BOND STRESS-SLIP RELATIONSHIP IN REACTIVE POWDER CONCRETE BEAMS

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ABSTRACT

Studying the bond strength-slip relationship, development length, compression strain and the maximum load capacity of beams made of reactive powder concrete are the main targets of this work. In order to achieve these goals twelve large-scale beams were made, cured and tested. Several parameters like compressive strength, steel fiber content, tension bar size, development length and concrete cover thickness and their effects on the main study objectives are examined. The test results show that the bond strength increasing ratio is about 12.669%, and the recorded slip decreased by ratio of 67.411% as the compressive strength increased from 70 MPa to 90 MPa. As the steel fiber ratio increased from 0% to 2% the slip decreased by ratio of 29.6% and the bond strength increased by the ratio 54.234%. Also, the decreasing in bar diameter from 25 mm to 16 mm made the bond strength raised with ratio of 40.361%. Oppositely the recorded slips decreased and 16 mm bar provide the lowest slips with the descending ratio of 62.189%. The increase in cover thickness from 25 mm to 50 mm raises the bond strength with ratio of 17.538%, while a slight reduction in slip can be noticed. Finally, the bond strength increased with the increasing of development length.

Keywords: reactive powder concrete, bond strength, slip, development length, large-scale beam.

Cite this Article: Dr. Eyad Kadhem, Sameh Badry Tobeia and Dr. Ammar A. Ali, Bond Stress-Slip Relationship in Reactive Powder Concrete Beams, International Journal of Civil Engineering and Technology, 9(4), 2018, pp. 1078–1089.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=9&IType=4
1. INTRODUCTION:
Reinforced concrete is a non-homogeneous composite material, basically reinforced concrete members designed to resist both tension and compression stresses, in which concrete and steel reinforcement carry compression and tensile stresses respectively. In order to reach the design purposes of structural members made with reinforced concrete, these members should behave as a one structural unit. Thus, the bond strength between reinforcing steel bars and the surrounding concrete considered an important factor in determining the maximum load carrying capacity of the reinforced concrete members. The bond strength usually influenced the concrete members after crack appearance, therefore, the width of the cracks and the deflection of the members are governed by the bond strength that distributed along the steel bars and the slip between steel bars and concrete.\(^{(1&2)}\)

Development length is known as the sufficient embedded length of the steel bar to prevent the slippage between reinforcing steel and the surrounding concrete to ensure enough stresses transformation between them. If the bond strength available along the developed bars length is not enough, the reinforced concrete behaves as a plane concrete and sudden failure may occurs.

As new types of concrete appears in the last years especially modern types of ultra-high performance concrete such as reactive powder concrete, the needs for further investigation to make a better understanding for bond strength-slip relationship between steel reinforcement and the surrounding concrete, and the development length is necessary. In which, some studies based on pull-out were made but in the other hand experimental studies done on large-scale structural members made of reactive powder concrete is not found.

2. AIM OF THE WORK:
This work aimed to experimentally investigate the bond stress-slip relationship, strain in both steel and concrete, maximum load capacity and mid span deflection in reactive powder concrete beams. For this purpose twelve large-scale beams made of reactive powder concrete have been made and tested under flexural loading up to failure.

3. BOND MECHANISMS:
The Mechanism of the bond between concrete and steel reinforcing bars mainly depends on three components which represented by the chemical adhesion, the friction and the mechanical interlocking between steel bars and surrounding concrete. In case of using smooth bars the first two components were valid to provide the bond strength, while when deformed bars used the importance of mechanical interlock appears. The mechanical interlock mainly depends on the relative rib area of the deformed bars which is highly affects the general behavior of the bond, in addition to the area of the bar ribs other parameters like development length of the bar and bar size have significant effects on the bond strength of the bars that being developed.\(^{(3&4)}\)

Usually, the bond strength assumed to be uniformly distributed along the length of developed bar, thus the bond stress can be calculated as in Eq. (1):

\[
u = \frac{f_s \cdot d_b}{4 \cdot l_d}
\]

Where:
- \(u\) = bond stress in MPa.
- \(f_s\) = stress in reinforcing steel bars in MPa.
- \(d_b\) = diameter of the developed bar in mm.
- \(l_d\) = development length of the bar in mm.
4. BOND STRENGTH AND REACTIVE POWDER CONCRETE:
In the last decade of the twenty century, reactive powder concrete as a new type of ultra-high performance concrete appears, a dense and durable concrete type made with extremely fine materials: cement, fine sand with maximum particles size of 600µ, silica fume and in most cases steel fibers. Reactive powder concrete can be recognized by its high strength, low porosity and low water/cement ratio, in which the compressive strength can reach 800 MPa under certain curing condition, the properties of reactive powder concrete were highly affected by the ratios and the finesses of its materials.\(^{(4\&5)}\)

Several researchers and specifications adopted different formulas to estimate the bond strength between the reinforcing steel bars and the surrounding concrete some times as a function of bond strength-slip relationship, and the development length of the reinforcement. While, most of these formulas essentially derived for conventional types of concrete, a vital need for further examination for bond strength-slip relationship of concrete members made of reactive powder concrete significantly appears.

5. EXPERIMENTAL PROGRAM:
In this work, twelve large-scale beams made with reactive powder concrete are casted, cured and tested in order to experimentally investigate the bond strength-slip relationship, the materials properties, mixes design, the studied mix parameters and beams geometry as well as test procedure are listed below:

1. **Materials properties:** the mechanical properties of reactive powder concrete are highly affected by the properties and the particles size of its components, therefore the physical and chemical properties of these materials must agree with the valid specifications. Materials used in this work and their properties are listed below:
   - **Cement:** Ordinary portland cement type (I) has been used and its properties matching the requirements of the Iraqi specification NO.5/1984.\(^{(6)}\)
   - **Fine sand:** fine quartz sand with particles size of 300µ -600µ a product from DCP (Don Construction Products) company is used in this study to produce reactive powder concrete and agree with the Iraqi standard NO.45/1984.\(^{(7)}\)
   - **Silica fume:** usually used as a percentage of cement weight, silica fume produced by (BASF) company is used in this work and its physical and chemical specifications agree with ASTM C1240\(^{(8)}\) requirements.
   - **Superplasticizer:** ViscoCrete-5930 from Sika is used to improve the workability of the fresh paste of the reactive powder concrete, the properties of ViscoCrete-5930 type agree with the requirements of ASTM C494.\(^{(9)}\)
   - **Steel fibers:** micro steel fibers with aspect ratio of 75 (15 mm in length and 0.2 mm in diameter) and tensile strength of of 2850 MPa has been used.
   - **Tap water** has been used for all process of production (mixing and curing processes).

2. **Reactive powder concrete: mix design and mechanical properties:** In order to study the effect of reactive powder concrete mechanical properties on the relationship of bond strength-slip between the steel reinforcing bars and the surrounding reactive powder, six concrete mixes has been designed and used to investigate the effects of compressive strength and the content of steel fibers as a volumetric ratio. The content of the cement and the fine sand are 900 kg/m\(^3\) and 990 kg/m\(^3\) respectively, also a steady superplasticizer (ViscoCrete-5930) content of 6% is used for all mixes. Silica fume content, steel fibers volumetric ratio and the water/cement ratio are varied as
explained in table(1). Mechanical properties like compressive strength, flexural strength, splitting tensile strength and modulus of elasticity of reactive powder concrete mixes has been experimentally examined and found in this work, where cylindrical specimens of (150 mm diameter × 300 mm height) were used in determining compressive strength, splitting tensile strength and modulus of elasticity while prism of 100 mm × 100 mm × 400 mm were used to find the flexural strength, table (1) summarized the strength tests results.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Steel fibers V_f</th>
<th>Silica fume</th>
<th>Compressive strength($f'_c$) MPa</th>
<th>modulus of rupture ($f_r$) MPa</th>
<th>splitting tensile strength($f_{ct}$) MPa</th>
<th>modulus of elasticity (Ec) MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1%</td>
<td>20%</td>
<td>73.214</td>
<td>17.842</td>
<td>9.609</td>
<td>41286.951</td>
</tr>
<tr>
<td>M2</td>
<td>1%</td>
<td>25%</td>
<td>84.301</td>
<td>20.760</td>
<td>10.148</td>
<td>42617.255</td>
</tr>
<tr>
<td>M3</td>
<td>1%</td>
<td>20%</td>
<td>96.500</td>
<td>22.224</td>
<td>10.362</td>
<td>44327.260</td>
</tr>
<tr>
<td>M4</td>
<td>0%</td>
<td>25%</td>
<td>72.462</td>
<td>6.400</td>
<td>4.033</td>
<td>38924.274</td>
</tr>
<tr>
<td>M5</td>
<td>1.5%</td>
<td>15%</td>
<td>73.936</td>
<td>21.101</td>
<td>11.944</td>
<td>43924.827</td>
</tr>
<tr>
<td>M6</td>
<td>2%</td>
<td>12%</td>
<td>74.804</td>
<td>26.830</td>
<td>12.896</td>
<td>44568.264</td>
</tr>
</tbody>
</table>

6. STEEL REINFORCEMENT:
In this work, five different sizes of steel bars has been used in reinforcing the reactive powder concrete beams, three bars are used as a tension bar Ø16 mm, Ø 20 mm and Ø25 mm each alone where each beam contain one tension bar. Two bars with Ø8 mm are used as stirrups holder and stirrups are provided with Ø 12 mm with spacing of 100 mm see Fig.(1). The yield strength of steel with diameters of Ø8, Ø12, Ø16, Ø20 and Ø25 are 506.00 MPa, 667.45 MPa, 624.00 MPa, 575.86 MPa and 590.43 MPa respectively.

![Figure 1 Steel reinforcement details](http://www.iaeme.com/IJCIET/index.asp)

7. BEAMS GEOMETRY AND TEST PROCEDURE:
Twelve large-scale reactive powder concrete beams of 2000 mm length with cross section of 200 mm × 300 mm are tested under two static point loads up to failure, all beams were designed to fail in bond (anchorage loss) according to ACI 318M-14(10) and tested in inverse position, two notches of 100 mm × 80 mm were made during the cast in order to expose the tension bar where measurements can be taken, for the same reason, the end of tension bar were exposed, Fig.(2) illustrates beam geometry. Relative slip between reactive powder concrete and the main tension bar are measured in four positions two at the notches at the max bending moment and the other two measured at the free ends of the tension bar, concrete compression strain also has been measured at two positions at the compression face of concrete at the maximum bending moment. In this work, development length $l_d$ can be defined as the distance between the support and the nearest point load. The mid span deflection was measured using dial gauge of 0.001 accuracy.
Bond Stress-Slip Relationship in Reactive Powder Concrete Beams

Figure 2 Beams geometry

8. PARAMETRIC STUDY:

Table 2 Beams parameters studied in this work

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Beam</th>
<th>Concrete compressive strength f’c</th>
<th>Steel fiber volumetric ratio (Vf)</th>
<th>Tension bar diameter d_b</th>
<th>Developed length l_d</th>
<th>concrete cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control group</td>
<td>B1-S0-R</td>
<td>70 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Set 1</td>
<td>B2-S1-80</td>
<td>80 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>B3-S1-90</td>
<td>90 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Set 2</td>
<td>B4-S2-0</td>
<td>70 MPa</td>
<td>0 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>B5-S2-1.5</td>
<td>70 MPa</td>
<td>1.5 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>B6-S2-2</td>
<td>70 MPa</td>
<td>2 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Set 3</td>
<td>B7-S3-16</td>
<td>70 MPa</td>
<td>1 %</td>
<td>16 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>B8-S3-25</td>
<td>70 MPa</td>
<td>1 %</td>
<td>25 mm</td>
<td>250 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Set 4</td>
<td>B9-S4-200</td>
<td>70 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>200 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>B10-S4-300</td>
<td>70 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>300 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Set 5</td>
<td>B11-S5-25</td>
<td>70 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td></td>
<td>B12-S5-50</td>
<td>70 MPa</td>
<td>1 %</td>
<td>20 mm</td>
<td>250 mm</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

Several parameters has been studied in this investigation, some parameters are related to the reactive powder concrete components ratios like silica fume content, steel fiber volumetric ratio and water/cement ratio. The effect of concrete compressive strength are studied with three different values of 70 MPa, 80 MPa and 90 MPa, as well as steel fibers volumetric ratio varied with four ratios of 0%, 1%, 1.5% and 2%. Other parameters that studied in this work, are represented by the development length in which three different values are examined (200 mm, 250 mm and 300 mm), concrete cover at tension side (25 mm, 40 mm and 50 mm) and the size of tension bar which also three diameters of 16 mm, 20mm and 25 mm are examined, table (2).
9. BEAMS TEST RESULTS AND DISCUSSIONS:
All beams fail by concrete cover splitting along the anchorage length (bond failure between the steel bars and the surrounding reactive powder concrete) except beam B7-S3-16 which is failed by flexure, the effect of different parameters on the bond strength-slip relationship and on the maximum flexural capacity of the beams are investigated in this work and can be summarized as below. Fig.(3) shows the crack patterns of the control beam B1-S0-R and beam B8-S3-25 as sample of the tested beams. Bond stress between steel reinforcing bars and the surrounding reactive powder concrete calculated in this work by using Eq.(1), two types of strain gauges are used to measure the strain in steel bars and reactive powder concrete at maximum moment zone, as well as LVDTs are used in measuring the slips in both notches and free ends of the tension bar. Only one dial gauge has been used to measure the mid span deflection. Table (3) lists the test results for all beams.

![Beams tested in this work](image)

<table>
<thead>
<tr>
<th>Beam</th>
<th>First crack load kN</th>
<th>Max. load kN</th>
<th>Mid span deflection mm</th>
<th>Max. stress in tension bar (fs)* MPa</th>
<th>Maximum concrete compressive strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1-S0-R</td>
<td>159.424</td>
<td>558.234</td>
<td>9.100</td>
<td>343.740</td>
<td>0.00442</td>
</tr>
<tr>
<td>B2-S1-80</td>
<td>174.370</td>
<td>603.812</td>
<td>9.475</td>
<td>355.017</td>
<td>0.00395</td>
</tr>
<tr>
<td>B3-S1-90</td>
<td>179.352</td>
<td>629.895</td>
<td>11.361</td>
<td>387.317</td>
<td>0.00343</td>
</tr>
<tr>
<td>B4-S2-0</td>
<td>104.622</td>
<td>489.522</td>
<td>8.328</td>
<td>260.973</td>
<td>0.00282</td>
</tr>
<tr>
<td>B5-S2-1.5</td>
<td>199.280</td>
<td>647.312</td>
<td>10.448</td>
<td>376.359</td>
<td>0.00477</td>
</tr>
<tr>
<td>B6-S2-2</td>
<td>259.064</td>
<td>688.663</td>
<td>11.183</td>
<td>402.538</td>
<td>0.00523</td>
</tr>
<tr>
<td>B7-S3-16</td>
<td>114.586</td>
<td>426.460</td>
<td>6.383</td>
<td>500.540</td>
<td>0.00345</td>
</tr>
<tr>
<td>B8-S3-25</td>
<td>249.100</td>
<td>847.998</td>
<td>13.680</td>
<td>228.221</td>
<td>0.00492</td>
</tr>
<tr>
<td>B9-S4-200</td>
<td>154.442</td>
<td>587.093</td>
<td>9.272</td>
<td>311.757</td>
<td>0.00455</td>
</tr>
<tr>
<td>B10-S4-300</td>
<td>139.496</td>
<td>506.459</td>
<td>9.001</td>
<td>364.019</td>
<td>0.00413</td>
</tr>
<tr>
<td>B11-S5-25</td>
<td>174.370</td>
<td>600.850</td>
<td>7.815</td>
<td>316.445</td>
<td>0.00427</td>
</tr>
<tr>
<td>B12-S5-50</td>
<td>149.460</td>
<td>545.072</td>
<td>10.309</td>
<td>371.951</td>
<td>0.00457</td>
</tr>
</tbody>
</table>

*fs measured at failure within ld
a) The effects of concrete compressive strength:
Three beams with three different mixes provide concrete compressive strength of 73.214 MPa, 84.3 MPa and 96.5 MPa has been experimentally investigated. The increasing in concrete compressive strength from 73.214 MPa to 96.5 MPa increased the ultimate load carrying capacity of the beams by a ratio of 12.837%, as well as mid span deflection increased by ratio of 24.846%, Fig.(4). The bond strength-slip relationship is highly affected by the increasing in compressive strength as shown by the results of slips measured in both notches the free ends of the tension bar, the bond strength between tension steel bar and the surrounding reactive powder concrete is positively affected and increased as the compressive strength increased, while the recorded slips values decrease with the increasing of the compressive strength. Thus, the recorded slip at the notches decreased by ratio of 67.411% as compressive strength increased from 73.214 MPa to 96.5 MPa, while bond strength increasing ratio is about 12.669% for the same increasing in compressive strength. The same behavior can be noticed at the bar end measurements, Figs.(5&6). Also, the concrete strain is affected and decreased as the compressive strength increased but the higher compressive strength provide higher bond strength as illustrated in Fig.(7). In all tests the maximum concrete strain was less than the failure compressive strength for reactive powder concrete ($\varepsilon_{cu}$ more than 0.005)\(^{(11)}\).

**Figure 4** Mid span load-deflection for beams with different compressive strength  
**Figure 5** Bond stress-notch slip relationships for beams with different compressive strength  
**Figure 6** Bond stress-free end slip relationships for beams with different compressive strength  
**Figure 7** Bond stress-concrete strain relationships for beams with different compressive strength
b) The effects of steel fibers content:
Steel fibers content highly influenced the beams measurements, in which four beams with four different reactive powder concrete mixes contain steel fiber ratios of 0%, 1%, 1.5% and 2% are experimentally investigated. The maximum load capacity, the load of first crack, mid span deflection, bond strength and concrete strain increased with increasing in steel fibers volumetric ratio, while slip values measured at both notches and free ends decreased with increasing in steel fibers volumetric ratio; Figs.(8,9,10&11) respectively. When steel fiber ratio increased from 0% to 2%, slip at notches and at the free ends decreased by ratios of 29.611% and 28.436% respectively, also, the bond strength and the compressive concrete strain increased by 54.234% and 85.461% respectively.

Similarly, an increasing ratio of 40.681% is recorded for the maximum load capacity as the steel fiber ratio increased from 0% to 2%, as well as the mid span deflection and the first crack load increased by ratios of 34.282 % and 147.619% respectively.

![Figure 8](image8.png) Mid span load-deflection for beams with different steel fibers content

![Figure 9](image9.png) Bond stress - notch slip relationships for beams with different steel fibers content

![Figure 10](image10.png) Bond stress-free end slip relationships for beams with different steel fibers content

![Figure 11](image11.png) Bond stress-concrete strain relationships for beams with different steel fibers content

c) The effects of bar size:
The maximum load capacity increased almost twice as the tension bar increased from 16 mm to 25 mm Fig.(12). The use of different sizes of tension bar shows significant effects on bond stress-slip relationship. As the bar diameter decreased from 25 mm to 16 mm an obvious enhancement in bond strength can be noticed and raised with ratio of 40.361%. Oppositely the recorded slip values show a huge descending with the decreasing in bar size, where the 16 mm bar provides the lowest slips at notches and free end with descending ratios of 62.189% and 35.548% respectively; Figs.(13&14), this behavior occurred due to the increase in
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(surface area/volume) ratio for bars with smaller sizes. Similarly the strain of concrete shows the same behavior as in Fig.(15).

**Figure 12** Mid span load -deflection for beams with different tension bar size

**Figure 13** Bond stress - notch slip relationships for beams with different tension bar size

**Figure 14** Bond stress-free end slip relationships for beams with different tension bar size

**Figure 15** Bond stress-concrete strain relationships for beams with different tension bar size

d) The effects of concrete cover:

Figs.(16,17,18&19) illustrate the load-deflection relationship, the relationship of bond stress-slip and the compression strain of concrete respectively, for beams of three different concrete cover at tension side of 25 mm, 40 mm and 50 mm, these figures refer to a remarkable enhancement in bond strength with slight reduction in slip values as the concrete cover increased. In which the increase in cover thickness from 25 mm to 50 mm raises the bond strength with ratio of 17.538%. In opposite manner for the same cover thickness increasing, the maximum load capacity decreased by 9.283%. Also, slight increasing in concrete compression strain is noticed with the increase in concrete cover.

**Figure 16** Mid span load-deflection for beams with different concrete cover thickness

**Figure 17** Bond stress-notch slip relationships for beams with different concrete cover thickness
e) **The effects of development length:**

In this work, development length of tension bar is defined as the distance from support to the nearest applied point load, three beams having the same mix and materials properties but different developed length are tested. The development lengths are 200 mm, 250 mm and 300 mm respectively. The load-deflection relationship, the relationship of bond stress-slip and concrete strain are illustrated in Figs.(20,21,22&23) respectively. Where, the bond strength increased with the increasing of development length with ratio of 16.76% accompanied by remarkable reduction in slips in both notches and free ends as the development length increased from 200 mm to 300 mm. The increasing in bond strength appeared due to the increasing in surface area of the developed bar immersed in reactive powder concrete.
10. CONCLUSIONS:
The following conclusions can be obtained from test results discussed above:

1. The increasing in compressive strength provides several effects, beside the increasing in ultimate flexural load capacity. The bond strength-slip relationship is highly affected by this increasing. In which, a good enhancement in bond strength is noticed with the increasing of compressive strength accompanied by decreasing with the slip values. Also, the strain recorded at the compression side of reactive powder concrete beams slightly decrease with the increasing in compressive strength.

2. Generally, the increasing in the steel fibers volumetric ratio increases each of ultimate load capacity, bond strength and compressive strain of reactive powder concrete beams. While slip values decreased with the increasing in steel fibers content.

3. The use of higher diameter of steel reinforcing bars highly increased the ultimate load capacity of the beam, contrary the bond strength provided by the smaller bar sizes are higher than bond strength provided by larger bar sizes, also lesser slip as well as concrete compressive strain values can be noticed with the decreasing in bar diameters.

4. As the concrete cover increased the effective depth of the beam decreased therefore the ultimate capacity of beam decreased, but oppositely the bond strength increased with increasing of concrete cover at tension face of the beams. Also, slip values decreased and compressive strain increased with the increasing of concrete cover.

5. The increasing in development length of the tension bar causes the increasing in bond strength and the concrete compressive strain, in the other hand the slip decreased with increasing in development length.

REFERENCES:


