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Bonding Properties Between Steel Bar and Reactive Powder Concrete - A Mini-Review

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Abstract. Reviewing the research on reinforced reactive powder concrete's bonding properties from three perspectives: bonding test methods, influencing factors of bonding properties and bonding stress-slip constitutive relationship. For the central pull-out test, steel bar and concrete's bond stress state deviates from the actual engineering structure, and the beam test is closer to the actual stress situation. The relevant experimental research at home and abroad and the bond-slip constitutive model based on the test are described in detail, and various factors affecting the bonding performance are analyzed and summarized. Finally, the shortcomings of the research direction and the trend of further research are analyzed to provide some reference for the design of practical engineering structures.

Keywords: Reactive powder concrete, bonding properties, constitutive relation.

1. Introduction

Reactive powder concrete (RPC) has been concerned by scholars at home and abroad since its successful development. Similar to normal reinforced concrete, the bonding problem at the interface between steel bars and RPC has always attracted much attention, and numerous studies have been conducted by scholars in the field. Bonding is the basis of its component work. Once the steel bar and RPC lose the bonding effect, the component will not be able to bear the load normally, and the structure may fail. Therefore, it must be ensured that there are good bonding properties between steel and RPC. Based on a large number of studies at home and abroad, the research on the bonding behaviors between rebars and RPC is reviewed and discussed in this paper from three perspectives: bonding test methods, bonding influencing factors and bond stress-slip constitutive relationship. The future research is prospected in order to provide references for the design of reinforced RPC.

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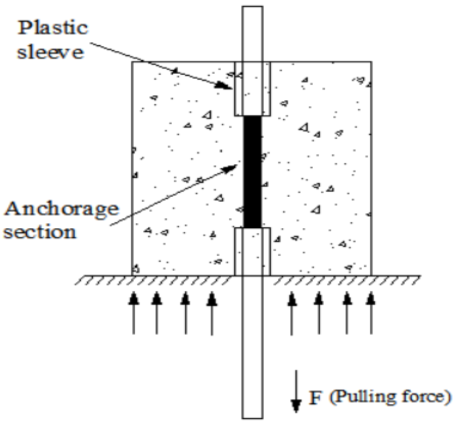
2. Experimental Study of Bonding Properties

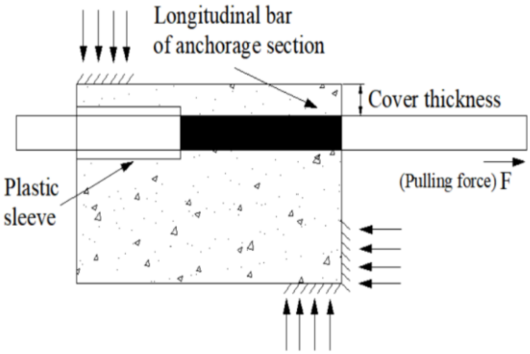
2.1. Experimental Study Methods

The bonding characteristics of normal concrete have been the subject of numerous experimental studies, and have two common test methods: beam test and pull-out test. For RPC, the test methods still adopt the methods of normal reinforced concrete, in which the pull-out test is the main research method. Figure 1 displays the test method's schematic diagram.

The center pull-out test has the advantages of simple specimen preparation, convenient loading and lower cost, and the test data is easier to measure. The RPC is compressed in this method, while the steel bar is in tension, which is inconsistent with the actual structure. Additionally, because the loading end constraint prevents RPC from cracking, the bond strength measured by the central pull-out test is higher. Therefore, this method is suitable for the qualitative analysis of the factors affecting the bonding properties.



(a) Central pull-out test.



(b) Beam test.

Figure 1. The schematic diagram of the test method.

In this study, the pull-out test of the strain gauge in the steel bar was used to examine the distribution and variation trend of the bond stress between the rebar and the RPC under various loads in the bond area. The bond-slip constitutive relationship of each specimen is obtained through regression analysis of the measured free end, loading end, and corresponding load, and the anchorage length of the plain steel bar and the deformed steel bar is determined by Zhao [1].

The effect of RPC-steel bonding properties was studied by central pull-out test by Choi H K, and analyzed how steel fiber volume fractions affect bond strength [2].

The central pull-out test was used to study the bonding characteristics between RPC and deformed steel bars. It was found that the presence of steel fibers prevents the specimen from failing suddenly under the ultimate load, and as a result, the descending section of the bond slip curve was obtained by Jia [3].

The pull-out test was used to examine the effects of fiber morphology, bond length, water-to-cement ratio, and curing conditions on the bonding properties between fiber and RPC by Beglarigale [4].

By using a pull-out test to examine the bonding characteristics between HRB500 steel bar and RPC, the bond slip curve between RPC and high strength steel bar was discovered by Zhang. The effects of steel bar diameter, protective layer thickness, anchorage length and strength grade on the bond strength between RPC and steel bar were discussed [5].

The bonding properties between HRB400 and HRB600 steel bars and RPC were examined by Qin using the factors of steel bar strength grade, steel bar diameter, and bond length. The results indicate that bond length is the primary factor affecting bond strength [6].

The central pull-out test was used to examine the bonding properties between coarse aggregate ultra-high performance concrete (UHPC) and steel bar, taking into account factors like steel bar diameter, bond length, and cover thickness by Zhao. The outcomes show that splitting-pull-out failure and pull-out failure, which are both failure modes for both RPC and UHPC specimens, are similar [7].

By performing a central pull-out test on circular specimens, the bonding characteristics between RPC and steel bars at various ages and with 35% slag content were investigated by Piccinini. It was found that the type of steel bars (smooth circle and thread) had a great influence on the bonding properties between RPC and steel bars, and the calculated value of bond strength is lower than the test value [8].

The central pull-out test was used to examine the bonding characteristics between 8 different types of nano-modified RPC and steel bar, the bond mechanism was explored, and the bond-slip relationship model between nano-modified RPC and steel bar was established by Wang [9].

The bonding properties between steel bar and reactive powder concrete were studied by beam test by An. The influence of steel fiber content, cover thickness and bond length on anchorage characteristic value is analyzed. The empirical formula of anchorage characteristic value under the influence of various factors is fitted in accordance with the test data, and a four-fold line constitutive bond stress-slip model is established [10].

The bond between corroded reinforcements and basalt fiber high strength concrete (BFHSC) was assessed by test by Wang. And comparison tests were run on reinforcement-BFHSC bonding samples that had not yet corroded. On the crack width, bond strength, and ultimate slip, the effects of the BFHSC cover thickness and reinforcement corrosion rate were examined [11]. Figure 2 is the pattern of the test failure specimens.

Figure 2. The pattern of the test failure specimens [11].

The ideal method for simulating the actual state of flexural members is the beam test. Compared with the central pull-out specimens, the fabrication of beam specimens is more complicated and prone to shear failure, so a large number of stirrups should be configured. Compared with the beam end test, the beam end test specimen is simplified. Chana [12] first proposed a beam end specimen, and then some scholars improved it. At present, foreign scholars gradually began to use beam end test to study the bonding performance, such as Hanjari [13], Law [14], Sharma [15]. However, there are few experimental studies on the beam end test of RPC.

2.2. Influencing Factors of Bonding Properties

According to previous studies at home and abroad, the main factors affecting the bonding performance include:

(1) Strength grade of RPC. With an increase in $\sqrt{f_{cu}}$ (f_{cu}: cube strength of concrete), the characteristic values (τ_0: the initial bond strength. τ_s: splitting bond strength. τ_u: ultimate bond strength. τ_r: residual bond strength) of bond strength between steel bar and RPC also increase linearly. When RPC reaches splitting, the steel slip s_s changes little, and when it fails, the steel slip s_r corresponding to the residual bond strength also changes slightly, but the ultimate bond slip s_u of steel decreases first and then increases.

(2) Cover thickness. When the cover thickness is too great, the specimen no longer splits, and the bond strength tends to stabilize even though the bond strength increases as the cover thickness does. The cover thickness is no longer effective at this point, and the bond failure mode switches from splitting failure to pull-out failure.

(3) Steel fiber volume fraction. The initial bond strength and splitting bond strength do not significantly change as the steel fiber volume fraction rises; however, when the steel fiber volume fraction is between 0-2%, ultimate bond strength and residual bond strength rise as well, whereas at 2.5%, ultimate bond

strength declines. The steel bar slip corresponding to the residual bond strength first decreases and then increases with an increase in the steel fiber volume fraction, the steel bar slip when RPC reaches splitting, and the ultimate bond slip of steel change little.

(4) Steel bar diameter. As the diameter of the steel bar increases, the splitting bond strength changes little, the ultimate bond strength decreases, and the residual bond strength increases. When RPC reaches splitting, the steel bar slip increases initially before decreasing, the steel's ultimate bond slip also declines, and the steel bar slip corresponding to the residual bond strength barely changes.

(5) Steel bar type. The bonding characteristics between RPC and steel bars are significantly influenced by regular steel bars (round or thread). Round steel bars have a bonding stress that is about 20% lower than thread steel bars. The use of fiber bars also slightly increases the bond strength.

(6) Steel bar strength. Bond stress increases with the increase of steel strength, on the one hand, because of high strength steel cross rib is higher, on the other hand, high strength steel yield strength is higher.

(7) Bonding length. The splitting bond strength changes little with increasing bonding length, the steel bar slip when RPC reaches splitting decreases first and then increases, the steel bar slip for the steel ultimate bond slip increases first and then decreases, and the steel bar slip corresponding to the residual bond strength decreases linearly with increasing bonding length.

Scholars from both home and abroad have currently conducted a significant amount of research on the factors that affect the bond performance between steel bars and RPC, and each factor's effects have been thoroughly examined [16]. The coupling effect of various influencing factors has also been studied. However, more research is required because there are still few studies on the repeated load, more types of steel bars, RPC modification, and environmental coupling factors such as steel corrosion or freeze-thaw cycles.

3. Bond Stress-Slip Constitutive Relation

Steel bar and concrete interaction throughout the process can be described using the local bond stress-slip constitutive relationship. Because of this, the reasonable finite element simulation results should be based on the precise local bond stress-slip constitutive relationship in the numerical analysis of the component [17].

Taking the relative cover thickness and the relative effective bond length as the main variables by An, the bond stress-slip constitutive relationship of the pull-out specimens without transverse reinforcement is fitted [18], as shown in Equation (1).

$$\tau = a_0 + a_1 s^2 - a_2 s^3 + a_3 s^4 \tag{1}$$

a_0, a_1, a_2, a_3, the coefficients related to relative cover thickness and relative effective bond length; τ, the bonding stress; s, the slip amount.

Form-based $\tau = As + B_1 s + B_2 s^2$ fitting of the bond-slip constitutive relationship between steel bars and RPC by Zhao [1], as shown in Equation (2).

$$\tau = 7.72 + 9.85s - 0.99198s^2 \quad (2)$$

The bond stress-slip constitutive relationship of the pull-out specimens is fitted using the steel fiber volume fraction as the primary variable by Jia [3], as shown in Figure 3.

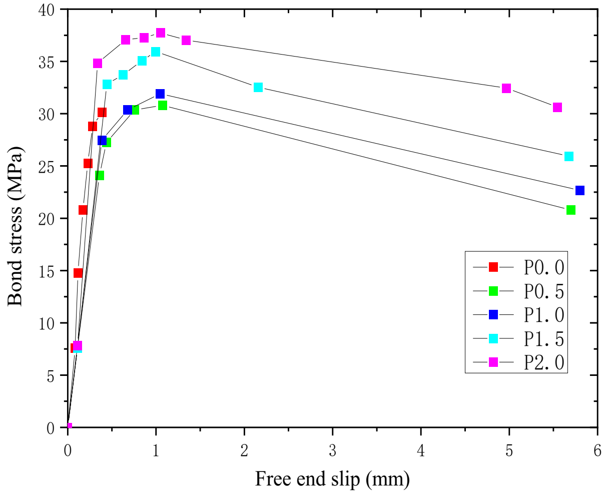


Figure 3. Different steel fiber volume fraction τ-s curve [3].

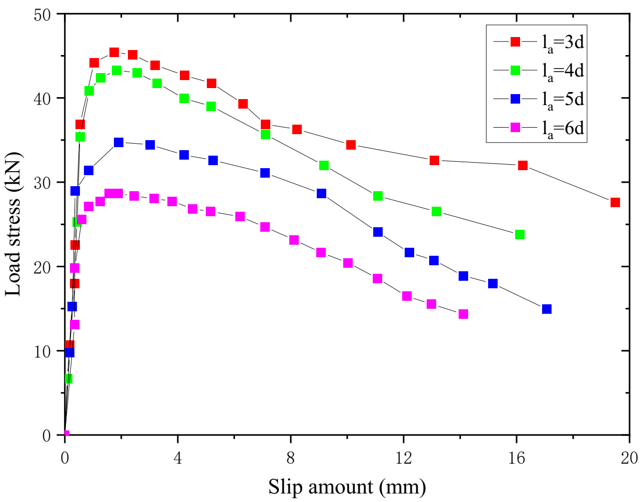


Figure 4. The bond-slip curves [5].

Figure 4 displays the results of fitting specimens with different anchorage lengths' bond-slip curves by Zhang [5].

The deformed rebar and RC reactive powder concrete average bond stress-slip constitutive model is divided into five stages: non-slip, slip, slip acceleration, descent, and residual. The relationship between bond stress and slip value in these five stages is expressed in piece-wise function form, as shown in Equation (3). Finally, the bond slip constitutive is expressed as a product of its function with the fitted bond position [19].

$$\bar{\tau} = \begin{cases} k_1 s + \tau_0, s_s \leq s < s_u \\ k_2 + k_3 s + k_4 s^2, \quad 0 < s < s_s \\ k_5 + k_6 s, \quad s_u \leq s < s_r \\ \tau_r, \quad s \geq s_r \end{cases} \tag{3}$$

k_1~k_6, formula coefficients, according to the characteristics of τ-s curve and the characteristic value of bond anchorage, it is calculated.

Unlike normal reinforced concrete, most studies have now fitted the descending section of bond slip to a curve. However, most of the considered loads are monotonic loads, and there are few studies on repeated loads, and also few studies on the bonding characteristics between the steel bar and RPC when it is corroded.

4. Conclusions and Prospects

This essay examines the bond slip of steel bar and RPC research findings from three perspectives: bond slip test method, influencing factors and constitutive model. For promoting the further development and improvement of bond-slip research, the research results and the contents to be further studied are summarized as follows:

(1) At present, the research methods of bonding properties between steel bar and RPC at home and abroad still adopt the central pull-out method or beam test method, and most of them adopt the former, but the beam test method can better reflect the real stress state of the results, so if it can be made easier to operate, the application range of the beam test method will be broader.

(2) Three general categories can be used to summarize the numerous main factors that influence the bond strength between steel bar and RPC. The first is the impact of the properties of the RPC material, such as its compressive and tensile strength; the second is the impact of the properties of the steel material, such as its diameter, shape characteristics, yield strength, number of steel bars; and the third is the relationship between steel and concrete, such as anchorage length, thickness of protective layer, and various other factors affecting the quality and strength of the two.

(3) For the establishment of the bond-slip relationship, there are relatively many studies on monotonic load. However, there are still few studies on the repeated load, more types of steel bars, RPC modification, and environmental coupling factors such as steel corrosion or freeze-thaw cycles. Therefore, it is essential to conduct more in-depth analysis in the upcoming research, establish a corresponding bond-slip constitutive relationship, and enhance the conceptual framework of bond-slip between steel bars and RPC.

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