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Bond Stresses between Reinforcing Bar and Reactive Powder Concrete

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ABSTRACT

A good performance of reinforced concrete structures is ensured by the bond between steel and concrete, which makes the materials work together, forming a part of solidarity. The behavior of the bond between the reinforcing bar and the surrounding concrete is significant to evaluate the cracking control in serviceability limit state and load capacity in the ultimate limit state. In this investigation, the bond stresses between reinforcing bar and reactive powder concrete (RPC) was considered to compare it with that of normal strength concrete (NSC). The push-out test with short embedment length is considered in this study to evaluate the bond strength, bond stress-slip relationship, and bond stress-crack width relationship for reactive powder concrete members. The compressive strength of concrete, the nominal diameter of reinforcement, concrete cover, and amount of steel fibers and embedded length of reinforcement were considered as variables in this study.

The test results show that the ultimate bond stress increased with increasing of the compressive strength of concrete, decreasing the nominal diameter of the reinforcing bar, increasing the concrete cover and increasing steel fiber content. In a bond stress-slip relationship, the NSC specimen shows a very short softening zone after reaching the peak point in comparisons with RPC specimen. In RPC, bond stress-slip relationship shows stiffer behavior when the steel fiber content was increased. RPC shows stepper softening zone due to the presence of steel fiber, and the absence of steel fiber cause push-out failure without descending part after peak point. Using NSC instead of RPC in anchorage between reinforcement and concrete, decrease the crack width produced due to radial tensile stresses through the push-out of reinforcing bar. In RPC, the absence of steel fiber, decrease the nominal diameter of the reinforcing bar, increase the concrete cover, decrease the embedded length of reinforcing bar cause push-out failure and vice versa cause splitting failure.

Key Words: bond stresses, reactive powder concrete, push-out specimen, bond stress-slip behavior.

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اجهادات الترابط بين قضيب التسليح و خرسانة المساحيق الفعالة

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الخلاصة

الاداء الجيد للخرسانة المسلحة مضمون بالترابط بين خرسانة وحديد التسليح والذي يجعل المادة تعمل كقطعة واحدة .لمعرفة تصرف الترابط بين الخرسانة وحديد التسليح هو مهم للسيطرة على التشققات بالحدود الخدمية وبقوة التحمل بحدود المقاومة القصوى.

في هذه الدراسة, اجهادات الترابط لخرسانة المساحيق الفعالة وحديد التسليح تم اخذها ومقارنتها مع الخرسانة العادية. تم اخذ فحص اجهاد الدفع لدراسة اجهادات الترابط, علاقة اجهاد الترابط مع التزحلق، علاقة اجهاد الترابط مع عرض التشقق. مقاومة الانضغاط، القطر الاسمي لحديد التسليح، الغطاء الخرساني، كمية الياف الحديد، طول التثبيت للقضيب تم اخذها كمتغيرات لهذه الدراسة. النتائج اظهرت ان اجهاد الترابط يزيد مع زيادة مقاومة الانضغاط، مع نقصان قطر القضيب، زيادة الغطاء الخرساني، مع زيادة كمية الياف الحديد. نموذج الخرسانة العادية اظهر نزول صغير بعد وصوله لاعلى نقطة مقارنة بخرسانة المساحيق الفعالة. علاقة اجهاد الترابط مع التزحلق اظهرت صلادة عالية للنموذج الذي يحتوي على اعلى نسبة الياف. خرسانة المساحيق الفعالة اظهرت نزول تدريجي بعد الوصول لاعلى نقطة بسبب وجود الياف الحديد، وبغيابه فشل الدفع لحديد التسليح سوف يحصل وبدون اي نزول بمنحني اجهاد الترابط-النزحلق. استخدام الخرسانة العادية بدل خرسانة الباودر التفاعلي سوف يقلل من عرض التشقق السطحي. في خرسانة الباودر التفاعلي غياب الياف الحديد، نقصان قطر القضيب، زيادة الغطاء الخرساني، نقصان طول الغرز للقضيب تؤدي الى فشل الدفع الخارجي والعكس يسبب فشل التشظي.

الكلمات الرئيسية : اجهادات الترابط خرسانة المساحيق الفعالة نموذج الدفع الخارجى سلوك اجهاد الترابط –التزحلق.

1. INTRODUCTION

In **1990, Richard and Cheyrezy** had developed a cementitious material named reactive powder concrete (RPC), this material has higher axially tensile and compressive strength in comparison with the normal strength concrete (NSC). The density of RPC is higher than that of NSC and it does not have a coarse aggregate. However, the cementitious compositions of RPC cause brittle failure in tension or compression, therefore steel fibers were added.

The mechanism of bonding between reinforcing bar and concrete means combining the features of the two materials to produce the composite material called reinforced concrete. The mechanism of bonding is activated when the concrete cracks are presented and the cracks are crossed by conventional reinforcement. The latter links the two surfaces of the crack and their stress is distributed into the concrete by the mechanism of the bond. Because of that, the structural behavior of concrete elements depends mainly on the bond mechanism. The bond stress-slip relationships can be obtained from the two well-known tests: pull-out or push-out.

The concrete cover and mechanical properties of concrete (tension and compression) significantly affect on the bonding between the concrete and reinforcing bar. The main parameters in the ultimate bond stress design equations of NSC were calculated based on the experimental results. The characteristics of RPC are different than that of NSC, therefore ultimate bond stress equation and development length of reinforcing bar definitely different. Hence, the aim of the present study is to investigate the bonding behavior between RPC and reinforcing bar using push-out tests. In addition, many design equations of the ultimate bond strength of NSC were presented and compared with the experimental results of this present investigation.

Through the push-out test, the bond stresses assumed to be uniformly distributed through the length of the reinforcing bar, and the force F which has been transmitted on the length l_d and the circumference U relates to the bond stress τ_b.

$$\tau_b = (F / (U \cdot l_d)) \quad (1)$$

The bonding strength between reinforcing bar and concrete is governed by a combination of three components: adhesion, friction and mechanical anchorage. The last has the dominant role in bond strength between the reinforcing bar and the concrete.

According to **MC2010**, two type of failure modes in the anchorage of reinforcement in concrete are: failure of specimens with sufficient concrete cover (referred to as push-out failure) and failure of specimens with insufficient concrete cover (referred to as splitting failures), see **Fig. 1.**

Park and Paulay, 1975 concluded that the geometrical properties of the reinforcing bar affect the ultimate bond stress. The pull-out failure occurs when the distance between ribs are very small and the height of the ribs is relatively high. The splitting failure occurs when the cylindrical tensile forces at the surface of the concrete caused by wedging action exceeding the tensile strength of concrete**. Baek, et al., 2016** studied the bond strength between reactive powder concrete and reinforcing bar through the pull-out tests. The main parameters were steel fibers content, concrete cover, and compressive strength of the concrete. The test results showed that the ultimate bond strength between RPC and reinforcing bar increased with compressive strength, concrete cover and steel fiber content increases.

Tepfers, 1979 modeled the stress surrounding the concrete around the loaded reinforcing bar to determine the splitting strength. This type of failure occurs due to components of the bearing concrete force which distributed in radial directions in a plane perpendicular to the direction of the loaded bar, as shown in **Fig. 3**. The tensile strength of concrete and the cover of concrete are the main factors for improving the confinement of the reinforcing bar. Tepfers′s bond strength model is applied when the concrete surrounding the steel bar is in an elastic range, plastic range, and an elastic-plastic range.

To calculate ultimate bond stress between reinforcing bar and normal concrete, many researchers suggested codes and empirical equations, these are listed in **Table 1**. **MC2010** one of the most well-known codes that define the type of failure in calculating the bond strength in NSC. In **Table 1**, the significant factors in calculating the bond strength are the nominal diameter of the reinforcing bar, the compressive strength of concrete and the cover of concrete.

According to the review of previous experimental results, there is no clear understanding to most effective parameters that effect on bond stress between reinforcing bar and RPC, modes of failure through push-out tests and bond stress-crack width behavior.

2. SCOPE OF WORK

The purpose of the present investigation was:

- Determining the bond stress-slip relationship between the reinforcement and RPC.

- Determining the bond stress-crack width relationship between reinforcement and RPC.
- Investigation the effect of concrete compressive strength, amount of steel fiber, embedded length, the nominal diameter of reinforcing bar and cover of concrete on the ultimate bond stress in RPC.
- Study the modes of failure through the push-out test.
- Checking the applicability of the design codes and researchers equations to predict the ultimate bond stress in RPC.

Also, in this study, the applicability of design codes and researchers equations will be checked for the bond stress of NSC on RPC.

3. BOND STRESS BETWEEN CONCRETE AND REINFORCING BAR

According to **Table 1**, many design codes and researchers**, MC2010 and Tepfers 1979**. define equations to predict the ultimate bond stress of NSC. These equations are used to find the development length of reinforcing bar in concrete members.
The ACI-318-11 provisions were applied to calculate the development length of the compressive strength of concrete up to 70 MPa. **Fig. 2** shows the relation between the development length of reinforcing bar and the compressive strength of normal concrete according to the provisions of ACI. Using reinforcing bar with a yield strength of 420 MPa, concrete cover to the diameter of the bar (c/d_b=2.5), f_c'= 40 MPa and K_{tr} = 0.
This needs development length of the reinforcing bar of NSC is 1.93 times longer than that of concrete with a compressive strength of 150 MPa in RPC material without considering the limitation of the compressive strength in ACI code as in **Table 1**.

4.RELATIVE RIB AREA

For each reinforcing bars were used in this study of; ϕ12 mm and ϕ16 mm, the height and spacing of the deformation (ribs) were measured at ten places on both sides of bars, and the average relative rib areas were calculated according to ACI 408/03.
Relative rib area (f_r) is the ratio between the bearing area to the shearing area of the deform reinforcing bar. In this study, the calculated rib area is measured using the simplified equation of ACI 408/03 (equation 2), which is, the ratio between rib height (h_r) and rib spacing (S_r), corrected by a constant that can be ranged from 0.8 to 0.9. **Fig. 4** shows the parameters of the deformed steel bar.

$$f_r = (\text{bearing area}/\text{shearing area}) \approx (0.8 \text{ to } 0.9) \times (h_r/S_r) \qquad \text{....(2)}$$

The horizontal rib angle was found 47^0, rib spacing of 0.7ϕ, rib height equal to 0.09ϕ and the relative rib area for ϕ12 and ϕ16 according to equation 2 was 0.11.

5. TEST SPECIMENS

In this study, the specimens with a single reinforcing bar are embedded with short anchorage length in plain concrete cubic. This small anchorage length of reinforcing bar well-defined the bonding zone and provide uniform stress along the anchorage length.

The push-out specimens were cast in a metal form with the conventional reinforcement. The dimensions of the tested specimen were 150 x150 x120 mm, and the embedded length is between 5ϕ and 10ϕ in diameter as indicated in **Table 4**. The bond length is located at the middle of the specimen and the rest of the specimen (i.e at the top and bottom of the specimen) is debonded by 2.5ϕ using small PVC pipe, see **Fig. 5**.

6. CONCRETE MIXTURE

Two type of concrete was used in this investigation, NSC, and RPC. The compositions of NSC was; ordinary portland cement –type I with specific gravity 3.15; coarse aggregate, 5-19 mm with specific gravity 2.62; fine aggregate with specific gravity 2.57 and fineness modulus 3.05, the mix proportion was presented in **Table 2** and the target compressive strength of 150 x 150 x 150 mm cubic was 30 MPa.

The content of cement in the mix compositions of RPC (more than 800kg/m^3) is higher than that of NSC; secondary binder is also used of silica fume. Glenium-54 was used as superplasticizer to reduce the water/cementitious ratio. Finally, quartz sand of the maximum particle size of 0.5 mm was used as aggregate. Steel fiber has a length of 15 mm and diameter of 0.20 mm were used in constructed the RPC. The mix proportion of RPC adopted in this study was presented by **Hirschi and Wombacher, 2012** as in **Table 3**, and the average compressive strength of cubic was 105 MPa.

7. EXPERIMENTAL PROGRAM

The experimental work was conducted in the Structural and Materials Laboratories – Building and Construction Department at the University of Technology, Iraq. The experimental program can be described as follows:

A total of seven specimens, one from NSC and six from RPC with steel fiber were investigated to test the anchoring capacity of the reinforcing bar in the concrete. The influence of the compressive strength of concrete on the anchorage capacity of reinforcement in concrete was studied on two specimens (NC1-fc30 and RPC2-Ref). The nominal bar diameter effect was studied on two specimens (RPC2-Ref and RPC3-D16). The concrete cover was investigated by comparison of two specimens (RPC2-Ref and RPC4-cover200). The influence of the amount of steel fiber on reinforcement anchorage was studied by comparisons of three specimens (RPC2-Ref, RPC5-fib1%, and RPC6-fib0%) and finally, the influence of embedded length of reinforcing bar was studied on two specimens (RPC2-Ref and RPC7-10ϕ). The characteristics of the tested specimens are summarized in **Table 4.**

8. PUSH-OUT TEST

In push-out tests, the concrete along the embedded length was under compression. The conventional reinforcement was pushed from one end of the test specimen to produce the slippage between the reinforcing bar and the concrete.

The hydraulically testing machine with a capacity of 180 kN was used to apply monotonic displacement (displacement control test). The vertical displacement (slip of the reinforcing bar) was measured at the end of the loaded steel bar using actuator displacement increments. Two dial gauges at the mid-height of the specimen were used to measure the crack width in two

perpendicular directions. After pouring the concrete, the specimens were cured in a water bath for 28 days, after that, the specimens laid at laboratory temperature till the date of testing.
The load was applied in displacement control of 0.5 mm / minute. The time spent for testing one specimen was about 30 to 40 minutes. **Fig. 6** shows the specimens under test.

9. TEST RESULTS

This section presents test results of:

- Study the effect of the compressive strength of concrete, the nominal diameter of reinforcement, concrete cover amount of steel fiber, an embedded length of reinforcing bar on the ultimate bond stress in RPC.
- Bond stress-slip behavior.
- Bond stress-crack width behavior.
- Modes of failure.

The bond strength in this test results was calculated according to Equation 3.

$$\tau_{ult} = P_{ult} / (\pi D * l_d) \qquad .....(3)$$

Where; τ_{ult} is the ultimate bond stress; P_{ult} is the ultimate applied force; D is the nominal diameter of steel bar and l_d is the embedded length of reinforcing bar in concrete.

9.1 Effect of Compressive Strength of Concrete

As mentioned before, two types of concrete were adopted in this investigation to study the effect of the compressive strength of concrete on the bond strength between the reinforcement and concrete. The first specimen constructed from NSC (f_{cu} = 30 MPa) and the other from RPC (f_{cu}= 105 MPa) with 0.5% steel fiber content. The results were listed in **Table 5**.
From **Table 5**, the ultimate bond stresses were increased by 253.6% when used RPC instead of NSC. This is due to the fact that, the cementitious compositions of RPC with the maximum size of a particle of 0.5mm and the presence of steel fiber increase the bond stresses between the reinforcing bar and the concrete.

9.2 Effect of Nominal Diameter of Reinforcing Bar

Comparisons between specimen RPC2-Ref with a nominal diameter of 12 mm and specimen RPC3-D16 with a nominal diameter of 16 mm were used to study the effect of nominal diameter on the bond strength between reinforcement and RPC. The results were listed in **Table 6**, in which, the bond stresses decrease by 36% when the nominal diameter of the reinforcing bar increase from 12 mm to 16 mm. This is due to, increase the contact surface area between the reinforcement and the concrete.

9.3 Effect of Concrete Cover

Comparisons between the RPC2-Ref specimen and the RPC4-Cover200 specimen were used to study the effect of confinement on the bond strength in RPC. The concrete cover of RPC2-Ref specimen was 150 mm and 200 mm for the RPC4-cover specimen. The ultimate bond strength increased by 3.8% when the concrete cover increased from 150 to 200 mm, as in **Table 7**. This is due to, increase the confinement of concrete decreases the tensile stresses produced by push-out the reinforcing bar from the specimen.

9.4 Effect of Amount of Steel Fiber

The effect of steel fiber content on the bond strength was studied by comparison the test results of the RPC2-Ref specimen with 0.5% steel fiber, the RPC6-fib0% specimen with 0% steel fiber and the RPC5-fib1% specimen with 1% steel fiber. According to **Table 8**, the ultimate bond stress increased by 140.1 % and 182.8% when the steel fiber content increased from 0% to 0.5% and from 0% to 1% respectively. This is expected, due to the confinement produced by steel fiber.

9.5 Effect of embedded length of reinforcing bar

Two embedded lengths of reinforcing bar were used to study the effect of anchorage capacity of reinforcement in RPC. The RPC2-Ref specimen has an embedded length of 5ϕ, while the RPC7-10ϕ specimen has an embedded length of 10ϕ. From test results listed in **Table 9**, doubling the embedded length from 5ϕ to 10ϕ decrease the bond stresses by 57.2%, this is true, due to increasing the contact surface area between the reinforcement and concrete.

9.6 Bond Stress-Slip Relationship

The bond stress calculated according to equation 3 was considered the contact area between the reinforcing bars and concrete is a cylindrical area equal to πD multiplied by the embedded length. Whereas, the slip between the concrete and the reinforcement was measured through the control displacement test machine with displacement increments of 0.5 mm/min.

From **Fig. 7**, the bond stress-slip behavior of reinforcement in RPC has three stages: first, the linear part up to 55% of the ultimate bond stress. Second, pronounced nonlinear behavior till the ultimate bond stresses. Third, softening behavior after reaching the peak point.

The NSC specimen (NC1-fc30) shows a very short softening zone in comparisons with RPC specimen (RPC2-Ref), this is due to cementitious compositions and inclusion of steel fibers in RPC.

The PRC5-fib1% specimen shows the stiffer bond stress-slip relationship, this is due to the confinement effect of higher content of steel fiber on the reinforcement.

The descending part of bond stress-slip relationship shows different behavior; the specimens RPC2-Ref, RPC7-10ϕ, RPC3-D16, RPC5-fib1% and RPC4-cover200 show the steeper softening. There is no softening zone in PRC6-fib 0% specimen.

9.7 Bond Stress-Crack Width Relationship

As already pointed, the dial gauges were placed at the edge of mid-height of the specimen in two perpendicular directions to measure the crack width. **Table 10** shows the average crack width at failure, in which, the minimum crack width occurs at RPC specimen without steel fiber (RPC6-fib0%) and maximum crack width occurs at a specimen with 16 mm nominal diameter (RPC3-D16).

Using NSC instead of RPC in anchorage between reinforcement and concrete decrease the crack width that occurred at the surface of concrete due to push-out of reinforcing bar by 62.7%. Increasing the diameter of the reinforcing bar from 12 mm to 16 mm increased the crack width by 23.5%. Increasing the concrete cover from 150 mm to 200 mm decreased the crack width by 19.6%. Increasing the steel fiber from 0.5% to 1% decreased the crack width by 56.8%. Increasing the embedded length from 5ϕ to 10ϕ decreased the crack width by 68.6%. Finally, for the specimen RPC6-fib0%, the crack width of 0.08 mm was enough to cause spall-off the specimen into two pieces.

9.8 Modes of Failure

In the push-out test, with load increments, the failure starts with adhesion and friction failure which normally occurs at the end of the linear part in the bond stress-slip relationship. Then, the actual bond strength starts with the nonlinear behavior until the ultimate bond strength. After reaching the peak point, the steeper drop in bond strength occurs (softening zone) and the maximum cylindrical tensile stresses in a plane perpendicular to the direction of push-out of the reinforcing bar are produced. The surface cracks occur when these tensile stresses in the surface of concrete reach the value of maximum tensile strength of concrete (f_t). With load increments, the crack growth tills the reinforcing bar push-out from the other side of loading.

Two type of failure occurred in the push-out test; first, the failure of splitting caused by the radial tensile stresses produced by the wedge action of rebar ribs through pushing the reinforcing bar downward. Second, push-out failure caused by partial shear key failure between two ribs, which occurred due to push-out the reinforcing bar from the other side of loading, this occurred without surface tension cracks**. Fig. 7** shows the modes of failure for each tested specimen, in which, the RPC3-fib0%, RPC4-cover200, RPC 3-D-16, RPC2-Ref, RPC5-fib1% specimen show splitting failure, whereas, RPC7-10ϕ, NC1-fc30 shows push-out failure.

It is important to mentioned that, the reinforcing steel bar reach the yield stresses in the case of splitting failure (failure of RPC3-fib0%, RPC4-cover200, RPC3-D-16, RPC2-Ref and RPC5-fib1% specimen) and was below the yield stress (f_y = 420 MPa) in the case of push-out failure (RPC7-10ϕ and NC1-fc30 specimen).

10. PREDICTION OF ULTIMATE BOND STRESS IN RPC

In **Table 1**, many researchers and codes have suggested equations to predict the ultimate bond strength in NSC. Experimental results in the present study were evaluated with the equations presented in **Table 1** to assess the applicability of these equations on RPC. Most predicted methods were derived from direct pull-out, direct push-out, lap splices in beams with flexural stress state. **Fig. 9** shows the relations between the predicted ultimate bond strength based on equations in **Table 1** and the test results conducted in the present study.

As illustrated in **Fig. 9: Huang, et al., 1996** equation for predicting the ultimate bond stress was under-estimated for all specimens. **Elgenhausen, 1983** equation was over-estimated for RPC3-fib0% and RPC7-10ϕ specimen and under-estimated for RPC2-Ref, RPC4-Cover200, RPC5-fib1% specimen. **Esfahani and Rangung, 1998** equation was over-estimated for RPC3-D16, RPC6-fib0% and RPC7-10ϕ specimen. **Orangun, et al., 1977** equation was over-estimated for RPC3-D16, RPC4-Cover200, RPC6-fib0% and RPC7-10ϕ. **MC90** equation was under-estimated for RPC2-Ref RPC3-D16 RPC4-Cover200 and RPC5-fib1% specimen. The **MC2010** equation was under-estimated for all specimens. The **ACI-318-14** equation was under-estimated for all specimens. **Tepfer, 1979** equation in the elastic range was under-estimated for all specimens and over-estimated for all specimens for plastic and elastic-plastic equation.

As a summary, the codes and researchers equations of the ultimate bond stress of NSC cannot be applied to RPC, due to the cementitious composition of this material, lack of aggregate, and presence of steel fiber in comparison with NSC, so, this material need a new equation to be determined.

11. CONCLUSIONS

- The ultimate bond stresses of RPC increased with increasing the compressive strength of concrete, decreasing the nominal diameter, increasing the concrete cover, increasing the fiber content and decreasing the embedded length of the reinforcing bar.
- The NSC specimen shows a very short softening zone after reaching the peak point in comparisons with RPC specimen in a bond stress-slip relationship.
- In RPC, bond stress-slip relationship shows stiffer behavior when the fiber content is increased.
- RPC shows stepper softening zone in a bond stress-slip relationship due to the presence of steel fiber.
- Use NSC instead of RPC in anchorage between reinforcement and concrete decrease the width of surface cracks width produced due to radial tensile stresses through the push-out of reinforcing bar.
- In RPC, the absence of steel fiber, decrease the nominal diameter, increase the concrete cover, decrease the embedded length cause push-out failure and vice versa cause the splitting failure.
- Codes and researchers equations of the ultimate bond stress of NSC cannot be applied to RPC and a new design equation for bond stress in RPC should be determined.

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NOMENCLATURE

$\mathbf{A_{tr}}$ = area of transverse reinforcement, mm^2.
c = concrete cover, mm.
D = the nominal diameter of steel bar, mm.
$\mathbf{d_b}$ = diameter of reinforcing bar, mm.
F= the force which has been transmitted on the length of the reinforcing bar, N.
$\mathbf{f_c'}$= concrete cylinder strength, Mpa.
$\mathbf{f_{ct}}$ = tensile strength of concrete, Mpa.
$\mathbf{f_{cu}}$ = concrete cubic strength, Mpa.
$\mathbf{f_r}$ = relative rib area.
$\mathbf{f_t}$ = maximum tensile strength of concrete, Mpa.
$\mathbf{f_y}$ = yield stress of steel reinforcement, Mpa.
$\mathbf{h_r}$ = rib height, mm.
Ktr = transverse reinforcement index ($40A_{tr}$/S.n)
$\boldsymbol{l_d}$ **=** the embedded length of reinforcing bar in concrete, mm.
n = the number of bars.

$\mathbf{P_{ult}}$ = the ultimate applied force, N.
s = spacing of transverse reinforcement, mm
$\mathbf{S_r}$ = rib spacing, mm.
U= circumference of the reinforcing bar, mm.
$\boldsymbol{\tau_b}$= bond stress between reinforcing bar and concrete, Mpa.
$\boldsymbol{\tau_{ult}}$ = the ultimate bond stress, Mpa.
Ψ_e = coating factor.
Ψ_s = coefficient related to the diameter of conventional rebar.
Ψ_t = reinforcement location factor.

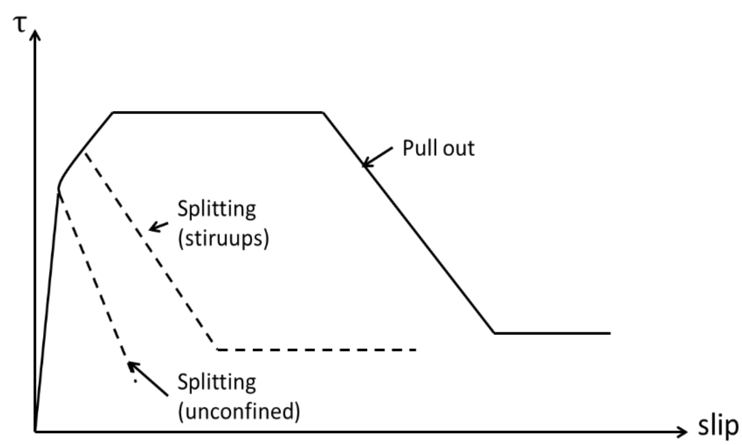

Figure 1. Bond stress-slip relationship according to **MC 2010**.

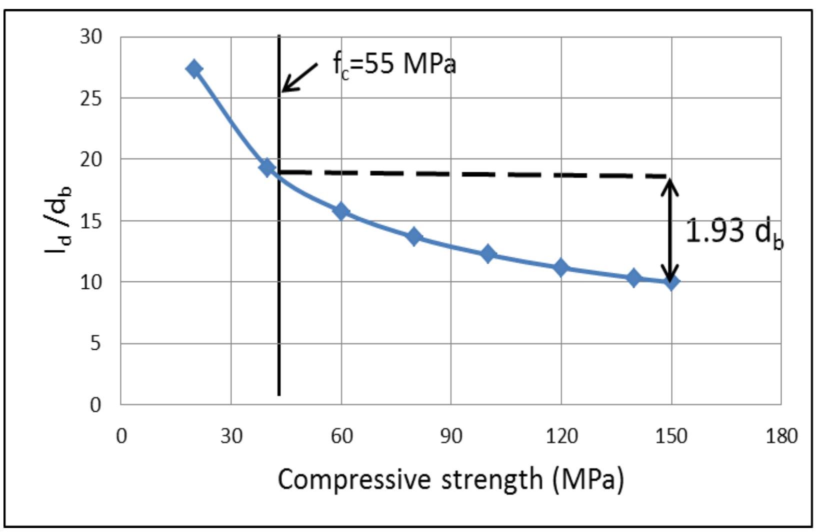

Figure 2. ACI-318-11 provisions for development length of reinforcing bar.

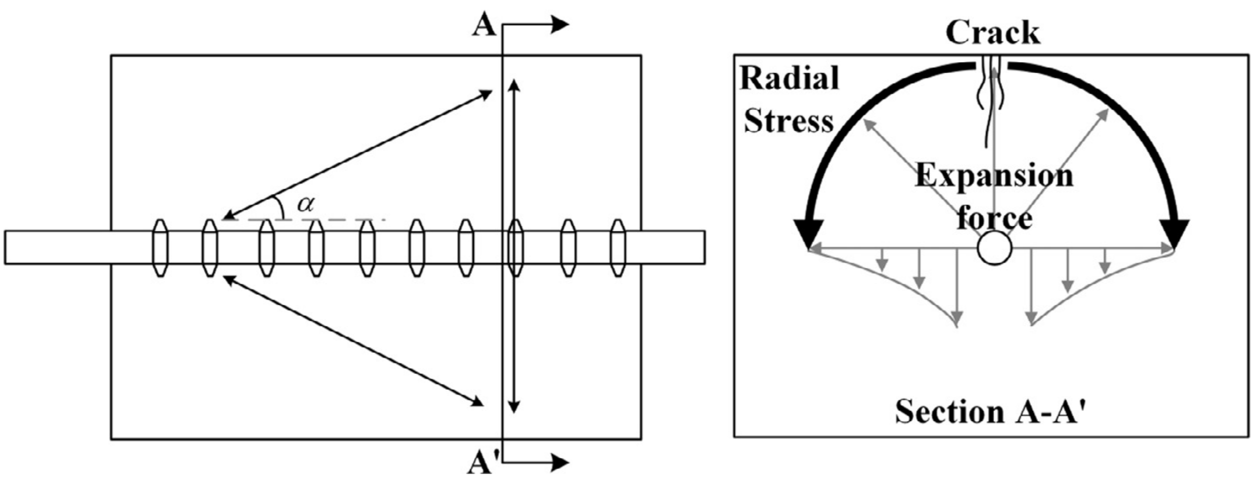

Figure 3. Mechanism of bond stresses.

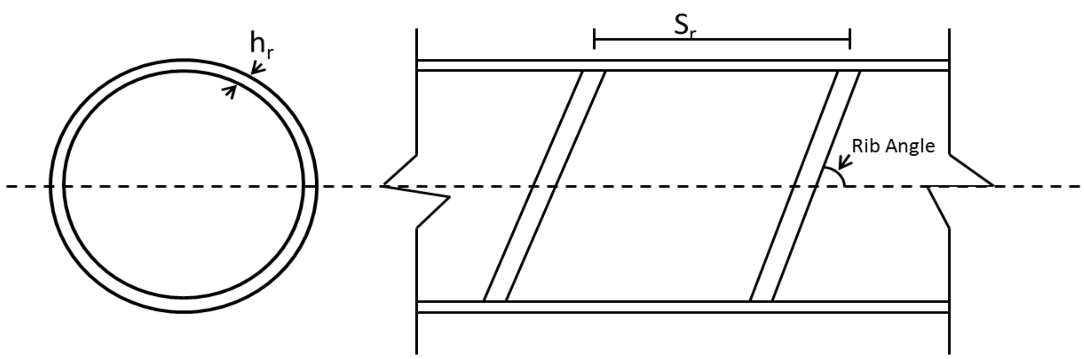

Figure 4. Parameters of the deformed steel bar.

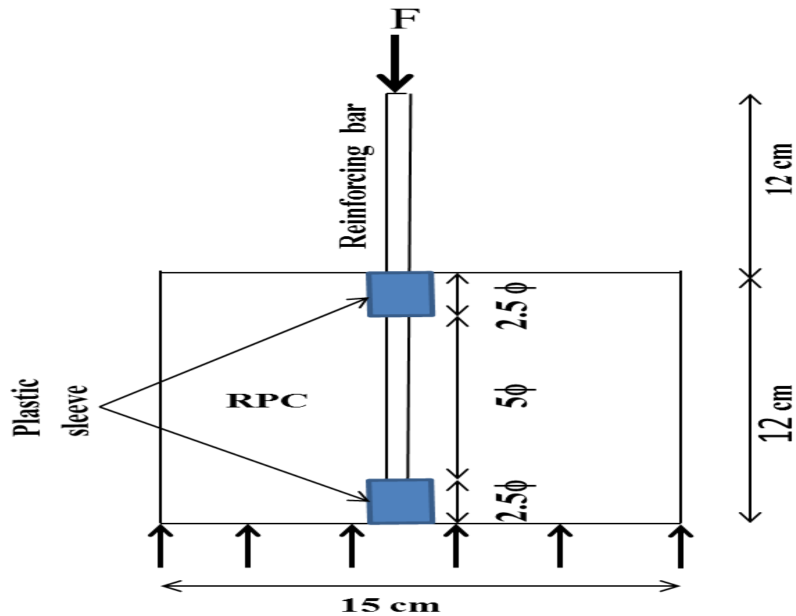

Figure 5. Test specimen.

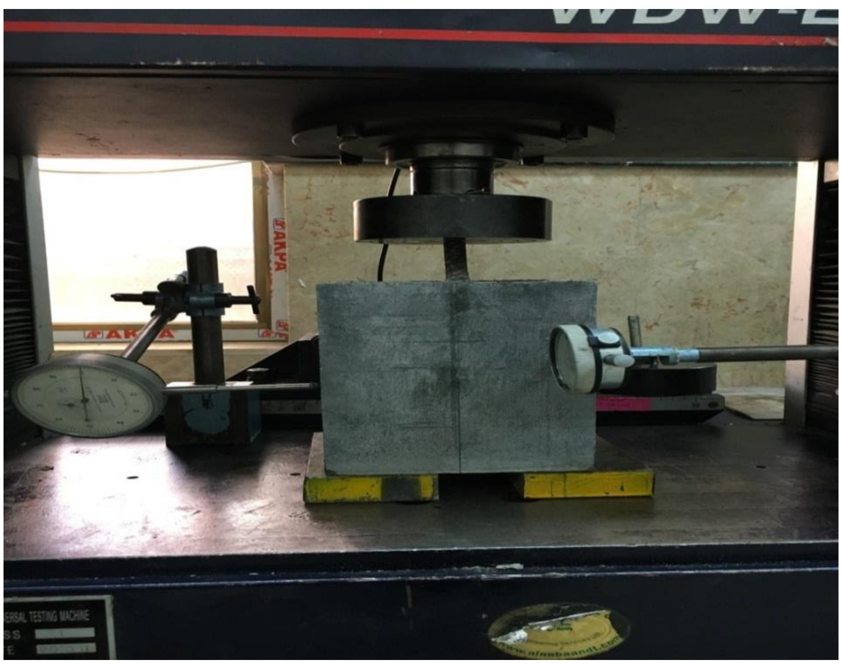

Figure 6. The specimen under test.

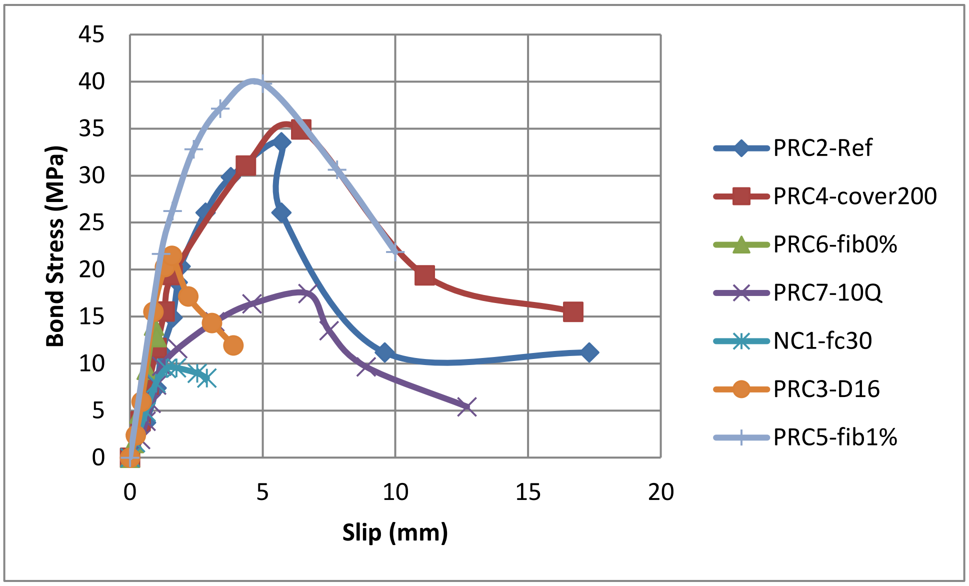

Figure 7. Bond stress-slip relationship.

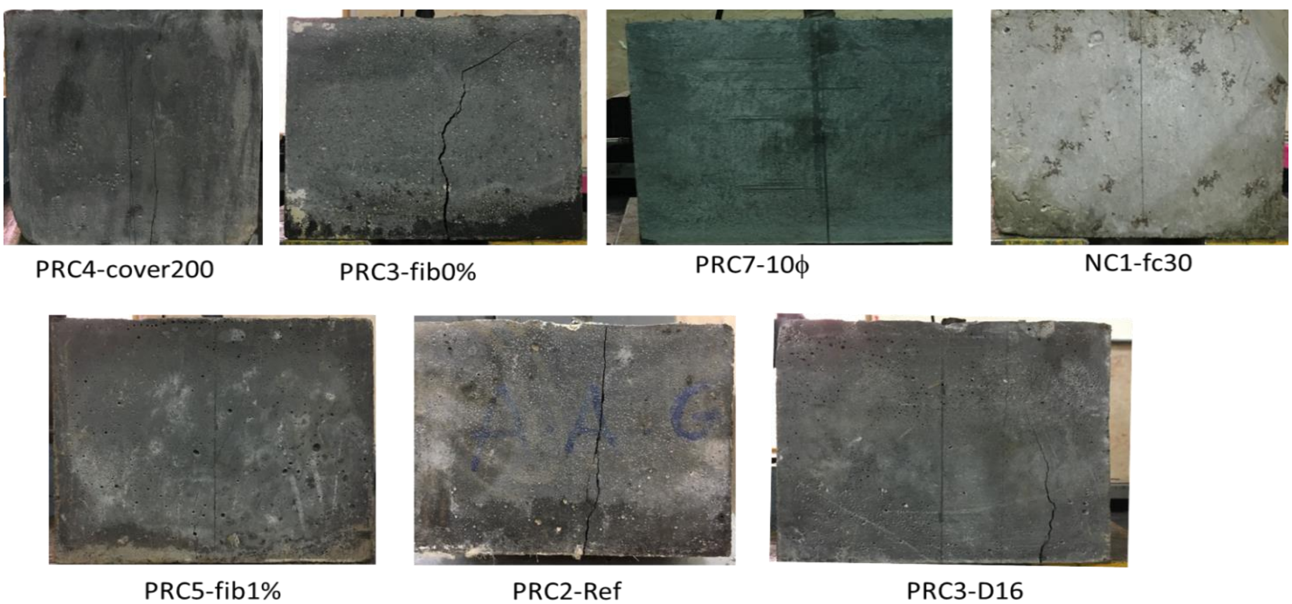

Figure 8. Modes of failure of tested specimens.

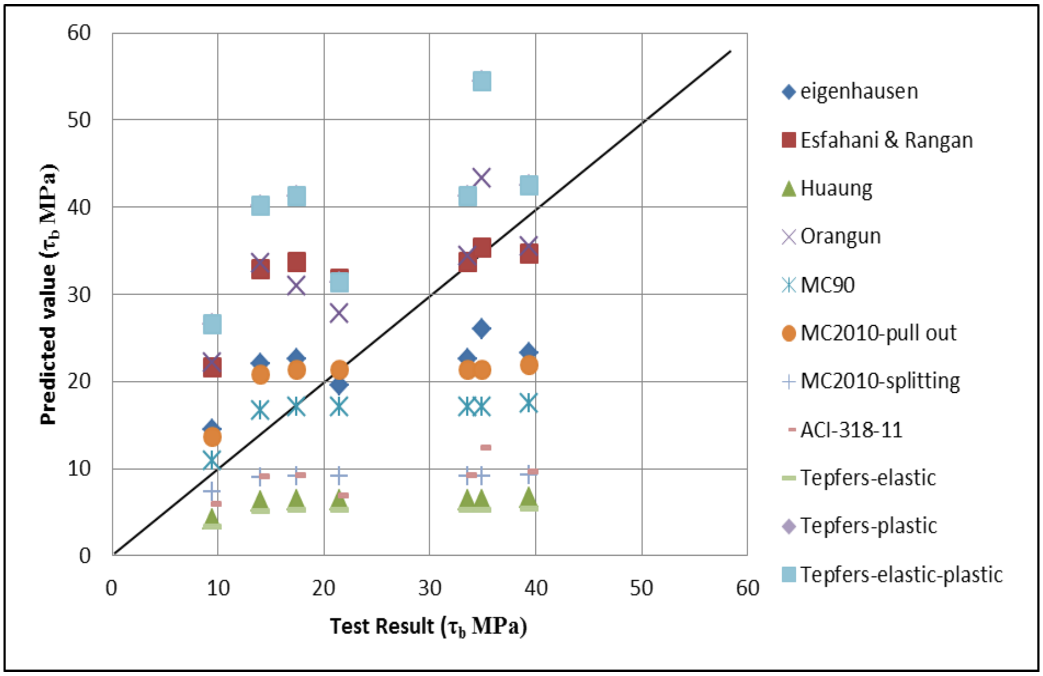

Figure 9. Predicted ultimate bond stress vs. test results.

Table 1. Ultimate bond stresses.

Researcher	Ultimate bond strength (MPa)	The range of Compressive strength (MPa)	Type of tests
Elgenhausen, 1983	$\tau_b = 0.75\sqrt{c/d_b}\sqrt{f_c'}$	30-55	Direct pull out
Esfahani and Rangan, 1998	$\tau_b = 4.9\,\frac{\frac{c}{db}+0.5}{\frac{c}{db}+3.6}\sqrt{f_c'}$	50	Beam ended pull-out
Huang, 1996	$\tau_b = 0.75\sqrt{f_c'}$	60-120	Direct pull-out
Orangum, 1979	$\tau_b = 0.083045(1.2+3\frac{c}{db} + 50\frac{db}{lb})\sqrt{f_c'}$	~70	Lap
MC90	$\tau_b = 2.0\sqrt{f_c'}$	~80	Direct pull-out
MC 2010	$\tau_b = 2.0\sqrt{f_c'}$ (pull out failure) $\tau_b = 7.0\,(f_c'/25)^{0.25}$ (splitting failure)	~120	Direct pull-out
ACI 318, 2014	$\tau_b = 0.275\,\frac{\lambda\sqrt{fc}}{\pi}\,\frac{\frac{cb+ktr}{db}}{\Psi t\,\Psi e\,\Psi s}$, $k_{tr} = \frac{40Atr}{s\pi}$	~70	Lap
Tepfer, 1979	$\tau_{el} = f_{ct}\,\frac{\left(cy+\frac{d}{2}\right)^2-(\frac{d}{2})^2}{\left(cy+\frac{d}{2}\right)^2+(\frac{d}{2})^2}$ (elastic) $\tau_{pl} = f_{ct}\,\frac{2cy}{d}$ (plastic) $\tau_{pl,el} = f_{ct}\,\frac{cy+d/2}{1.664d}$ (elastic-plastic)	~70	Direct pull-out

In **Table 1**, τ_b: ultimate bond strength, c: the cover of concrete, d_b: diameter of reinforcing bar, f_c': compressive strength of concrete, f_{ct}: tensile strength of concrete, Ψ_t : the location of reinforcement parameter, Ψ_e: coating parameter, Ψ_s parameter deals with the spacing of reinforcing bars, A_{tr} : area of transverse reinforcement, s: spacing of transverse reinforcement, n: the number of bars.

Table 2. Mix proportion of NSC.

Material	Weight (kg/m^3)
Cement (Kg/m3)	375
Gravel	1130
Sand	660
Water	195
Water/Cement	0.52

Table 3. Mix proportion of RPC.

Material	Weight (kg/m^3)
Cement	810
Silica Fume	190.9
Quartz Sand	631.8
Superplasticizer	36.4
Steel fiber (0.5%)	39.25
Water	172.7

Table 4. Characteristics of tested specimens.

Specimens	f_{cu} (MPa)	Nominal diameter (mm)	Concrete cover (mm)	Amount of steel fibers (%)	embedded length (l_b)
NC1-fc30	30	12	150	0.5	5ϕ
RPC2-Ref	105	12	150	0.5	5ϕ
RPC3-D16	105	16	150	0.5	5ϕ
RPC4-Cover200	105	12	200	0.5	5ϕ
RPC5-fib1%	105	12	150	1	5ϕ
RPC6-fib0%	105	12	150	0	5ϕ
RPC7-10ϕ	105	12	150	0.5	10ϕ

Table 5. Effect of compressive strength of concrete on bond strength.

Specimen	f_{cu} (MPa)	τ_{ult} (MPa)
NC1-fc30	30	9.5
RPC2-Ref	105	33.6

Table 6. Effect of nominal diameter on bond strength.

Specimens	Diameter	τ_{ult} (MPa)
RPC2-Ref	12	33.6
RPC3-D16	16	21.5

Table 7. Effect of concrete cover on bond strength.

Specimen	Concrete cover	τ_{ult} (MPa)
RPC2-Ref	150	33.6
RPC4-Cover200	200	34.9

Table 8. Effect of fiber content on bond strength.

Specimen	Fiber content (%)	τ_{ult} (MPa)
RPC6-fib0%	0	14.0
RPC2-Ref	0.5	33.6
RPC5-fib1%	1	39.4

Table 9. Effect of embedded length on bond stresses.

Specimen	Embedded length	τ_{ult} (MPa)
RPC2-Ref	5ϕ	33.6
RPC7-10ϕ	10ϕ	17.38

Table 10. Crack width of tested specimens.

Specimen	crack width at failure (mm)
NC1-fc30	0.19
RPC2-Ref	0.51
RPC3-D16	0.63
RPC4-Cover200	0.41
RPC5-fib1%	0.22
RPC6-fib0%	0.08
RPC7-10ϕ	0.16