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Bond Behaviour for Normal and High Strength Concrete

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Abstract

This study includes a series of pullout tests which contain fifty four specimens with short bonded length ($5d_b$) to study the effect of many variables on bond strength for normal and high strength concrete. The variables are: (bar diameter, concrete compressive strength and cover). The study also studies the effect of each variable on bond strength, and suggests two equations to link bond strength with the variables mentioned above. The test results show that, the bond strength increases with the increase of compressive strength and/or cover and decreases with the increase of bar diameter and vice versa. Also, the test results obviously show that, increasing compressive strength reduces the need for cover, where with the increase of the compressive strength from 20 MPa to 75 MPa, the need for cover reduces by34% for the same bar diameter depending on nonlinear regression analysis for the resultant of experimental work, two equations are suggested in this study, the first links the variables (bar diameter, concrete compressive strength and cover) with bond strength where the value of (R) is 0.923. While the second equation links the ultimate bond strength with the variables mentioned above where the value of (R) is 0.927.

الخلاصـــة

*تتضمن هذه الدراسة سلسلة من فحوصات السحب المتكونة من أربعة وخمسون نموذجاً بطول ربط قصير ($5d_b$) لدراسة تأثير عدة متغيرات على مقاومة التلاصق للخرسانة الاعتيادية والعالية المقاومة. المتغيرات التي تم دراستها هي :(قطر حديد التسليح ،مقاومة انضغاط الخرسانة ،الغطاء الخرساني) حيث تم دراسة تأثير كل متغير على مقاومة التلاصق بين حديد التسليح والخرسانة. وكذلك تضمنت هذه الدراسة اقتراح معادلتين لربط مقاومة التلاصق بين الخرسانة وحديد التسليح مع المتغيرات المذكورة أعلاه. بينت نتائج الفحوصات إن مقاومة التلاصق تزداد بزيادة مقاومة الانضغاط وسمك الغطاء الخرساني وتقل بزيادة قطر حديد التسليح والعكس صحيح .كذلك بينت نتائج الفحوصات إن زيادة مقاومة الانضغاط تقلل الحاجة في سمك الغطاء الخرساني حيث بزيادة مقاومة الانضغاط من **(20MPa)** إلى **(75MPa)** فأن الحاجة في سمك الغطاء الخرساني تقل بنسبة ٣٤ % لنفس قطر حديد التسليح. وبالاعتماد على نتائج الانحدار اللاخطي لنتائج العمل التجريبي، تم استنتاج معادلتين ،الأولى تربط المتغيرات (قطر حديد التسليح، مقاومة انضغاط الخرسانة، الغطاء الخرساني) مع مقاومة التلاصق حيث كانت القيمة التقريبية **(R)** تساوي **0.923** . بينما المعادلة الثانية تربط أعلى مقاومة ربط مع المتغيرات المذكورة سابقاً حيث كانت قيمة التقريبية **(R) 0.927.***

1. Introduction

Reinforcement for concrete to develop the strength of a section in tension depends on the compatibility of the two materials (concrete and steel) to act together in resisting the external load. Bond strength results from a combination of several parameters, such as the mutual adhesion between the concrete and steel interfaces and the pressure of the hardened concrete against the steel bar or wire due to the drying shrinkage of concrete. Additionally, friction interlock between the bar surface deformations and the concrete caused by the micro movements of the tensioned bar results in an increased resistance to slippage [1].

1-1 Objective

Bond stress increases with the decrease in bar diameter or the increase in compressive strength or concrete cover, otherwise bond stress decreases. The main purpose of this study is to study the individual and combined effects of these parameters on bond behavior for normal and high strength concrete and to investigate a general function to link the bond stress with these parameters (bar diameter, compressive strength, and cover).

2. Experimental Work

2-1 Test Program

The test program consists of fabricating and testing 54 specimens (36 different specimens and 18 replicates), the replicates are chosen randomly to test the accuracy of the experimental work. Three different variables are investigated, these variables are:

1. Bar diameter (10, 16, and 19) mm.

2. Compressive strength (20, 45, 60, and 75) MPa.

3. Cover (20, 40 and 60) mm.

The embedment length is defined as a function of the bar diameter which is taken equal to five times the bar diameter [2]. The pull-out specimens are divided into four groups. Each group consists of 9 different specimens with different steel reinforcement diameters and concrete covers. In group A, 6 specimens are duplicates, while in group (B and C), 5 specimens are duplicated, and finally in group D, 3 duplicates are tested. **Table (1)** gives the details of these specimens. The notations used are as follows:

The specimen B19-60-1, the letter B represents a specimen with strength of 45 MPa, bar diameter of (19 mm) and 60 mm cover and the last number represents first or second specimens (replicate).

Table (1) Pull-Out Test Specimens Details

Group	Design Nation	Normal Compressive Strength MPa	Bar Diameter mm	Bonded Length mm	Cover mm
A	A10-60-1	20	10	50	60
	A10-60-2		10	50	60
	A16-60-1		16	80	60
	A16-60-2		16	80	60
	A19-60		19	95	60
	A10-40-1		10	50	40
	A10-40-2		10	50	40
	A16-40		16	80	40
	A19-40-1		19	95	40
	A19-40-2		19	95	40
	A10-20-1		10	50	20
	A10-20-2		10	50	20
	A16-20-1		16	80	20
	A16-20-2		16	80	20
	A19-20		19	95	20
B	B10-60-1	45	10	50	60
	B10-60-2		10	50	60
	B16-60-1		16	80	60
	B16-60-2		16	80	60
	B19-60		19	95	60
	B10-40-1		10	50	40
	B10-40-2		10	50	40
	B16-40		16	80	40
	B19-40		19	95	40
	B10-20		10	50	20
	B16-20-1		16	80	20
	B16-20-2		16	80	20
	B19-20-1		19	95	20
	B19-20-2		19	95	20

Table (1) Continued

Group	Design Nation	Normal Compressive Strength MPa	Bar Diameter mm	Bonded Length mm	Cover mm
C	C10-60-1	60	10	50	60
	C10-60-2		10	50	60
	C16-60-1		16	80	60
	C16-60-2		16	80	60
	C19-60-1		19	95	60
	C19-60-2		19	95	60
	C10-40		10	50	40
	C16-40-1		16	80	40
	C16-40-2		16	80	40
	C19-40		19	95	40
	C10-20		10	50	20
	C16-20-1		16	80	20
	C16-20-2		16	80	20
	C19-20		19	95	20
D	D10-60	75	10	50	60
	D16-60		16	80	60
	D19-60-1		19	95	60
	D19-60-2		19	95	60
	D10-40		10	50	40
	D16-40-1		16	80	40
	D16-40-2		16	80	40
	D19-40		19	95	40
	D10-20		10	50	20
	D16-20		16	80	20
	D19-20		19	95	20

*A10-60
A: Nominal compressive strength
10: Bar diameter in mm, 60: Cover in mm

2-2 Fabrication and Details of Specimens

In this study, prism pull-out specimens are chosen. The prism length is defined as a function of the bar diameter, this length is ($5d_b$), while the width equals (304) mm and the thickness is chosen according to the cover [3]. The specimens are reinforced with a single central reinforcing bar with a bonded length (i.e. embedment length) of five times the bar diameter ($L_b=5d_b$), which is bounded by two unbounded zones (Lu), where ($Lu = (L-L_b)/2$).

2-3 Materials

2-3-1 Cement

Ordinary Portland cement (Type 1) is used in this study. The cement is of Lebanese origin. The chemical and physical properties of this cement comply with the Iraqi standard specification IQS: No.5:- 1984 [4] requirements.

2-3-2 Fine Aggregate

Fine aggregate obtained from Karbala was used. The grading of the fine aggregate is conformed to the requirements of IQS: No.45 [5]:

2-3-3 Coarse Aggregate

The coarse aggregate is crushed river gravel from Alnibaey region with a maximum size of aggregate of 10 mm for nominal compressive strength equal to 75 MPa and 20 mm for nominal compressive strength equal to (20, 45 and 60) MPa. The coarse aggregate is washed. The aggregate is used in saturated surface dry condition. Gradation of coarse aggregate conforms to requirements of IQS: No.45 [5].

2-3-4 Reinforcing Steel

Deformed steel bars of (10, 16, 19) are used, with yield strength of (467,517,532) MPa respectively.

2-3-5 Superplastsizer

The Superplastsizer used in this study is Daracem SP3, which is in the form of liquid. The typical properties of Daracem SP3 are shown in **Table (2)**. The dosage of Daracem SP3 used in this work is 1.0 Ltr. /100 kg of cement for mix B and 1.5 Ltr./100 kg of cement for mixes C and D.

2-3-6 Concrete Mix Proportion

Four concrete mixes are designed according to British mix design method [6], to yield nominal compressive strength of (20, 45, 60, 75) MPa (cubes). The mix proportions of these mixes are as given in **Table (3)**.

Table (2) Properties of Superplastsizer (Daracem SP3)

Form	Viscous liquid
Dry substance	Approx 95%
pH 10% sol	4.5/0.5
Chloride content	Traces
Toxicity	Non-Toxic

Note: 100% water-soluble

Table (3) Mix Proportion for Groups (A to D)

Mix	Water Ltr./m^3	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Superplastsizer Ltr/ 100 kg Cement
0.7:1:2.36:3.7	215	308	727	1139	-
0.45:1:2:3.2	161	358.5	717	1147	1
0.33:1:1.37:2.18	161	488.6	669.4	1065	1.5
0.28:1:1.13:1.74	154	550	715	1000.5	1.5

Note: o.7:1:2.36:3.7: water / cement ratio: cement: fine aggregate: coarse aggregate

2-3-7 Molding, Casting and Curing

Wood moulds were used to cast all the pull-out specimens. After curing the specimens were tested 24 hours after removing them from water. The test results of compressive strength show that the average compressive strength values were (18, 47, 58, 73) MPa for nominal compressive strength values of (20, 45, 60, 75) MPa. The concrete was mixed for about three minutes by a horizontal rotary mixer of 0.19 m^3 capacities. The specimens were then cast into three layers; each of which was compacted by a table vibrator. The pull-out specimens were cast in groups, each group is of six prisms with three cubes (150x150x150) mm to investigate the compressive strength of concrete.

2-3-8 Test Setup and Instrumentation

The pull-out specimens were tested by a specially fabricated testing frame as shown in **Fig.(1)**. The frame consisted of a fixed part made from steel sections, which consisted of two standing parts. The upper heads of the standing parts were fastened to a bearing plate by screws and welding. The bearing plate had a central hole which permits the prisms, reinforcing bar to pass through. The two standing sections together with the bearing plate formed an inverted U shape, which was fastened to the steel base by means of screws and welding. Six (3 Ton) capacity hydraulic jacks were fastened to the steel base by screw. The upper heads of the hydraulic jacks were also fastened by screw to stiffen the moving section, which had a central hole located exactly on the bearing plate hole. The hydraulic jacks were controlled by a hydraulic machine, which enabled the jacks to supply the same loads. With this machine three types of jacks could be used, 1 Ton, 2 Ton and 3 Ton hydraulic jacks. For every type of jacks, there is a loaded gage. The pull-out prisms were held inside the inverted U section. The loaded end (top end) of tested prism is pressed on the inside face of the bearing plate. The reinforcing bar passes through the two holes and is screwed at the upper face of the moving head [7]. The slip is measured at the unloaded end by a dial gage with an accuracy of 2.5 cm.

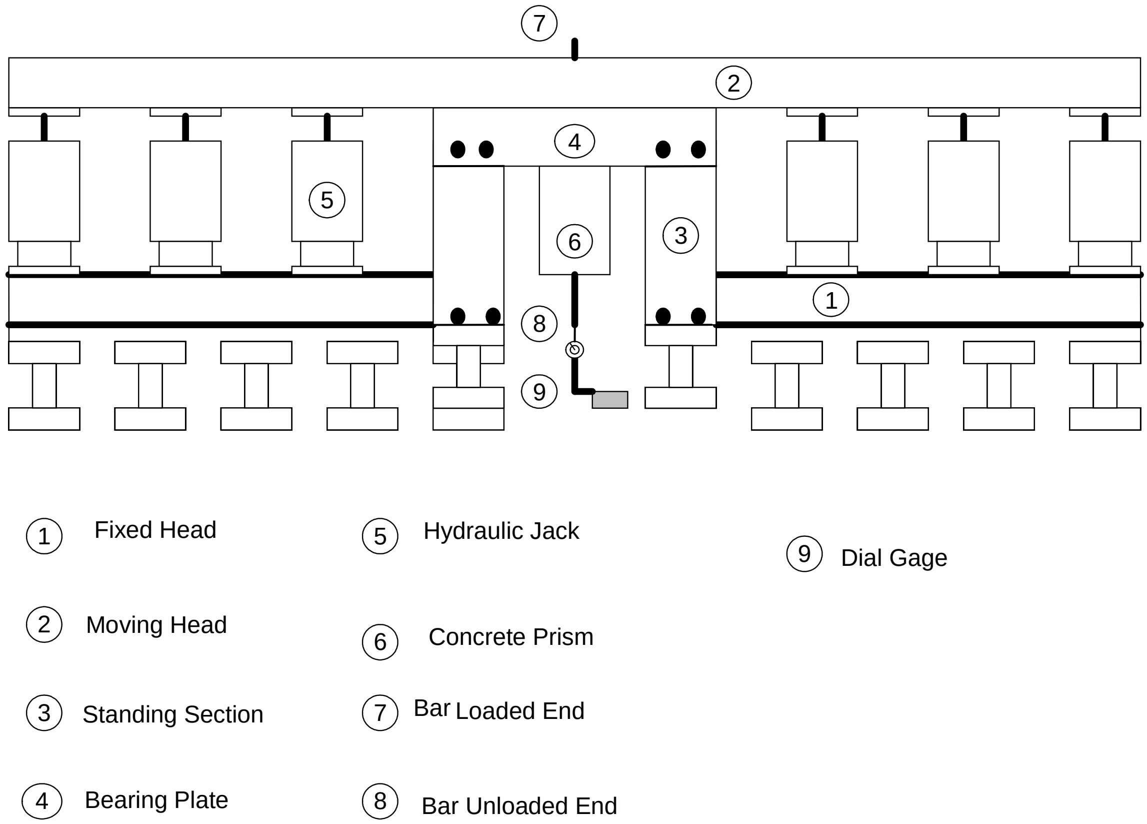

Figure (1) Testing Frame Details

3. Results and Discussion

3-1 Failure Modes

In the pull-out specimens presented in this study, one of the following four failure mechanisms takes place:

1. Splitting of the concrete prism. The load at which the prism splits is considered as the maximum or the ultimate load.

2. The bar being pulled out from the surrounding concrete media without causing any splitting cracks.

3. Yielding of the steel bar followed by pullout of the bar or splitting of the concrete prism.

4. Fracture of steel bar due to excessive stress in bar which exceeds the pullout tensile stress of steel with splitting or pullout.

Tables (4) to **(7)** indicate the type of failure which takes place in each group of specimens. It is noticed that the splitting failure is the predominant type of failure observed in this study, and all 54 specimens failed by splitting failure, except eleven specimens. Of these eleven specimens, four specimens failed by pullout of the steel bar from the concrete prism. Two of these specimens are with bar diameter of 10 mm, f_{cu}=20 MPa and cover = 60 mm, while the other two specimens are also with bar diameter of 10mm, f_{cu}=45 MPa and cover=60 mm (pullout failure is a character of small bar diameter, normal strength concrete and large or sufficient cover). Other three specimens fail by fracture of the steel bar, and these specimens are with bar diameter of 10 mm, compressive strength of 60 or 75 MPa and concrete cover=60 mm (small bar diameter, high strength concrete and large or sufficient cover). The remaining four specimens fail by yield of the steel bar (without fracture), three of which are with bar diameter of 16 mm, f_{cu}=60 or 75 MPa and concrete cover =60 mm and the fourth specimen is with bar diameter 10 mm, compressive strength =75 MPa, cover = 40 mm (in these specimens, the steel bar stress exceeds the yielding strength of the steel bar, but does not reach the ultimate strength of the steel). Thus, these specimens show splitting failure of concrete after the yield of the steel bar.

Table (4) Test Results of Pullout Specimens of Group A

Specimen Identification	Actual f_{cu} MPa	Maximum Slip (mm)	Failure Force kN	Ultimate Bond Strength MPa	Failure Mode	$\frac{C}{d_b}$
A10-20-1	18.5	1.21	15	10.18*	Splitting	2
A10-20-2	18.5	2	17		Splitting	2
A16-20-1	18.5	1.00	22	5.97*	Splitting	1.25
A16-20-2	18.5	1.43	26		Splitting	1.25
A19-20	18.5	5.9	28	4.93	Splitting	1.05
A10-40-1	17	2.52	16	12.73*	Splitting	4
A10-40-2	17	3.2	24		Splitting	4
A16-40	17	2.22	32	7.95	Splitting	2.5
A19-40-1	17	8.34	36	7.05*	Splitting	2.1
.A19-40-2	17	9.66	44		Splitting	2.1
A10-60-1	19	2.3	24	17.83*	Pullout	6
A10-60-2	19	3.4	32		Pullout	6
A16-60-1	19	2.5	40	10.94*	Splitting	3.75
A16-60-2	19	3	48		Splitting	3.75
A19-60	19	18.75	56	9.87	Splitting	3.16

* Average of two specimens

Table (5) Test Results of Pullout Specimens of Group B

Specimen Identification	Actual f_{cu} MPa	Maximum Slip (mm)	Failure Force kN	Ultimate Bond Strength MPa	Failure Mode	$\frac{C}{d_b}$
B10-20	45	1.389	20	12.73	Splitting	2
B16-20-1	45	1.6	36	9.94*	Splitting	1.25
B16-20-2	45	1.85	44		Splitting	1.25
B19-20-1	45	9.76	40	7.76*	Splitting	1.05
B19-20-2	45	12	48		Splitting	1.05
B10-40-1	48	1.7	28	15.28*	Splitting	4
B10-40-2	48	2.1	20		Splitting	4
B16-40	48	2.23	52	12.93	Splitting	2.5
B19-40	48	15.56	68	12	Splitting	2.1
B10-60-1	48	1.4	30	20.37*	Pullout	6
B10-60-2	48	0.94	34		Pullout	6
B16-60-1	48	3.4	90	23.87*	Splitting	3.75
B16-60-2	48	4.34	102		Splitting	3.75
B19-60	48	7.76	112	19.75	Splitting	3.16

*Average of two specimens

Table (6) Test Results of Pullout Specimens of Group C

Specimen Identification	Actual f_{cu} MPa	Maximum Slip (mm)	Failure Force kN	Ultimate Bond Strength MPa	Failure Mode	$\frac{C}{d_b}$
C10-20	58	2.92	24	15.28	Splitting	2
C16-20-1	58	2.1	40	11.93*	Splitting	1.25
C16-20-2	58	3.24	56		Splitting	1.25
C19-20	58	3.26	52	9.17	Splitting	1.05
C10-40	58	1.76	32	20.37	Splitting	4
C16-40-1	57	2	52	14.92*	Splitting	2.5
C16-40-2	57	3.1	68		Splitting	2.5
C19-40	57	3	72	12.697	Splitting	2.1
C10-60-1	54	3.5	40	28.04*	Break	6
C10-60-2	54	4.9	48		Break	6
C16-60-1	54	4.6	96	25.86*	Yielding	3.75
C16-60-2	54	3.71	112		Yielding	3.75
C19-60-1	54	5.9	112	20.45*	Splitting	3.16
C19-60-2	54	10.5	120		Splitting	3.16

*Average of two specimens

Table (7) Test Results of Pullout Specimens of Group D

Specimen Identification	Actual f_{cu} MPa	Maximum Slip (mm)	Failure Force kN	Ultimate Bond Strength MPa	Failure Mode	$\frac{C}{d_b}$
D10-20	73	1.3	32	20.37	Splitting	2
D16-20	73	2.01	52	12.93	Splitting	1.25
D19-20	73	3.84	64	11.28	Splitting	1.05
D10-40	70	1.58	40	25.46	Yielding	4
D16-40-1	70	4.25	68	17.9	Splitting	2.5
D16-40-2	70	3.01	76		Splitting	2.5
D19-40	70	3.05	84	14.813	Splitting	2.1
D10-60	70	1.48	44	28.04	Break	6
D16-60	70	5.02	112	27.85	Yielding	3.75
D19-60-1	70	8.23	124	23.27*	Splitting	3.16
D19-60-2	70	11.27	140		Splitting	3.16

* Average of two specimens

3-2 Mathematical Regression for Bond Strength-Slip Relation

The non-linear regression analysis technique is used to create a useful equation that could predict the bond strength as a function of bar diameter, compressive strength, cover and also to the relative slip between the steel reinforcement and concrete. The type of regression used is in the form:

$$Y = a_0 * X_1^{a_1} * X_2^{a_2} * X_3^{a_3} * \ldots\ldots\ldots * X_n^{a_n} \quad \textbf{\ldots\ldots\ldots (1)}$$

where:

Y: is the independent variable

$x_1, x_2, \ldots\ldots\ldots x_n$: dependent variables

$a_1, a_2, \ldots\ldots\ldots a_n$: regression constant

An empirical relationship is obtained which relates the bond strength with the bar diameter, concrete compressive strength, concrete cover to reinforcement and to the relationship between the steel bar and the surrounding concrete. Thus, the amount of developing bond stress of any stage of loading can be predicted according to the value of slip taking place. This relationship is given below. **Figure (2)** shows a comparison between experimental and predicted bond stress. From this figure, it becomes clear that most of the data is within $\pm$ 20% deviation from the line of equality.

$$U = 0.628\Phi^{-1} f_{cu}^{\frac{4}{5}}\ C^{\frac{3}{5}}\ S^{\frac{1}{3}} \qquad (R=0.922) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. \ \textbf{(2)}$$

where:

U: Bond strength (MPa).

Φ: Bar diameter (mm)

C: Concrete cover to reinforcement (mm)

f_{cu}: Concrete compressive strength (MPa) of (150 x 150 x 150) mm cubes

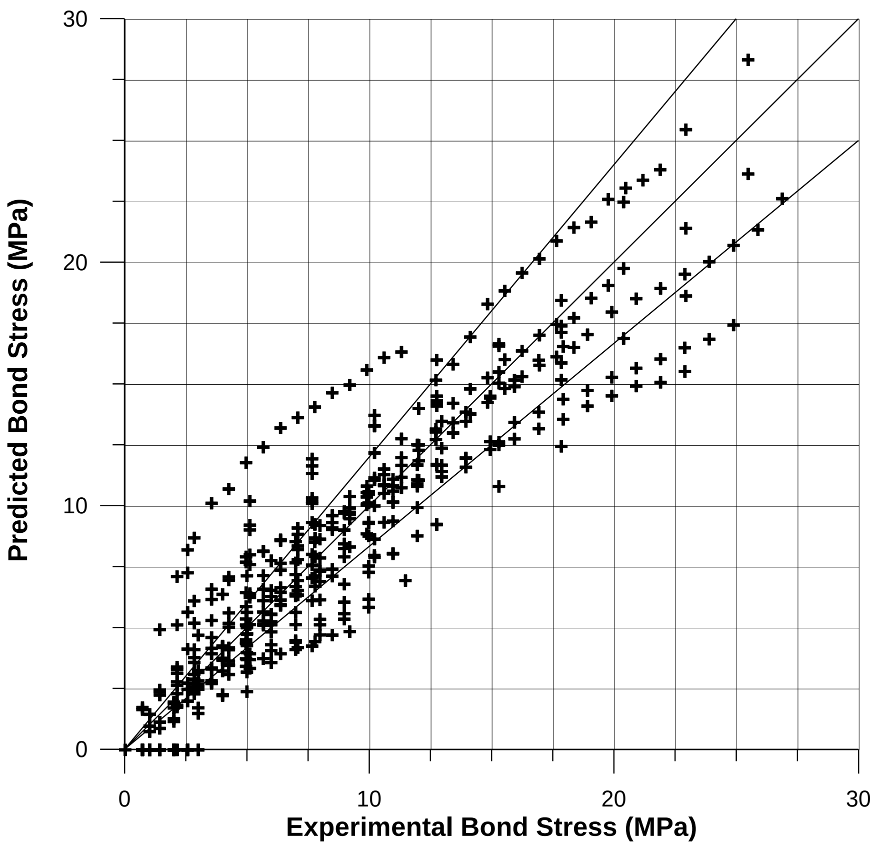

Figure (2) Comparison between Experimental and Predicted Bond Stress

3-3 Ultimate Bond Strength

Another empirical equation is proposed to find the relationship between the ultimate bond stress and the variables (bar diameter, cover and compressive strength), as follows. **Figure (3)** shows a comparison between experimental and predicted values for the ultimate bond stress.

$$U = 0.644\,\Phi^{-0.375} f_{cu}^{0.5} C^{0.6} \qquad (R=0.927) \text{ .... } \mathbf{(3)}$$

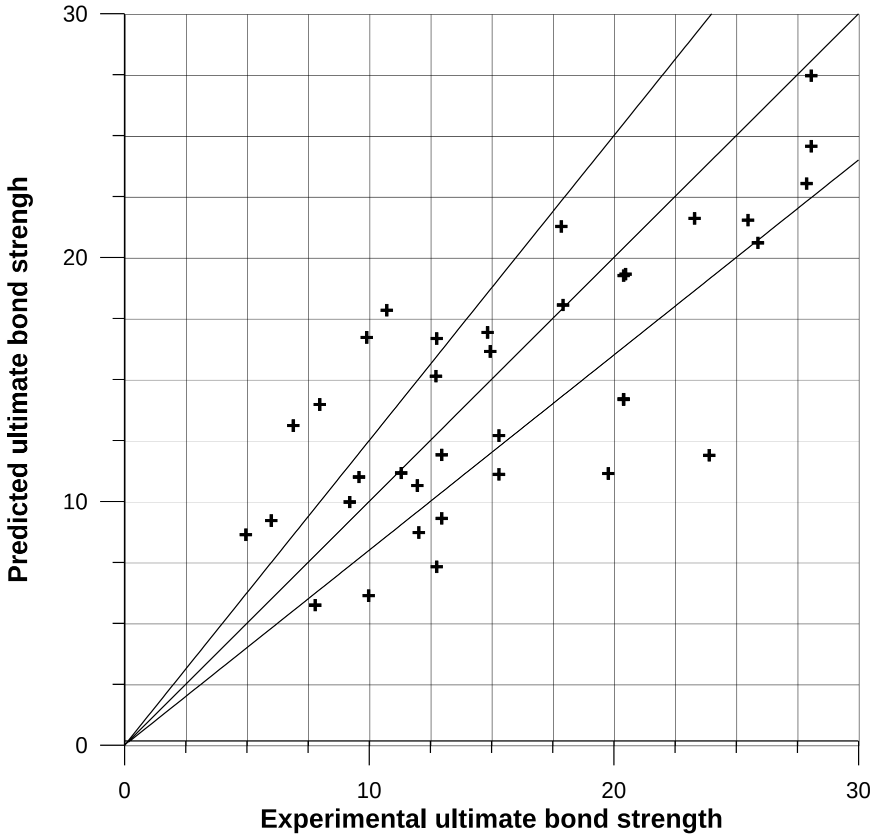

Figure (3) Comparison between Experimental and Predicted Ultimate Bond Stress

3-4 Effects of the Investigated Parameters on Bond Strength

As mentioned earlier, the studied parameters in this study are the concrete compressive strength, steel reinforcement, and the cover to steel reinforcement on the bond strength. In this section, the test results, which reveal the effect of these parameters on the bond strength, are discussed

3-5 Effect of Bar Diameter on Bond Stress Slip Relationship

Figures (4) to **(7)** clearly show the effect of bar diameter on bond stress-slip relationship for compressive strength varying between (20-75 MPa) and cover (20, 40, and 60) mm. From these figures it is obvious that the bond strength for bar diameter 10 mm is grater than that for bar diameter (16 and 19) mm for the same compressive strength and for the same cover, also the values of slip for bar diameter 10 mm are smaller than that for bar diameter (16 and 19) mm for the same bond strength and for the same (cover and compressive strength).

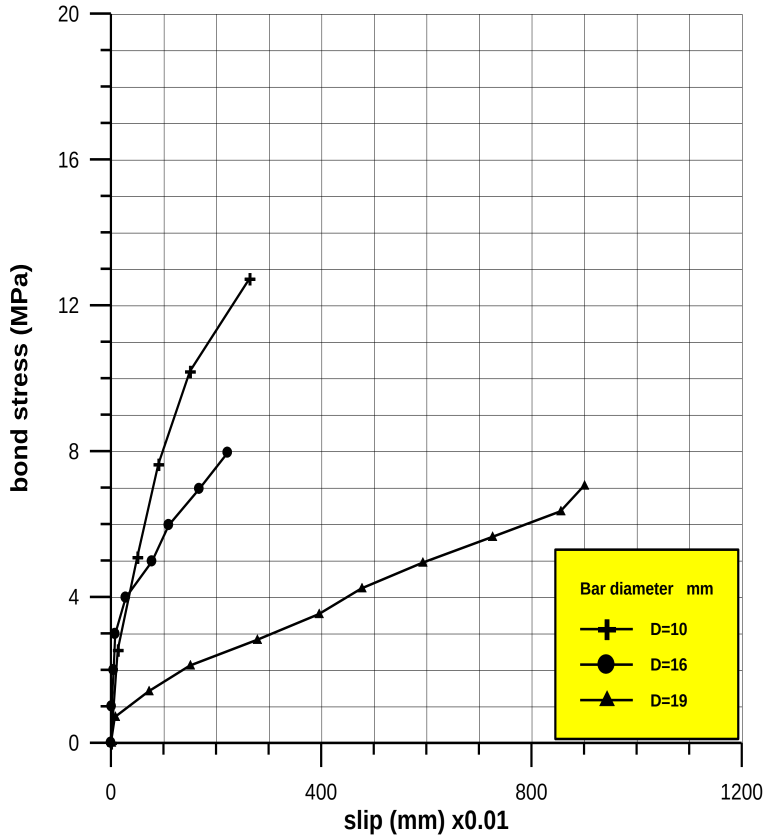

Figure (4) Effect of Bar Diameter on Bond Stress Slip Relationship for Compressive Strength =20MPa, Cover =40 mm (Experimental Results)

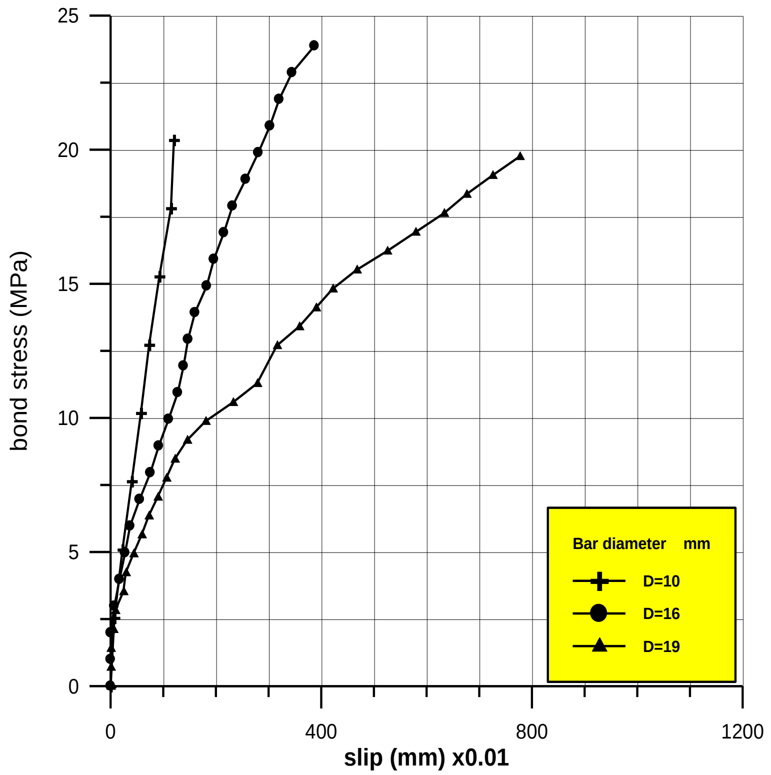

Figure (5) Effect of Bar Diameter on Bond Stress Slip Relationship for Compressive Strength=45MPa, Cover=60mm (Experimental Results)

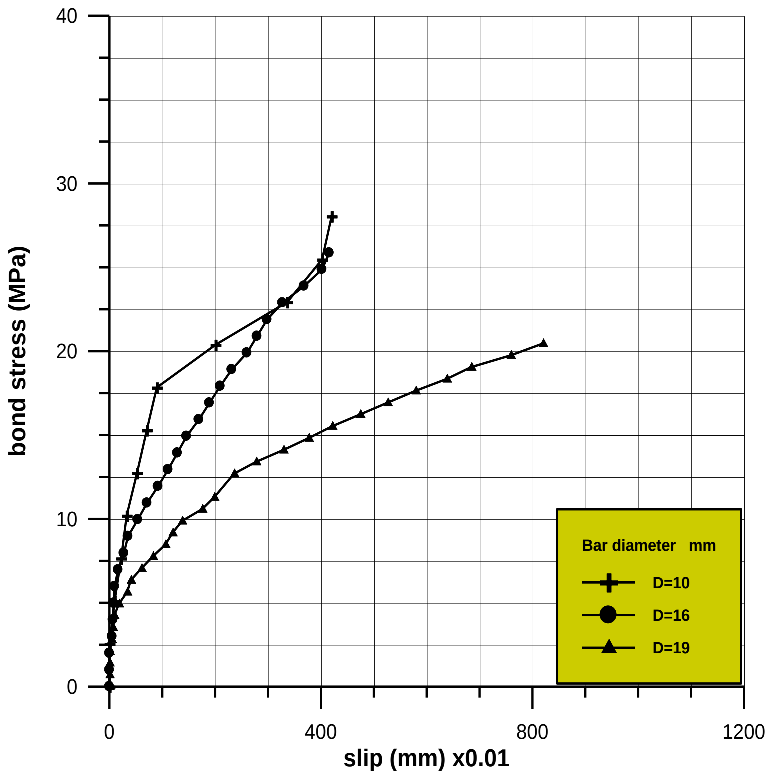

Figure (6) Effect of Bar Diameter on Bond Stress Slip Relationship for Compressive Strength=60MPa, Cover=60mm (Experimental Results)

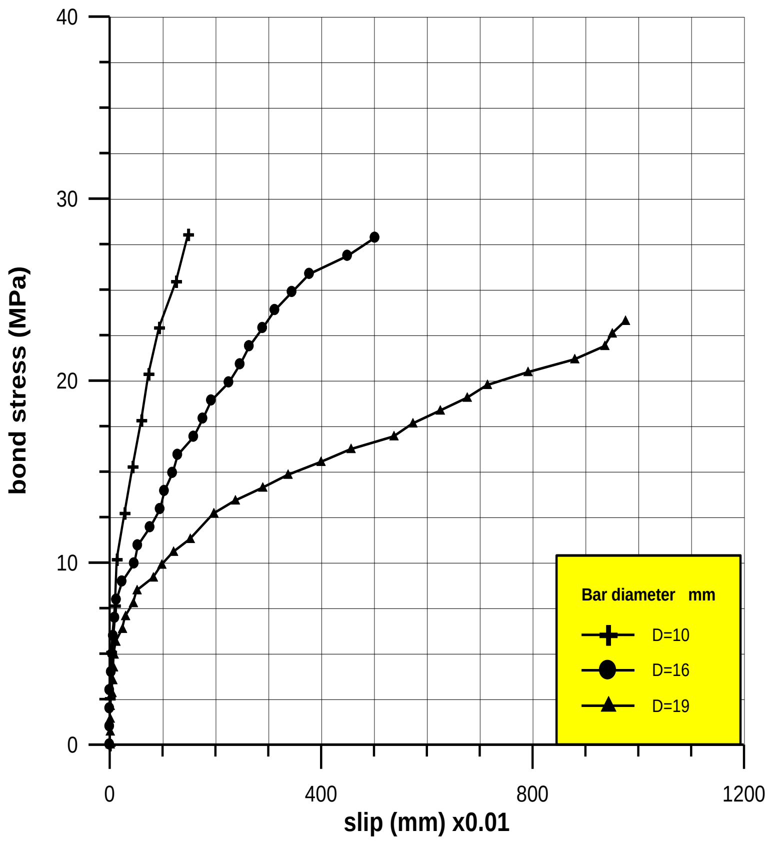

Figure (7) Effect of Bar Diameter on Bond Stress Slip Relationship for Compressive Strength=75MPa, Cover=60mm (Experimental Results)

3-6 Effect of Concrete Compressive Strength on Bond Strength

From the results of the tested specimens, it is clear that the increase in concrete compressive strength results in an increase in the bond strength. The important matter here is to consider the type of failure taking place in the concrete specimen and whether the combined effects of the values of the concrete compressive strength and concrete cover to reinforcement are sufficient to mobilize high bond strength, before an immature failure (pullout or splitting) takes place. From **Table (8)**, it can be seen that for a given cover, increasing the concrete compressive strength will change the mode of failure of the specimen. For example, in specimens with 10 mm bars and concrete cover of 60 mm, increasing the concrete strength from 20 MPa to 75 MPa changes the type of failure from pullout of the steel bar to the fracture of the steel bar. Therefore, in order to eliminate splitting failure of concrete, either the concrete strength or concrete cover must be increased. In addition, the failure of normal strength concrete specimens (f_{cu}=20, 45 MPa) is gradual, while that of the high strength concrete specimens is sudden and the specimens explode upon failure, especially in specimens with cover of 40 mm &60 mm.

Table (8) The Ultimate Bond Strength for Tested Specimens in N/mm²

Specimens	Group A	Group B	Group C	Group D
10-20	10.28 S	12.73 S	15.28 S	20.37 S
16-20	5.97 S	9.94 S	11.93 S	12.93 S
19-20	4.93 S	7.76 S	9.17 S	11.28 S
10-40	12.73 S	15.28 S	20.37 S	25.46 Y
16-40	7.95 S	12.93 S	14.92 S	17.9 S
19-40	7.05 S	12.00 S	12.70 S	14.80 S
10-60	17.83 P	20.37 P	28.04 B	28.04 B
16-60	10.94 S	23.87 S	25.86 Y	27.85 Y
19-60	9.87 S	19.75 S	20.45 S	23.27 S

10-20: bar diameter=10mm cover=20 mm
S= splitting failure, P=pullout failure, B= fracture failure, Y: yield failure

3-7 Effect of Cover to Bar Diameter Ratio on Ultimate Bond Strength

In order to verify the thickness of the concrete cover required for any concrete section, a new variable is used. This variable is the concrete cover to bar diameter ratio (C/d_b). The relationship between C/d_b and the ultimate bond strength is plotted in **Fig (8A-8D)** for different concrete compressive strengths of 20, 45, 60 and 75 MPa. All the relationships obtained are linear.

From **Fig.(8A)**, it can be seen that for f_{cu}=20 MPa, increasing the C/d_b ratio from 1 to 6 increases the ultimate bond strength from 4.93 MPa to 17.82 MPa. Increasing the concrete strength results in an increase of ultimate bond strength for the same C/d_b ratio. From **Fig.(8B)**, it can be seen that increasing C/d_b from 1 to 6, increases the ultimate bond strength from (7.76-23.87 MPa) for f_{cu}=45 MPa and corresponding values for (f_{cu}= 60 and 75 MPa) are (9.17-28.04 MPa) and (11.38-28.04 MPa) respectively.

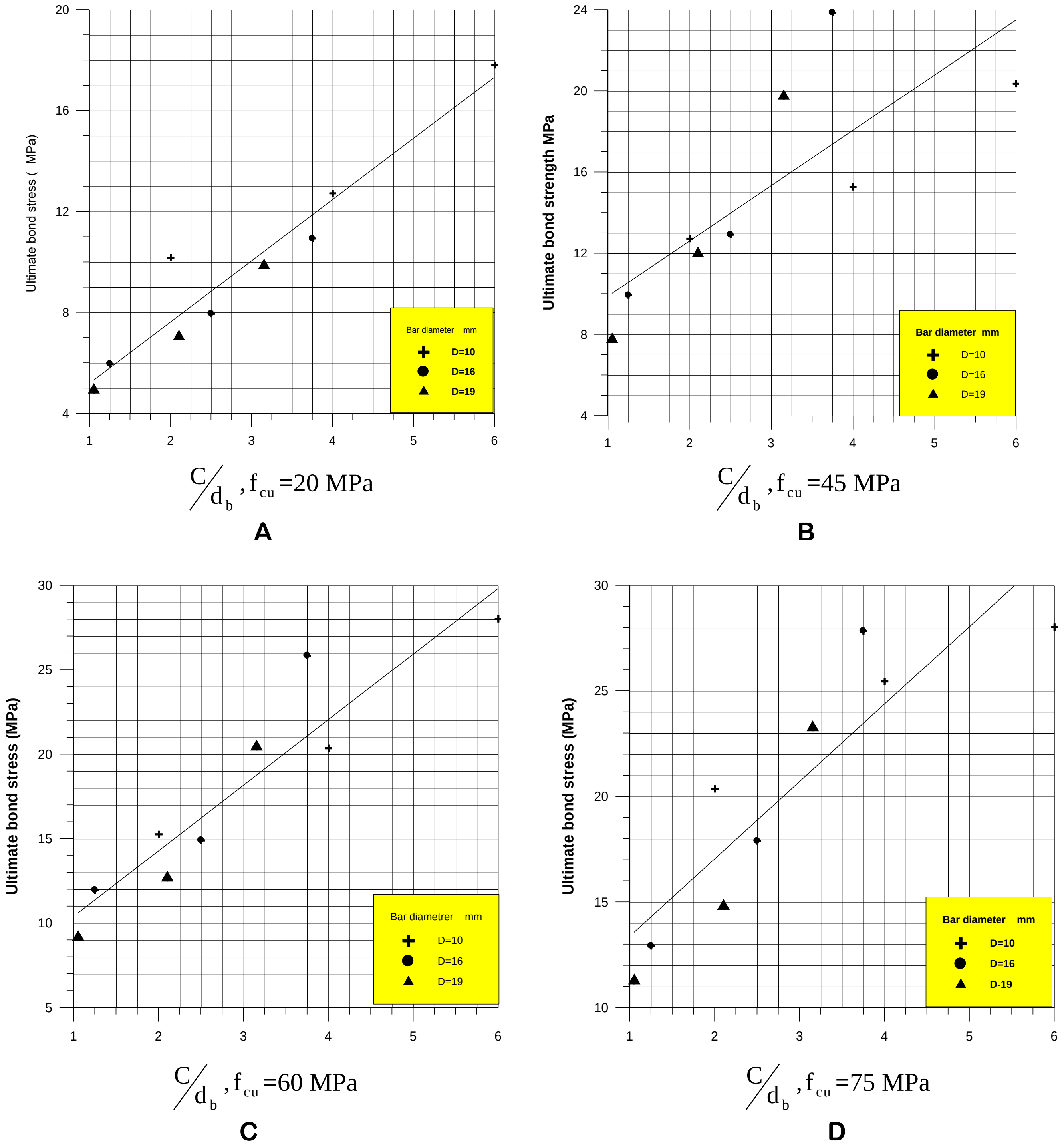

Figure (8) Effect of (Cover/Bar Diameter) on Ultimate Bond Stress for Different Compressive Strength and Different Bar Diameter

As a result, an increase in concrete compressive strength will make it possible to decrease the concrete cover or the increases in the bar diameter will be required to increase the concrete cover. This is shown clearly in **Fig.(9)** which illustrates the relationship between bond strength and the rate (C/d_b) for compressive strength varying from (20 to 75) MPa. For example, to get bond strength equal to 15MPa (bonded length equal to $5\,d_b$, the rate of C/d_b needed is (5.0625, 2.75, 2.25, 1.49) for compressive strength (20, 45, 60 and 75) MPa respectively.

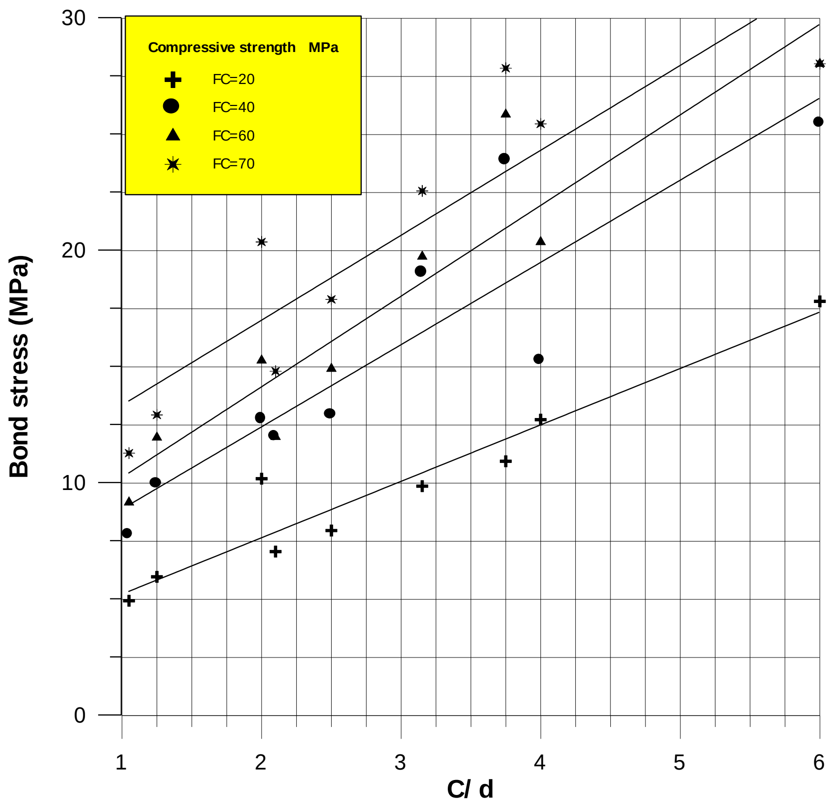

Figure (9) Effect of Compressive Strength on the Ultimate Bond Strength

4. Conclusions

Depending on the test results of this study, the following conclusions are obtained:

1. Bond strength increases with decreasing bar diameter. The bond strength for bar diameter 10 mm is greater than that for bar diameters of (16, 19) mm.

2. Bond strength increases with the increase of compressive strength for the same bar diameter and for the same cover. The bond strength increases at rates of (53%, 73%, 87%) when compressive strength increases from 20 MPa to (45, 60, 75) MPa respectively.

3. With the increase in compressive strength, the need for cover reduces

4. Regression analysis of 54 pullout tests results in a nonlinear equation, which represents the relationship between the bond strength and the variables (bar diameter, cover, and compressive strength) and slip. The equation has a coefficient of correlation (R) of 0.923. Another equation is suggested between the ultimate bond strength and the variables (bar diameter, cover, and compressive strength). The correlation coefficient (R) for this equation is 0.927. Predicted values for both regressions are compared with experimental results which are found to give good correlation between bond strength and the variables investigated

5. A multi-linear curve is suggested to represent the relationship between the bond strength and the ratio (C/d_b). This suggested curve shows that by increasing the rate (C/d_b), bond strength increases.

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