Research Article

Experimental Study on Bonding Properties between Finishing Rolled Rebar and Grouting Material

Jinyan Wang, Yi Zhao, Jimin Li, Changhong Lu, Xiaosan Yin, and Yijie Bao

School of Architecture and Civil Engineering, Zhongyuan University of Technology, Zhengzhou 451191, China

Correspondence should be addressed to Yi Zhao; 6357@zut.edu.cn

Received 17 November 2022; Revised 17 May 2023; Accepted 14 June 2023; Published 12 July 2023

Academic Editor: Yuri Ribakov

In bearing capacity testing of prestressed concrete pipe piles, grouting material is filled up to the bottom of the pipe pile, which is equipped with a finishing rolled rebar. The reaction force of the reaction beam is transferred to the anchor pile through the bonding force between the finishing rolled rebar and grouting material. Therefore, investigating the bonding properties between the finishing rolled rebar and grouting material is essential to remove barriers to the application of the anchor pile method in bearing capacity testing of the prestressed concrete pipe pile. In this study, the bonding properties of 11 groups of specimens were studied through pull-out tests, and the effects of the cover thickness, diameter, and anchorage length of reinforcement on the bond strength between finishing rolled rebar and grouting material as well as on the bond stress-slip curve were explored. The test results showed that the bond stress-slip curve between finishing rolled rebar and grouting material can be divided into two stages, i.e., slip stage and splitting failure stage. In the slip stage, a linear relationship exists between bond stress and slip amount, and microcracks appear in the grouting material around the finishing rolled rebar. In the splitting failure stage, the slip amount increases rapidly under uplift load. Finally, the grouting material around the finishing rolled rebar forms a failure zone, and splitting failure occurs. The bonding capacity and bond strength between finishing rolled rebar and grouting material increase with the increasing cover thickness of the rebar. The bond strength is the maximum for a relative cover thickness of 3.0, and the difference between the maximum and minimum values is more than 9%. The bonding capacity between rebar and grouting material increases slightly with the increasing rebar diameter, but the bond strength decreases with the diameter, and the difference between the maximum and minimum bond strengths is more than 21%. As the contact area between finishing rolled rebar and grouting material increases, the bonding capacity between them increases with the increasing anchorage length of the rebar. However, the bond strength first increases, then decreases, and finally stabilizes with the increasing anchorage length, and the difference between the maximum and minimum bond strengths exceeds 14.64%.

1. Introduction

Bearing capacity testing of foundation piles is an effective method to ensure the quality of the pile foundation, and the commonly used counterforce devices include weight platform counterforce devices and anchor pile counterforce devices. The former devices are large and expensive and require a long installation period, while the latter devices (Figure 1) are compact, low cost, and convenient in terms of installation. Thus, anchor pile counterforce devices are recommended in technical specifications, such as Technical Code for Testing of Building Foundation Piles, Standard Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling, and Design and Construction of Pile Foundations–Code of Practice [1–3].

The main problem of anchor pile counterforce devices lies in the connection between anchor piles and reaction beams. Unlike in the case of the cast-in-place pile, in prestressed concrete pipe pile (hereafter referred to as pipe pile), the longitudinal reinforcement does not extend out of the pile top. Therefore, when the pipe pile is used as the anchor pile, the connection between anchor piles and reaction beams remains a technical challenge. To deal with this issue, Xi et al. [4] proposed a core-filling concrete method. They poured concrete inside the pipe pile and then connected the reaction beam with the newly configured rebars. However,
Bearing capacity testing by their method is considerably delayed by shortcomings such as excessive wet construction and long curing period of the postpoured concrete, so this core-filling concrete method has not been widely applied in the field. In this study, a core-filling grouting material method (Figure 2) is proposed to ensure a reliable and convenient connection between the pipe pile (anchor pile) and reaction beams and to shorten the curing period. To conduct this method, the grouting material is poured into the inner wall of the pipe pile, and the finishing rolled rebar is configured. The grouting material exhibits rapid hardening and has good fluidity, high early strength, and strong bonding capacity with the inner wall of the pipe pile. The finishing rolled rebar has high elastic modulus and tensile strength, and it is equipped with connectors for rapid connection to the reaction beam. The reaction force of the reaction beam is transferred to the anchor pile through the bonding between finishing rolled rebar and grouting material. Therefore, understanding the bonding properties between grouting material and finishing rolled rebar is of great importance.

Ordinary steel bar is often used in engineering structures, it is made of carbon steel or low alloy steel, with a certain strength and toughness, and it is generally used for strengthening concrete structures, building concrete components, and manufacturing reinforced concrete. The connection mode of ordinary steel bars generally adopts binding, welding, and mechanical connection, and the binding mode is not suitable for the tensile situation of ordinary steel bars. In the test of the foundation pile, welding and mechanical connection are expensive and inconvenient to operate.

Compared with an ordinary steel bar, finishing rolled rebar is a straight steel bar with discontinuous external thread without longitudinal ribs made by heat rolling, waste heat treatment, or heat treatment. The steel bar can be connected or anchored with a matching shape at any section. The finishing rolled rebar has the advantages of high yield strength and a large elasticity model. The connection of the rebar and the reverse cross beam can be easily realized with the matching connector.

Studies on the bonding properties between concrete and reinforcement can provide reference to research on the bonding properties between grouting material and finishing rolled rebars. Studies on the bonding mechanism between normal concrete and ordinary reinforcement, the calculation method of bonding capacity, and design anchorage length are numerous and relatively mature, and the achievements of these studies have been included in relevant concrete design specifications. Currently, examination of the bonding properties between different kinds of concrete and reinforcement has become a hot spot: for example, the bonding properties between recycled coarse aggregate concrete and reinforcement [5], between steel fiber reinforced concrete and reinforcement [6], between alkali-activated slag concrete and reinforcement [7], between geopolymer concrete and reinforcement [8], and between high-strength concrete and reinforcement [9] have been examined. Experiments were mainly conducted to analyze the effects of parameters such as the replacement rate of recycled concrete, steel fiber content, reinforcement cover, and concrete splitting tensile strength on the bond strength between concrete and reinforcement.

Figure 1: Anchor pile counterforce device.
The characterization of the bond stress-slip curve between concrete and reinforcement is important in corresponding theoretical analysis and finite element analysis. The classical bond stress-slip curve proposed by Eligehausen et al. is usually used in the simulation analysis of the bonding performance between grouting material and ordinary reinforcement [10, 11]. Meanwhile, experimental studies showed that cycling load, confining pressure, grouting material strength, reinforcement diameter, anchorage length, and cover thickness all affect the bond stress-slip curve between grouting material and ordinary reinforcement [12–16]. A nonlinear relationship exists between bond strength and confining pressure; a spiral stirrup can significantly improve the bond strength between grouting material and ordinary reinforcement. The failure modes of specimens are also affected by anchorage lengths; the lateral constraint of ordinary reinforcement can effectively avoid the splitting failure of specimens. The bond strength increases with the curing age of the grouting material. Grout sleeve connection, a common type of reinforcement connection in prefabricated concrete members, was also used in studies on the bonding properties between grouting material and ordinary reinforcement. Under uniaxial tensile load, the grout sleeve joint experiences two failure patterns, i.e., splitting failure and pull-out failure. Shear failure occurs at the interface between cement-based grouting material and ordinary reinforcement when the reinforcement is pulled out. The grout sleeve joint is considered to meet the design requirement only when the reinforcement fracture occurs outside the sleeve [17–20].

Most researchers have focused on the bonding properties between concrete and ordinary reinforcement and between grouting material and ordinary reinforcement, but the bonding properties between grouting material and finishing rolled rebar have rarely been studied. To further study the bonding properties between them, 11 groups of specimens were designed by considering the effects of the cover thickness, diameter, and anchorage length of reinforcement. The bond-slip formula for calculating the bond strength between grouting material and rebar was established by comparing with the existing bonding performance tests on the grouting material-ordinary reinforcement component to provide sufficient data for calculating the anchorage length of the finishing rolled rebar in the grouting material and finite element analysis.

2. Materials and Methods

2.1. Materials. The finishing rolled rebars used in the test were purchased from Tianjin Tiantie Rolling Secondary Steel Co., Ltd. The rebar samples were subjected to uniaxial tensile tests according to the Tensile Test of Metallic Materials—Part 1: Test Method at Room Temperature (GB/T 228.1–2021) [21]. Their yield strength $f_{y}$, ultimate tensile strength $f_{u}$, and elongation $e$ were 931.3 MPa, 1050.7 MPa, and 8.4% respectively. The core-filling grouting materials comprised high-strength superfine cement, fine aggregate, expansive agent, and slag and were purchased from Zhongde Xinya Building Materials Co., Ltd. Grout material is a kind of cement as the basic material adding an appropriate amount of fine aggregate, a tiny amount of concrete admixture and other materials composed of dry mixed material. Currently, grout material has been applied to the reinforcement and repair of engineering structures because of its large mobility, early strength, heat resistance, fatigue resistance, and so on. Although the splitting strength is higher than that of concrete, the grout adopts a stress-strain relationship similar to that of concrete in finite element simulation [22]. The strength of the materials was controlled by adjusting the water-material ratio. Strength tests were conducted on the grouting material based on Cement Mortar Strength Test Method (GB/T17671–2021) [23]. The water-material ratio, compressive strength, and tensile strength of the grouting material were 100:12.5, 73.3 MPa, and 3.98 MPa, respectively.
2.2. Specimen Design. In all, 11 groups of specimens were designed to investigate the effects of cover thickness $c$, diameter $d$, and anchorage length $l_a$ of the finishing rolled rebar on the bonding properties between rebar and grouting material. The details of the specimens are listed in Table 1.

The dimensions of the hardened grouting material were $150 \times 150 \times 150$ mm [24, 25]. Figure 3 shows the cover thickness $c$ and anchorage length $l_a$ of the rebar. Different cover thicknesses and anchorage lengths were designed by adjusting the diameter and length of the surrounding PVC pipe.

2.3. Test Device and Loading. A lifting Jack was used to apply uplift load on the finishing rolled rebar, the value of which was measured by a weighing sensor set on the upper part of the Jack (Figure 4). The monotonic loading method was adopted in the test. The size of the load value is displayed in real time by the resistance strain meter, and according to the loading value and time of each sampling, the loading rate of the manual hydraulic oil pump is about $100$ N/s. Displacement sensors were arranged at the upper and lower ends of the finishing rolled rebar, as shown in Figure 3.

As the AD segment of the finishing rolled rebar is the free end and does not bear the load, it can be considered that the displacement measured at point A is equal to displacement $S_F$ at point D. The displacement at point C of the loading end is $S_L$, and the average value of bond-slip in the anchorage section of finishing rolled rebar is calculated as follows:

$$S = \frac{1}{2} (S_L + S_F),$$

(1)

where the deformation of the BC segment of the finishing rolled rebar is considered in $S_L$.

The average bond stress $\tau$ between finishing rolled rebar and grouting material can be expressed as follows:

$$\tau = \frac{F}{\pi dl_a},$$

(2)

where $F$ is the uplift load; $l_a$ is the anchorage length; $d$ is the finishing rolled rebar diameter.

When the uplift load reaches the maximum value $F_m$, it is called the bond-bearing capacity of the specimen. The average bond stress thus obtained is called the bond anchorage strength $\tau_a$, which corresponds to the slip value of $S_m$.

3. Results and Discussion

3.1. Specimen Failure Mode. Similar to the bond stress between deformed steel and concrete, the bond stress between finishing rolled rebar and grouting material has three main parts: (1) chemical bonding between the cement colloid of the grouting material and the outer surface of the rebar; (2) friction on the contact surface between grouting material and rebar; (3) mechanical interlocking force between grouting material and surface threads of the rebar. The chemical bonding is relatively small and negligible in the early stage of the application of uplift load. As the uplift load increases, friction and interlocking force start contributing to the pulling force resistance. The bond stress is the resultant force with an axial force component and a radial force component along the finishing rolled rebar. The longitudinal stress on the grouting material mainly arises from the axial shear stress of the rebar, while the circumferential tensile stress on the grouting material originates mainly from the radial force of the rebar.

In the early loading stage, the grouting material between the threads of the rebar exhibited elastic deformation; the relative slip between rebar and grouting material was insignificant, and microcracks appeared and developed gradually. As the tension increased, the deformation of the rebar also increased, resulting in a gradual increase in the shear stress of the grouting material generated by the tangential component. The grouting material was partially split. Meanwhile, the relative slip between the rebar and the grouting material also increased, and the deformation of the grouting material between threads of the rebar entered the plastic stage. When the external load continued to increase, the degree of damage to the grouting material between threads of the rebar was further aggravated, and the deformation range was further extended, finally causing squeezing failure and delamination. When the maximum bearing capacity was reached, the grouting material underwent splitting failure, as shown in Figure 5. The test results showed that the possibility of grouting material experiencing splitting failure increases with decreasing cover thickness.

3.2. Parameter Analysis for Bond Strength

3.2.1. Relative Cover Thickness. The cover thickness of the rebar was the distance from its outer surface to the exterior surface of the cubic specimen (grouting material). Different cover thicknesses (listed in Table 1) were designed by eccentric settings of the rebar. The relative cover thickness is the ratio of cover thickness to the rebar diameter and is expressed as $c/d$. Table 2 lists the test results of the bond strength of specimens with different cover thicknesses. According to these results, the bond strength between grouting material and rebar increases with the increasing $c/d$. When $c/d$ reaches a threshold, the increase in bond strength becomes insignificant and the bond strength tends to a constant value. With the cover thickness remaining constant, the relative cover thickness decreases with the
increasing rebar diameter. The contact surface and chemical bonding between grouting material and rebar increase with the increasing rebar diameter. However, when the rebar diameter increases, the protruding thread height on the surface does not increase much, and hence, the friction and mechanical interlocking force between grouting material and rebar do not show a significant increase. Since the ratio of chemical bonding in the bond strength between grouting material and rebar is relatively small, the bonding capacity increases slightly with the increasing rebar diameter, but the bond strength decreases with the increasing rebar diameter. Therefore, the bond strength increases with the increasing relative cover thickness.

Huang [26] experimentally examined the bonding performance of normal concrete and a high-strength steel bar and obtained the relationship between bond strength and relative cover thickness:

$$
\frac{f_{tu}}{f_t} = 1.98 + 0.64\left(\frac{c}{d}\right)
$$

(3)

Yao [27] added ceramsite to high-strength concrete and investigated the bonding performance between ceramsite concrete and steel bar. The following relationship between bond strength and relative cover thickness was obtained:
Table 2: Test results of bond strength of specimens with different cover thicknesses.

<table>
<thead>
<tr>
<th>Number/C</th>
<th>C (mm)</th>
<th>D (mm)</th>
<th>c/d</th>
<th>( F_u ) (kN)</th>
<th>( \tau_u ) (MPa)</th>
<th>( \frac{\tau_u}{f_t} ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1-1</td>
<td>40</td>
<td>20</td>
<td>2.0</td>
<td>147.38</td>
<td>19.56</td>
<td>3.98</td>
</tr>
<tr>
<td>A1-2</td>
<td>40</td>
<td>20</td>
<td>2.0</td>
<td>146.43</td>
<td>19.43</td>
<td>3.91</td>
</tr>
<tr>
<td>A1-3</td>
<td>45</td>
<td>16</td>
<td>2.8</td>
<td>154.48</td>
<td>19.30</td>
<td>3.87</td>
</tr>
<tr>
<td>A2-1</td>
<td>50</td>
<td>20</td>
<td>2.5</td>
<td>152.94</td>
<td>20.29</td>
<td>4.04</td>
</tr>
<tr>
<td>A2-2</td>
<td>50</td>
<td>20</td>
<td>2.5</td>
<td>151.56</td>
<td>20.11</td>
<td>4.03</td>
</tr>
<tr>
<td>A2-3</td>
<td>50</td>
<td>20</td>
<td>2.5</td>
<td>153.31</td>
<td>20.34</td>
<td>4.05</td>
</tr>
<tr>
<td>A3-1</td>
<td>60</td>
<td>20</td>
<td>3.0</td>
<td>159.67</td>
<td>21.19</td>
<td>4.69</td>
</tr>
<tr>
<td>A3-2</td>
<td>60</td>
<td>20</td>
<td>3.0</td>
<td>159.50</td>
<td>21.17</td>
<td>4.67</td>
</tr>
<tr>
<td>A3-3</td>
<td>60</td>
<td>20</td>
<td>3.0</td>
<td>159.33</td>
<td>21.14</td>
<td>4.67</td>
</tr>
<tr>
<td>A4-1</td>
<td>60</td>
<td>20</td>
<td>3.25</td>
<td>162.70</td>
<td>21.58</td>
<td>4.34</td>
</tr>
<tr>
<td>A4-2</td>
<td>60</td>
<td>20</td>
<td>3.25</td>
<td>149.40</td>
<td>19.83</td>
<td>3.91</td>
</tr>
<tr>
<td>A4-3</td>
<td>60</td>
<td>20</td>
<td>3.25</td>
<td>153.25</td>
<td>20.33</td>
<td>4.04</td>
</tr>
<tr>
<td>B1-1</td>
<td>65</td>
<td>16</td>
<td>4.06</td>
<td>160.94</td>
<td>26.69</td>
<td>4.22</td>
</tr>
<tr>
<td>B1-2</td>
<td>65</td>
<td>16</td>
<td>4.06</td>
<td>130.02</td>
<td>21.56</td>
<td>3.41</td>
</tr>
<tr>
<td>B1-3</td>
<td>65</td>
<td>16</td>
<td>4.06</td>
<td>167.68</td>
<td>27.80</td>
<td>4.98</td>
</tr>
<tr>
<td>B2-1</td>
<td>65</td>
<td>18</td>
<td>3.61</td>
<td>125.63</td>
<td>18.53</td>
<td>3.26</td>
</tr>
<tr>
<td>B2-2</td>
<td>65</td>
<td>18</td>
<td>3.61</td>
<td>148.00</td>
<td>21.83</td>
<td>4.14</td>
</tr>
<tr>
<td>B2-3</td>
<td>65</td>
<td>18</td>
<td>3.61</td>
<td>153.98</td>
<td>22.71</td>
<td>4.07</td>
</tr>
<tr>
<td>B3-1</td>
<td>65</td>
<td>25</td>
<td>2.6</td>
<td>146.43</td>
<td>15.54</td>
<td>3.55</td>
</tr>
<tr>
<td>B3-2</td>
<td>65</td>
<td>25</td>
<td>2.6</td>
<td>166.17</td>
<td>17.64</td>
<td>4.25</td>
</tr>
<tr>
<td>B3-3</td>
<td>65</td>
<td>25</td>
<td>2.6</td>
<td>167.40</td>
<td>17.77</td>
<td>4.33</td>
</tr>
</tbody>
</table>

\[
\frac{\tau_u}{f_t} = 0.391 + 0.3328 \left( \frac{c}{d} \right) \quad (4)
\]

According to (3) and (4), bond strength and relative cover thickness are linearly related. Linear regression analysis was performed according to the test data in Table 2 (Figure 6), and the following relationship between bond strength and relative cover thickness was obtained:

\[
\frac{\tau_u}{f_t} = 3.143 + 0.684 \left( \frac{c}{d} \right) \quad (5)
\]

In the linear equation fitted in Figure 7, the correlation coefficient \( R^2 \) is 0.761, which is greater than the critical value of the correlation coefficient of 0.754. That is, the linear relationship between bond strength and relative cover thickness is statistically significant [28–30].

The intercept and slope of (5) are higher than those of (3) and (4). That is, with the increasing relative cover thickness, the bond strength between grouting material and rebar increases to greater extents than that between normal concrete and steel bar or between ceramsite concrete and steel bar. The main reason for this difference is that both normal concrete and ceramsite concrete contain coarse aggregate, and the concrete contains initial cracks. These cracks begin to expand and further develop under the disturbance of an external load, finally inducing splitting failure under an uplift load. However, the core-filling grouting material does not contain coarse aggregate and has a high density after hardening. Therefore, this material has smaller initial internal cracks and undergoes slower crack development. Thus, the improved core-filling method based on the work of Xi et al. [4] by using grouting material instead of concrete is not only convenient for construction but also realizes greater bond-bearing capacity.

3.2.2. Anchorage Length. Table 3 lists the test results of bond strength of specimens with different reinforcement anchorage lengths. According to the test results, the average bond strength first increases, then decreases, and finally stabilizes with increasing anchorage length. The longitudinal distribution of bond stress is not uniform at the thread of the rebar: the bond stress at the loading end is larger than that at the free end. For small anchorage lengths, the distance between the free end and anchorage end is relatively small, and hence, the bond stress on these two parts differs slightly. Thus, the distribution of bond stress is relatively uniform, and the average bond strength \( \bar{\tau} \) is close to the maximum bond strength \( \tau_{\text{max}} \). In contrast, for large anchorage lengths, the free end and anchorage end are far apart, and they experience a quite different bond stress. Hence, the average bond strength \( \bar{\tau} \) is less than the maximum bond strength \( \tau_{\text{max}} \). With further increase in the anchorage length, the difference between these two parts in terms of the bond stress is large, and the proportion of the average bond stress between these two parts to the bond stress along the total length is larger. Therefore, when the anchorage length increases to a certain level, the average bond strength stabilizes.

The data in Table 3 show the differences in bond strength with different anchorage lengths; it is seen that the difference in bond strength is smaller than that in anchorage length. As the contact area between rebar and grouting material increases, the bonding capacity between them increases with the increasing anchorage length.

3.3. Bond Stress-Slip Curve. Figure 7 shows the average bond stress (\( \bar{\tau} \))-slip (\( s \)) curve of each group of specimens. Although the failure modes of the specimen groups are different, the variation law of \( \bar{\tau}-s \) curve is roughly the same and can be divided into two stages.
Slip stage: In the early loading stage, the bond force was mainly provided by the mechanical interlocking force between reinforcement threads and grouting material. There was a basically linear change between bond stress and slip amount, and the slip amount was small. The basically linear $\tau$-s curve had a large slope. In this stage, the grouting material around the finishing rolled rebar developed microcracks, which gradually spread to the surface of the specimens. At the end of the straight-line section, the grouting material between threads of the finishing rolled rebar showed signs of failure.

Splitting failure stage: As the slip continued to increase, the grouting material between the threads of the rebar was continuously squeezed, and the shear failure phenomenon occurred. As the load continued to increase, the bond stress increased to about 80% of the bond strength, and slip increased rapidly; the slope of $\tau$-s curve started to decrease continuously. A large area of the grouting material between threads of the finishing rolled rebar was crushed and destroyed, and an annular failure zone was gradually formed around the finishing rolled rebar. The specimens yielded in the splitting failure stage.

4. Conclusions

To study the bonding properties between finishing rolled rebar and grouting material, 11 groups of specimens were designed considering the effects of the cover thickness, diameter, and anchorage length of reinforcement on the bonding properties. The following conclusions were drawn:

Table 3: Bond strengths of specimens with different reinforcement anchorage lengths.

<table>
<thead>
<tr>
<th>Number</th>
<th>$l_a$ (mm)</th>
<th>$F_u$ (kN)</th>
<th>$\tau_u$ (MPa)</th>
<th>$\tau_{u,m}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1-1</td>
<td>60</td>
<td>78.56</td>
<td>20.85</td>
<td></td>
</tr>
<tr>
<td>C1-2</td>
<td>80</td>
<td>93.68</td>
<td>18.65</td>
<td>21.61</td>
</tr>
<tr>
<td>C1-3</td>
<td>100</td>
<td>156.70</td>
<td>24.95</td>
<td>23.72</td>
</tr>
<tr>
<td>C2-1</td>
<td>123.46</td>
<td>143.90</td>
<td>22.91</td>
<td></td>
</tr>
<tr>
<td>C2-2</td>
<td>149.40</td>
<td>146.40</td>
<td>23.31</td>
<td>23.72</td>
</tr>
<tr>
<td>C2-3</td>
<td>153.25</td>
<td>156.70</td>
<td>24.95</td>
<td></td>
</tr>
<tr>
<td>A4-1</td>
<td>162.70</td>
<td>185.48</td>
<td>21.10</td>
<td></td>
</tr>
<tr>
<td>A4-2</td>
<td>176.73</td>
<td>176.73</td>
<td>20.88</td>
<td></td>
</tr>
<tr>
<td>A4-3</td>
<td>183.60</td>
<td>183.60</td>
<td>20.69</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: $\tau$-s curves of specimens. (a) A1 specimens. (b) A2 specimens. (c) A3 specimens. (d) A4 specimens. (e) B1 specimens. (f) B2 specimens. (g) B3 specimens. (h) C1 specimens. (i) C2 specimens. (j) C3 specimens. (k) C4 specimens.
(1) The bonding capacity and bond strength between rebar and grouting material increase with the increasing cover thickness of the rebar but decrease with the increasing rebar diameter. The bond strength is the maximum for a relative cover thickness of 3.0, and the difference between the maximum and minimum values is more than 9%.

(2) The bonding capacity between finishing rolled rebar and grouting material increases with increasing anchorage length of the rebar. However, the bond strength first increases, then decreases, and finally stabilizes with the increasing anchorage length, and the difference between the maximum and minimum bond strengths exceeds 14.64%.

(3) The bond stress-slip curve between rebar and grouting material can be divided into two stages—the slip stage and splitting failure stage. In the former stage, a linear relationship exists between bond stress and slip amount, and microcracks appear in the grouting material around the rebar. In the latter stage, the slip amount increases rapidly under uplift load. Finally, the grouting material around the finishing rolled rebar forms a failure zone, and splitting failure occurs.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that there are no conflicts of interest.

Acknowledgments
The authors are grateful to the key scientific research project plan of colleges and universities Key Scientific Research Project Plan of Colleges and Universities in Henan Province, China (grant no. 20zx009).

References


[26] Y. C. Huang, Experimental Study on Bonding and Anchoring Performance of New High Strength Steel Bar and concrete, Chang'an University, Xi'an, China, 2019.

[27] R. Yao, Experimental Study on Bonding and Anchoring Properties of High Strength Ceramsite concrete and High Strength Steel Bar, Zhengzhou University, Zhengzhou, China, 2017.

