripheral concrete, and the two materials can achieve deformation coordination through the transfer of bond stress to ensure the joint work. This effect is essentially the bond stress [1-6]. The bonding force is mainly composed of the chemical bonding force, friction resistance and mechanical biting force between the steel bar and concrete and is expressed as a shear stress along the length of the steel bar macroscopic. With the action of external load, there will be relative sliding between reinforcement and concrete, and whether the strength of reinforcement can be fully exerted depends on the bond strength of the two. In recent years, the investigation on earthquake disasters shows that many reinforced concrete bridge piers are destroyed in weak bond anchorage locations under strong earthquakes, and bond degradation often leads to the loss of bond in joint areas under earthquake action, and the stiffness is significantly reduced or even the strength is lost [7-12].

Polyurethane (PU) is a kind of polymer elastic material with excellent performance. The polyurethane cement composite material (elastic concrete) formed by mixing it with cement has the advantages of chemical corrosion resistance, rapid hardening, light weight and high strength compared with traditional building materials [13-15]. It can replace traditional building materials to a certain extent. Haleem K. Hussain et al. [16-18] used polyurethane and fly ash to make polyurethane cement (PUC) material. The flexural and compressive tests of the composite material were carried out, and the stress-strain curve relationship of the material under different densities was obtained. At the same time, the elastic modulus, Poisson's ratio and bonding strength of the material to

concrete are also studied. Based on the material research, the bending reinforcement tests of seven T-section beams under different failure degrees were carried out. The results show that the ultimate bearing capacity of the beams strengthened by polyurethane cement (PUC) material can be significantly improved, and the cracks of the beams can be significantly reduced. Liu Guiwei et al. [19] prepared polyurethane cement (MPC) material to reinforce Baixi Bridge in Ningbo, Zhejiang. The results show that polyurethane concrete material can better improve the bearing capacity of the structure and can carry out construction operations without stopping traffic.

The combination of polyurethane cement (PUC) and reinforcement can give full play to the superior mechanical properties of the two, and obtain more excellent crack prevention, earthquake resistance and crack control ability. However, there is still a lack of systematic experimental study on bond anchorage between reinforcement bar and PUC. Due to the significant difference between PUC material and ordinary concrete in mechanical properties, the existing research results on the bond properties of ordinary concrete to steel bar are not applicable to the bond properties of PUC material to steel bar. In this paper, through the pull-out test of PUC material and steel bar, the bond anchorage performance of steel bars and PUC material was studied by the test parameters of steel bar type, anchorage length, protective layer thickness and so on. Meanwhile, the bond slip constitutive relationship between PUC material and steel bar is analyzed.

## ADHESIVE PULL-OUT PROPERTY TEST OF PUC AND STEEL BAR

The bond anchorage tests currently used can be divided into three categories according to their purposes: The first is the center drawing test, which is used to compare the bonding and anchorage properties of different steel bars. The second is beam type test or simulated beam type test, which is used to determine the design service strength and related construction requirements of bond anchorage. The third is the local bond slip test, which mainly studies the basic law of bond stress and deformation. Pull-out test has the advantages of simple method, eliminating the interference of other factors on the test results, the results are easy to analyze and so on. For a long time, it has been used as the basis for the relative comparison of the bonding properties of materials, and it is also the widely used benchmark test in all countries. Therefore, the method of drawing test is used in this paper, in order to study the bond anchorage performance of steel bar.

### Experimental material

#### *Polyurethane cement (PUC)*

Polyurethane cement is a kind of polymer concrete material, whose main component is the polymerization of polyurethane raw material and cement. Polyurethane is a polymer with excellent performance, which is mainly composed of isocyanate and polyether polyol. The main raw material components are shown in Table 1.

The hardness range of polyurethane materials is 10-100 (IRHD), where 0 (IRHD) represents an elastic modulus of 0, 100 (IRHD) represents an infinite elastic modulus. Polyurethane material has good wear resistance, chemical corrosion resistance, fluidity, bonding and molding properties.

*Tab.1 - Composition of polyurethane raw material*

Raw material		Percentage (%)
Polyols	polyether	49
	Silicone oil	1
	Water	0-1
Isocyanate		50-51

Polyurethane cement raw materials are mixed in accordance with the mass ratio, and the mass ratio is polyol: isocyanate: cement =1:1:2. High density polyurethane cement material is

prepared, as shown in Table 2. Polyol, isocyanate and cement were the main raw materials in the mixture ratio. The PUC material was cured in dry environment for 7 d.

*Tab. 2 - Composition of PUC*

PUC	Percent (%)
polyether polyol	25
isocyanate	25
cement	50

The main mechanical properties of polyurethane cement are as follows:

*Tab. 3 - Main mechanical properties of PUC*

Index	Density (kg/m <sup>3</sup> )	Compress stress (MPa)	Flexural stress (MPa)	Axial tensile strength (MPa)
PUC	1500	59.3	41.5	31



*Fig. 1 - PUC material mixing diagram*

*Fig. 2 - Pouring drawing of PUC*

### **Steel bar**

The steel bars used in this test are ribbed steel bars and round steel bars, and the steel bars basically have no corrosion. In the process of specimen making, the same batch of steel bars are selected to conduct tensile test to determine the tensile yield strength, elongation and other parameters of steel bars. During the test, the spacing of reinforcement is the diameter of reinforcement, and the test results are shown in Table 4.

*Tab. 4 - Basic mechanical properties of steel bar*

Diameter (mm)	Yield strength (N/mm <sup>2</sup> )	Ultimate strength (N/mm <sup>2</sup> )	Elasticity modulus (N/mm <sup>2</sup> )	Extend rate (%)
12 (HRB335)	373	560	2.0×10 <sup>5</sup>	32
16 (HRB335)	385	552	2.0×10 <sup>5</sup>	27
20 (HRB335)	375	585	2.0×10 <sup>5</sup>	30
20 (HPB335)	286	410	2.1×10 <sup>5</sup>	34

## SPECIMEN DESIGN AND FABRICATION

The cement was dried at 100 °C ~ 110 °C for 24 h, and then mixed with polyurethane raw materials and defoaming agent, mechanically mixed for 3 ~ 5 min, and the mixture was poured into a 150 mm × 150 mm × 150 mm cube mold. After hardening, the specimen was demoulded and cured at room temperature for 28 d, with dimensions as shown in Figure 3 and Figure 4. The dumbbell shaped sheet specimens were made of PUC material separately. The sizes were shown in Figure 5. The thickness of the specimens was 10 mm, the width in the middle was 25 mm, and the width on both sides was 40 mm. The mold test in the casting process is self-designed, as shown in Figure 6.

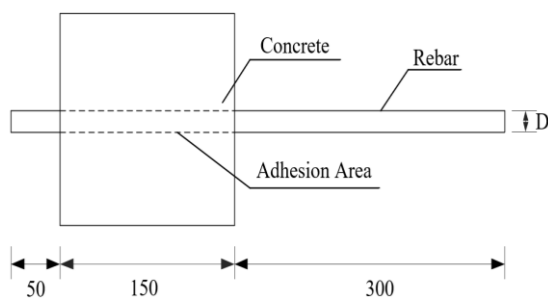


Fig. 3 - Detail of specimen (unit: mm)

Fig. 4 - Pouring diagram of specimen

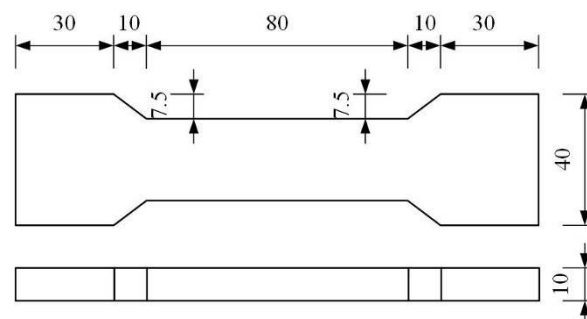
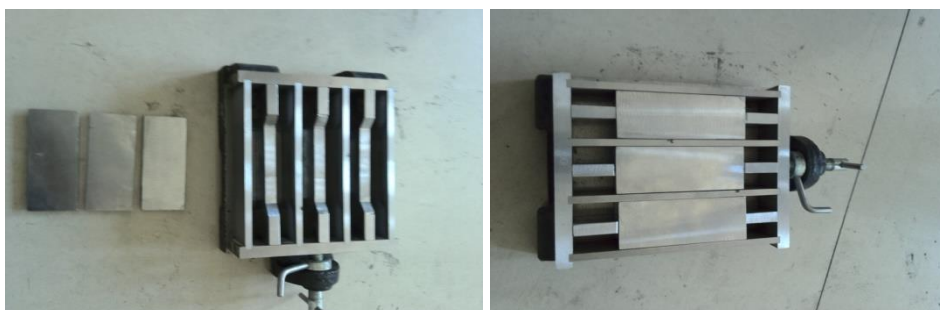


Fig. 5 - Dimensions of polyurethane cement material axial tensile specimen (unit: mm)



(a) apart

(b) Assembly diagram

Fig. 6 - Steel formwork diagram of dumbbell type specimen

This test uses the center pull-out test to test the bond property of steel bar and PUC and the pull-out specimens were made according to the Chinese code (Test Rules for Cement and Cement Concrete in Highway Engineering) [20-22]. A total of 45 specimens were made in the test. Considering the influence of three parameters, including the thickness of the protective layer, the

diameter and shape of the steel bar, and the anchorage length, the number and parameters of the specimens are shown in Table 5.

*Tab.5 - List of pull-out specimens*

Specimen number	Thickness of protective layer c (mm)	Anchorage length la (mm)	Steel bar diameter d (mm)	Number of specimens
1	70	30	16	3
2	70	50	12	3
3	70	50	16	3
4	70	50	20	3
5	70	50	20 (plain round bar)	3
6	70	80	12	3
7	70	80	16	3
8	70	80	20	3
9	70	80	20 (plain round bar)	3
10	70	100	16	3
11	40	80	16	3
12	50	80	16	3
13	60	80	16	3
ZL	—	—	—	6

## LOADING AND MEASURING SCHEME

The testing machine adopts the universal testing machine with the maximum range of 10 t to carry out direct pull-out test. During the test, the displacement value is directly read by the testing machine, and the strain is measured by static resistance strain gauge. The loading process is as follows : (1) Fix the test fixture to the universal testing machine, connect the strain gauge wire to the static resistance strain gauge, and debug the instrument to ensure the data stability of the acquisition system. (2) The maximum load that the steel bar can bear is taken as the ultimate pull-out load P to determine the test loading scheme. The test is divided into 20 levels of loading, and the load of each level is 0.05 P. In the first step of the test, preloading was carried out with a load of 0.05P. Displacement and strain values were recorded and then unloaded. (3) Formal loading. After the loading of each stage is completed, the anchorage end and the whole of the specimen are photographed to record the state of the specimen. After the data are stable, the strain and displacement values are recorded. (4) Loaded to the specimen failure, the failure load was recorded, displacement and strain data were recorded, and photos of the specimen failure were collected. The loading device diagram is shown in Figure 5. PUC material test was carried out on a small-range tester with a loading speed of 50 N/s. The resistance strain gauge was pasted in the middle of the specimen and pasted symmetrically on both sides along the stretching direction to measure the strain change in the stretching process. The dynamic strain acquisition instrument was used for data acquisition.

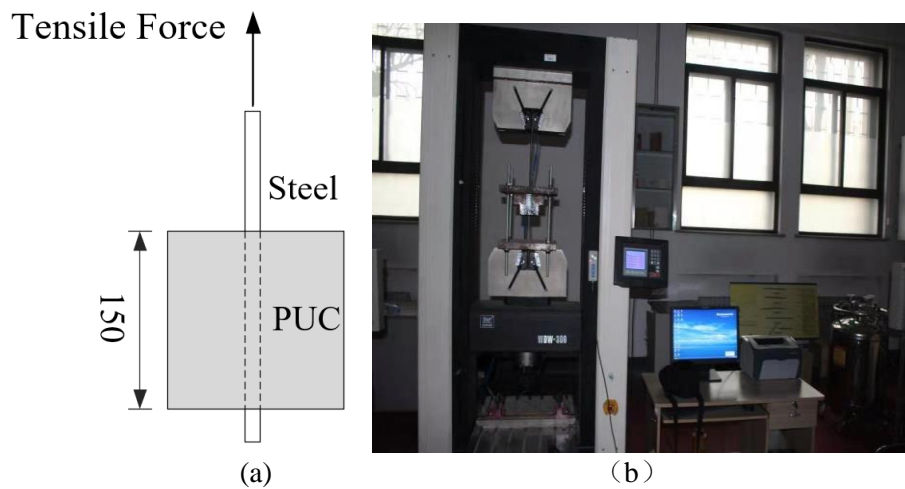


Fig. 7 - Detail of specimen arrangement

According to the measured value of the drawing force, the average bond stress can be obtained by the following formula:

$$\tau = \frac{P}{\pi d l_a} \quad (1)$$

Where P — the pulling force,

$\tau$  — the average bond stress

d — bar diameter

$l_a$  — anchorage length

As can be seen from the formula, the bond stress is obtained by comparing the force with the surface area by simplifying the reinforcement bar in the anchorage section into a smooth cylinder macroscopic. Therefore, the bond stress at all points on the anchorage length is the same, so it is the average bond stress on the anchorage length.

## INFLUENCE OF ANCHORAGE CONDITIONS ON BOND STRENGTH

### Tensile strength of PUC

According to the data in Table 6, the average axial tensile strength of polyurethane cement material is 31.0 MPa, and the straight-tension elastic modulus is calculated to be 4200 Mpa - 5700 MPa according to the stress-strain curve relationship.

Tab. 6 - Table of axial tensile strength of PUC material

Number	ZL01	ZL02	ZL03	ZL04	ZL05	ZL06	Average value
Strength (MPa)	30.5	31.8	31	32.1	31.6	28.9	31.0

According to the tensile force and the corresponding strain data collected during the test, the stress-strain relationship curves of the six specimens in straight tension were drawn, as shown in Figure 8. According to the straight-tension measurement results of the test block, the average stress-strain curve of straight-tension is obtained, as shown in Figure 9.



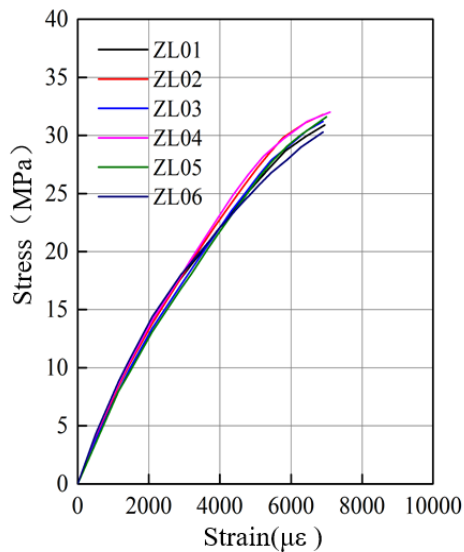


Fig. 8 - Direct tensile stress-strain curve

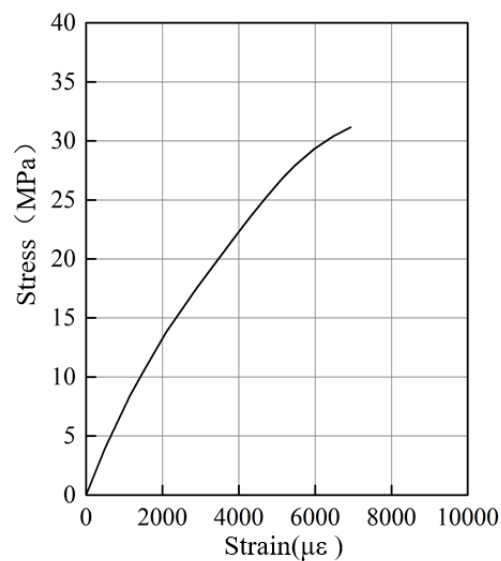


Fig. 9 - Stress-strain curve in direct tension (average)

According to the stress and strain relationship points of axial tensile specimens, the stress-strain relationship curve is fitted, as shown in Figure 10. The fitting formula is as follows:

$$\sigma = 0.496 + 6977.3\varepsilon - 365682.2\varepsilon^2 \quad R^2 = 0.999 \quad (2)$$

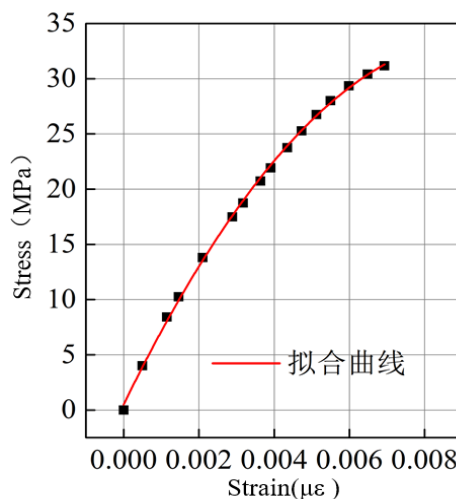


Fig. 10 - Fit curve of axial tensile stress-strain relationship

### Coverage thickness

In the test, there are three groups of pullout specimens represented by  $\Phi 16$ mm ribbed steel bar, and the conditions in each group are the same. The thickness of the protective layer of steel bar in each group is 40 mm, 50 mm, 60 mm and 70 mm. After calculating the average value of the bond stress in each group, the influence of the thickness of the protective layer on the bond anchorage performance of steel bar and polyurethane cement is studied. Figure 11 is the comparison diagram of bond stress under each protective layer thickness, and Figure 12 is the average bond stress diagram of the three groups of specimens. It can be seen from the figure that the thickness of the protective layer has a significant effect on the bond strength of the deformed reinforcement, because the significant characteristic of the anchorage failure of the deformed reinforcement is led by splitting.

The thicker the protective layer is, the greater the constraint effect on splitting will be. For PUC specimens, the increase in the thickness of the protective layer can limit the propagation of splitting cracks, or even prevent the occurrence of cracks, but this restriction is not infinite. It can be seen from the figure that the bond strength increases with the increase of the thickness of the protective layer. When the thickness of the protective layer is 40 mm, the average bond stress is 10.53 MPa. When the thickness of the protective layer is C50, the average bond stress is 12.36 MPa, which increases by 17.38% compared with that of 40 mm. When the thickness of the protective layer is 60, the average bond stress is 14.00 MPa, which increases by 13.27% compared with that of 50mm. When the thickness of the protective layer is 70 mm, the average bond stress is 16.38 MPa, which increases by 17.00% compared with that of 60 mm.

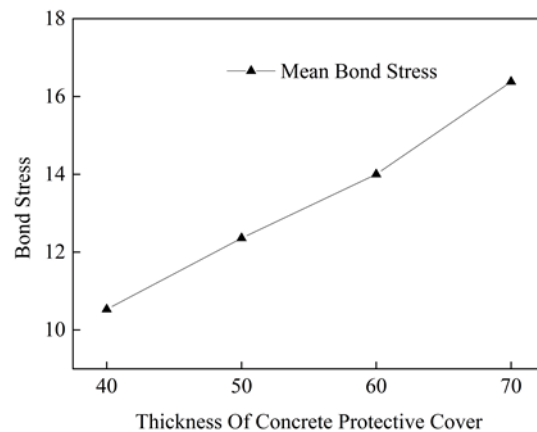
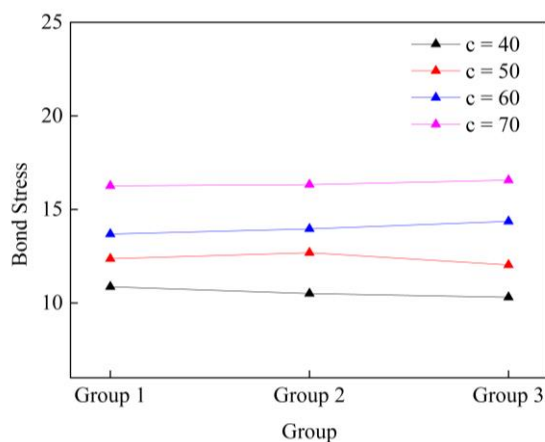


Fig. 11 - Bond stress under each protective layer thickness Fig. 12 - Average bond stress

### Anchorage length of steel bar

This test selected  $\Phi 16$  ribbed steel bar as the representative of the pull-out specimens, a total of 3 groups, each group of 4 total specimens, anchoring length of 30 mm, 50 mm, 80 mm, 100 mm. The test results show that the average bond strength decreases with the increase of the anchorage length, because the pull-out force of the specimen is closely related to the bond area, and the pull-out force increases with the increase of the anchorage length and the bond area. However, from the analysis of the bonding mechanism between ribbed reinforcement and concrete, the average bonding stress in the anchorage section decreases with the increase of the anchorage length. Since the bond stress distribution in the anchorage section is not uniform, when the ultimate bond stress is constant, the longer the anchorage section is, the lower the average bond stress will be. The results of this test accord with the above law. It can be seen from the figure that the bond strength decreases with the increase of the anchoring length. When the anchoring length  $l_a$  is 30 mm, the average bond stress is 19.55 MPa. When the anchoring length  $l_a$  is 50 mm, the average bond stress is 16.47 MPa, which is 15.75% lower than that when  $l_a$  is 30 mm. When the anchorage length  $l_a$  is 80 mm, the average bond stress is 13.33 MPa, which is 19.06% higher than that when  $l_a$  is 60 mm. When the anchorage length  $l_a$  is 100 mm, the average bond stress is 10.65 MPa, which increases by 20.11% compared with 70 mm.



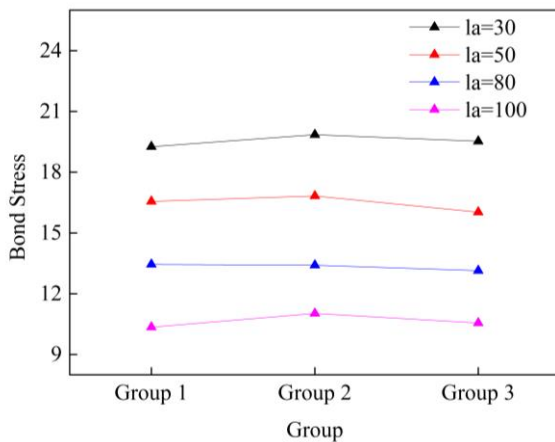


Fig. 13 - Bond stress under each anchorage length

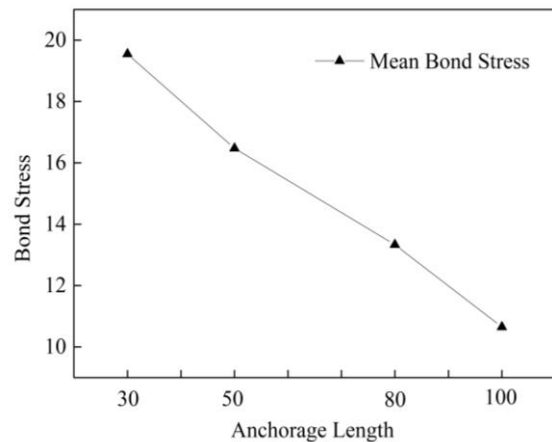


Fig. 14 - Average bond stress diagram

### Diameter and shape of steel bar

The bonding properties of  $\Phi 12$  ribbed bars,  $\Phi 16$  ribbed bars,  $\Phi 20$  ribbed bars and  $\Phi 20$  straight round bars under two different anchorage lengths were compared. The bond area of ribbed steel bar, circular steel bar and surrounding concrete is proportional to the perimeter length of the section, while the tensile force is proportional to the section area. The ratio of the two reflects the relative bond area of the steel bar. The relatively small bonding area of steel bars with larger diameter is not conducive to the improvement of ultimate bonding strength. In general, under the same anchoring condition, the bond strength between bars and PUC decreases with the increase of the diameter, and the bond stress between bars with the same diameter and PUC decreases with the increase of the anchoring length under different anchoring lengths, and the bond strength of ribbed bars is obviously higher than that of rounded bars. Figure 15 shows the comparison diagram of bond stress between steel bars of different diameters with anchorage length  $L_a$  of 50 mm and polyurethane cement, and Figure 16 shows the summary diagram of average bond stress. As shown in the figure, the bond strength decreases with the increase of diameter. When the diameter is 12 mm, the average bond stress is 17.97 MPa; when the diameter of reinforcement is 16 mm, the average bond stress is 16.47 MPa, which is 8.35% lower than that when  $d$  is 12 mm. When the diameter of steel bar is 20 mm, the average bond stress is 13.5 MPa, which is 18.03% lower than that when  $d$  is 16 mm. The bond stress of 20 mm diameter round steel bar is only 6.4MPa, which is only 47.4% of ribbed steel bar under the same condition, mainly because the bond strength of ribbed deformation steel bar is mainly determined by the mechanical bite force, while the bond strength of round steel bar is mainly determined by the friction resistance. For the concrete drawing specimens equipped with smooth circular bars, the interfacial friction resistance under load will make the microcracks in the concrete specimens develop and extend continuously, and the interface slip between the stress bars and concrete will increase, resulting in a rapid reduction of the friction resistance and a significant reduction of the corresponding interfacial bond stress.

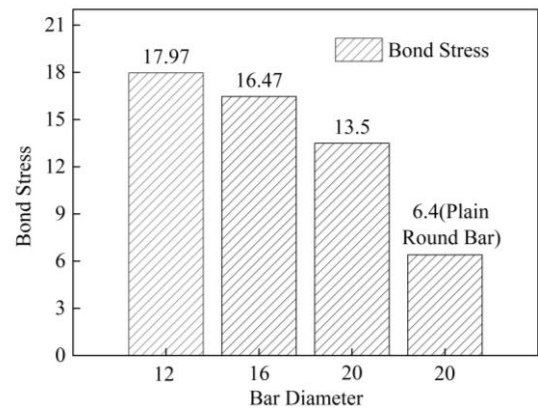
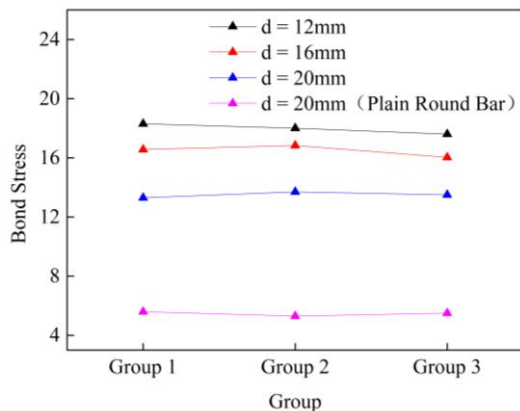


Fig. 15 - Bond stress under each steel bar diameter ( $l_a=50$ )      Fig. 16 - Average bond stress

Figure 17 shows the comparison diagram of bond stress between steel bars with different diameters and polyurethane cement with anchorage length  $l_a$  of 80 mm, and Figure 18 shows the summary diagram of average bond stress. As shown in the figure, when the diameter is 12 mm, the average bond stress is 14.37 MPa. When the diameter of reinforcement is 16 mm, the average bond stress is 13.33 MPa, which is 7.24% lower than that when  $d$  is 12 mm. When the diameter of steel bar is 20 mm, the average bond stress is 12.07 MPa, which is 9.45% lower than that when  $d$  is 16 mm. The bond stress of 20 mm diameter circular steel bar is only 6.4 MPa, which is only 32.31% of ribbed steel bar under the same condition.

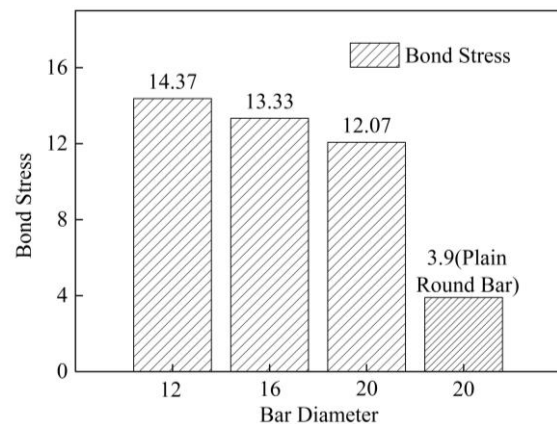
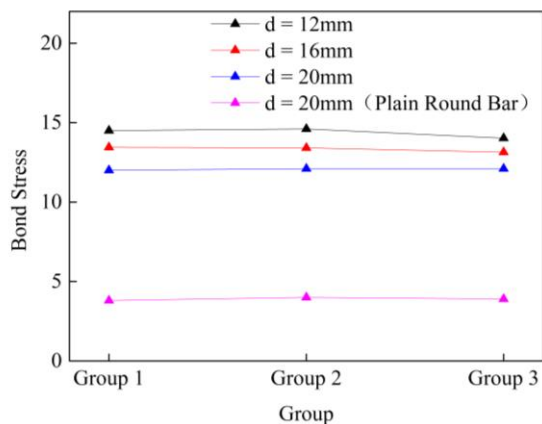


Fig. 17 - Bond stress under each anchorage length ( $l_a=80$ )      Fig. 18 - Average bond stress

## BONDING STRESS-SLIP CURVE

The bond stress and the corresponding slip under different loads are plotted in the same coordinate plot to form a bond - slip ( $\tau$ -s) curve. The values of bond stress and slip are the average values. In order to compare the variation trend of the bond-slip curve of PUC of HRB335 steel bar, the typical bond-slip curve in each group of specimens was selected for comparative analysis in this test. See Figure 19 and Figure 20 for the bond-slip curve.

From the point of view of bond-slip curve, similar to the bond-slip curve of reinforced concrete, the curve is divided into three parts: rising section, falling section and residual section. According to the bond-slip curve, the stress process of the pull-out specimen can be divided into the following stages:

1) The rising stage: At the early stage of loading, the bond stress increases rapidly, the loading end slip is small, and the free end has no slip. The bond-slip ( $\tau$ -s) curve shows a linear relationship

with a large slope. At this stage, the bonding stress is mainly borne by the bonding force of reinforcement and concrete. When the load increases to about 70% of the ultimate drawing force, part of the pre-ribbed concrete is crushed due to the extrusion effect of the transverse ribs on the interribbed concrete, and the interribbed concrete produces micro-cracks. As a result, the bond stiffness decreases, the slope of the bond slip curve becomes smaller, showing a nonlinear relationship, and soon reaches the ultimate bond stress. In the contrast test, the ultimate bond stress of the deformed steel bar is obviously higher than that of the circular steel bar.

2) Descending section: when the bond stress reaches the limit value, the concrete in front of each rib in the anchor length is basically destroyed, and the bond stress begins to decline. With the increase of the slip amount, the broken zone of intercostal concrete also expands continuously, the mechanical bite force gradually loses, and the bond slip curve decreases rapidly and ends at the point where the curvature of the underconcave curve reaches the maximum.

3) Residual stage: when the load drops to a certain degree, the bond slip curve enters the residual stress section, and the bond force will not disappear at this time. For the circular steel bar, the load is basically unchanged, and the binding force is mainly provided by the friction force between the steel bar and the PUC material. For the deformed ribbed steel bar, the curve shows that the load tends to rise and then to fall, and so on, until the steel bar is completely pulled out. This phenomenon indicates that the mechanical bite force of reinforcement and steel still exists at this stage. Therefore, in this stage, the bonding force of ribbed reinforcement is still composed of mechanical bite force and friction force.

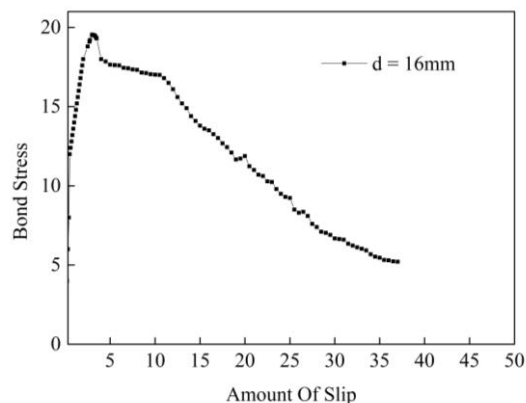
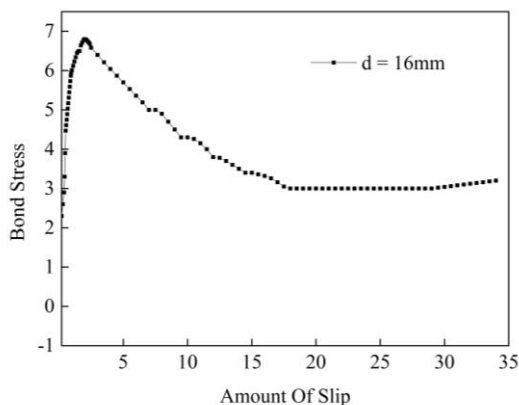


Fig. 19 - Bond-slip curve of deformed steel bar Fig. 20 - Bonding slip curve of circular steel bar

## CONCLUSION

In this paper, the test results of pull-out specimens are analyzed. The effects of the thickness of the protective layer, the anchoring length, the diameter of the steel bar and the surface shape of the steel bar on the bond anchoring performance were studied. The conclusions are as follows:

The average axial tensile strength of PUC material is 31 MPa, and the Poisson's ratio of the material is 0.27. The bending tensile stress-strain curve and the axial tensile stress-strain curve are obtained through fitting.

Contrastive analysis of pull-out specimens with different thickness of protective layer shows that the bond strength between steel bar and PUC material increases with the increase of thickness of protective layer. When coverage thickness is 70 mm, the average bond stress is 16.38 MPa, and when coverage thickness is 40 mm, the average bond stress is 10.53 MPa, which is only 76.50% of that when coverage thickness is 70 mm.

The average bond strength of pull-out specimens with different anchoring lengths decreases with the increase of anchoring length. When anchoring length ( $l_a$ ) is 30 mm, the average bond stress

is 19.55 MPa, and when anchoring length ( $l_a$ ) is 100 mm, the average bond stress is 10.65 MPa, which is only 54.48% of the average bond stress when anchoring length ( $l_a$ ) is 30mm.

By comparing and analyzing the pull-out specimens with different steel bar diameters, it is found that the bond strength between steel bar and PUC decreases with the increase of diameter under the same anchoring condition, and the average bond stress decreases with the increase of anchoring length under different anchoring lengths. The bond strength of the round steel bar is significantly lower than that of the deformed steel bar, and the maximum bond strength is about 47.4% of that of the deformed steel bar under the same condition.

The bond slip curve of PUC material is similar to the bond slip curve of reinforced concrete, and the bond anchorage stress process can be divided into three stages: rising stage, falling stage and residual stage.

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